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Sediment yields from unit-source semiarid watersheds at Walnut Gulch

M. A. Nearing,[1] M. H. Nichols,[1] J. J. Stone,[1] K. G. Renard,[1] and J. R. Simanton[1]

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[1] This study reports sediment yields from seven small (0.18–5.42 ha) watersheds in Southern Arizona measured from 1995 to 2005. Sediment concentrations and total event sediment yields were related to storm-runoff characteristics, and statistical relationships were developed to estimate sediment yields for events with missing data. Precipitation ranged from 263 to 298 mm yr^{-1}, runoff ranged from 8.2 to 26.4 mm yr^{-1}, and sediment yields ranged from 0.07 to 5.7 t ha^{-1} yr^{-1}, with an areal average of 2.2 t ha^{-1} yr^{-1}. For six of the seven watersheds, between 6 and 10 events produced 50% of the total sediment yields over the 11-year period. On the seventh watershed, two storms produced 66% of the sediment because of differences in the geomorphology and vegetation characteristics of that area. Differences between sediment yields from all watersheds were attributable to instrumentation, watershed morphology, degree of channel incision, and vegetation.

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1. Introduction

[2] Information on sediment export rates from small, upland watersheds in semiarid regions is limited. The nature of rainfall in semiarid climates is such that sediment-producing runoff events are infrequent, highly variable both spatially and temporally, and are often characterized by high runoff velocities and short durations when they do occur [*Renard and Laursen*, 1975]. Because of this high variability and infrequency, long measurement records are generally necessary in order to be able to characterize sediment export rates [*Reid et al.*, 1994].

[3] The Walnut Gulch Experimental Watershed (WGEW) has operated since the mid-1950s [*Renard and Nichols*, 2003]. During that time, various techniques have been used for measuring runoff and sediment export from several unit-source watersheds within Walnut Gulch (J. J. Stone et al., Long-term runoff database, WGEW, Arizona, USA, submitted to Water Resources Research, 2007; M. Nichols et al., Long-term sediment database, WGEW, Arizona, USA, submitted to *Water Resources Research*, 2007). A ''unit-source'' watershed is described by *Kincaid et al.* [1966] as ''a natural drainage area that has relatively homogeneous soils and vegetation cover, that is subject to essentially uniform precipitation,'' and is ''intermediate (in research approach) between small plots, in which certain runoff and sediment generative influences can be isolated, and large watersheds, the yields of which are influenced by the hydraulics of their complex channel systems.''

[4] *Simanton et al.* [1993] investigated the effect of sediment sampling equipment on measured sediment yields from Lucky Hills watersheds 63.103 and 63.104 in Walnut Gulch using data collected from 1973 through 1980. These watersheds were monitored with V notch weirs with stilling basins from 1973 to 1976 for 63.103 and from 1973 to 1977 for 63.104. Suspended sediment was collected using a pump sampler and a depth-integrating sampling tube (the sampling tube was attached to a float that raised the top of the tube to the top of the flow level). From 1977 for 63.103 and 1978 for 63.104, flow was measured with a supercritical flow, Santa-Rita style flume [*Smith et al.*, 1981] and sediment was sampled with a depth-integrated, ''total load'', traversing slot sampler [*Renard et al.*, 1986]. The analysis of *Simanton et al.* [1993] showed that the ratio of measured sediment yield (kg/ha) to runoff depth (mm) was approximately two and a half times greater for the total load sampler compared to the suspended load sampler. However, when the event sediment yield computed on the basis of pump samples was adjusted by adding the mass of sediment deposited behind the weir after each event, the ratio of measured sediment yield (kg/ha) to runoff depth (mm) per event was statistically the same as those calculated from the traversing slot sampler data.

[5] *Osborn et al.* [1978], using data collected from 1973 to 1976, compared sediment yields from three shrub watersheds (63.103, 63.104, and 63.105) in the Lucky Hills area to a grass site in the Kendall area (63.112). Note that watersheds 63.103 and 63.104 were the same used by *Simanton et al.* [1993], discussed above. Their primary conclusion was that sediment yields from the shrub sites, which reportedly ranged from 1.8 to 6.4 tonnes ha^{-1} yr^{-1}, was as much as 10 times greater than that from the grassland site (0.14 tonnes ha^{-1} yr^{-1}). However, these values were later refined, as reported in publications such as those of *Osborn and Simanton* [1989] and *Simanton et al.* [1993]. Both of those papers reported average annual values of sediment yields of 3.56 and 1.21 tonnes ha^{-1} yr^{-1} for 63.103 and 63.104, respectively, for the time period 1973 through 1980.

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[1] Southwest Watershed Research Center, USDA-ARS, Tucson, Arizona, USA.

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Table 1. Watershed Characteristics (Size, Slope, Cover)

Watershed	Area, ha	Watershed Gradients, %	Mean Watershed Elevation, m	Predominant Cover Type
102	1.46	10.5	1365	Shrub, Creosote, Whitethorn
103	3.68	7.8	1365	Shrub, Creosote, Whitethorn
104	4.53	10.5	1360	Shrub, Creosote, Whitethorn
105	0.18	10.3	1364	Shrub, Creosote, Whitethorn
106	0.34	8.9	1364	Shrub, Creosote, Whitethorn
112	1.86	12.5	1518	Grass, Blue and Black Grama
121	5.42	10.3	1376	Shrub, Creosote, Whitethorn

[6] *Nearing et al.* [2005] showed that the differences in sediment yields between the grass and shrub sites were controlled predominantly by watershed morphology rather than by cover conditions per se. In that study, ^{137}Cs measurements were used to quantify hillslope erosion and deposition rates within watersheds 63.103 (shrub at Lucky Hills) and 63.112 (grassland at Kendall) and to compute the net losses and gains from the two watersheds on the basis of the erosion and deposition rates. Results of that study indicated that the mean erosion rates on areas of net erosion were 5.6 and 3.2 t ha^{-1} y^{-1} on the shrub and grass watershed, respectively, but that the grass site had a swale area at the bottom of the hillslopes where nearly all of the eroded material from the hillslopes was deposited.

[7] The objective of the current study was to quantify sediment export rates from seven unit-source watersheds located in southeastern Arizona for the time period from 1995 to 2005. Sediment concentrations and event sediment yields were related to storm-runoff characteristics. Statistical relationships were developed to estimate sediment yields for events with missing data and then used to estimate total sediment yields for the period of record for each of the watersheds. Data were interpreted within the context of the geomorphology and vegetation characteristics of the area.

2. Methods

2.1. Site Information

[8] The unit-source watersheds studied were located in southeastern Arizona on the Walnut Gulch Experimental Watershed located near Tombstone, AZ, USA, which is operated by the US Department of Agriculture (USDA)-Agricultural Research Service (ARS) Southwest Watershed Research Center located in Tucson, AZ. The seven watersheds ranged in size from 0.18 to 5.42 ha (Table 1 and Figure 1). Representative watershed gradients and mean elevations reported in Table 1 were calculated from 1-m-grid Lidar measured elevations.

[9] Watersheds 63.102, 63.103, 63.104, 63.105, and 63.106 are located in what is referred to as ‘‘Lucky Hills,’’ which has been the site of a variety of intensive scientific studies since the 1960s. Watersheds 63.102 and 63.106 are nested within 63.104. The vegetation in the area is dominated by desert shrub. Canopy cover in Lucky Hills during the rainy season is approximately 25%, and approximately two thirds of the ground area is covered with rock (alluvial outwash consisting predominantly of gravel- and cobble-sized material) and the remaining one-third is bare soil. The shrub plant community is dominated by creosotebush (*Larrea divaricata*), whitethorn Acacia (*Acacia constricta*), mariola (*Parthenium incanum*), and tarbush (*Flourensia Cernua*) (D King et al., Assessing vegetation change temporally and spatially in Southeastern Arizona, submitted to *Water Resources Research*, 2007, hereinafter referred to as King et al., submitted manuscript, 2007). Watershed 63.121 is located in a similar type of shrub-dominated ecosystem.

[10] Watershed 63.112, located in an area referred to as ‘‘Kendall,’’ is located at a higher elevation in the watershed

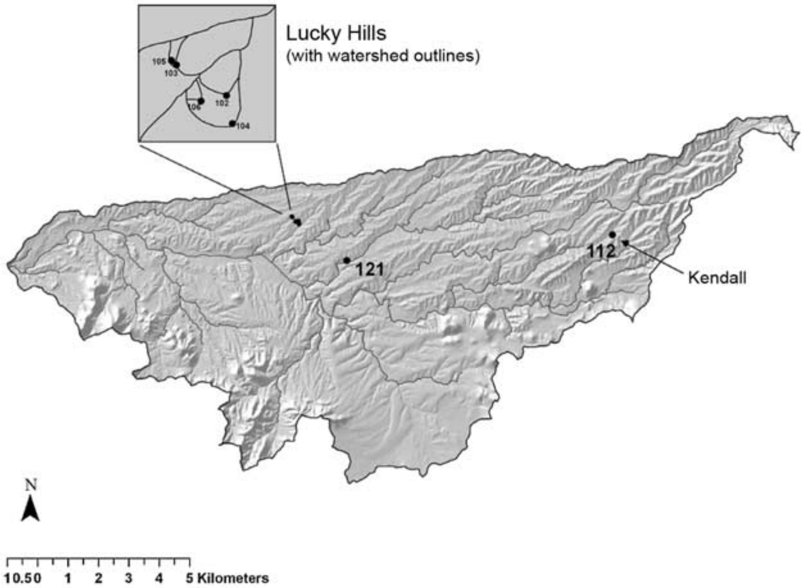

Figure 1. Map of Walnut Gulch with location of the watershed instrumentation.

(Table 1). In contrast to the Lucky Hills watersheds, vegetation on the Kendall watershed is dominated by grass and forbs with a trace of shrubs and succulents. Canopy cover is approximately 35%. Ground cover during the rainy season has been measured at 28% rock, 42% litter, and 14% basal cover (area covered by plant bases). The Kendall site is dominated by herbaceous vegetation, predominately black grama (*Bouteloua eriopoda*), side-oats grama (*Bouteloua curtipendula*), three-awn (*Aristida sp.)*, Lehman's Lovegrass (*Eragrostis Lehmanniana*), and cane beardgrass (*Bothriochloa barbinodis*) (King et al., submitted manuscript, 2007).

[11] The mean annual temperature at Walnut Gulch Experimental Watershed is approximately 18°C. Average monthly maximum temperatures of 35°C occur in June, with an average monthly minimum temperature of 2°C in December. Two thirds of the annual precipitation falls during the "monsoon" season from July through September, and much of the remainder is concentrated in the winter months of December through February [*Nichols et al.*, 2002]. The channels in Walnut Gulch Experimental Watershed are dry approximately 99% of the time.

[12] These watersheds have historically served as grazing land for cattle and horses. The shrubland was probably severely eroded by the early 1900s because of an overgrazing period from approximately 1880 to 1930. The Kendall (63.112) watershed apparently experienced less severe degradation during that time than did the other watersheds, probably because of the fact that it is located farther from available water sources.

[13] The watersheds are located on a deep, Cenezoic alluvial fan. The soil in the shrub areas is a gravelly sandy loam with approximately 52% sand, 26% silt, and 22% clay. At Kendall (63.112), the soil is gravelly sandy loam with approximately 55% sand, 20% silt, and 25% clay. The organic carbon content of the soils is generally low (less than 1%), though slightly greater in 63.112 (between 1 and 2%) than in the other watersheds studied.

[14] Watersheds 63.102, 63.103, 63.104, and 63.121 are drained by well-developed, incised channel networks that efficiently deliver eroded particles to the watershed outlets. Watersheds 63.105 and 63.106 are smaller than the others and do not have highly incised channels, but also do not have toe-slope areas of noticeable deposition and sediment storage. Watershed 63.112 is drained by concentrated flow paths that terminate in a swale above the outlet. The swale is a site of water and sediment storage within the watershed [*Nearing et al.*, 2005].

2.2. Instrumentation

[15] Runoff and sediment were measured with calibrated, Santa-Rita type supercritical flumes and traversing slot sediment samplers at the outlets of watersheds 63.102, 63.103, 63.104, and 63.121 [*Smith et al.*, 1981], H flumes and pump samplers at watersheds 63.105 and 63.106, and with a V notch weir and pump sampler at watershed 63.112 [*Simanton et al.*, 1993].

[16] The Santa Rita flumes were designed such that flow accelerates to supercritical velocities in order to ensure that sediment was not deposited in the flume bottom. Flow stage was measured with a standard stilling well and float. Sediment was sampled by an automatic traversing slot sampler, which took a depth-integrated sample at specified time intervals within a flow event [*Renard et al.*, 1986]. Between flows, the traversing arm of the slot sampler rested in an out-of-flow position. At a prescribed flow depth threshold, the arm was activated to begin the sampling process. The sampling arm traversed the width of the flow at a uniform velocity until a minimum 1-liter volume was captured. The slot sampled at 3-min intervals for the first 15 min of the runoff, at 5-minute intervals for the next 15 min, and after that at 10-min intervals. The sampler inlet was 13 mm wide. Calibration tests of the traverse slot sampler showed measurements well correlated to depth-integrated samples taken with a US D-48 or dip sampler [*Renard et al.*, 1986].

[17] Sediment passing through the H flumes and V notch weir was sampled with automatic pump samplers that collected depth-integrated samples [*Brakenseik et al.*, 1979]. A perforated pump tube was anchored to the center floor of the flume or weir pond, and a float raised the free end of the tube in response to flow, thus sampling the full depth of the flow. The size of the sampled sediment was limited by the 6.4-mm-diameter perforations on the sampler arm. Sampling intervals were similar to those of the traversing slot samplers.

[18] The number of events for which sediment yield values were computed is less than the number of flow events for a variety of reasons. In many cases, either the flows did not exceed the threshold runoff rates needed to trigger sampling, or the flow duration was so short that the minimum of three samples were not taken. Given the variability in the sampled sediment concentrations, we arbitrarily set a threshold of three samples as a minimum for calculating reliable values of event sediment yields. An event was considered to have been "successfully" sampled if the hydrograph was successfully obtained and three or more sediment samples were collected. In addition to hydrologic limitations for obtaining sediment samples, mechanical failures were not uncommon. The traversing slot system failed in cases where debris was caught between the slot arm and the flume causing the device to cease functioning. Other problems included mechanical or sensor failure that resulted in overfilled bottles, rat's nests or other debris in bottles, and sample bottles that broke or spilled.

[19] Rainfall was measured with weighing-type recording raingages. The 150 km^2 Walnut Gulch Experimental Watershed is instrumented with 88 such gages, and the gages located nearest to each of the seven unit-source watersheds were used (D. C. Goodrich et al., Long-term precipitation database, Walnut Gulch Experimental Watershed, Arizona, United States, submitted to *Water Resources Research*, 2007) for analyses. Raingage 384 was used for watersheds 63.102, 63.104, and 63.106; raingage 386 was used for watersheds 63.103 and 63.105; raingage 398 was used for watershed 63.121; and raingage 82 was used for watershed 63.112. The maximum distance from raingage to watershed boundary was 20 m in the case of watershed 63.106.

2.3. Data Analyses

[20] Data were compiled for six of the seven watersheds for the period of 1995–2005. For 63.102, sediment data were not collected prior to 1998, so for the period 1995 through 1997, rainfall and runoff data were included in the analysis and the sediment data were treated as missing events. Data included rainfall, within-storm runoff rates

Table 2. Measured Precipitation and Runoff for the Seven Watersheds Over the 11-Year Time Period 1995–2005

	Total Measured Precipitation Depth		Average Annual Precipitation	Total Measured Runoff Volume		Average Annual Runoff Depth	
Watershed	Event Count	mm	mm	Event Count	m^3	mm	Percent of Precipitation
102	726	2893	263	73	2935	18.3	7.0
103	734	2935	267	78	7604	18.8	7.0
104	726	2893	263	60	5340	10.7	4.1
105	734	2935	267	70	522	26.4	9.9
106	726	2893	263	67	891	23.8	9.0
112	796	3274	298	28	1669	8.2	2.8
121	718	2958	269	73	8337	14.0	5.2

(hydrographs), total storm-runoff volumes, and within-storm sediment concentrations.

[21] Linear statistical correlations were computed between sediment concentrations and characteristics of the intra-storm dynamics. This was done in order to determine statistical significance between sediment concentrations and both flow-discharge rates and time from runoff initiation. Event sediment yields were computed by integrating the measured sediment concentrations multiplied by flow rates over the time of the runoff. Total storm sediment yields were computed for every event that had a minimum of three sediment samples collected. Linear correlations were run between storm sediment yields and event runoff volume and peak runoff rate, and then stepwise regression (α = 0.05) was used to develop statistical models for each watershed. These models were used to estimate the sediment yields for all of the events lacking sediment data, thus creating a complete estimated sediment record for all seven watersheds for the period 1995–2005. Comparison between the measured and estimated sediment yields provided insight into the effectiveness of the sampling methods for quantifying total sediment exports for these types of watersheds.

[22] Frequency distributions of sediment yields were created by ranking the sediment yield values from greatest to least for each watershed and then computing total sediment yield as a function of percentage of events contributing.

3. Results

3.1. Precipitation and Runoff

[23] Average annual measured precipitation during the period of record ranged between 263 and 298 mm, which came from between 718 and 796 measured precipitation events over the 11-year period (Table 2). Average annual runoff depth (runoff volume divided by area of watershed) ranged from 8.2 to 26.4 mm, which represented between approximately 3 and 10% of the annual rainfall depth. The fraction of precipitation events that produced runoff was of the order of 10% or less.

3.2. Sediment Concentrations

[24] The number of successfully sampled sediment events from each flume ranged from 19 to 41 for the 11-year period (Table 3). Sediment collection success rates ranged from approximately 70 to 80% (Table 3), with the exception of watershed 63.102, which was not in operation during the first 3 years of the period. Average sample concentrations from the watersheds varied greatly. Mean concentrations ranged from 0.8 to 3.0% (8–30 mg l^{-1}) for samples taken by the slot samplers, 0.2 to 0.3% (2–3 mg l^{-1}) for

Table 3. Number of Runoff Events That Were Measured for Sediment and Those not Measured for Sediment Because Runoff did not Exceed Minimum Thresholds of Rate or Time, Event Occurred When Equipment was Inactive, or Sampling Failed

	Runoff Event Count	Events Below Collection Thresholds[a]	Flume not Operational[b]	Sediment Sampling Failures	Successfully Measured Sediment Events	Success Rate[c]
Watershed	n	n	n	n	n	%
102	73	9	19	22	23	51
103	79	27	1	10	41	80
104	60	8	1	17	34	67
105	70	22	2	15	31	67
106	68	15	4	11	38	78
112	34	9	0	6	19	76
121	74	26	0	8	40	83

[a] Events for which either the flow depth did not exceed the minimum flow depth threshold so as to trigger sediment sampling or flow duration above the minimum flow depth threshold was not long enough to obtain three sediment samples.

[b] Period when sediment instrumentation was inactive either because it was during the winter or, for the case of 17 events at flume 102, it was before the sediment sampler was installed and first operational in 1998.

[c] Fraction of flows above threshold depth and duration that were successfully measured.

Table 4. Measured Sediment Concentrations for the Watersheds for the 11-Year Time Period 1995–2005, Pearson Correlation Coefficients Between Sediment Concentrations, Instantaneous Flow-Discharge Rate, and Time During Storm

Watershed	Number of Concentration Samples n	Mean Sediment Sample Concentrations % (mg l^{-1})	Standard Deviations of Sample Concentrations %	Flow Discharge Rate	Time During Storm
102	126	1.27 (12.7)	0.47	NS	−0.178[a]
103	255	2.96 (29.6)	1.74	NS	−0.271[c]
104	184	1.35 (13.5)	0.95	NS	−0.144[a]
105	147	0.22 (2.2)	0.19	+0.432[c]	−0.338[c]
106	221	0.28 (2.8)	0.26	+0.409[c]	−0.249[b]
112	127	0.061 (0.61)	0.055	+0.339[c]	NS
121	288	0.77 (7.7)	0.68	+0.404[c]	−0.325[c]

NS indicates not significant at $P = 0.05$.

[a] Indicates significance at the $P = 0.05$ level.

[b] indicates significance at the $P = 0.01$ level.

[c] indicates significance at the $P = 0.001$ level.

concentration samples from the pump samplers at the H flumes, and 0.06% (0.6 mg l^{-1}) for samples from the pump sampler at the weir (Table 4). Statistical analyses showed significant correlations between concentrations and both flow-discharge rates and time during the storms (Table 4).

3.3. Measured Sediment Yields for Storm Events

[25] Sediment yields calculated by summing the measured event yields for the 11-year period of 1995–2005 ranged from 768 to 172,645 kg for the seven watersheds (Table 5). These values do not represent total yields for the watersheds for the time period because they do not include estimates for unsampled events (Table 3). Event sediment yields were very significantly correlated to event runoff volumes for every watershed (Table 6).

3.4. Regression Equations for Filling Gaps in the Sediment Record

[26] Sediment yields were statistically correlated to runoff volume, peak runoff rate, and the squares of both of those variables for all of the watersheds (Table 6). However, the strength of the correlation to these variables varied among the watersheds. Therefore, in developing regression equations, we chose to use a stepwise regression approach with the four independent variables of runoff volume, peak runoff rate, square of runoff volume, and square of peak runoff. Results for both regression with intercept and regression through the origin are shown in Table 7. Nonlinear regressions aimed at more precisely defining the exponents of runoff and peak runoff for predicting sediment yields did not appreciably improve results over the exponent values (1 and 2) reported in Table 7.

3.5. Estimated Sediment Yields for Period of Record

[27] The regression equations from Table 7 were used to estimate sediment data for runoff events during the period of 1995–2005 where measured sediment yields were missing. We found that the use of the regression equations with nonzero intercepts were superior for estimating sediment yields for large storms, which are most important for determining sediment totals for the watersheds. However, for most of the watersheds, the use of the regressions with nonzero intercepts overestimated sediment yields for the smallest events. Therefore we used the zero-intercept equations to estimate sediment yields for events where the flow rate did not exceed the threshold value for collecting sediment, and the nonzero-intercept equations were used in the absence of measured sediment for the larger events.

[28] A summarization of the combined measured and estimated sediment totals are reported in Table 8. Average annual sediment yields ranged from 0.07 to 5.7 tonnes ha^{-1} yr^{-1}. The modeled sediment yield constituted between 8 and 49% of the total estimated sediment loads. The areally weighted average over the seven watersheds was 2.2 tonnes ha^{-1} yr^{-1}.

Table 5. Measured Rainfall, Runoff, and Sediment Yields for Events With Measured Sediment Yields the Seven Watersheds for the 11-Year Time Period 1995–2005[a]

Watershed	Event Count	Rainfall Depth, mm	Runoff Volume, m^3	Runoff Depth, mm	Measured Sediment Yield, kg
102	23	495	1,688	116	20,720
103	41	787	5,813	158	172,645
104	34	691	4,815	106	53,974
105	31	558	278	154	768
106	38	722	683	201	2419
112	19	617	1498	81	1289
121	40	837	6,620	122	68,333

[a] This does not represent total yields for the watersheds but only the yields for events with measured sediment.

Table 6. Pearson Correlation Coefficients Between Storm Sediment Yields and Runoff Volume, Peak Runoff Rate, Square of Runoff Volume, and Square of Peak Runoff for Storm Events for the 11 Year Time Period 1995–2005

Watershed	Number of Measured Events	Event Runoff Volume	Event Peak Runoff	Event Runoff Volume Squared	Event Peak Runoff Squared
102	23	0.954	0.904	0.916	0.904
103	41	0.838	0.913	0.838	0.913
104	34	0.851	0.895	0.753	0.906
105	31	0.692	0.880	0.537[a]	0.888
106	38	0.857	0.899	0.825	0.922
112	19	0.866	0.830	0.754	0.745
121	40	0.938	0.921	0.831	0.875

All other correlations were significant at $P = 0.001$.

[a] Indicates significance at the $P = 0.01$.

[29] Frequency distributions of sediment yields for each watershed are displayed in Figure 3. For all of the seven watersheds, the largest sediment-producing storm value was measured and not estimated.

4. Discussion

4.1. Sediment Concentrations

[30] In cases where sediment concentrations were significantly correlated to flow-discharge rate within the storm period, the correlations were positive (Table 4). Greater flow rates corresponded to greater concentrations. For most of the watersheds, concentration was negatively correlated to time during the event (Table 4). This could be due to a flushing of readily available sediment early in the storm event. However, the correlation coefficients were not exceedingly high, and not every storm showed the pattern of decreasing concentration with time. Evidence from another study (B. T. Yuill et al., Characteristics of sediment transported in a low-order ephemeral watershed, submitted to Hydrological Processes, 2007) using sediment data from Walnut Gulch suggested that the within-storm time dependence of sediment concentrations is complex and is related to the size distribution of the sediment material. That study suggests that different size classes of sediment exhibit different within-storm concentration trends, with finer particles generally showing greater concentrations early in the flow and with concentration of coarser particles remaining steady or peaking later in the period of flow. In the current study we did not measure the particle size distributions of the sediment.

[31] The within-storm time-dependence of sediment concentration has implications for the way in which the data can be analyzed. If the concentration samples were randomly variable within events, then the calculations of total event sediment yields would have been a straightforward matter of multiplying the average sediment concentrations of the storm with the total storm discharge. Also, we would have been able to directly calculate statistical confidence intervals for sediment yields. Since such was not the case, sediment yield totals for storms were derived by integration of the sediment concentration curves multiplied with the hydrographs, as described in section 2 above, and we did not address the issue of confidence intervals for sediment measurements in this study.

4.2. Measured Sediment Yields for Storm Events

[32] A plot of the logarithm of sediment yields for measured events to the logarithm of runoff volumes showed that the data could be roughly separated into three groupings (Figure 2). These groupings correspond to sampling equipment and the influence of physical and biological characteristics of the watersheds. The watersheds with traversing slot samplers, which are all located on shrub sites and had drainage areas greater than a hectare in size, fell into the category of having the greatest sediment yields as a function of runoff volume. This makes sense in light of the greater sediment concentrations from those watersheds

Table 7. Regression Equations Between Measured Sediment Yields, SY (kg), and Storm Characteristics Based on Data From the 11-Year Time Period 1995–2005[a]

Watershed	Number of Measured Events	Best fit Regression Equation	r^2
102	23	SY = 11.49 × ROV + 57.64	0.91
103	41	SY = 25,450 × Peak + 8.98	0.83
104	34	SY = 13,155 × Peak2 + 430.67	0.85
105	31	SY = 39,274 × Peak^2 + 6.48	0.79
106	38	SY = 27,355 × Peak^2 + 17.38	0.85
112	19	SY = 0.843 × ROV + 1.37	0.75
121	40	SY = 10.48 × ROV − 25.57	0.88

Watershed	Number of Measured Events	Best fit Regression Equation through Origin	[b]r^2
102	23	SY = 11.98 × ROV	0.91
103	41	SY = 25,476 × Peak	0.83
104	34	SY = 14,821 × Peak^2	0.85
105	31	SY = 1,618.7 × Peak	0.77
106	38	SY = 20,221 × Peak^2 + 1.497 × ROV	0.86
112	19	SY = 0.847 × ROV	0.75
121	40	SY = 6.48 × ROV + 4,018.2 × Peak	0.91

[a] Stepwise regression was used with $\alpha = 0.01$ set as criteria for both entry and exit of variables into and out of the model. Storm characteristics used in the regressions included runoff volume, ROV (m^3), peak runoff rate, peak (m^3/s), and the squares of each of those values.

[b] In the case of the regressions through the origin, true coefficients of determination cannot be directly calculated from sum of squares methods. These reported values were calculated on the basis of regression of the sediment yield values calculated by the regression equation and the measured sediment yields so as to be more directly comparable to the corresponding r^2 values for the standard regressions.

Table 8. Measured Runoff and Estimated Sediment Yields for Events With Measured Runoff for the Seven Watersheds for the 11-Year Time Period 1995–2005[a]

Watershed	Event Count	Runoff Volume, m^3	Runoff Depth, mm	Estimated Sediment Yield, kg	Average Annual Sediment Yield, t ha^{-1} yr^{-1}	Ratio of Measured to Total Estimated Sediment, %
102	73	2,935	201	37,065	2.31	56
103	78	7,604	207	229,071	5.66	75
104	59	5,340	118	68,005	1.36	79
105	70	522	290	1,493	0.75	51
106	67	891	262	2,993	0.80	81
112	28	1,669	90	1402	0.07	92
121	73	8,337	154	87,219	1.46	78

[a] This represent total estimated sediment yields for the watersheds using the combination of measured data and sediment yields computed from the regression equations in Table 7.

(Table 4). The second grouping of data is that from the smaller watersheds located on shrub sites that have H flumes with pump samplers, and the third grouping is the lone watershed 63.112, which has a pump sampler behind a V notch weir and is located on a grassed site (Figure 2). Watershed 63.112 also had the lowest measured concentrations of sediment (Table 4).

[33] Figure 2 clearly shows the general differences between the three classes of sediment data and thus provides a basis for discussion of the results from this study. The equations displayed in Figure 2 could be useful for calculating rough estimates of sediment yields from similar ungaged unit-source watersheds in this or similar areas. They are not, however, the best relationships to use for the purpose of estimating gaps in the sediment record. For example, the function 5.26 × runoff volume $(ROV)^{1.231}$ underrepresents sediment yield for watershed 63.103 by an average of 40% for the measured storms, whereas the equations for that watershed shown in Table 7 produce an unbiased estimate of the sediment yields for each storm.

4.3. Differences Between Data From the Slot Samplers and the H Flumes With Pump Samplers

[34] The differences displayed in Figure 2 between the data from the traversing slot and those from the pump samplers on the H flumes are probably due to two factors. For one, we know that the pump samplers can sample only up to about 6.4-mm particles, while the traversing slot can sample up to 13-mm-diameter material. In these watersheds, where there exists a high level of coarse material in flow, those differences would be expected to be significant. Secondly, watersheds 63.105 and 63.106 have less incised channels to act as sources of sediment.

[35] *Simanton et al.* [1993] developed zero-intercept regression equations between sediment yield and runoff volume for data from watersheds 63.103 and 63.104 for data collected with the traversing slot samplers for the time periods of 1977–1980 for 63.103 and of 1978–1980 for 63.104. Using units compatible with those used here, *Simanton et al.* [1993] reported:

$$SY = 19.3\ ROV\left(r^2 = 0.88\right) \tag{1}$$

and

$$SY = 8.0\ ROV\left(r^2 = 0.86\right) \tag{2}$$

for watersheds 63.103 and 63.104, respectively, where SY (kg) is event sediment yield and ROV (m^3) is event runoff volume. The same analysis on the current data for the period of 1995–2005 gave:

$$SY = 27.3\ ROV\left(r^2 = 0.83\right) \tag{3}$$

and

$$SY = 10.3\ ROV\left(r^2 = 0.84\right) \tag{4}$$

for watersheds 63.103 and 63.104, respectively. Our results show approximately 30–40% greater ratios of sediment to runoff than the previously reported values. The reasons for this could be that the watersheds have changed in the intervening years from 1980 to 1995, perhaps because of a degradation of the soil, loss of soil organic matter, or changes in vegetative cover. The instrumentation used in this study is the same as that used by *Simanton et al.* [1993], and methods of analyzing the data are also similar. However, both the data from the earlier study and this

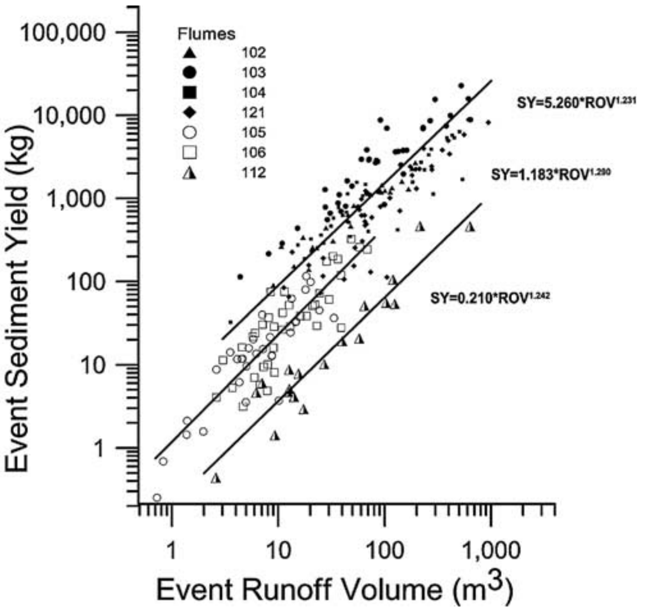

Figure 2. Sediment yields for each measured sediment event versus the runoff volume for each event.

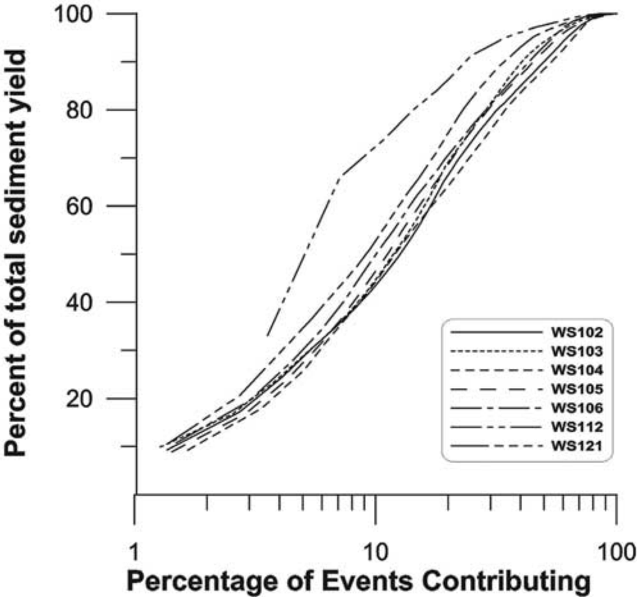

Figure 3. Sediment yield (expressed as percentage of total) versus the storm events required to produce that sediment (expressed as the percentage of the total number of sediment-producing events as reported in Table 3 and ranked from greatest to least).

one showed approximately a two and a half times greater ratio of sediment to runoff for 63.103 as compared with 63.104. This difference between 63.103 and 63.104 is consistent with the concentration differences reported in Table 4.

4.4. Geomorphic and Vegetative Controls on Sediment Production: Watershed 63.112

[36] Watershed 63.112 behaved very differently in many ways than did the other watersheds. While the fraction of precipitation events that produced runoff on the other watersheds ranged from 8 to 11%, that percentage for watershed 63.112 was 3.5% (Table 2). Sediment concentrations from 63.112 were 4–5 times less than those from pump samplers at 63.105 and 63.106 (Table 4). Figure 2 clearly illustrates a difference for 63.112 in terms of sediment yield versus runoff. The frequency distribution of sediment yields for 63.112 was also very different from the others (Figure 3). For six of the watersheds, the single largest storm on the record contributed between 9 and 11% of the total sediment yield, and approximately 50% of the sediment yield came from between 6 and 10 events during the 11 years. For watershed 63.112, the largest and second largest together accounted for 66% of the sediment export for the time period studied.

[37] A part of the reason that watershed 63.112 sediment data is different may be due to the use of the weir and pump sampling combination at that site. However, part of the standard operating procedure for watershed 63.112 includes a cleaning of deposited sediment in the pond behind the weir after storm events when necessary. At no time during the current study was sufficient sediment accumulated behind this weir to warrant cleanout. This indicates that not only were sediment loads small but that the material moving out of this watershed was also quite fine, since coarse material would deposit behind the weir if it were present in large quantity. Clearly, instrumentation is not the primary reason for the low sediment loads from this watershed.

[38] In order to understand why this watershed behaves so differently, we must describe both the geomorphic and vegetation influences on runoff and sediment production in Walnut Gulch. The San Pedro River, into which Walnut Gulch flows, underwent a period of down-cutting in the late 1800s, thus lowering the base level and initiating a period of headcutting within Walnut Gulch (W. R. Osterkamp and M. H. Nichols, Geomorphic and physiographic characteristics and processes of the Walnut Gulch Experimental Watershed, Arizona, United States, submitted to Water Resources Research, 2007, hereinafter referred to as Osterkamp and Nichols, submitted manuscript, 2007). There are a series of large headcuts on the order of 3 m deep in several of the large channels within Walnut Gulch that are located approximately halfway between the Kendall area and Lucky Hills. In general, the unit-source watersheds in the areas below the headcuts (at lower elevations) tend to be incised and have a very efficient system for moving eroded sediment from hillslopes to the larger channels. These lower watersheds also are vegetated predominately by shrubs with very little grass. Above the large headcuts in Walnut Gulch, the unit-source watersheds tend to have relatively flat swales at the base of the hillslopes that act as deposition zones for the sediment before it reaches a well-incised channel as it moves downstream. Also, these higher elevation watersheds tend to be predominantly vegetated by grass and forbs.

[39] The question arises as to whether the different vegetation cover is the cause of the different morphologies of the unit watersheds, or whether the down-cutting due to base-level change has caused a shift in vegetation from grass to shrubs. The most likely scenario seems to be the latter for a couple of reasons. The base level lowering of the San Pedro River followed a pattern of general base level lowering that occurred across the southwestern United States, and the lower Colorado River basin particularly, during the same time period of the late 1800s (Osterkamp and Nichols, submitted manuscript, 2007). This would suggest that the geomorphological differences in the unit watersheds were a result of forces larger than changes in vegetative cover. Secondly, anecdotal reports suggest that Lucky Hills itself was predominantly covered by grass (gramas) up to the early 1900s. The most reasonable scenario of cause and effect is that base level lowering of the San Pedro River caused a period of heavy incision and headcutting in Walnut Gulch that is still ongoing, as evidenced by the presence of the large headcuts described above. Once the headcutting reached the level where the unit watersheds were affected, as they have at Lucky Hills, the channels within the unit watersheds became incised, depositional swales were removed. This reduced the storage capacity of water within, and increased the efficiency of water movement out of, the small watersheds. With less water storage, more erosion, loss of soil organic matter, and degradation of soil structure, the grass cover could not be sustained. In essence, a threshold was crossed for sustaining a soil and hydrologic system for maintaining grass cover.

[40] Both the vegetation and the geomorphology of the small watersheds influenced both the runoff responses and sediment yields. With regard to runoff, as mentioned above, a much smaller percentage of the events on 63.112 produced runoff from the watershed as compared to all of the other watersheds. An explanation for this difference is related to water storage on that watershed, which would limit runoff for small events. The greater water storage on the grass site is due to both differences in vegetation and watershed morphology. The grass cover and litter on watershed 63.112 causes water to pond behind small litter and debris dams as it moves downslope, which has the effect of backing up water and allowing more time for infiltration. If the runoff event is large enough to break the debris dams on the hillslopes, water is allowed to move more freely down the slope. There is also significant water storage in the deposited sediments in the swale on watershed 63.112, so that water coming off the hillslopes that reaches the toe-slopes infiltrates the sandy material in the swale. As with the case of the debris dams on the hillslopes, this has a largest effect for the smallest storms.

[41] With regard to sediment, again the primary differences for watershed 63.112 were due to vegetation and geomorphology. In a previous study, ^{137}Cs data from 63.103 and 63.112 [*Nearing et al.*, 2005] clearly showed that hillslope erosion rates (ca. 3.2 t ha^{-1} yr^{-1}) in watershed 63.112 are only slightly less than those within watershed 63.103 (ca. 5.6 t ha^{-1} yr^{-1}) (Lucky Hills). This relatively small difference in average hillslope erosion rate is probably due to the vegetation differences (grass versus shrub). However, analyses of the distributions of ^{137}Cs on that watershed [*Nearing et al.*, 2005] indicated that the sediment delivery ratio for 63.112 was very low because of large areas and high rates of deposition in the swale. This deposition caused both a drastic reduction in sediment loads and a strong sorting of the sediment prior to its leaving the watershed. Essentially all of the coarse material transported from the hillslopes during most storms did not reach the pond behind the weir.

4.5. Estimated Sediment Yields for Period of Record

[42] Average erosion rates for grazing-lands in the state of Arizona have been reported by the USDA Natural Resources Conservation Service [*USDA*, 2000] to be of the order 0.2 tonnes ha^{-1} yr^{-1}. Similar magnitudes of erosion were reported for surrounding states. Those numbers are based on the application of the RUSLE model [*Renard et al.*, 1997] to a statistical sampling of sites cross the state of Arizona. The low erosion rate numbers reported by the USDA might suggest that erosion by water on rangelands in Arizona is not a serious problem. The sediment yield rates measured in this study show rates of erosion at Walnut Gulch to be an order of magnitude greater than the state average reported by the USDA. We believe that they are great enough to effect soil degradation on this landscape, where already soil organic matter content is low and soil structure is poor.

5. Conclusions and Recommendations

[43] Analysis of the 11-year record of sediment yields from seven unit-source watersheds on the WGEW addresses the practical problems of sediment sampling and estimating missing data, as well as providing a basis for interpreting the physical watershed characteristics that influence variations in sediment yield among semiarid watersheds. Our data clearly shows that because of the high year-to-year variability in records from semiarid watersheds, short term monitoring records are not sufficient for characterizing sediment yields. The 11-year record that was analyzed in this paper is longer than many seen in the scientific literature, but a multidecade record would undoubtedly be necessary for a relatively complete analysis of frequency distributions for sediment events. In particular, a longer data record would be needed to understand the contribution of very erosive storms. Our results also show that a method to estimate event-based sediment yields from measured event flow data is a critical for complimenting the measured data record. Instrumentation and measurement problems are invariably present in monitoring on these types of systems, and the error associated should be considered.

[44] The Walnut Gulch data suggest that geomorphology is the dominant factor controlling runoff and sediment yields from these types of watersheds. While it is tempting to attribute the differences in sediment loads to vegetation or management, at least in this case, the degree of channel incision and efficiency of sediment transport from the watershed are dominant factors. Down-cutting of the San Pedro River in the late 1800s initiated a period of head-cutting within the Walnut Gulch drainage. In areas of the watersheds below the headcuts, channels are highly incised and the efficiency of transferring runoff water and eroded sediment out of unit-source watersheds is very high. Thus, unit watersheds below the headcuts in Walnut Gulch have less water storage and more erosion, loss of soil organic matter, and degradation of soil structure than those above the headcuts. In these lower small watersheds, a threshold has been crossed for sustaining a soil and hydrologic system necessary for maintaining grass cover, and the area has been invaded by shrubs.

[45] The hillslope erosion rate in the grassed watershed is only slightly less than that in the shrub watersheds and, in both cases, are higher than generally acknowledged. Yet sediment yields are an order of magnitude less in the grassed watershed than at the shrub site. This is because the swale in the grassed watershed acts as an effective deposition zone for the sediment generated from the hillslopes. The swale also acts as a water storage zone for runoff from the hillslopes.

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M. A. Nearing, M. H. Nichols, K. G. Renard, J. R. Simanton, and J. J. Stone, Southwest Watershed Research Center, USDA-ARS, 2000 E. Allen Rd., Tucson, AZ 85719, USA. (mnearing@tucson.ars.ag.gov)