

Spatial Variability in Rainfall Erosivity and Sediment Yield within a Semiarid Woodland

Brian K. Hastings, David D. Breshears, and Freeman M. Smith

ABSTRACT

Accelerated erosion is of concern in many semiarid ecosystems, where precipitation—a driving force in erosion—can be intense and spatially variable. Although previous studies have quantified how rainfall depth can vary within small semiarid watersheds, the spatial variability in rainfall erosivity—a more direct determinant of sediment yield—has not been quantified. We measured the spatial variability of rainfall erosivity using 12 tipping-bucket rain gauges within a 40-ha area of a piñon-juniper woodland in north central New Mexico. Our study period encompassed 14 rainfall-runoff events derived from convective summer thunderstorms occurring over a 2-year period (2000-2001). Each rain gauge was instrumented with 1-minute resolution electronic data loggers to determine rainfall erosivity. The spatial variability in rainfall erosivity had a median coefficient of variation across all storms of 22% (range: 9-73%), which exceeded the coefficient of variation for rainfall depth, which was 15% (range: 5-26%). The most spatially variable storm, relative to rainfall erosivity, had a rainfall erosivity gradient that varied by a factor of five (5 to 25 N hr⁻¹) in less than a 300-meter distance and was the second largest of the 14 storms. We confirmed that these spatial differences in rainfall erosivity impacted site sediment yield using data from 4 of the 12 rain gauges for which we also measured sediment yield via water erosion in small (<0.1 ha), replicated microwatersheds. Sediment yield was positively correlated with rainfall erosivity ($r^2 = 0.67$; $p < 0.001$), indicating the importance of spatial variability in rainfall erosivity as a determinant of sediment yield. Our results highlight the importance of accounting for spatial variability in rainfall erosivity—which can be even greater than spatial variability in rainfall depth—when predicting soil loss or sediment yield.

INTRODUCTION

Watershed managers are increasingly interested in using empirical soil loss

models, such as the Revised Universal Soil Loss Equation (RUSLE), to predict soil loss from upland areas (Davenport et al., 1998; Sydoriak, et al., 2000), survey erosion from burned watersheds (BAER, 2001), or to test the effectiveness of treatment applications that can reduce sediment yield (Hastings et al. unpublished manuscript). Soil loss/sediment yield can be spatially variable, dependent on several factors. A key factor that can drive spatial variability in soil loss/sediment yield is spatial variation in precipitation characteristics. Previous studies have quantified how rainfall depth can vary spatially within semiarid watersheds of the American Southwest (Goodrich et al., 1995, Bowen, 1996).

Semiarid areas, dominated by convective thunderstorms and orographic effects, can exhibit considerable temporal variability in storm, season, and annual rainfall characteristics, all of which can vary spatially. Spatial variation in mean rainfall depth has been shown to vary by as much as 4-14% within a 100 m distance (Goodrich et al., 1995). Several researchers have noted that measurements from a single rain gauge can lead to large uncertainties in rainfall depth for any region, and that such variation in rainfall depth has important implications for modeling runoff (Schilling and Fuchs, 1986; Krejci and Schilling, 1989; Bonacci, 1989; Faures et al., 1995).

A more direct characteristic of precipitation in determining sediment yield is rainfall erosivity—the ability of rain to erode soil. Rainfall erosivity has been shown to be a better predictor of sediment yield than rainfall depth (Wischmeier and Smith, 1958; Foster et al., 1982) and is commonly used in modeling soil loss/sediment yield. Improving estimates of

rainfall erosivity is important because it is directly proportional to changes in soil loss in models such as RUSLE when all other considered variables are held constant. The recommended approach for estimating rainfall erosivity uses the interaction between the highest 30-minute rainfall intensity (mm hr^{-1}) and the storm energy (MJ ha^{-1}) to compute rainfall erosivity (N hr^{-1}) or EI_{30} , where storm energy is determined empirically using the method of Brown and Foster (1987 *in* Renard et al. 1997).

In the southwestern USA, spatial variability in rainfall erosivity is particularly important during the summer monsoon, when erosivity is greatest. For instance, Renard and Simanton, (1975) quantified that 85-93% of the annual rainfall erosivity occurred during the summer monsoon period in Arizona and New Mexico. However, lacking are studies that quantify the spatial variability of rainfall erosivity.

The objective of this study was to document the spatial variability in rainfall erosivity within small semiarid watershed and associated variation in rainfall depth and sediment yield. Our results, which indicate higher spatial variability in rainfall erosivity than in rainfall depth, have important implications for modeling soil loss/sediment yield.

STUDY AREA

The study area is located in the piñon-juniper woodlands of Bandelier National Monument, New Mexico ($36^{\circ} 46' 25'' \text{ N}$, $106^{\circ} 16' 21'' \text{ W}$) between 1948-1986 meters above mean sea level. Bandelier National Monument is located on the Pajarito Plateau, a volcanic landform sloping southeasterly from the Jemez Mountains. The plateau receives annual average precipitation between 350-400 mm, increasing with elevation (Bowen, 1996). 40-60% of the annual precipitation is recorded during the monsoon months of July, August, and September, and is a period characterized by short duration, high intensity thunderstorms. This study area is the site of an ecotone shift

during the 1950s (Allen and Breshears, 1998) and is further described in Jacobs and Gatewood (1999), Jacobs et al. (2000), and Hastings (2002).

METHODS

Rainfall was characterized using 12 tipping-bucket rain gauges (20.3 cm diameter) that were randomly located in a 40 ha watershed. The difference in elevation between the lowest and highest rain gauge was only 20 m. We obtained high temporal resolution data from each rain gauge, using electronic data loggers to record precipitation depth, time, and intensity with one-minute resolution. Data were analyzed to estimate the highest 30-minute storm intensities and to calculate storm energy. Storm energy was calculated after Brown and Foster (1987 *in* Renard et al. 1997), multiplied by the highest 30-minute intensity, and converted to Newtons per hour (N hr^{-1}) using a factor of 1.702 (Renard et al. 1997). The product of each storm's energy and highest 30-minute intensity represents each storm's rainfall erosivity (EI_{30}). We calculated the summary statistics across gauges ($n=12$) and the coefficients of variation within storms ($n = 14$) for rainfall depth and rainfall erosivity.

To verify the relationship between rainfall erosivity and sediment yield, we measured sediment yield at the outlets of 4 microwatersheds associated with 4 adjacent rain gauges. These 4 microwatersheds were selected because of their similar characteristics related to contributing area, soils, topography, and vegetation (Table 1). Sediment yield was measured by collecting sediment from check dams at the outlets of each microwatershed. The soil was then air-dried and weighed to the nearest 0.1 kg. Microwatershed contributing areas were surveyed using a total station survey unit

Table 1. Microwatershed characteristics for 4 microwatersheds selected to measure sediment yield and rainfall erosivity relationships

Microwatershed	Area	Canopy Cover	Ground Cover†	Slope	Aspect	Soil Taxonomy
	m ²	%	%	%		
1	860	55	14/8	13	west	Inceptisol
2	550	33	6/5	13	west	Inceptisol
3	320	49	8/4	14	west	Alfisol
4	710	57	11/11	16	west	Alfisol

† average pre and post growing seasons (June 2000-2001 / September 2000-2001)

and prism. Sediment yield (kg ha^{-1}), for each microwatershed, was calculated for each storm by dividing the total dry mass of sediment (kg) by the microwatershed area (ha). Additional methodological details are described in Hastings (2002); additional related analyses of an expanded portion of this data set are reported in Hastings et al. (unpublished manuscript).

RESULTS

We recorded 14 rainfall-runoff events (>1 mm) that varied in several characteristics over the course of the study. Mean storm duration was 54 minutes (range = 16 – 111 minutes), with peak rainfall intensities commonly only 1-2 minutes in duration. The maximum peak 1-minute intensity, recorded from any one rain gauge and across all storms, was 168 mm hr^{-1} .

We measured the spatial variation of rainfall depth and erosivity across 12 rain gauges ($n=12$) (Figure 1a) and the coefficient of variation of both rainfall characteristics across each storm ($n=14$) (Figure 1b). The coefficient of variation over all storms for rainfall depth ranged from 5-26%, with a median of 15%. The coefficient of variation over all storms for rainfall erosivity was much more variable than that for the coefficient of variation for rainfall depth, ranging from 9-73%, and also having a greater median of 22%.

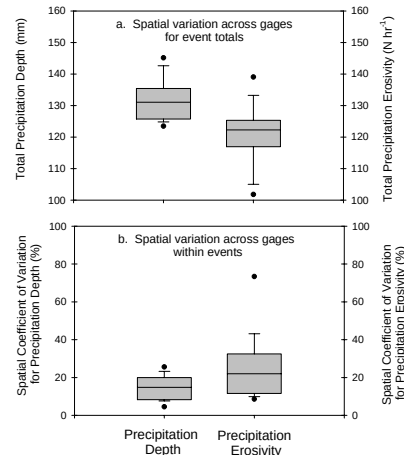


Figure 1. Precipitation depth and erosivity distributions across 12 rain gauges for 14 convective thunderstorms ($n=12$) between June–September, 2000 and 2001(a); Coefficient of variation for precipitation depth and rainfall erosivity across 14 storms ($n=14$)(b). The horizontal line represents the median. Boxes represent 25th and 75th percentiles and the vertical lines extend from the 10th and 90th percentiles. Closed circles represent observations outside the 10th and 90th percentile ranges.

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The most spatially variable storm, relative to rainfall erosivity (August 9, 2000) had a rainfall erosivity gradient that varied by a factor of five (5 to 25 N hr^{-1}) in less than a 300-meter distance (Figure 2). This storm was the second largest magnitude storm (EI_{30}) of the 14 total storms recorded.

To confirm that spatial differences in rainfall erosivity impacted site sediment yield, we measured sediment yield in 4 small (<0.1 ha), replicated microwatersheds associated with 4 of the 12 rain gauges. Median total sediment yield from all 14 storms for the 4 microwatersheds was $6,380 \text{ kg ha}^{-1}$. The coefficient of variation for sediment yield ranged from 23-151%, with a median of 32% ($n=14$). Spatial variation was high. For example, one microwatershed

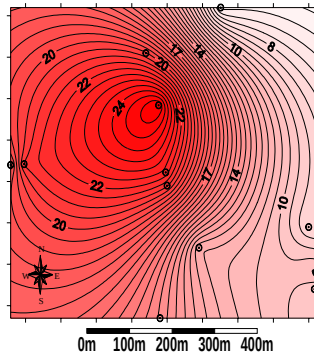


Figure 2. August 9, 2000 rainfall erosivity gradient map for 12 rain gauges. Rain gauges are indicated by the open circles and rainfall erosivity units are N hr^{-1} .

exhibited 2.6 times more sediment yield than an adjacent microwatershed, separated by only 200 m. However, we found that sediment yield was positively correlated with rainfall erosivity ($\log y = 0.17 [\log x]^{2.8}$; $r^2 = 0.67$; $p < 0.001$), indicating the importance of spatial variability in rainfall erosivity as a determinant of soil loss/sediment yield (Figure 3).

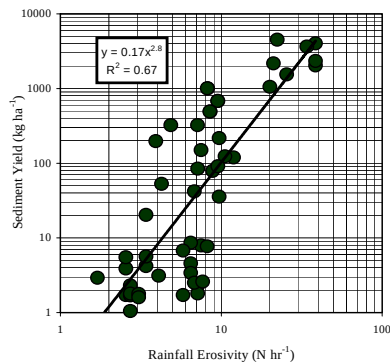


Figure 3. Relationship of rainfall erosivity vs. sediment yield (log/log) for 4 selected microwatersheds and associated rain gauges over 14 convective thunderstorms or rainfall-runoff events.

DISCUSSION

Improved estimates of sediment yield are a priority for large portions of the extensive piñon-juniper woodlands in the western USA. Large portions of these areas are eroding as a result of past land management (e.g., over grazing), drought, and fire (Allen and Breshears, 1998; Davenport et al., 1998; Wilson et al., 2001). Furthermore, as climate change progresses, more extreme precipitation events are expected (IPCC, 2001), leading to increased erosivity (Nearing, 2001). Effective management of these lands is needed to address diverse issues ranging from grazing to carbon management (Davenport et al. 1998; Breshears and Allen, 2002). Higher spatial resolution estimates of sediment yield and/or improved estimates of spatial variability will be needed to address some aspects of these issues.

The short duration of the peak intensities that we observed underscore the importance of obtaining high temporal resolution precipitation data. We obtained 1-minute resolution data, as opposed to 15 minute resolution data that are commonly collected. Our 1-minute resolution rainfall data increases our ability to capture the temporal variability and detail of rainfall intensity, and hence, EI_{30} . The short 1-2 minute duration peaks of rainfall intensity recorded at such high resolution are the impetus for significant runoff and potential sediment yield. For the intense convective storms, such as those we studied, 15 minute resolution data may be insufficient to detect critical periods of high erosivity that drive sediment yield, especially since monsoon generated convective storms can be as short as 15 minutes in duration.

The high degree of spatial variability in rainfall erosivity that we have documented is also important in assessing sediment yield and associated runoff. Faures et al. (1995) determined that the spatial variability of precipitation depth could translate into large variations in

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modeled runoff in a semiarid area of less than 5 hectares. They were able to reduce the coefficient of variation of predicted runoff by $>10\pm\%$ by increasing the number of rain gauges from 1 to 8 within a 4.4 ha watershed. However, watershed managers need to allow for some variation and decide what maximum coefficient of variation is acceptable if data collection, time, and budget are limited. Similarly, Osborn et al. (1972) recommended that one centrally located rain gauge would be sufficient for watersheds up to about 50 ha in southeastern Arizona. However, we show extreme gradients in rainfall erosivity over short distances in watersheds smaller than 50 ha for north central New Mexico. Dunne and Leopold (1978) further report that sparse rain gauge networks in semiarid areas tend to underestimate rainfall characteristics required for planning, conservation practices, and engineered structures

In summary, in this study we measured substantial variability in rainfall erosivity (EI_{30}) and sediment yield within a 40 ha area from 14 rainfall-runoff events. The spatial variation in rainfall erosivity, largely unstudied to date, was greater than the observed spatial variation in rainfall depth. Further, we verified that the spatial variation in soil erosivity is directly correlated with sediment yield, as assumed in models such as RUSLE. Our study is a cautionary note regarding the use of a limited number of rain gauges and the importance of high-resolution precipitation data for predicting sediment yield in a semiarid system. Convective thunderstorms in the southwestern USA are commonly less than 30 minutes in duration. Peak intensities were found to be 2 minutes or less in duration. The assumption of uniform rainfall characteristics from a single rain gauge can lead to large errors in sediment yield predictions. Recording rain gauges, even recording at 15-minute intervals, are likely to underestimate rainfall intensity, and therefore, are underestimating rainfall erosivity. Our findings of the spatial variability of rainfall erosivity (EI_{30}) have important implications for predicting spatial

variation in sediment yield and how this loss responds to changes in climate and land management.

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