Long-term runoff and sediment yields from small semiarid watersheds in southern Arizona

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[1] This study presents analysis of 34 years of precipitation, runoff, and sediment data collected from eight small (1.1–4.0 ha) semiarid rangeland watersheds in southern Arizona, USA. Average annual precipitation ranged between 354 and 458 mm with 53% of the total rainfall occurring from July through September. Runoff depth was 3.5%–13.9% of annual precipitation depth for individual watersheds and 9.2% on average. Runoff events with missing sediment data were estimated to account for 30% of the total sediment yield. Sediment yields were highly variable, ranging between 0.85 t ha^{-1} yr^{-1} and 6.69 t ha^{-1} yr^{-1} with an average of 2.4 t ha^{-1} yr^{-1}. Ten percent of rainfall events with the largest sediment yields produced over 50% of the total sediment yield during the 34 year period. Linear regression models were developed to relate precipitation and runoff characteristics to watershed sediment yield. Maximum 30 min precipitation intensity was the primary factor affecting runoff, and runoff was the best predictor for sediment yield, explaining up to 90% of its variability. Fire and drought may have significantly altered the hydrologic and sediment response on some of the watersheds, but lack of continuous monitoring of vegetation on the watershed areas complicated interpretation of both fire and grazing management effects.

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1. Introduction

[2] Our ability to understand and manage semiarid ecosystems and their response to anthropogenic pressure depends on establishing relationships between rainfall, runoff, and sediment yield and determining the key factors that influence these relationships.

[3] The Santa Rita Experimental Range is a 20,000 ha area managed by the University of Arizona and is located 45 km south of Tucson on the western slopes of the Santa Rita Mountains. Semiarid brush and grass rangelands of the southwestern United States similar to that of Santa Rita Experimental Range cover an area of over 60 × 10^6 ha in the Chihuahuan and Sonoran deserts. They are vulnerable and sensitive to change because of limited water resources [*Newman et al.*, 2006], and the region is facing many challenges, including water redistribution [*Mueller et al.*, 2007], rapid urbanization [*Brown et al.*, 2005], proliferation of trees and shrubs [*Browning et al.*, 2008], increased erosion associated with vegetation change [*Parsons et al.*, 1996], increasing agricultural pressure [*Renard et al.*, 1993], and wildfires [*Desilets et al.*, 2007]. The majority of existing research on small watersheds with ephemeral flow has been conducted in temperate and humid regions [*Martinez-Mena et al.*, 1998; *Wilcox et al.*, 2003] or on cultivated land. Studies of small watersheds in semiarid environment are limited [*Coppus and Imeson*, 2002; *Martinez-Mena et al.*, 2001; *Nearing et al.*, 2007; *Nichols*, 2006; *Osborn et al.*, 1978].

[4] Semiarid environments are characterized by low annual precipitation (250–500 mm) that is much less than annual potential evaporation, and their erosion dynamics are defined by high-magnitude, low-frequency rainfalls [*Coppus and Imeson*, 2002; *Martinez-Mena et al.*, 2001; *Osborn and Renard*, 1988]. As a result, long periods of observation are required to evaluate impacts of management and land use on runoff and sediment yield [*Lane and Kidwell*, 2003]. Long-term data series that contain the number of observations sufficient for credible statistical analysis are scarce and limited to few geographic locations [*Bartley et al.*, 2006; *Nearing et al.*, 2007]. Measurements of sediment yields are therefore systematically underestimated on average because of lack of data on rare, large events.

[5] The need for small watershed research remains great for understanding and modeling hydrological relationships. A wide range of erosion rates have been reported for semiarid regions [*Mulligan*, 1998]. Sediment yields determined under the National Sedimentation Program varied from 0.7 to 19 t ha^{-1} yr^{-1} on watersheds in Arizona and New Mexico [*Nichols*, 2006]. In the Walnut Gulch Experimental Watershed in southern Arizona, sediment yields ranged from 0.07 to 5.7 t ha^{-1} yr^{-1} on watersheds less than 5 ha [*Nearing et al.*, 2007] and from 0.5 to 3.0 m^3 ha^{-1} yr^{-1} on watersheds 35–159 ha [*Nichols*, 2006].

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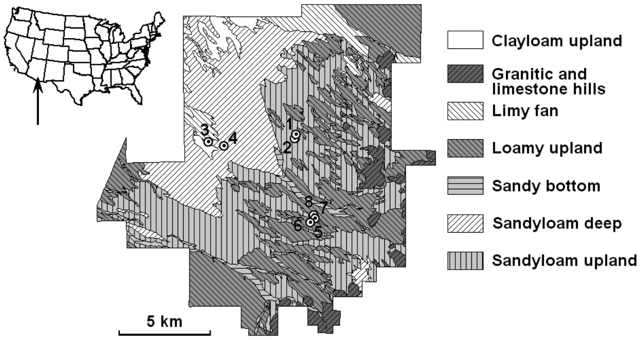

Figure 1. Location of Santa Rita Experimental Range and eight unit source watersheds.

[6] There are a number of unique features that distinguish semiarid watersheds and determine their erosion and sediment transfer dynamics. It has been proposed that a vegetation cover of approximately 40% constitutes a threshold below which runoff and erosion increase significantly in semiarid tropical pastures [*McIvor et al.*, 1995]. Patchy vegetation tends to concentrate and channelize flow, and in arid savannas, it is known to increase runoff 6–9 times and sediment loss up to 60 times relative to areas that have similar density but uniform cover [*Bartley et al.*, 2006]. The change of hillslope cover from grasses to shrubs leads to increased overland flow velocities and greater runoff and erosion rates [*Parsons et al.*, 1996]. Antecedent moisture conditions have relatively little effect on storm runoff in southeast Arizona because of high soil permeability [*Schreiber and Kincaid*, 1967]. Finally, a well-developed channel network (area-to-channel ratio) is a significant factor in the runoff-sediment yield relationship [*Nichols*, 2006].

[7] The aim of this study was to better understand and quantify runoff and sediment yield from small semiarid, grazed watersheds based on 34 years of data from southern Arizona, USA. Specifically, our objectives were to (1) summarize runoff and sediment yield data from eight small semiarid watersheds for the period from 1975 to 2008; (2) develop statistical relationships among rainfall, runoff, and sediment yields; and (3) identify the primary hydrologic controls on runoff generation and sediment yield.

2. Methods

2.1. Description of the Experimental Site

[8] The study was conducted in Santa Rita Experimental Range (SRER) located on the southwestern alluvial fans of the Santa Rita Mountains 45 km south of Tucson in southern Arizona, USA (31°48′55.2″N; 110°51′4.4″W). The SRER represents the middle elevation, eastern parts of the Sonoran Desert and is composed of both shrub/succulents and desert grassland communities that extend westward into the Chihuahuan Desert (Figure 1). It has a total area of 210 km^2 and is located between elevation of 900 and 1400 m. The primary land use on the range for over 150 years has been cattle grazing. Fires were common in the area (approximately once every 10 years) before the establishment of SRER in 1902 [*McClaran*, 2003; *McClaran et al.*, in press.

[9] The climate at SRER is semiarid with highly spatially and temporally varying precipitation dominated by North American Monsoon [*Adams and Comrie*, 1997] in the summer months. Precipitation has a pronounced peak in July–September and a lesser increase in December–March. The mean annual precipitation varies between 282 mm at an elevation of 914 and 492 mm at an elevation of 1310 m, indicating an orographic effect of 53 mm of precipitation per 100 m of elevation change [*Lane and Kidwell*, 2003]. Average daily temperature at elevation of 1340 m is 26.4°C in July and 8.6°C in January [*Lawrence*, 1996].

[10] The vegetation at SRER is represented by shrubs (mesquite, *Prosopis velutina* Woot.; hackberry, *Celtis pallida* Torr.; catclaw acacia, *Acacia greggii* Gray), cacti (cholla, *Opuntia spinisor* Engelm; prickly pear, *Opuntia engelmanni* Salm-Dyck; fishhook barrel, *Ferocactus wisilizenii* Britt. & Rose), and grasses (black grama, *Bouteloua eriopoda* Torr.; Lehmann lovegrass, *Eragrostis lehmanniana* Nees; Arizona cottontop, *Digitaria californica* Benth.; Santa Rita threeawn, *Aristida glabrata* Vasey) [*Martin and Morton*, 1993].

[11] Eight unit source watersheds (WS 1 through WS 8) ranging in area from 1.1 to 4.0 ha (Table 1) were instrumented by the U.S. Department of Agriculture (USDA) Agricultural Research Service in 1975 to measure rainfall, runoff, and sediment and investigate the effects of manipulative treatments on hydrological processes. The watersheds are located on a deep alluvial fan at three elevations: 970 m (WS 3 and WS 4), 1040 m (WS 1 and WS 2), and 1160 m (WS 5, 6, 7, and 8), which represent different ecological conditions. All watersheds have a well-developed second- to third-order channel network. Main channels are steep (3%–5%) and contain large amounts of coarse alluvium with particles 1–3 mm. Channel depth at the flumes range 0.5–0.9 m, except for watersheds 1 and 2 that are shallower (0.15–0.2 m). The soils throughout the study area are well drained, with low organic content and saturated hydraulic conductivity between 50 and 150 mm h^{-1} [*USDA*, 2003].

[12] In 1974, before the commencement of runoff and sediment data collection, watersheds 2, 4, 6, and 7 were treated to remove mesquite. Diesel oil was applied basally to kill the plants and reapplied later on as needed to keep the watersheds mesquite-free (other shrubs being intact). The results of this treatment have been reported earlier [*Martin and Morton*, 1993]. The available plant cover data on the watersheds are limited to the period between 1974 and 1986; hence, it is not used in statistical analysis and is provided only as background information. The grass density between 1974 and 1986 varied between 11 and 15 plants m^{-2} with greater densities on mesquite-free watersheds and on those at higher elevation. Over the same period, shrub canopy cover on treated watersheds, where it was initially 27%, declined by two thirds by 1977, then regained half the loss by 1986 mostly because of increases in the small shrub burroweed. Shrub cover on untreated watersheds steadily increased from 21% to 33% (twice that of treated) over the same period and was greater at the upper elevation [*Martin and Morton*, 1993].

[13] The watersheds received two types of grazing treatments: rotation and continuous grazing. Watersheds under rotation treatment had 3 year cycles with 8 (March–October) and 4 (November–February) months of grazing in the first 2 years, respectively, and were not grazed in the third year [*Mashiri et al.*, 2008]. Watersheds under con-

tinuous treatment were grazed year around (Table 1). Grazing intensities were set to maintain <50% utilization of the total yearly grass production [*Mashiri et al.*, 2008]. Stocking rate of cattle, measured in animal unit month (AUM), amount of forage needed to graze by one animal unit for a month, varied with elevation, average annual precipitation, and plant cover. Stocking rate in 1975–2008 were specified to include low rates (0.18 AUM ha^{-1} yr^{-1}) grazing on watersheds 3 and 4; intermediate rate (0.36 AUM ha^{-1} yr^{-1}) grazing on watersheds 1, 2, 7, and 8 (all in the same 1800 ha pasture with 1030–1185 m elevation range); and high rate (0.45 AUM ha^{-1} yr^{-1}) grazing on watersheds 5 and 6. This scheme continued through the 34 years of observation on all watersheds, except 5 and 6, where stocking rates almost doubled (to 0.85 AUM ha^{-1} yr^{-1}) in 1985, and rotation treatment was replaced by rapid (1–3 month) rotation among small pastures (Table 1).

Table 1. Watershed Properties and Soil Description

ID	Area (ha)	Elevation (m)	Average Slope (%)	Main Channel Length (m)	Soil Texture	Clay (%)	Erodibility (K-factor)[a]	Soil Classification	Mesquite Treatment	Grazing Intensity and Treatment AUM[b] (ha^{-1} yr^{-1})
WS 1	1.6	1040	4.1	160	Comoro sandy loam	5–20	0.24	coarse-loamy, mixed thermic Typic Torrifluvents	live	0.36 continuous
WS 2	1.8	1042	4.0	176	Comoro sandy loam	5–20	0.24	coarse-loamy, mixed thermic Typic Torrifluvents	treated	0.36 continuous
WS 3	2.8	959	2.8	170	Anthony fine sandy loam	10–18	0.24	coarse-loamy, mixed (calcareous) thermic Typic Torrifluvents	live	0.18 rotation
WS 4	2.0	976	3.7	205	Anthony fine sandy loam	10–18	0.24	coarse-loamy, mixed (calcareous) thermic Typic Torrifluvents	treated	0.18 rotation
WS 5	4.0	1164	3.9	195	Continental sandy loam	5–20	0.17	fine, mixed, thermic Typic Haplargids	live	0.45/0.85[c] rotation/rapid rotation
WS 6	3.1	1159	3.5	98	Comoro loamy sand	5–20	0.24	coarse-loamy, mixed thermic Typic Torrifluvents	treated	0.45/0.85[c] rotation/rapid rotation
WS 7	1.1	1161	4.0	211	Continental sandy loam	5–20	0.17	fine, mixed, thermic Typic Haplargids	treated	0.36 continuous
WS 8	1.1	1161	4.2	165	Continental sandy loam	5–20	0.17	fine, mixed, thermic Typic Haplargids	live	0.36 continuous

[a] *USDA* [2003].
[b] Animal unit month (AUM) is the amount of forage required by an "animal unit" for 1 month.
[c] Two values refer to grazing intensity before and after 1985. Watersheds not grazed after October 2006.

[14] Watersheds 5, 6, 7, and 8 were affected by a fire on 2 June 1994 that burned 4000 ha in the southern central part of SRER [*Huang et al.*, 2007]. A survey of the general area conducted 8 years after the fire indicated that in the affected area, 9% of the mesquite trees remained root killed, 65% shoot killed, while 8% showed no visible damage [*Gottfried et al.*, 2003]. No data has been collected in the watersheds to describe postfire response of vegetation.

2.2. Instrumentation and Sampling

[15] Precipitation and runoff data and runoff samples were collected on eight watersheds between 1975 and 2008 (Figure 1). Precipitation was measured using a high-resolution weighing-type rain gauges located on each of the watersheds [*Goodrich et al.*, 2008]. The exception was watersheds 7 and 8 that were adjacent to each other and shared one rain gauge.

[16] Each watershed was equipped with a Smith-type supercritical flow flume [*Smith et al.*, 1981], a stage recorder, and a sediment sampler. The flume is rated for flows of up to 1.4 m^3 s^{-1} and designed to prevent sediment deposition on the flume floor. The stage recorder consisted of stilling well, float, and recorder. Sediment samples were collected using a traversing slot sampler that obtains a depth-integrated sample of runoff [*Nichols et al.*, 2008]. The sampler arm with 13 mm opening is triggered when the flow depth in the flume exceeds 0.05 m. The sampler arm then moves at a uniform speed across the outlet of the flume and directs a portion of the flow into a conduit below the flume and further into plastic 2 L bottles placed in a conveyer. If less than 1 L of runoff is captured in one traverse, the sampling is repeated. The sampling intervals are 3 min during the first 15 min of runoff, 5 min between 15 and 30 min of runoff, and 10 min if runoff continues after 30 min. This ensures that the beginning of the hydrograph, which changes more rapidly, is more frequently sampled. Further details on sampler design and calibration is given by *Renard et al.* [1986]. After collection, runoff samples were weighed, oven dried, and weighed again to determine total sediment concentration. In 1999, the analog data recorder system was upgraded to a digital system that included new digital clocks, stage recorders, and data loggers.

2.3. Data and Analysis

[17] The data sets collected included (1) hyetographs of rainfall events with a temporal resolution of 5 min (analog data) and 1 min (digital data) and sensitivity of 0.25 mm,

Table 2. Names and Definitions of Variables Used in the Regression Analysis

Group	ID	Definition	Unit
Precipitation	P_t	Precipitation	mm
	P_i	Precipitation average intensity, event	mm h^{-1}
	P_d	Precipitation duration, event	min
	P_p	Precipitation peak intensity	mm h^{-1}
	I2	Maximum 2 min rainfall intensity	mm h^{-1}
	I5	Maximum 5 min rainfall intensity	mm h^{-1}
	I10	Maximum 10 min rainfall intensity	mm h^{-1}
	I15	Maximum 15 min rainfall intensity	mm h^{-1}
	I30	Maximum 30 min rainfall intensity	mm h^{-1}
	E	Energy of precipitation event (*Renard et al.* [1997])	MJ ha^{-1}
	API	Antecedent precipitation index	-
	MS	Precipitation season, monsoon or dry	
Runoff	Q_t	Runoff amount	mm
	Q_i	Runoff average rate, event	mm h^{-1}
	Q_p	Runoff peak rate	mm h^{-1}
	Q_d	Runoff duration	min
Sediment	S_y	Sediment yield	t ha^{-1}
	S_c	Sediment concentration	g L^{-1}
Watershed	A	Watershed area	ha
	S	Watershed average slope	-
	CR	Channel length-to-watershed area ratio	m ha^{-1}

(2) hydrographs with a temporal resolution of 1 min (analog data) and 0.25 min (digital data), and (3) sediment concentrations in the runoff samples. Sediment yield was calculated by integrating the product of sediment concentration, flow rate, and corresponding time interval. Total sediment yield was calculated for the events where three or more sediment samples were obtained. Runoff events with fewer sediment samples were considered to be inadequately sampled [*Nearing et al.*, 2007].

[18] Five groups of variables were compiled and used in the statistical analysis: precipitation, runoff, sediment, watershed, and management characteristics (Table 2). Antecedent precipitation index (API) was used to characterize antecedent moisture conditions in the absence of the actual soil moisture data. API can be an important factor that determines runoff and sediment generation [*Fedora and Beschta*, 1989] and was included in regression analysis. API on the watersheds was determined for every rainfall event using the following equation based on exponential decay [*Osborn and Lane*, 1969]:

$$\mathrm{API} = \sum_{i=1}^{n} P_i K^t, \tag{1}$$

where P is the precipitation (mm) in 1 h interval t hours before the event and the value of the coefficient K was 0.94.

[19] Rainfall, runoff, and sediment events were matched with each other based on their start and end time. Runoff events with missing rainfall data were assigned precipitation from the nearest rain gauge. The data were examined for outliers, leverage and influence, normal distribution of variables and residuals (Shapiro-Wilks and Kolmogorov-Smirnov normality test), linearity of model relationship, and collinearity.

[20] Linear regression models were used to describe relationship among runoff (Q_t), sediment yield (S_y), and independent variables [*Nearing et al.*, 2007] for each watershed separately and all watersheds combined (Table 2). The stepwise method [*SAS*, 2008], which combined forward-selection and backward-elimination steps, was used to select the most significant predictor variables. Relationships between S_y and some of these variables have elements of nonlinearity [*Bartley et al.*, 2006; *Nearing et al.*, 2007]; therefore, squares of predictor variables were also included in the analysis. In this procedure, the choice of optimal predictors is obtained from a sequence of F tests. The number of predictor variables in the resulting models was limited to one or two depending on the task. This prevented the models from being too closely tailored to a particular set of data, which could result in poor predictive precision and unstable regression coefficients. Obtained regression models were used to estimate the S_y for the events that either lacked sediment data or were inadequately sampled. These estimates were compared with the data collected in the field. In all statistical tests, $P = 0.05$ was used, unless otherwise indicated.

3. Results and Discussion

3.1. Rainfall Characteristics

[21] Average annual precipitation (P_t) during the period of record varied from 354 (gauge 4) to 458 mm (gauge 8) (Table 3). Average annual P_t was not significantly different

Table 3. Average Rainfall Characteristics on Watersheds in Santa Rita Experimental Range Between 1975 and 2008

		Month													
	Gauge	1	2	3	4	5	6	7	8	9	10	11	12	Year	n
P_t (mm)	1	23.3	23.6	20.5	8.9	6.5	8.3	78.1	66.1	38.4	28.8	16.9	29.3	349	2316
	2	24.2	23.4	21.5	9.2	6.9	9.3	80.0	70.6	40.7	29.9	17.9	30.1	364	2300
	3	24.2	24.2	21.3	9.8	7.5	7.5	73.7	67.3	38.3	28.9	17.6	31.3	352	2336
	4	23.2	23.9	21.2	9.3	7.1	7.2	75.0	66.5	36.8	27.7	16.4	30.5	345	2318
	5	25.8	24.6	23.7	10.1	7.6	12.0	96.2	85.6	43.2	31.1	18.8	31.5	410	2600
	6	27.2	25.3	24.5	10.1	7.7	11.7	97.2	87.3	43.5	32.7	20.7	30.5	418	2491
	8	30.6	28.4	27.7	11.8	8.5	13.1	105.5	94.5	47.9	35.0	20.9	34.2	458	2566
	Mean	25.2	24.5	22.7	9.8	7.3	9.8	85.7	76.1	40.8	30.3	18.3	30.8	381	
Event average:*															
I30 (mm)		2.6^{e}	2.7^{e}	2.9^{e}	3.0^{e}	3.3^{e}	6.4^{c}	8.8^{a}	7.7^{b}	7.3^{b}	5.6^{d}	3.4^{e}	2.7^{e}	5.6	
E (MJ ha^{-1})		$0.48^{d,e}$	$0.52^{d,e}$	$0.55^{d,e}$	$0.51^{d,e}$	0.44^{e}	0.81^{c}	1.27^{a}	1.09^{b}	1.13^{b}	1.01^{b}	0.63^{d}	0.61^{d}	0.87	
P_i (mm h^{-1})		3.0^{d}	$3.7^{c,d}$	2.6^{d}	3.3^{d}	$3.9^{c,d}$	$6.5^{a,b}$	$6.6^{a,b}$	7.7^{a}	$5.9^{a,b,c}$	$4.8^{b,c,d}$	3.2^{d}	2.6^{d}	5.1	
P_p (mm h^{-1})		6.8^{e}	6.8^{e}	6.7^{e}	$8.2^{d,e}$	10.1^{d}	21.3^{c}	29.2^{a}	25.7^{b}	25.5^{b}	18.7^{c}	$9.0^{d,e}$	5.9^{e}	17.7	
n		1488	1290	1164	567	591	561	3140	3170	1582	1122	873	1379	16927	

*Duncan's test. Numbers with the same letter within a row are not significantly different from each other at $P = 0.05$.

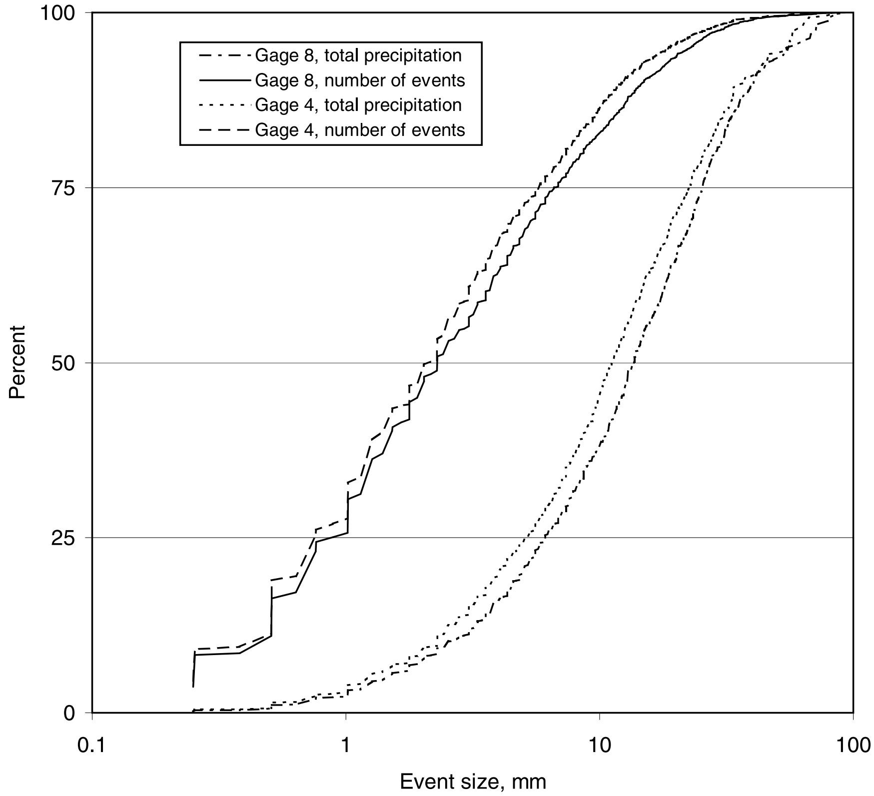

Figure 2. Relationship between size of rainfall events and their frequency and cumulative amount of precipitation (percent) that these events produce. The plot includes data from gauge 4 (smallest annual rainfall) and 8 (greatest annual rainfall) between 1975 and 2008.

among gauges 1, 2, 3, and 4 and among 5, 6, and 8 but was significantly different between these groups showing the effect of elevation on P_t (Tables 1 and 3). The monthly rainfall varied significantly, with 53% of the total rainfall occurring during the monsoon dominated months of July through September. The largest rainfall events, comprising only 10% of all events, accounted for nearly half of the total P_t (Figure 2). The magnitude of events with return periods of 1, 2, and 5 years was 33, 42, and 58 mm respectively. Average precipitation duration (P_d) varied throughout the year from 190 min in December to 50 min in June and was inversely correlated with precipitation average intensity (P_i), peak intensity (P_p), and maximum 30 min rainfall intensity (I30). The hyetograph pattern changed seasonally with the rainfall peak occurring approximately at one third of the length of the event during the monsoon and near the middle of the event for the rest of the year. Events with P_p less than 25 mm h^{-1} accounted for half of total P_t and 82% of the total number of events. The mean event energy (E), P_i, I30, and P_p at the different locations (gauges) were not significantly different from each other.

3.2. Runoff

[22] Overall, only 16% of rainfall events produced runoff. Average annual runoff depth (Q_t) varied depending on watershed between 7.7 and 39.7 mm with an overall average of 23 mm (Table 4). This represented between 1.9% and 11.5% of the amount of rainfall for individual watersheds and 6.4% on average.

[23] On all watersheds, I30 had the highest correlation to Q_t, explaining between 43% (WS 6) and 75% (WS 1) of its variation (Table 5). In five watersheds (WS 1–4 and WS 8),

Table 4. Runoff Characteristics on Watersheds in Santa Rita Experimental Range Between 1975 and 2008

	Watershed								
	1	2	3	4	5	6	7	8	Average
Number of events	365	288	482	548	382	270	383	346	
Average annual Q_t (mm yr^{-1})	18.8	16.4	33.1	39.7	21.8	7.7	21.3	24.8	23.0
Average event Q_t* (mm)	1.75^{a}	1.64^{a}	2.34^{a}	2.46^{a}	1.94^{a}	0.98^{b}	1.89^{a}	2.44^{a}	2.04
Q_t/P_t	0.078^{c,d}	0.073^{d}	0.117^{b}	0.139^{a}	0.082^{c,d}	0.035^{e}	0.070^{d}	0.094^{c}	0.092
Average Q_i (mm h^{-1})	1.87^{a,b,c}	2.04^{a,b}	1.82^{a,b,c}	2.18^{a}	1.54^{b,c}	0.67^{d}	1.45^{c}	1.99^{a,b}	1.75
Average Q_p (mm h^{-1})	7.24^{b,c}	7.53^{a,b}	7.02^{b,c,d}	9.16^{a}	5.62^{c,d}	2.65^{e}	5.37^{d}	8.06^{a,b}	6.83

*Duncan's test. Numbers with the same letter within a row are not significantly different among each other at P = 0.05.

Table 5. Regression Equation Coefficients for Runoff From the Watersheds[a]

Variables	Watershed 1	2	3	4	5	6	7	8	All Watersheds Combined
Intercept	−2.321 (285.3)[b]	−3.092 (104.1)	−2.645 (270.9)	−1.435 (107.2)	−2.031 (66.3)	−1.338 (34.0)	−2.109 (49.9)	−3.470 (116.9)	−2.458 (740.8)
P_t (mm)	0.073 (65.5)	0.076 (15.9)	0.148 (159.4)	0.428 (2074.3)				0.122 (51.4)	0.101 (293.0)
P_p (mm h^{-1})						0.009[c] (6.6)			
I05 (mm)					−0.038 (21.3)				
I10 (mm)							−0.126 (61.7)		
I30 (mm)	0.149 (476.5)	0.165 (124.6)	0.187 (337.2)		0.285 (262.7)	0.130 (12.8)	0.416 (217.9)	0.145 (134.6)	0.148 (989.1)
P_d (min)				−0.009 (430.4)					
n	365	288	482	548	382	270	383	346	3064
R^2	0.79	0.59	0.76	0.79	0.61	0.44	0.54	0.59	0.58

[a] $Q_t = k + a_1x_1 + a_2x_2$.
[b] F statistic for each parameter estimate is listed in parentheses.
[c] All parameters are significant at $P = 0.01$, except where indicated: $P = 0.05$.

the second most strongly correlated variable was P_t, which increased the regression's coefficient of determination (R^2) by additional 2%–9% and was a significant variable in all of these regression equations. On watersheds 5, 6, and 7, the second variable that improved the regression most significantly was I5, the maximum 5 min rainfall intensity. Additional variables assigned to the model further explained 1% (WS 6) to 5% (WS 8) of the variability. After limiting the number of predictor variables in the final model, we found that that the primary factor determining Q_t was not the total event precipitation P_t but the average intensity P_i and I5 through I30. Only small to moderate improvements to the models were achieved when the second and third variables were added. This could be attributed to the strong correlation (R^2 = 0.67–0.79) between P_t and I2 through I30.

[24] Antecedent precipitation index (API) varied between 0 and 24.3 with median value of 0.4 and was one of the four best predictor variables on six of the eight watersheds for Q_t. Although statistically significant, its contribution to the overall model improvement was small (1% improvement in R^2). Previous studies in Arizona [*Osborn and Lane*, 1969] and Spain [*Zabaleta et al.*, 2007] suggested that antecedent moisture conditions have limited effect on runoff in this type of environment, which is largely controlled by storm characteristics and soil permeability [*Schreiber and Kincaid*, 1967]. API could also have limited effect on regression because of low rainfall frequency. Only 15% of all rainfall events were preceded by another event within less than 24 h. Hence, most events occurred in "dry" antecedent conditions.

[25] Log transformation of predictor variables did not improve Q_t regression equations and produced lower correlation coefficients for all watersheds. Similar observations were made by *Osborn and Lane* [1969]. A possible explanation for such behavior is that the distribution of most of predictor variables was positively skewed, with many highly influential observations. When log transformed, these observations no longer had the leverage to favorably influence the coefficient of determination.

[26] When all watersheds were combined to produce a single model, I30 remained the primary predictor variable explaining 52% of Q_t variability, followed by P_t, P_i, and slope steepness (S), which added another 6% (Table 5). The slope steepness parameter had statistically significant but relatively little effect on the model, probably because the range of slopes among the watersheds was too narrow (2.8%–4.2%) to establish a robust relationship.

[27] The runoff threshold was estimated as an average for all watersheds using only the primary predictor variable (I30) in the regression equation. Ten mm of rainfall within 30 min was required in order for the runoff to initiate. *Osborn and Lane* [1969] reported a slightly lower value (8 mm) for similar sized semiarid watersheds in southeastern Arizona.

[28] Watershed 6 was the only watershed where mean Q_t, Q_i, and Q_p were significantly different from any other watershed (Table 4). In addition, it had the lowest regression R^2 and regression slope. The available set of variables did not provide an adequate explanation for this difference. However, visual observations suggest that WS 6 was less incised and better vegetated than the other watersheds and had partially vegetated channels.

3.3. Sediment

3.3.1. Measured Sediment Yields

[29] There were 824 successfully sampled sediment events on the eight watersheds during 34 years of observation (Table 6). On average, 26% of recorded runoff events produced sediment yields that were successfully measured. Most of the unsampled runoff events were not sampled for sediment because either the flows did not exceed the threshold runoff rates needed to trigger sampling, or the duration was too short so that the minimum of three samples were not taken. On average, an event generating 1.9 mm or more of runoff resulted in the collection of at least three sediment samples. Average annual S_y ranged between 0.85 on WS 6 and 6.69 t ha^{-1} yr^{-1} on WS 4 and was significantly different among watersheds. These values correspond well with the previously published data [*Lane et al.*, 1997; *Lane and Kidwell*, 2003; *Nearing et al.*, 2007; *Osborn et al.*, 1978] reporting sediment yields between 0.06 and 6.4 t ha^{-1} yr^{-1} on small watersheds less than 6 ha in southeastern Arizona.

[30] During the 34 years of observation, sediment yield was highly influenced by intense but infrequent events

Table 6. Sediment Yields From Watersheds in Santa Rita Experimental Range Between 1975 and 2008

	Watershed								
	1	2	3	4	5	6	7	8	Average
Measured for sampled runoff events									
n	126	75	111	199	123	57	49	84	103
Runoff events sampled (%)	35	26	22	36	32	20	13	24	26
Average* annual S_y** (t ha^{-1} yr^{-1})	1.43^{c,b}	1.10^{c}	3.81^{a,b}	5.48^{a}	3.91^{a,b}	0.44^{c}	1.03^{c}	1.63^{b,c}	2.35
Average S_c (g L^{-1})	9.4^{c}	7.8^{c,d}	16.9^{b}	16.3^{b}	24.5^{a}	5.2^{d}	7.9^{c,d}	10.7^{c}	13.9
Estimated for nonsampled runoff events									
n	243	220	379	358	267	226	341	265	
S_y per period (t ha^{-1})	17.9	22.9	117.0	89.4	107.8	7.3	32.5	22.4	
Average annual S_y (t ha^{-1} yr^{-1})	0.49	0.65	3.50	2.64	3.16	0.22	0.99	0.68	
Total for all runoff events									
Average annual S_y (t ha^{-1} yr^{-1})	1.92	1.75	7.31	8.12	7.06	0.66	2.02	2.31	
Estimated S_y (% of total)	27	38	48	33	46	33	49	29	

*Data for years 1975 and 2009 were incomplete and not used in calculation of annual average.
**Duncan's test. Numbers with the same letter within a row are not significantly different among each other at $P = 0.05$.

(Figure 3). For example, 10% of events with the largest sediment yields accounted for 66% of the total sediment yield on WS 6 and 48% of the total sediment yield on WS 7. In addition, the single greatest event on each watershed during the same period accounted for between 6% (WS 4, 10 t ha^{-1} yr^{-1}, 19 July 2007) and 22% (WS 6, 3.13 t ha^{-1} yr^{-1}, 14 August 2005) of the total sediment yield for the period.

3.3.2. Total Sediment Yields

[31] Statistical analysis showed that S_y was most strongly correlated with Q_t, Q_p, and P_t. The first step of the regression procedure was to find an equation with an intercept parameter and a single best predictor variable. Q_t was overall the best predictor for S_y on five out of eight watersheds and for the combined model (Table 7). The first variable entered into the model explained between 57% (WS 5) and 86% (WS 4) of S_y variation. The second variable added to the equation (not shown) increased regression R^2 by 1%–6%, and further expansion of the model yielded only minor improvements in R^2.

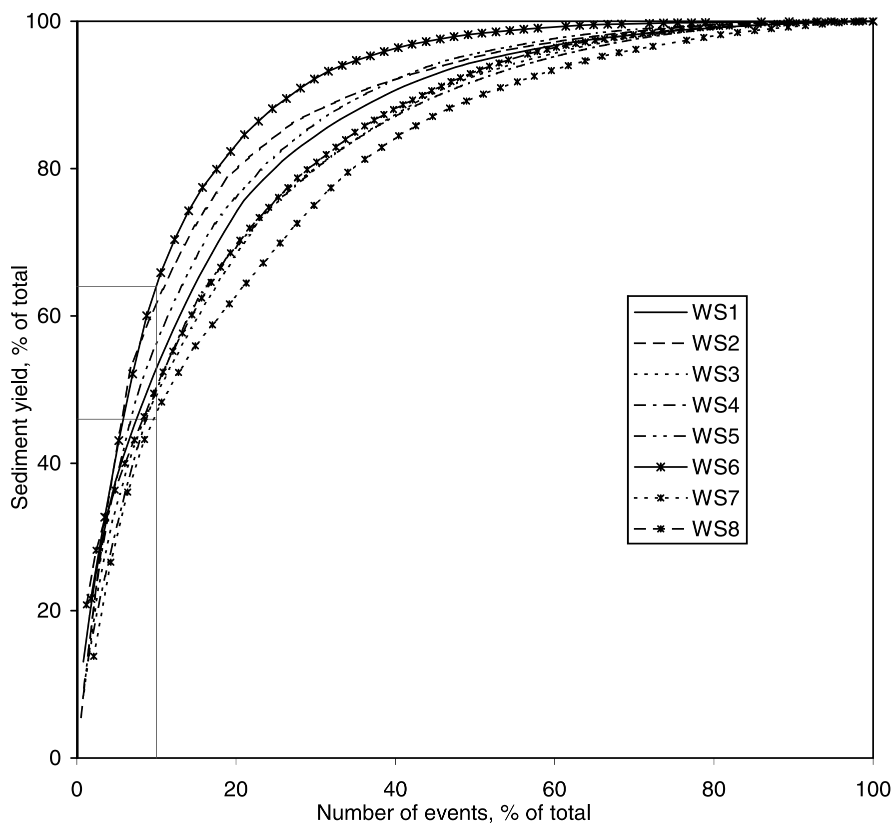

Figure 3. Relationship between frequency of sediment producing events (sorted from greatest to smallest) and sediment yield produced by these events.

Table 7. Regression Equation Coefficients for Sediment Yield From the Watersheds[a]

Variables	Watershed 1	2	3	4	5	6	7	8	All Watersheds Combined
n	124	74	111	197	121	57	49	83	816
Regression equation with nonzero intercept									
Intercept	0.124	−0.128[c]	−0.193[c]	−0.069[c]	−0.169[c]	−0.030[c]	0.115[c]	0.107[c]	0.069[b]
	(20.7)[d]	(3.7)	(3.6)	(2.0)	(1.2)	(0.6)	(2.4)	(1.4)	(2.9)
Q_t (mm)		0.113	0.247	0.215		0.090	0.067		0.150
		(258.2)	(443.9)	(1202.1)		(194.8)	(224.7)		(978.3)
Q_t^2 (mm^2)	0.008								
	(695.5)								
Q_p (mm h^{-1})					0.123				
					(156.5)				
Q_p^2 (mm^2 h^{-2})								0.001	
								(187.6)	
R^2	0.85	0.78	0.80	0.86	0.57	0.78	0.83	0.70	0.55
Regression equations using zero intercept									
Q_t (mm)		0.121	0.233	0.209		0.088	0.070		0.154
		(325.7)	(634.6)	(1744.1)		(252.3)	(330.6)		(1474.7)
Q_t^2 (mm^2)	0.009								
	(769.2)								
Q_p (mm h^{-1})					0.116				
					(236.9)				
Q_p^2 (mm^2 h^{-2})								0.001	
								(247.5)	

[a]$S_y = k + ax$.
All parameters are significant at $P = 0.01$, except where indicated: [b]$P = 0.05$ and [c]not significant.
[d]F statistic for each parameter estimate is listed in parentheses.
R^2 of regression equations with zero and nonzero intercept cannot be directly compared because of the different methods used to calculate sum of squared error.

[32] In four cases (WS 1, 7, 8, and the overall model), the intercept of the regression equation was positive, indicating positive predicted S_y at zero Q_t. In addition, the intercept parameter was not statistically significant for all but one (WS 1) equations. Relationships that include the intercept are biased toward larger events because only the data where sediment yield was successfully measured (three or more runoff samples) were used in the regression. Events with small S_y and/or small Q_t were underrepresented. Although these unsampled events, presumably, had little contribution to overall sediment yield, their exclusion from the regression analysis could result in the equation which underestimates large events and overestimates small events. This problem could be alleviated by forcing regression through the origin [*Nearing et al.*, 2007] or expanding the data set to include runoff events during which no sediment yield was recorded.

[33] These considerations warranted development of regression equations with a zero intercept (Table 7). Again, Q_t and Q_t^2 were the best overall predictors of S_y except on WS 5 and WS 8, where Q_p and Q_p^2 performed better. We used regression equations with nonzero intercept to predict S_y for events that produced more than 1.9 mm of runoff and equations with zero intercept for smaller events [*Nearing et al.*, 2007]. The results (Table 6) show that runoff events that were not sampled accounted for between 27% (WS 1) and 49% (WS 7) of the total S_y. Most of this amount (75%) was attributed to the events that had runoff greater than the threshold value of 1.9 mm and presumably were not sampled because of equipment failure.

[34] Several conclusions were drawn from the regression analysis. Q_t and Q_p were overall the most important factor for explaining variation in S_y. There was no significant correlation between S_y or S_c and API. In various studies API, which is an approximation for antecedent soil moisture conditions, was found to be a factor that influences runoff generation [*Osborn and Lane*, 1969] and sediment yield [*Seeger et al.*, 2004]. However, this may not be the case in watersheds characterized by flash flood-type runoff [*Zabaleta et al.*, 2007] or when majority of rainfall events occur in dry conditions (i.e., API = ~0), and the statistics did not show it to be a significant factor in this study.

[35] Contrary to expectations, topographic characteristics such as channel length to watershed area ratio (CR), watershed average slope (S), and watershed area (A) were not among the dominant factors controlling S_y in any of the regression equations. This can be attributed to the lack of major variation among the watersheds for these variables. Contributing area has been shown to be a good predictor of sediment yield in the semiarid environment [*Lane et al.*, 1997]. However, at this scale, which according to some definitions [*Lane et al.*, 1997] is a borderline between hillslope and subwatershed, sediment yield is largely controlled by rainfall amount, intensity, and ground cover rather than by area or channel characteristics. The latter become more important at larger scales.

3.3.3. Sediment Concentrations

[36] Total event Q_t and sediment concentrations (S_c) were correlated (R^2 = 0.53), with the watershed-averaged S_c ranging between 5.2 (WS 6) and 24.5 g L^{-1} (WS 5). However, instantaneous Q_i and S_c were poorly correlated for most events. Other researchers [*Bartley et al.*, 2006] reported similar observations on watersheds with intermittent flow. Closer examination of this relationship revealed that S_c varied with time during an individual event. Events with a single runoff peak produced a clockwise hysteresis (Figure 4). Given the same discharge, the S_c on the rising limb of the hydrograph was greater than the S_c on the falling limb of the hydrograph. A majority of the runoff events, however, had

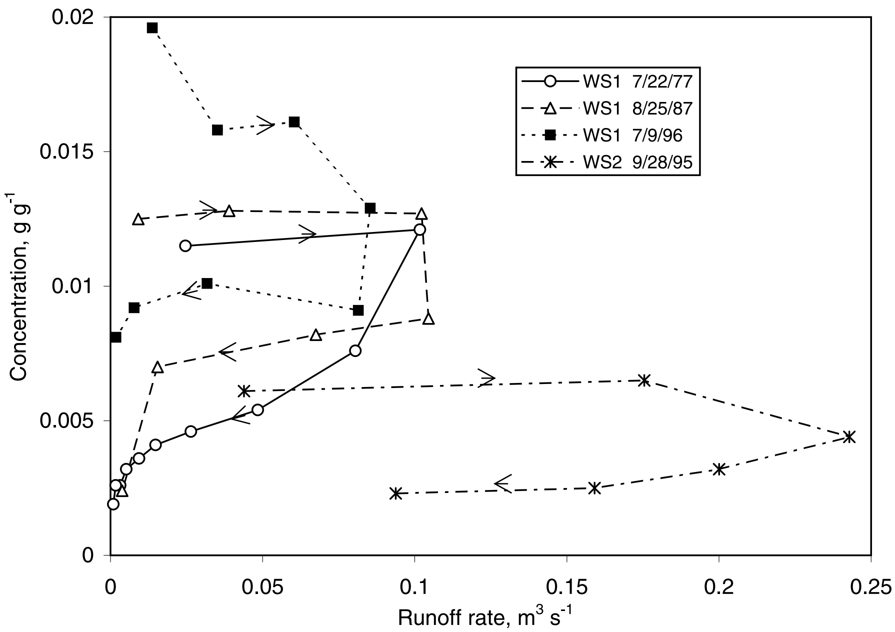

Figure 4. Hysteretic loops in relationship between discharge and sediment concentration for selected events with one runoff peak. All loops are clockwise.

two or more peaks and more complex patterns of instantaneous Q_i and S_c relationship, which could not be easily interpreted.

[37] This observation raises the question of antecedent sediment storage as a factor affecting S_y. Channel networks in this environment can store a considerable amount of loose sediment that may be readily available for transport [*Lane et al.*, 1997]. During the beginning of a runoff event, this material is easily entrained, resulting in high S_c. Further into the event the initial, readily available, source of loose sediment in the channels may become depleted, and new material must be detached from more consolidated slope areas. As a result, S_c cannot increase as rapidly as discharge, which results in a hysteretic loop. It is reasonable to assume that characteristics of the channel network, which transports the sediment through the watershed, define the form of the hysteretic loop. Similar sediment dynamics have been observed on other watersheds with a flash flood regime [*Zabaleta et al.*, 2007] and in perennial streams during flood events [*Doomen et al.*, 2008]. Redeposition of sediment in the channels complicates the relationship between erosion process and sediment yield [*Nichols*, 2006] and makes predicting the latter more difficult.

3.4. Temporal Changes in Runoff and Sediment Yield

[38] Temporal changes in hydrological processes were observed during the period of the study. The ratio of runoff to precipitation (Q/P) declined from the late 1980s through mid-1990s and also increased to high levels in the mid-2000s (Figure 5). Sediment yield (S_y) declined from mid-1980s through mid-1990s and increased to very high levels in the mid-2000s (Figure 6).

[39] Some of these changes may be the results of a statistically significant change in precipitation frequency distribution between 1975–1993 and 1994–2008 periods (Kolmogorov-Smirnov nonparametric test). Although the average event precipitation in 1975–1993 (5.6 mm) was greater and statistically different from the 1994–2008 period (4.6 mm), extreme events were more frequent during the later period. Rainfall events greater than 30 mm contributed 15% of the total precipitation in 1975–1993, whereas in 1994–2008, the contribution of same size rainfalls increased to 18% of the total. Mean annual value of I30 varied significantly between 3.5 (1995) and 8.8 mm (1999) but showed no particular temporal trend. The frequency distribution of I30 was not significantly different between the two periods. The decline of S_y during late 1980s and early 1990s is related to the absence of large sediment events (Figure 6). Examination of individual hyetographs and the resulting hydrographs of several major events during this period reveled that these were due primarily to low runoff amounts (Figure 5).

[40] Changes in vegetation abundance and composition may also account for some of the trends in S_y and Q/P after 1994. Increased S_y and Q/P between 1994 and 1998 may be associated with the temporary decline in grass and mesquite cover and long-term declines in burroweed cover [*McClaran et al.*, in press] following the 1994 fire on watersheds 5 through 8. The increase of S_y and Q/P after 2000 may be associated with the prolonged decline of grass cover (2.2%–0.4%) and density (9–4 plants m^{-2}) during the 2000–2006 drought [*McClaran et al.*, in press]. This has likely resulted in poorer soil protection from raindrop impact and affected water storage on watersheds, reducing the threshold at which runoff was initiated [*McIvor et al.*, 1995].

[41] In addition to these general patterns, WS 6 expressed a phase shift in S_y and Q/P in 1994, from anomalously low values between 1975 and 1994 to values more typical of the other watersheds. Sediment yield increased 140-fold from 0.006 in 1975–1993 to 0.96 t ha^{-1} yr^{-1} in 1994–2008,

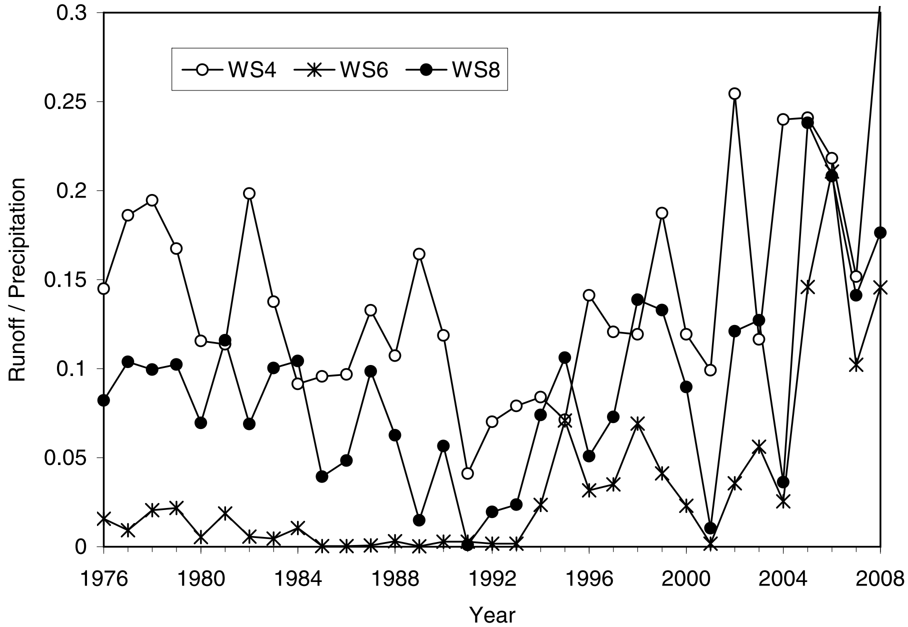

Figure 5. Annual runoff to precipitation ratio on watersheds 6, 4, and 8. The latter two receive, respectively, the smallest and the largest amount of annual precipitation among all watersheds.

whereas Q/P increased 13-fold during that time (Figure 5). On the basis of repeat photography of WS 6, fire- and drought-related changes in vegetation may have contributed to increased S_y and Q/P. However, it is possible that some of the phase shift is also the result of changes to the channel network (area-to-channel ratio) that began with the 1994 fire. Watershed 6 had the largest area-channel ratio (Table 2), and increasing S_y and Q/P may reflect recent channel development that is moving this watershed to the landscape norm.

[42] These long-term patterns clearly show that annual sediment yields were not entirely related to annual rainfall or large events. Rather, there may be complex interaction that involved plant surface cover (seasonal and long-term changes), rainfall timing when most erosive rainfalls of the year occur during the period of rapid plant growth and evolution of channel networks. Further research that includes measures of the size and density of drainage system in each catchment and vegetation conditions are needed to help resolve this issue.

4. Conclusions

[43] Measured runoff was 9.2% of the total amount of precipitation, and only 16% of rainfall events produced runoff. The primary factor that influenced runoff generation was the maximum 30 min precipitation intensity and to a lesser degree the total precipitation. This suggests that runoff generation was driven by the portion of rainfall that occurred at a high rate rather than its overall amount. Antecedent precipitation conditions had limited effect on runoff, which was largely controlled by storm characteristics and soil permeability. To initiate runoff 10 mm of precipitation must have had to occur within 30 min.

[44] On average, 26% of recorded runoff events produced sediment yields that were successfully measured. The range of average total sediment yields (0.7–8.3 t ha^{-1} yr^{-1}) in the current study was slightly higher than usually reported for similar size semiarid watersheds in the region. Total sediment yield consisted of measured and estimated parts. The latter was calculated for the events that were not sampled or undersampled using regression models with runoff amount as predictor variable. Two separate equations were utilized for events with runoff below and above an estimated sampling threshold of 1.9 mm. On average, unsampled and undersampled events were estimated to account for more than one third of the total sediment yield. This is a substantial amount, which means that smaller events cannot be disregarded as having negligible contribution to the overall watershed sediment yield. Antecedent sediment storage was thought to be an important factor controlling sediment yield. The presence of loose sediment in the channels readily available for transport at the beginning of event complicates establishing the relationship between runoff rate and sediment concentration.

[45] Long-term monitoring was found to be essential for accurate characterization of watershed processes. Runoff and sediment yields were highly variable. Between 6% and 22% of measured sediment yield for the eight watersheds for the entire 34 year period came from a single largest event. Therefore, lack of data on large events may lead to severe underestimation of sediment yield. In addition, sediment yields greatly increased following a fire and during a period of prolonged drought.

[46] Paired watersheds approach to study response to treatments may not be effective without pretreatment monitoring period. Watersheds are paired assuming their similar hydrologic conditions, which is rarely true. In our case, large differences in soils and vegetation existed between watersheds. Pretreatment period measurements are needed to more accurately determine the hydrological response to treatments. Grazing management effects could not be assessed because of lack of data to describe management. Long-term monitoring accompanied by more extensive and consistent field

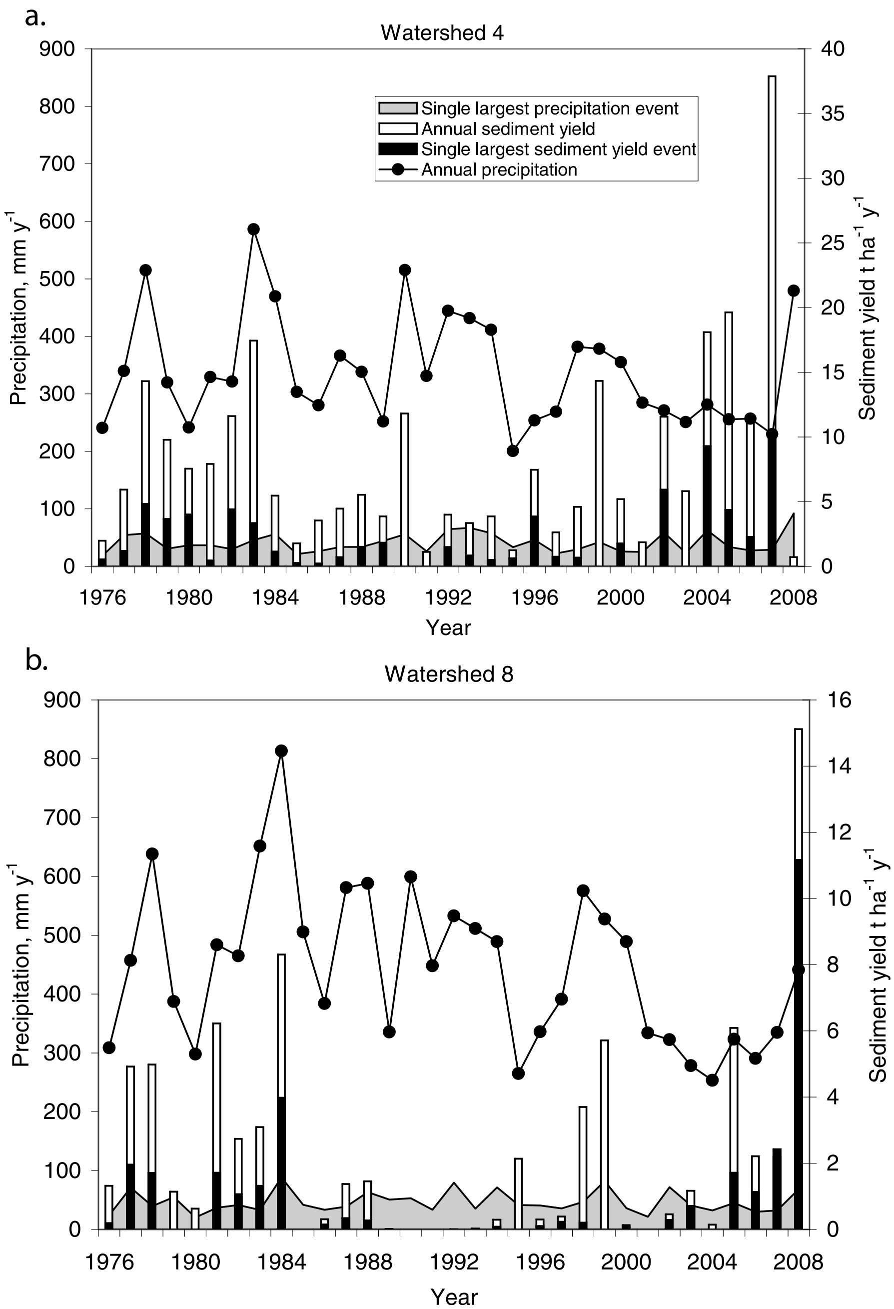

Figure 6. Precipitation and sediment yield on the watersheds with the smallest (watershed 4) and largest (watershed 8) average annual precipitation. Annual sediment yield combines measured values for sampled and predicted values for nonsampled events.

measurements of vegetation is critical for accounting for these factors.

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