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Temporal and elevation trends in rainfall erosivity on a 149 km^2 watershed in a semi-arid region of the American Southwest

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Abstract

Temporal changes in rainfall erosivity can be expected to occur with changing climate, and because rainfall amounts are known to be in part of a function of elevation, erosivity can be expected to be influenced by elevation as well. This is particularly true in mountainous regions such as are found over much of the western United States. The objective of this study was to identify temporal and elevation trends in rainfall erosivity on a 149 km^2 (58 miles^2) watershed in a semi-arid region of southeastern Arizona. Data from 84 rain gages for the years 1960–2012 at elevations ranging from 1231 to 1644 m (4038–5394 ft) were used in the analyses. The average annual erosivity over the watershed as a whole was 1104 MJ mm ha^{-1} h^{-1} yr^{-1} (65 hundreds of foot ton inch acre^{-1} h^{-1} yr^{-1}), and ranged from approximately 950 to 1225 MJ mm ha^{-1} h^{-1} yr^{-1} (56–72 hundreds of foot ton inch acre^{-1} h^{-1} yr^{-1}), with a statistical trend showing greater erosivity at the higher elevations. No statistically significant temporal changes in annual or summer erosivities were found. This result stands in contrast to recent modeling studies of runoff and erosion in the area based on downscaled GCM information that project significant levels of erosivity changes over coming decades. These results are consistent with known orographic rainfall effects, but contrast with recent studies that presented projections of significant trends of increasing erosivity in the future based on downscaled GCM outputs for the area. The results illustrate the need for testing and developing improved techniques to evaluate future erosion scenarios for purposes of making targeted soil conservation decisions.

Keywords: Climate change; *R*-factor; RUSLE; Semiarid; Soil erosion; Walnut Gulch

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1. Introduction

Rainfall erosivity is the capacity of rain to erode soil. Wischmeier (1959) used statistical analysis on data from erosion plots and found that the amount of soil loss measured was related to the value of EI, which is the energy of the storm, as estimated with a logarithmic function of rainfall intensity, multiplied by the maximum 30 min rainfall intensity during the storm. The EI index was used in the Universal Soil Loss Equation (Wischmeier & Smith, 1978) and then in the Revised Universal Soil Loss Equation (Renard, Foster, Weesies, McCool, & Yoder, 1997) to compute

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the annual average erosivity, or *R*-factor, for the entire United States. In cases where this relationship has been evaluated against independent erosion data it has been found to be statistically valid (e.g., Campos, Dasilva, Deandrade, & Lepurn, 1992; Salehi, Pesant, & Lagace, 1991), though variations have been proposed (e.g., Petan, Rusjan, Vidmar, & Mikos, 2010; Usan & Ramos, 2001), usually suggesting a shorter time period for the maximum prolonged intensity where such data are available.

Global precipitation has changed. Rainfall amounts and daily rainfall intensities generally increased in the United States between 1910 and 1996 (Karl & Knight, 1998). More than half of observed increases in total annual precipitation for the United States measured during that time were caused by increases in the frequency of heavy events, which were considered to be those in the upper 10 percentile of daily amount values. Also, the proportions of precipitation falling in heavy (> 95th percentile), very heavy (> 99th percentile), and extreme (> 99.9th percentile) daily precipitation events increased during the years 1910–1999 by 1.7%, 2.5%, and 3.3% per decade, respectively, on average across the United States (Soil and Water Conservations Society, 2003). This is a pattern that appears to be occurring in many parts of the world (Groisman et al., 2005; Meehl et al., 2007).

Future projections of climate suggest that rainfall amounts will continue to change. Seager et al. (2007) reported the results for the American Southwest of 19 General Circulation Models (GCM) included in the 4th Assessment Report of the Intergovernmental Panel on Climate Change, which they defined as "including all land between 125°W and 95°W and 25°N and 40°N." The overall averaged results showed a drying trend, as indicated by the value of precipitation minus evaporation, of 0.86 mm day^{-1} from the periods 1950 to 2000 compared to 2021 to 2040. However, their maps of the individual components of change, which included mean atmospheric circulation, specific humidity, and transient-eddy moisture convergence also showed significant spatial variation within the area, indicating both wetting and drying trends. It is not clear that the direct outputs of the GCMs can provide the spatial resolution needed to look at change in an area the size of the USDA-ARS Walnut Gulch Experimental Watershed (WGEW).

Historical rainfall erosivity is generally more difficult to assess than is rainfall amount because erosivity calculations require temporally high-resolution, breakpoint data. Such precipitation data from across the U.S. were compiled for the revision of the Universal Soil Loss Equation (Renard et al., 1997), and subsequently used to assess changes in annual and seasonal rainfall erosivity over the time period from 1972 to 2002 (Angel, Palecki, & Hollinger, 2005). Results for the interior western U.S. showed a statistically significant increase of 17% in rainfall erosivity during the summer months over the study period of 1972–2002, but it is not possible to pull out results from that study for specific areas such as Arizona or even the entire Southwest.

Rainfall erosivity has its special challenges in relation to interpretation of future climate projections. Global Circulation Model (GCM) outputs generally provide monthly outputs, and hence one must either use statistical relationships between erosivity and monthly rainfall (Nearing, 2001) or temporal downscaling methods must be used (Zhang, 2005, 2007; Zhang, Chen, Garbrecht, & Brissette, 2012; Zhang, Nearing, Garbrecht, & Steiner, 2004). There have been several studies that have used downscaled Global Circulation Model (GCM) outputs for projected future rainfall to look at the potential impacts of climate change on soil erosion (e.g., Zhang, 2012; Zhang, Nearing, Zhang, Xie, & Wei, 2010; Zhang & Liu, 2005). One recent such study conducted in southeastern Arizona (Zhang, Hernandez, et al., 2012) used output from seven GCMs for projections for the 2050s and 2090s. The results indicated that for southeastern Arizona, though there were no projected, statistically significant trends in total rainfall, erosion could increase by more than 100% over the next century. Since that study assumed no changes in vegetation, slopes, or soils, that projected shift can be interpreted to be due to projected rainfall erosivity changes, within the context of the GCM data and downscaling method used.

Humans living in mountainous areas have probably always been cognizant of the effects of elevation on rainfall. The effect has been scientifically documented and was discussed in the literature as early as 1945 (Bonacina, 1945), at which time it was referred to as an orographic effect, from the Greek work "*oros*" for mountain. Since that time the orographic effect has been identified and studied across the world (e.g., Al-Ahmadi & Al-Ahmadi, 2013; Goldreich, 1994; Katzfey, 1995; Sarker, 1966, 1967). Osborn (1984) analyzed data from across the state of Arizona and found a trend of increasing total, winter, and summer rainfall as a function of gage elevation. Karnieli and Osborn (1988) used data from 158 rain gages across Arizona to show that elevation explained between 67% and 94% of the variation in summer precipitation. They also reported that slopes of southerly aspect in southeastern Arizona had greater than otherwise expected summer precipitation. Michaud, Auvine, and Penalba (1995) developed a statistical model based on latitude, longitude, and elevation for the entire southwestern United States that explained between

60% and 70% of monthly average precipitation. All of these studies in the Southwest showed a general relationship between elevation and rainfall amounts, but it was also apparent in all of these studies that elevation was not the sole determinant of rainfall differences.

Very few studies have looked at the relationships between rainfall erosivity and orographic impact. Diodato and Bellocchi (2007) developed a statistical model for the Mediterranean that approximates erosivity based on monthly average precipitation amounts, elevation, and latitude. Elevations for data ranged from 3 to 1270 m (10–4166 ft). One of the conclusions of the study was that the model that utilized the elevation terms provided a better fit to the estimated erosivity data than the models without the elevation factor.

The objective of this study was to identify temporal and elevation trends in rainfall erosivity on a 149 km^2 (58 miles^2) watershed in a semi-arid region of the southwestern United States. Data from 84 high temporal resolution recording rain gages for the years 1960–2012 at elevations ranging from 1231 to 1587 m (4038–5205 ft) were used in the analyses. Data sets that have the temporal resolution required for detailed computation of EI values, with a large number of replications and more than 50 continuous years of record, are rare.

2. Materials and methods

2.1. Study site

The 149 km^2 (58 miles^2) Walnut Gulch Experimental Watershed (WGEW) is located in southeastern Arizona, USA, in and around the town of Tombstone. The watershed was established as an experimental site by the United States Department of Agriculture (USDA) in 1953 to conduct hydrologic and soil erosion research (Renard, Nichols, Woolhiser, & Osborn, 2008). Details on the watershed characteristics, data collection program, and selected research results may be found in the special section of *Water Resources Research*: fifty years of research and data collection (Moran et al., 2008). The mean annual temperature is approximately 18 °C, with maximum averages of 35 °C in June and average lows of 2 °C in December. Average annual rainfall has been measured at approximately 314 mm (12.3 in.) with approximately 60% of the annual precipitation falling from early July to mid-September during the monsoon season (Goodrich, Keefer, et al., 2008). Nearly all of the surface water runoff, and hence erosion, occurs during the monsoon season by the mechanism of infiltration-excess (Goodrich et al., 1997; Stone, Nichols, Goodrich, and Buono, 2008). The channels in Walnut Gulch Experimental Watershed are ephemeral, and are dry except during brief periods of storm water runoff. Nearly all of the runoff occurs during the monsoon (Stone et al., 2008). The minor amount of snow that occurs in this watershed is not a significant erosivity factor. Land use in the area includes grazing, mining, and low to medium density residential.

Walnut Gulch is formed on an alluvial fan of Cenozoic age. Soils are generally poorly sorted and rocky, with significant surface rock fragment cover common (USDA, 2003). The soil texture over the watershed varies, but across large areas it is approximately half sand, one-quarter silt, and one-quarter clay in the less than 2 mm fraction. The organic carbon content of the soils is generally low, typically ranging from less than 1% on lower elevations to 2% and more in upper elevations. Vegetation in lower elevations is a sparse shrub cover dominated by whitethorn Acacia (*Acacia constricta*), mariola (*Parthenium incanum*), creosotebush (*Larrea divaricata*), and tarbush (*Flourensia Cernua*). At higher elevations vegetation includes Lehman's lovegrass (*Eragrostis Lehmanniana*), black grama (*Bouteloua eriopoda*), cane beardgrass (*Bothriochloa barbinodis*), three-awn (*Aristida* sp.), and sideoats grama (*Bouteloua curtipendula*) (King et al., 2008).

2.2. Rainfall data

The precipitation data collection history for the WGEW was described in detail by Goodrich, Keefer, et al. (2008), and temporal and spatial aspects of the record were analyzed by Goodrich et al. (1997), Goodrich, Unkrich, et al. (2008) and Nichols, Renard, and Osborn (2002). This precipitation measurement network is one of the most densely monitored areas of greater than 10 km^2 (4 miles^2) in the world, with an average of one temporally high-resolution recording gage for every 1.77 km^2 (0.68 miles^2) (Goodrich, Keefer, et al., 2008). In this study we used rainfall data from 84 rain gages collected from 1960 to 2012. Elevations ranged from 1231 to 1644 m (4038–5394 ft). Storm hyetographs provide temporal resolution down to at least five minutes in the pre-digital, chart-based data prior to 2000, and to at least one minute in the digital data. Digital and chart-based data were previously compared for the transition period from 2000 to 2005 to ensure compatibility in the records (Keefer et al., 2008) Data were continuous on nine of the gages for the period from 1963 to 2012, with the record from six of those starting in 1960. There were several years during the 1970s and 1980s where data for the other 75 gages were only collected during the summer seasons of July–September (JAS), which includes and largely coincides with the monsoon season. We analyzed orographic and temporal relationships in erosivity for the annual precipitation totals using the nine gages with continuous record, and we used all 84 of the gages for summer erosivities, which is the primary period erosion.

2.3. Data analyses

Rainfall erosivities were calculated on a storm-by-storm basis according to the technique used for RULSE (Renard et al., 1997). In the eastern United States storms of less than 12.5 mm (0.5 in.) are omitted according to the methods, however this threshold is not used in RUSLE for calculations in the western U.S. (Renard et al., 1997, Appendix B), thus we did not omit storms based on a threshold in this study. Values of erosivity for individual storms are referred to as EI values (Wischmeier, 1959). Annual totals of rainfall EI were computed for each of the nine continuous gages, and summer totals were computed for each of the 84 gages. EI for each rainfall event is defined as

$$\mathrm{EI} = E \times I_{30} = \left(\sum_{r=1}^{m} e_r \, \Delta V_r \right) \times I_{30} \tag{1}$$

where E (MJ ha^{-1}) is the calculated energy, I_{30} (mm h^{-1}) is the maximum continuous 30 min rainfall intensity during a rainfall event, e_r (MJ ha^{-1} mm^{-1}) is the estimated energy per unit depth of rainfall and unit area, and ΔV_r (mm) is the depth of rainfall for the rth increment of the storm hyetograph (Renard et al., 1997, Appendix B). The unit energy is computed using RUSLE guidelines based on Brown and Foster (1987) as

$$e_r = 0.29[1 - 0.72\exp(-0.05 i_r)]$$

where i_r (mm h^{-1}) is the rainfall intensity for the rth increment of the storm hyetograph.

EI values were calculated for every storm in the rainfall record and summed by gage and by year to obtain values of erosivity, R_{yg} for each year and each gage. Average annual R-factors were computed for each gage as the average of R_{yg} for each year of the record.

Results were plotted for annual rainfall and erosivities against elevation of the gage and against time in years using the data from the nine gages with continuous precipitation records. Results were plotted for summer rainfall and erosivities against elevation of the gage and against time in years using the data from all the 84 gages with non-continuous precipitation records.

Linear regression and the Sen's slope methods were used to detect trends.

3. Results and discussion

Results for annual and summer average annual rainfall and calculated erosivity are presented in Table 1. Approximately 61% and 87% of the recorded precipitation and calculated erosivity, respectively, came during the summer months (JAS). This difference between the ratio of summer to total rainfall and erosivity is illustrative of the difference between the characteristics of the summer monsoon rainfall compared to winter rains. Summer rain is characterized by high intensity, short duration convective thunderstorms that often exceed soil infiltration rate to cause surface water runoff and overland flows (Stone et al., 2008). Winter rains generally are longer duration and lower intensity, and rarely cause runoff (Goodrich, Keefer, et al., 2008; Goodrich, Unkrich, et al., 2008; Nearing, Nichols, Stone, Renard, & Simanton, 2007). The variation of both rainfall and erosivity was greater between years than between gages, as evidenced by the standard deviation of annual averages being larger than the standard deviation of gage averages (Table 1). The nine average annual values from this study ranged from 935 to 1225 MJ mm ha^{-1} h^{-1} yr^{-1} (55–72 hundreds of foot ton inch acre^{-1} h^{-1} yr^{-1}), which are essentially the same as the values for the area found in the average annual erosivity (R-factor) maps published for RUSLE (Renard et al., 1997).

Table 1
Annual and summer average rainfall and calculated erosivities.

	Annual averages for the nine continuous gages		Summer (JAS) averages for all 84 gages		Summer (JAS) averages for the nine continuous gages	
	Rainfall (mm yr^{-1})	Erosivity (MJ mm ha^{-1} h^{-1} yr^{-1})	Rainfall (mm yr^{-1})	Erosivity (MJ mm ha^{-1} h^{-1} yr^{-1})	Rainfall (mm yr^{-1})	Erosivity (MJ mm ha^{-1} h^{-1} yr^{-1})
Average of gage averages[a]	314	1104	192	983	191	960
Standard deviation of gage averages	13	115	8	97	6	87
Average of annual averages[b]	312	1099	191	979	190	957
Standard deviation of annual averages	75	434	50	371	51	426

[a] "Gage averages" are the average values for each gage over all years of record (1960–2012, $n=53$).

[b] "Annual averages" are the average values for each year over all operating gages for that year.

Annual and summer rainfall and erosivities all showed significant elevation trends (Fig. 1). No temporal trends in any of the rainfall amounts or erosivities were found. Examples of the plots of rainfall and erosivities as a function of time, year by year, are shown in Fig. 2 for the case of summer measurements from all the gages.

The variability in the relationships between both rainfall and erosivity and elevation were greater when using all of the gages as compared to using only the nine gages of continuous operation. It is not entirely clear why this is the case, but it could be related to the influence of factors in addition to elevation that influence the rainfall patterns, or simply to natural variability. The reduced gage network has greater spacing between gages, obviously, thus the elevation differences between gages are greater for the reduced data set.

Goodrich, Unkrich, et al. (2008) plotted spatial trends in the Walnut Gulch data for the summer and non-summer rainfall using bivariate linear regression against easting and northing coordinates, essentially fitting a uniform plane to the averaged gage data by year. Overall they found trends of increasing summer rainfall moving from west to east, which essentially matches the upward elevation trend, but for the non-summer rain the overall trend was to the southeast, or slightly off the elevation trend direction. They suggested that this may be due also to larger scale climatic features, which could give it the southerly influence as well.

The temporal trend results for the rainfall itself are consistent with those of Goodrich, Unkrich, et al. (2008), which use much of the same data set, so it is perhaps not surprising that erosivity also showed no temporal trends.

However, studies have reported that erosivity can increase, even under conditions of no overall rainfall amount increases, because of changes in rainfall characteristics. Zhang, Hernandez, et al. (2012) used a temporal and spatial downscaling technique (Zhang, 2005, 2007; Zhang et al., 2004; Zhang, Chen, et al., 2012) to project future rainfall to look at the potential impacts of climate change on soil erosion in southeastern Arizona (Zhang, Hernandez, et al., 2012) using output from seven GCMs for projections for the 2050s and 2090s. Their study area specifically included the WGEW. The averaged results for that study projected no significant changes in the overall annual rainfall amounts for the projected future; however, they did show a dramatic increase in soil erosion over the next century. That study assumed no changes in vegetation, slopes, or soils, hence suggesting a dramatic future shift in rainfall erosivity. In fact, looking at results from individual GCM model outputs as reported by Zhang, Hernandez, et al. (2012), even for cases where overall rainfall amounts were projected to reduce, erosion went up in large amounts. It is not clear based on the results of the current study how such a discrepancy between historic trends and future projections in erosivity can be explained, and we believe that more investigation into the techniques of the downscaling for purposes of erosion modeling is warranted.

4. Summary and conclusions

The data used in this study were well suited to the study of elevation and temporal rainfall erosivity trends. Erosivity calculations require temporally high-resolution, breakpoint data, which are not as common as daily rainfall

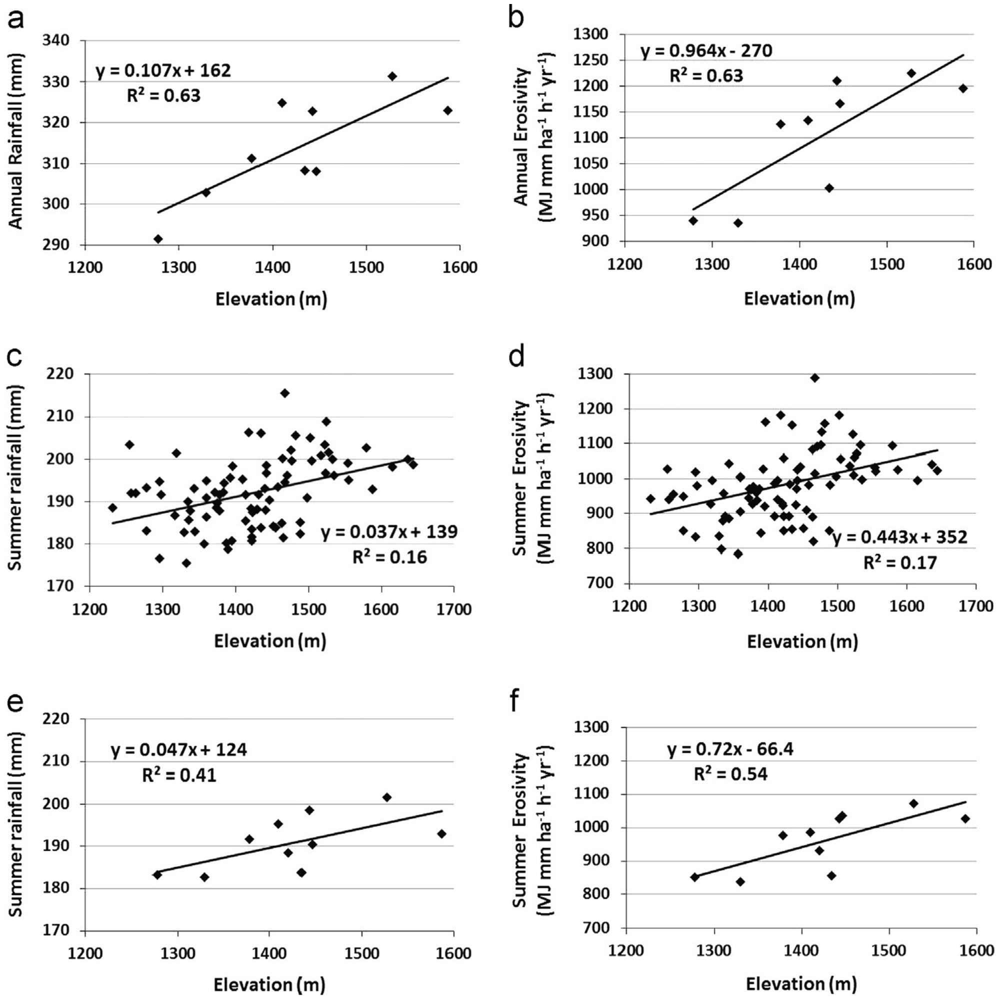

Fig. 1. Orographic effects on: (a) annual average rainfall for the nine continuously operated rain gages, (b) annual average erosivities for the nine continuously operated rain gages, (c) summer average rainfall for the 84 summer operated rain gages, (d) summer average erosivities for the 84 summer operated rain gages, (e) summer average rainfall for the nine continuously operated rain gages, and (f) summer average erosivities for the nine continuously operated rain gages.

data. We used breakpoint data from 84 gages over a 149 km^2 area in southeastern Arizona to directly calculate rainfall erosivity for a 53 year period since 1960 according to standard methods used in RUSLE. The elevation differences between the gages ranged over only about 350 m in total, yet annual erosivity increased by around 25% over that range as elevation increased. The large number of replications over the relatively small area, the high temporal resolution, and the long period of record provided a unique opportunity to look at temporal rainfall erosivity trends. None were found. GCM projections for the area have suggested that average annual rainfall may not change significantly in the future, yet combined climate temporal downscaling and erosion modeling methods have suggested that erosion rates could increase by very large amounts (Zhang, Hernandez, et al., 2012). The discrepancy between the lack of trends in the historical data and the downscaled projected GCM and erosion modeling results, which suggest significant trends, suggest a need for further investigation into the downscaling techniques. The results have significant implications for planning soil conservation for the future. If we can identify general areas where erosivity is most likely to change, conservation planners will have a leg up on addressing future conservation needs. Not everywhere do we have the data necessary to make such projections in context with historical records. This study, taken in the context of previous modeling studies, highlights the fact that projecting the future of soil erosion is yet in its early stages.

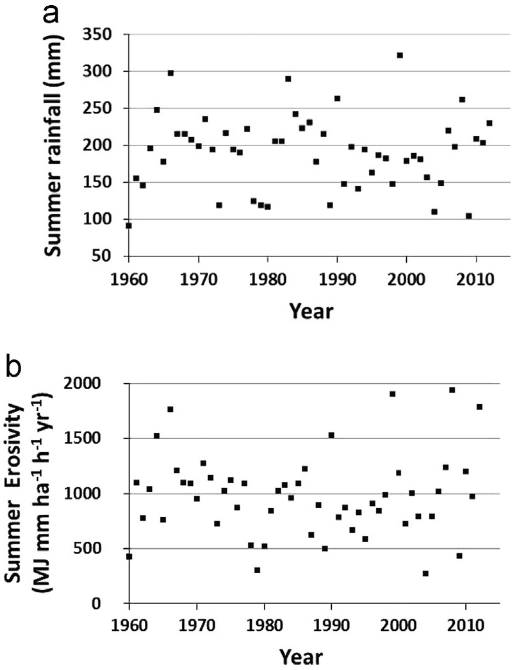

Fig. 2. Average summer rainfall (a) and summer erosivities (b) for the 84 summer operated rain gages from 1960 to 2012.

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