Spatial Variability in Rainfall Erosivity versus Rainfall Depth: Implications for Sediment Yield

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ABSTRACT

Rainfall depth within small semiarid watersheds can have high spatial variability, but spatial variability in rainfall erosivity, a more direct determinant of sediment yield, has not been quantified. Using 12 tipping-bucket rain gauges within a 40-ha piñon [*Pinus edulis* Engelm)–juniper (*Juniperus monosperma* (Engelm.) Sarg.] woodland in New Mexico, we measured rainfall erosivity (EI_{30}) and associated precipitation and erosion metrics for 14 convective thunderstorms. Spatial variability in EI_{30} had a median CV across storms of 22% (range: 9–73%), exceeded the median CV for rainfall depth (15%, range: 5–26%), and varied by up to a factor of five (5–25 N h^{-1}) within 300 m. EI_{30} was better correlated with sediment yield measured in <0.1-ha microwatersheds ($r^2 = 0.67$; $p < 0.001$) than rainfall depth ($r^2 = 0.43$; $p < 0.001$). Our results highlight the potential importance for erosion related assessments of spatial variability in erosivity, which can be as great or greater than spatial variability in rainfall depth. The spatial variability in rainfall erosivity that we document here is relevant to erosion and contaminant transport issues near Los Alamos National Laboratory and may be applicable to other extensive semiarid areas.

Several applied environmental problems require estimation of soil loss and associated sediment yield resulting from water erosion. Assessments of soil erosion are needed to evaluate contaminant mobility (Johansen et al., 2003), archeological site stability (Sydoriak et al., 2000), soil C reserves (Breshears and Allen, 2002), postfire hydrology (Beeson et al., 2001; Johansen et al., 2001, 2003; Wilson et al., 2001), indices of ecosystem health (Davenport et al., 1998), and efficacy of land management treatments (Hastings et al., 2003). Hydrological models are often essential tools for such assessments and vary greatly in the level of complexity included. Generally these models are quite sensitive to some attributes of the input precipitation. Consequently, variation in precipitation input, spatially as well as temporally, can be quite important for assessments of soil erosion and sediment yield.

Soil erosion and sediment yield are, of course, dependent on runoff and its associated variability. Here we focus on the largely unaddressed issue of spatial variability in rainfall erosivity and associated sediment yield. Rainfall erosivity and sediment yield can be measured much more cost effectively than runoff, an important consideration when studying spatial variability.

Variation in precipitation characteristics can be particularly high in semiarid areas, which are often dominated by convective thunderstorms and orographic effects. Semiarid environments 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 to 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 calculated using a number of combinations and intervals of precipitation characteristics (Wischmeier and Smith, 1958; Brown and Foster, 1987). The most general and most often recommended approach for estimating rainfall erosivity uses the interaction between the storm energy (E) (MJ ha^{-1}) and the highest continuous 30-min rainfall intensity (I_{30}) (mm h^{-1}). Storm energy is determined empirically using the method of Brown and Foster (1987). The product of these factors equals rainfall erosivity (N h^{-1}), noted as EI_{30}. EI_{30} 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 and sediment yield (Renard et al., 1997). Although rainfall erosivity is recognized as an important predictor of soil loss and associated sediment yield, and rainfall depth has been shown to vary substantially over short distances within the same watershed, spatial variability in rainfall erosivity has not been quantified over short distances of tens to hundreds of meters. Yet many models' simulations assume homogeneity within distances this short. Some models even depend directly on an estimate of EI_{30}, such as the simplistic Revised Universal Soil Loss Equation, which is widely applied to address a variety of erosion problems.

Our objective was to quantify spatial variability in rainfall erosivity within small semiarid watersheds and associated variation in rainfall depth and sediment yield. We focused on the most widely used metric of rainfall erosivity: the product of total rainfall energy and highest 30-min rainfall intensity, EI_{30}. In the semiarid regions of the southwestern USA, spatial variability in rainfall

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erosivity is particularly important during the monsoon season (July–September), when erosivity is greatest. For instance, Renard and Simanton, (1975) quantified that 85 to 93% of the annual rainfall erosivity occurred during the monsoon season in Arizona and New Mexico. To capture this important period, our measurements were obtained in a semiarid woodland in northern New Mexico for 14 storms for two consecutive monsoon seasons. Our results quantify a large degree of spatial variation in rainfall erosivity, highlighting the potential importance of this factor in studies, simulations, and assessments related to soil erosion.

Study Area

The study area is the site of an ecosystem boundary shift between a Ponderosa pine (*Pinus ponderosa* C. Lawson) savanna and a piñon–juniper woodland located in Bandelier National Monument, New Mexico (36°46′25″ N, 106°16′21″ W) at an elevation between 1948 and 1986 m above mean sea level. Reportedly, in a period of only 5 yr, the ecotone or ecosystem boundary between ponderosa pine forest and piñon–juniper woodland shifted some 2 km upslope during the 1950s because of extensive drought-induced mortality of ponderosa pines. (Allen and Breshears, 1998). 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 and 400 mm, increasing with elevation (Bowen, 1996). About 40 to 60% of the annual precipitation is recorded during the monsoon period of July, August, and September, a period characterized by short duration, high intensity convective thunderstorms. The study area was described in detail in Hastings et al. (2003), Jacobs et al. (2000), and Jacobs and Gatewood (1999). This study contributes to a larger regional effort to evaluate how runoff and erosion vary as a function of spatial scale in semiarid woodlands (Davenport et al., 1998; Reid et al., 1999; Wilcox et al., 2003a, 2003b). The study additionally provides specific information relevant to contaminant mobility and long-term stability of landfill covers, issues that are of concern for the nearby Los Alamos National Laboratory, as well as other sites in semiarid environments where contaminants are of concern.

MATERIALS AND METHODS

Rainfall was characterized using 12 tipping-bucket rain gauges (20.3-cm diameter) that were randomly located in a 40-ha watershed. Rain gauges were placed approximately 0.3 m above the ground surface to avoid rainsplash catch. The angle from the rain gauge orifice to the top of any nearby vegetation did not exceed a recommended maximum angle of 45° (Brakensiek et al., 1979). The difference in elevation between the lowest and highest rain gauge was only 20 m. We obtained 1-min resolution data from each rain gauge, using electronic data loggers to record precipitation depth, time, and intensity. Manufacturer's accuracy rating for these instruments is reported at 0.5% for a rainfall intensity of 12.7 mm h^{-1}. The highest 30-min rainfall intensities measured in this study rarely exceeded a value of 10 mm h^{-1}. In spite of the reported accuracy rating, the measurement error associated with larger events is small relative to the large spatial variability in rainfall erosivity reported for this study. Peak 1-min rainfall intensities may, however, be underestimated as a result of errors associated with a tipping bucket rain gauge.

Data were analyzed to quantify total storm depth, highest continuous 30-min storm intensity period, and storm energy. Storm energy was calculated after Brown and Foster (1987), multiplied by the highest 30-min intensity, and converted to newtons per hour using a factor of 1.702 (Renard et al., 1997). Calculations of storm rainfall intensity for storms <30 min in duration followed Renard et al. (1991, 1997). We calculated the summary statistics across gauges ($n = 12$) and the coefficients of variation within storms ($n = 14$) for rainfall depth and rainfall erosivity. Rainfall erosivity gradients were mapped (Surfer 7.0, Rockware, Golden, CO) for significant events across all 14 rain gauges.

Sediment yield was quantified at the outlets of four microwatersheds associated with four of the 12 adjacent rain gauges. These four microwatersheds were selected because of their similar characteristics related to contributing area, soils, topography, and vegetation (Table 1). The microwatersheds are located in a degraded piñon–juniper woodland that is characterized as having high hydrologic connectivity between intercanopy spaces at the scale of our study (Davenport et al., 1998; Reid et al., 1999; Wilcox et al., 2003a). Sediment yield was measured by collecting sediment from check dams at the outlets of each microwatershed. Check dams were constructed of silt fence geotextile and reinforced with rebar secured in the ground. A small excavated basin, uphill of the silt fence, was lined with plastic sheeting and secured to the ground surface with landscape staples. After each rainfall–runoff event, high water marks (e.g., organic matter) were observed on the silt fence. In two of the storm events, two check dams appeared to have over-spilled. An estimated 5% or less was lost through a constructed rectangular weir in the top center of the silt fence. The material lost was likely comprised of suspended sediment and organics. On the basis of a particle distribution analysis of a complete sediment yield catch, we concluded these constituents comprised a small proportion of the total mass of material generated by these larger storms.

The soil was excavated, air-dried, and weighed to the nearest 0.1 kg with a bucket and spring scale. Microwatershed contributing areas were surveyed using a total station survey

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

Microwatershed	Area	Canopy cover	Canopy type	Ground cover†	Slope	Aspect	Soil taxonomy	Soil texture‡
	m^2	%		%	%			
1	**860**	**55**	**piñon-juniper**	**14, 8**	**13**	**west**	**Inceptisol**	**Sandy loam**
2	**550**	**33**	**piñon-juniper**	**6, 5**	**13**	**west**	**Inceptisol**	**Sandy loam**
3	**320**	**49**	**piñon-juniper**	**8, 4**	**14**	**west**	**Alfisol**	**Sandy loam**
4	**710**	**57**	**piñon-juniper**	**11, 11**	**16**	**west**	**Alfisol**	**Sandy loam**

† Average pre and post growing seasons (June 2000–2001, September 2000–2001).

‡ Soil textures completed from a five-way composite sample from each microwatershed and using a USDA sieve analysis.

unit and prism with area accuracy to the nearest 0.001 ha. 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 were described in Hastings (2002); additional related analyses of an expanded portion of this data set were reported in Hastings et al. (2003).

RESULTS

We recorded 14 rainfall–runoff events (>1 mm) that varied in several characteristics both spatially and temporally. Total precipitation for the study periods equaled 148.5 mm between 20 June and 30 Sept. 2000, and 129.2 mm between 1 June and 30 Sept. 2001. Precipitation totals are low when compared with a 76-yr, long-term precipitation average of 201 mm for the same period of time (Bandelier National Monument, 2001). Mean storm duration was 54 min (range: 16–111 min), with peak rainfall intensities commonly only 1 to 2 min in duration. The maximum peak 1-min rainfall intensity, recorded from any one rain gauge and across all storms, was 168 mm h^{-1}. Temporal variability in the measured parameters of rainfall depth, erosivity, and sediment yield for each of the four microwatersheds for which sediment yield was measured is represented in Table 2. The results in Table 2 exhibit consistent variation across all 14 storms for each parameter and highlight the greater temporal variation in rainfall erosivity relative to rainfall depth.

We measured the spatial variation of rainfall depth and erosivity (EI_{30}) across 12 rain gauges (n = 12) (Fig. 1a) and the CV of both rainfall characteristics across each storm (n = 14) (Fig. 1b). The CV over all storms for rainfall depth ranged from 5 to 26%, with a median of 15%. The CV over all storms for rainfall erosivity was much more variable than that for the CV for rainfall depth, ranging from 9 to 73%, and also having a greater median of 22%. Furthermore, 5 of 14 storms exceeded 30% CV in rainfall erosivity across 12 rain gauges. The most spatially variable storm, relative to rainfall erosivity (August 9, 2000), had a rainfall erosivity gradient that varied by a factor of five (5–25 N h^{-1}) in <300-m distance (Fig. 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 collected within the check dams of the four small (<0.1 ha), replicated microwatersheds. Sediment yields were compared with (i) rainfall depth and (ii) rainfall erosivity calculated from four rain gauges, each adjacent to or within an associated micowatershed. Median total sediment yield from all 14 storms for the four micro-

Table 2. Mean hydrologic characteristics and associated CVs for each of the four microwatersheds for which sediment yield was measured, reflecting temporal variability across 14 storm events.

Microwatershed	Mean† precipitation	CV‡	Mean† rainfall erosivity	CV‡	Mean† sediment yield	CV‡
	mm	%	N h^{-1}	%	kg ha^{-1}	%
1	9.83	72	9.0	110	291.6	197
2	10.37	69	9.9	102	507.2	218
3	9.43	68	8.8	101	767.1	189
4	10.11	70	9.3	104	404.4	199

† Mean value across all 14 storm events.

‡ Coefficient of variation for each parameter and across all 14 storm events for each microwatershed.

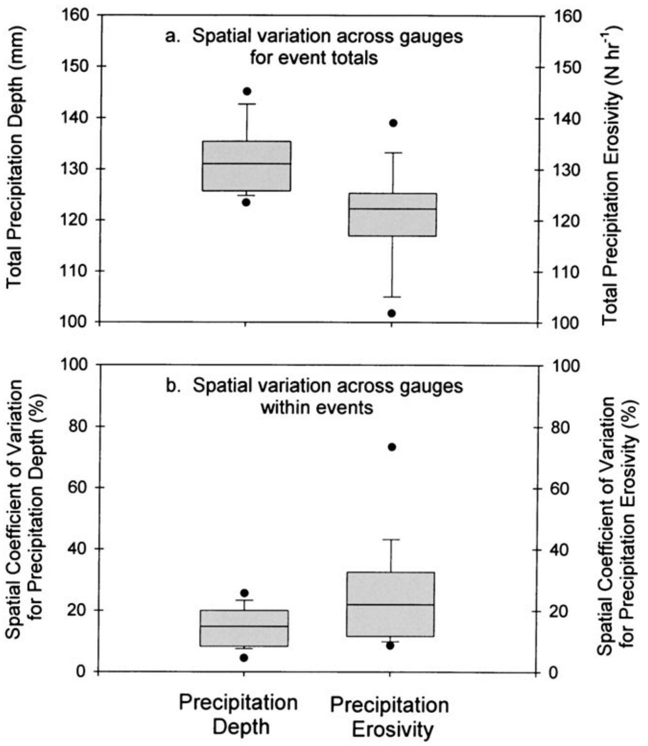

Fig. 1. (a) Precipitation depth and erosivity distributions across 12 rain gauges for 14 convective thunderstorms (n = 12) between June and September 2000 and 2001. (b) Coefficient of variation for precipitation depth and rainfall erosivity across 14 storms (n = 14). The horizontal line represents the 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.

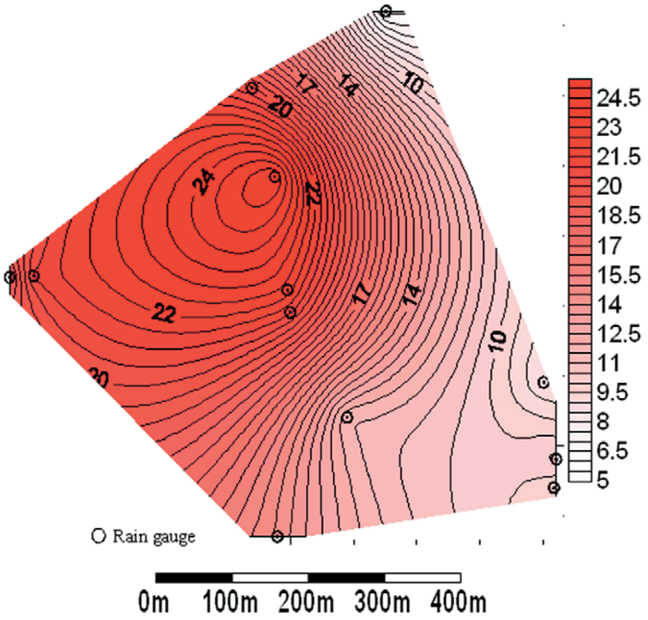

Fig. 2. Storm rainfall erosivity gradient across 12 rain gauges for 9 Aug. 2000. Rain gauges are indicated by the open circles. Rainfall erosivity units are newtons per hour.

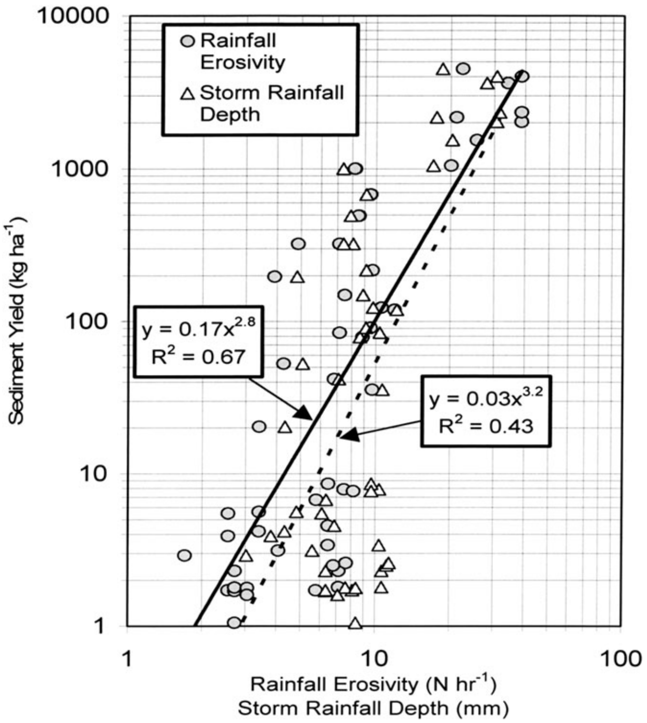

Fig. 3. Relationship of rainfall erosivity vs. sediment yield (log/log) and rainfall depth vs. sediment yield (log/log) for four selected microwatersheds and associated rain gauges across 14 convective thunderstorms or rainfall–runoff events.

watersheds was 6380 kg ha^{-1}. The CV for sediment yield ranged from 23 to 151%, with a median of 32% (n = 14). Spatial variation was high. For example, one microwatershed exhibited 2.6 times more sediment yield than an adjacent microwatershed, separated by only 200 m. However, we found that when storm sediment yields from each microwatershed were compared with storm values of rainfall depth and rainfall erosivity evaluated from their associated rain gauges, rainfall erosivity exhibited a stronger positive correlation than rainfall depth (Fig. 3). This provides an indication of the magnitude of spatial variability in rainfall erosivity even for locations within close proximity to one another.

DISCUSSION

Our results document a high degree of spatial variation in rainfall erosivity as well as in rainfall depth across gauges within <300 m of one another. Notably, rainfall erosivity varied by as much as a factor of 5 within a storm, and the spatial variation in rainfall erosivity was usually at least as large as that in rainfall depth, often exceeding it. The degree of spatial variation varies with storm and could be amplified or dampened depending on storm types and the evaluation period. Although our study may not have been long enough to determine how these patterns might vary over multiyear intervals, it is nonetheless sufficient to highlight the large degree of spatial variation in rainfall erosivity and provides an initial estimate of the magnitude of spatial variation for a system within the intensively studied woodland complex near Los Alamos.

Spatial variation in rainfall depth and rainfall erosivity has important implications for site estimates of these values and for model simulations that depend on them as input. Osborn et al. (1972) recommended that one centrally located rain gauge would be sufficient for watersheds up to about 50 ha in southeastern Arizona, but here we document extreme gradients in rainfall erosivity in short distances in watersheds smaller than 50 ha for north-central New Mexico. Dunne and Leopold (1978) further reported that sparse rain gauge networks in semiarid areas tend to underestimate rainfall characteristics required for planning, conservation practices, and engineered structures. The potential effects of such spatial variation need to be considered in concert with modeling or assessment objectives. Faures et al. (1995) determined that the spatial variability of precipitation depth could translate into large variations in modeled runoff in a semiarid area of <5 ha. They were able to reduce the CV of predicted runoff 10% by increasing the number of rain gauges from 1 to 8 within a 4.4-ha watershed.

Our results also highlight the importance of considering temporal variation with respect to high temporal resolution precipitation data. A common standard in rainfall data records is 15-min resolution. We suggest that our 1-min resolution rainfall data increases the ability to capture the temporal variability and detail of rainfall intensity, which in turn helps us to quantify the spatial variability of rainfall erosivity. The short 1- to 2-min duration peak rainfall intensities recorded at such high resolution may be the impetus for significant runoff and influence behind generating rainfall erosivities that drive sediment yield. For intense convective storms, such as those we studied, 15-min resolution data would be insufficient to detect critical periods of high erosivity, especially because several of the storms analyzed for this study were ≤15 min in duration.

Improved estimates of sediment yield are needed to address a variety of issues in semiarid woodlands. Large portions of these areas are experiencing accelerated erosion as a result of cumulative impacts of past land management (e.g., overgrazing), drought, and fire (Allen and Breshears, 1998; Davenport et al., 1998; Wilson et al., 2001) or recent land development. For all of these cases, accurate estimates of runoff and sediment yield are important for understanding ecosystem response and cost-effective planning and design (Mendez et al., 2003). Furthermore, as climate change progresses, more extreme precipitation events are expected (IPCC, 2001), leading to increased erosivity (Nearing, 2001). Effective management of these woodlands is needed to address diverse issues include grazing, carbon management (Davenport et al., 1998; Breshears and Allen, 2002), and contaminated sediment transport (Johansen et al., 2003). Higher spatial resolution estimates of sediment yield and/or improved estimates of spatial variability and the mechanisms that drive sediment yield will be needed to address some critical aspects of these issues.

SUMMARY AND CONCLUSIONS

In summary, we document that spatial variation in rainfall erosivity within distances of a few hundred meters can be substantial, both within and across storms. Indeed, the spatial variation in rainfall erosivity, previously unquantified, can be as great or greater than that for rainfall depth. In this study, rainfall erosivity is a more important determinant of soil loss and associated sediment yield than rainfall depth, as verified by additional measurements at our site. High resolution (1-min interval) precipitation data are needed to rigorously evaluate rainfall erosivity. Several recent studies have highlighted the potential importance of spatial variation in precipitation depth in interpreting field measurements, driving models, and conducting assessments. We build on these studies to highlight that rainfall erosivity, a more direct measure of the ability of precipitation to erode soil, can vary as much or more than rainfall depth, a finding that should be considered in concert with the objectives of future field studies, model simulations, and associated assessments.

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