

A sediment budget for a small semiarid watershed in southeastern Arizona, USA

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ABSTRACT

A sediment budget was developed for a 43.7 ha and a nested 3.7 ha semiarid, shrub dominated watershed based on hydrologic, geomorphic, erosion, and sediment data collected from 1963 through 2006 on the USDA-ARS Walnut Gulch Experimental Watershed in the southwestern US. Sediment budgets based on such extensive and intensive field campaigns over several decades are rare. The sediment budget was balanced with a high degree of confidence because the study watershed is controlled by an earth dam at the outlet. Although the channel network is well developed and incising in the steeper reaches of the watershed, hillslopes are the dominant source of sediment, contributing 85% of the overall total sediment yield. Erosion and sediment redistribution were driven by highly variable rainfall and runoff during July, August, and September. Sediment transfers are influenced by channel abstractions and the presence of the outlet dam, which created conditions for deposition in the pond approach reach. Although earth dams are ubiquitous throughout the southwestern US, and they can provide a measure of outlet sediment yield, these outlet measurements may be insufficient to interpret temporal and spatial variability in watershed sediment dynamics. Identification of dominant processes and sediment sources is critical for determining management actions that will improve rangeland conditions.

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1. Introduction

Semiarid areas are among the highest sediment producing regions in the world (Graf, 1988, p. 138). Sediment production is often quantified based on watershed outlet measurements or model simulations, and is usually expressed in units of volume or mass per time, typically on an annual basis (Chow, 1964). Such values provide an integrated measure of surficial and fluvial erosion, transport, and deposition processes and thus are of limited value for inferring internal watershed processes. In semiarid regions, the origin and fate of mobilized sediment are only imprecisely related to watershed sediment yield because of the complexity of highly variable rainfall and flash flooding response (Goodrich et al., 1997) and internal watershed sediment storage dynamics. In fact, sediment storage can exceed watershed export (Trimble, 1999; Nearing et al., 2007). Depending on the temporal dynamics of hydrologic inputs and responses, sediment delivered to the watershed outlet may include recently deposited bed material, and the amount of this material may actually exceed the amount of sediment expected to be produced by hillslope erosion and channel scour (Clapp et al., 2000). The sediment budget concept seeks to account for internal watershed processes (Dietrich and Dunne, 1978; Reid and Dunne, 1996); however, data sufficient to develop simple sediment budgets is generally lacking (Graf, 1983). As a result, with few exceptions (Leopold et al., 1966; Schick, 1977; Schick

and Lekach, 1993; Bartley et al., 2007) very few sediment budgets have been developed for arid and semiarid watersheds.

Bartley et al. (2007) presented a sediment budget for a semiarid watershed in Australia based on measured erosion from hillslopes, gullies and streambank erosion, bank erosion, channel bed erosion and storage, and fine sediment export at the watershed outlet collected during a 6-year study period. As pointed out by the authors, the study was conducted during a period of drought. In semiarid regions long term records are required to characterize precipitation and flash flood dynamics that drive sediment transfers. These records are required to provide context for extreme events and to understand the lag time between cause and effect (Moran et al., 2008). Because data collection is difficult in semiarid regions, coupled hydrologic and sediment measurements over long time periods are limited in number. In contrast, sediment budgets developed for longer time periods (Graf, 1983; Trimble, 1999) are usually based on limited measured data and a general lack of information on land use/cover conditions that can affect interpretations of long-term averages.

Data collected over four decades on the USDA-ARS Walnut Gulch Experimental Watershed (WGEW), near Tombstone, Arizona, offer the rare opportunity to develop a sediment budget using data collected at high spatial resolution during a multi-decadal, temporally bounded period of concurrent measurement and known land use and condition history. Since the 1960s intensively instrumented subwatersheds within the WGEW have supported plot scale erosion research (Simanton et al., 1986; Polyakov et al., 2010), field experiments to characterize runoff and sediment processes within “unit

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source” watersheds (Kincaid et al., 1966), and long term studies to quantify channel evolution (Osborn and Simanton, 1986, 1989) and watershed sediment yields (Nichols, 2006; Nearing et al., 2007). The primary use of these long-term datasets has been to support simulation model development and testing. Recently, several studies have been conducted to quantify erosion and sedimentation processes. These include rare earth element and ^{137}Cs tracer studies to understand soil redistribution on watershed uplands (Nearing et al., 2005; Ritchie et al., 2009), channel scour (Powell et al., 2005) and sediment transport dynamics (Yuill and Nichols, 2010; Yuill et al., 2010).

This study quantifies a multi-decadal sediment budget, accounting for sources, sinks, and re-distribution pathways, within a semiarid rangeland watershed based on research and data collection for the 44 year period from 1963 to 2006. Because the sediment budget is developed from data collected as part of the USDA instrumented watershed network, portions of the budget are developed from previously reported results. Long term precipitation, runoff, and sediment data providing spatially and temporally distributed measurements, coupled with results and interpretations from shorter term process based studies, are incorporated. We present a sediment budget including hillslope erosion and deposition, channel erosion and storage, and outlet sediment yield. The multi-decadal analysis incorporates event and seasonal variability in precipitation and runoff.

2. Study site

The study site is a 43.7 ha (108 acre), actively eroding, semiarid rangeland watershed (watershed 223) within the USDA-ARS Walnut Gulch Experimental Watershed in southeastern Arizona (Fig. 1). The relatively sparse vegetation on watershed 223 is dominated by shrubs including acacia, [*Acacia constricta* Benth.], tarbush [*Flourensia cernua* DC], and creosote [*Larrea divaricata* Cav.]. A sparse understory of grasses and forbs is also found (Weltz et al., 1994). During the rainy season canopy cover is approximately 25% with only minor amounts of litter on the ground. Although historically grazed, the upper end of watershed 223 has been fenced to exclude grazing since 1963, and the lower end was not grazed during the period of study. Because the watershed has been a research site during the entire period of data collection, the scientific staff has firsthand knowledge of general watershed conditions which have not changed over the last 40 years (Ken Renard, personal communication).

Elevations range from 1375 m at the top of the watershed to 1336 m at the watershed outlet. Soils on the watershed hillslopes are primarily gravely sandy loams with approximately 39% gravel, 32% sand, 16% silt, and 13% clay, and a high fraction (46%) of fragmented rocks (USDA, 2003). Rock covers approximately two thirds of the soil surface. Soils in watershed 223 are classified as Lucky Hills–McNeal – very deep, well drained nearly level to strongly sloping, gravely moderately coarse and moderately fine textured soils on fan terraces. The classifications for the Lucky Hills soils are coarse-loamy, mixed, thermic Ustic Haplocalcids, and the McNeal soils are fine-loamy, mixed, thermic Ustic Calcicargids. The gravely loam layer covers coarse textured calcareous soils that show little soil profile development (USDA, 2003).

Watershed 223 is a headwater watershed drained by a high density, ephemeral channel network superimposed on weakly consolidated Quaternary alluvial material shed from the Dragoon Mountains. The gully density has been reported as 13.29 km km^{-2} (Nichols, 2006). First order channels are strongly coupled to, and receive water and sediment from, rilled and scoured hillslopes. Channels are single thread and relatively steep with average channel slope ranging from 0.8% in the main channel to 9.2% in the first order channels (Table 1). Channels are narrow with bed sediment generally ‘very poorly sorted’ (Folk and Ward, 1957) with a median grain size (D_{50}) ranging from 1.02 to 2.91 mm. At the lower end of the watershed, hillslopes and channels are less strongly coupled and sediment is stored within a small, poorly developed, discontinuous flood plain and within the main channel. In general, the watershed is underlain by a conglomerate layer of gravels and pebbles locally cemented by caliché (carbonate material formed in soil in semiarid regions). This layer is relatively impervious and provides a local base level control.

Mean annual rainfall recorded on watershed 223 is approximately 292 mm. Approximately two thirds of the rainfall occurs during the July–September (and occasionally October) monsoon season (Goodrich et al., 2008). The streams in watershed 223 are ephemeral, and only contain water for a few hours out of the year. Thus runoff only occurs in distinct storm-generated events that last on the order of minutes to a few (usually less than two) hours. Runoff produced during monsoon season storms causes almost all of the water driven erosion and sediment redistribution on the watershed (Nearing et al., 2007; Nichols et al., 2008). Runoff from watershed 223 is controlled by an earthfill dam, 6 m high and 45 m long, across the main channel. The seasonal pond contained by the dam serves as a watershed outlet runoff and sediment measurement site.

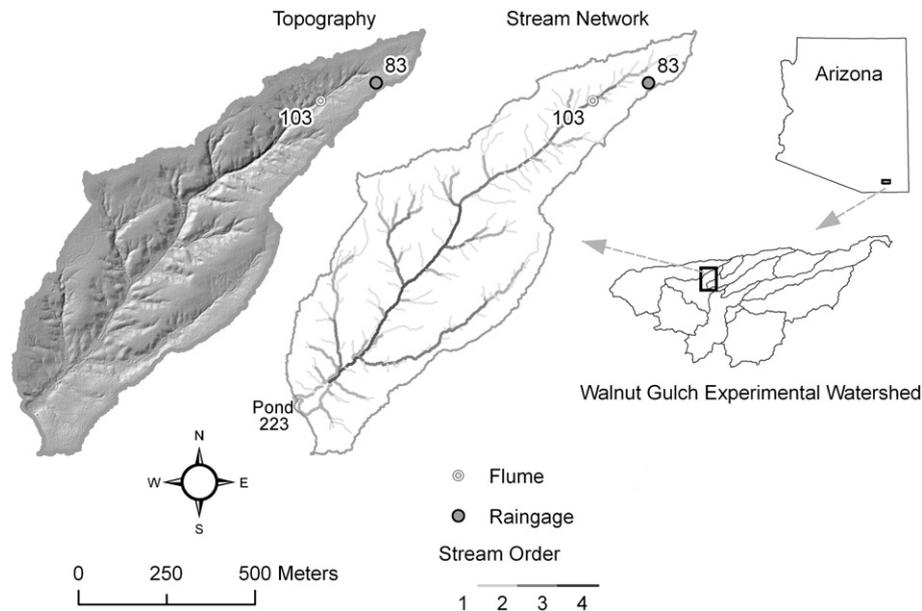


Fig. 1. Location map of the Walnut Gulch Experimental Watershed showing the measurement sites.

Table 1
Characteristics of watershed 223 channel network.

Stream order	Stream count	Total length (m)	Average length (m)	Average slope (%)
1	466	15,030	30	9.2
2	109	5130	50	6.7
3	26	2290	90	4.8
4	4	1800	450	1.7
5	1	520	520	0.8

In addition to the outlet measurement site at the pond, watershed 223 contains an internal measurement site in the Lucky Hills area (LH103). LH103 is a 3.7 ha subwatershed nested at the upper end of watershed 223, and has been monitored since the 1960s (Nichols et al., 2008; Stone et al., 2008). The correspondent measurements taken at LH103 allow for development of an independent sediment budget for that internal watershed, which will permit a comparison between sediment processes in the upper part of the watershed relative to the remainder.

3. Methods

The sediment budget is based on the concept of continuity where output is equal to input minus storage. Field measurements and data collection methods as described below were used to quantify the contributions of 1) hillslope erosion, 2) landscape deposition, 3) channel transport rates at LH103, 4) deposition in the approach to the pond, 5) deposition in the pond, and 6) sediment export from watershed 223 during overflows through the outlet spillway. A general summary of processes and data sources used to quantify them is presented in Table 2 with additional details below. Lack of detailed data dictated that there was no attempt made to differentiate particle size distributions of the sediment, thus the analysis is inclusive of all particle size classes.

3.1. Hillslope erosion and landscape deposition

Hillslope morphology was quantified from 1:2000 scale aerial stereo photos acquired in March of 2005. A digital elevation model (DEM) with a horizontal resolution of 0.30 m and a vertical resolution of 0.50 m was generated using stereo pairs and standard air photo analysis methods. Toeslopes were delineated based on breaks in slope in the DEM between hillslopes and channels. Delineated hillslope and toeslope areas were verified by field observation and visual evidence of erosion or sediment accumulation.

Soil redistribution patterns and rates of spatially distributed erosion and deposition were quantified based on ^{137}Cs measurements made by Nearing et al. (2005). Atmospheric nuclear weapons testing that peaked during the late 1950s and early 1960s distributed ^{137}Cs

throughout the globe, with an effective time zero for purposes of erosion calculations of 1963. In 2004, radioactive fallout ^{137}Cs inventories were measured within the upper 3.7 ha (LH103) of watershed 223 (Nearing et al., 2005; Ritchie et al., 2009), thus estimating an integrated four to five decade erosion rate. Based on field reconnaissance showing a high degree of homogeneity across the watershed in terms of soils, slopes, and vegetation, we assumed hillslope erosion and deposition rates determined through field experiments in the upper sub-watershed were indicative of these processes on hillslopes throughout the watershed. These measurements and subsequent analyses were used to determine spatial patterns of hillslope erosion and deposition. Based on the results of the Ritchie et al. (2009) ^{137}Cs study, an average erosion rate of $5.6 \text{ t}^{-1} \text{ ha}^{-1} \text{ yr}^{-1}$ was assumed for hillslopes within watershed 223, and an average deposition rate of $3.4 \text{ t}^{-1} \text{ ha}^{-1} \text{ yr}^{-1}$ was assumed for toeslopes.

3.2. Channel transport at LH103

Transported sediment is measured at the outlet of LH103 in conjunction with runoff with a traversing slot sediment sampler (Nichols et al., 2008) attached to a Santa Rita supercritical depth runoff measuring flume (Smith et al., 1982). Sediment yields computed for 37 events measured between 1995 and 2005 were used to develop a regression equation (Nearing et al., 2007) relating sediment yield to event runoff volume:

$$SY = 25,476 Q_p \quad (1)$$

where SY = sediment yield (kg) and Q_p = peak discharge ($\text{m}^3 \text{ s}^{-1}$).

Total and annual sediment discharge from 1963 to 2006 was calculated from measured data from sampled runoff events along with calculations from this regression equation to compute sediment yields for all runoff events where sediment was not measured during runoff.

The sediment slot sampler at LH103 is limited to a 13 mm opening of the slot. Based on limited data for the measurement of total loads, sediment particles coarser than that collected by the slot sampler constitute roughly 10% of the amount sampled (Nichols, unpublished data). Coarse load from LH103 was estimated based on total load, and is listed as an independent value in the overall sediment budget.

3.3. Deposition in the approach to the pond and monitoring of channel bed changes

In the absence of specific channel profile measurements in 1963, the longitudinal channel profile between the outlet dam and the upper reach of the watershed was reconstructed by extending the profile below the outlet dam through the cross-section centerline measurements from a topographic survey. This allowed for a calculation of the volume of the accumulated sediment wedge above the

Table 2
Summary of data sources and studies incorporated in watersheds 103 and 223 sediment budget.

Sediment budget component	Data and instrumentation	Citation
Hillslope erosion, transport, and deposition	40-year integrated measurement based on ^{137}Cs sampling in the upper 3.7 ha of watershed 223	Nearing et al. (2005), Ritchie et al. (2009)
Channel bed and bank erosion	Cross section and profile measurements Field surveys in 1976, 1980, 1984, 1997, 2002, and 2004	Osborn and Simanton (1986), Osborn and Simanton (1989)
Runoff and fluvial transport	44-year measurement record Santa Rita critical depth runoff measuring flume and traversing slot sediment sampler	Nearing et al. (2007), Nichols et al. (2008), Polyakov et al. (2010)
Deposition in outlet pond	44-year record of field topographic surveys in combination with recorded water level Note: sediment accumulation in the pond is an average value for the time period between surveys which ranges from 1 year to 10 years	Nichols (2006)
Sediment transported through pond spillway	44-year measurement record Sharp crested weir	Nichols (2006)

pond. In addition, but not used in the calculations of the sediment budget, orthophotos and aerial photos were used to quantify planform channel characteristics, and monumented channel cross sections established prior to the 1976 runoff season in the reach extending approximately 100 m above LH103 provide a measure of bank and bed change (Osborn and Simanton, 1989). In 1999, monumented cross sections were established between LH103 and the outlet pond. Complete channel profile and cross section surveys were conducted in 1999 and 2004. Changes in measured cross section area provided a basis for identifying reaches of channel aggradation and degradation.

3.4. Deposition in the pond and sediment export from watershed 223

Sediment reaching the pond at the outlet of watershed 223 either accumulated in the pond or passed through the pond spillway during pond overflows. The pond at the watershed outlet is instrumented to monitor water level, and pond capacity has been measured through periodic topographic surveys of the pond when dry (Nichols, 2006). The measured differences in pond capacity attributed to sediment accumulation were converted to sediment yields by Nichols (2006). Recorded water levels, in combination with the measured pond surface shape and spill volumes, were used to calculate event runoff volumes. The pond at watershed 223 is instrumented with a sharp-crested weir located in the spillway. In the absence of a spill, water depth was converted to volume based on the stage–volume relationship computed from topographic survey data. Pond spills, although rare, occur frequently enough that sediment lost through spillway overflow was estimated and included in this analysis. Spill volumes were computed using standard weir formulae (Brakensiek et al., 1979).

3.5. Compilation of the sediment budgets

Sediment budgets for watershed 223 (43.7 ha) and its upper end, LH103 (3.7 ha) were both calculated. For the upper watershed LH103, rates of hillslope erosion and landscape deposition, based on the study of Nearing et al. (2005), were multiplied by the areal extent of the erosion and deposition areas to obtain total sediment generation and storage values, respectively. Outflow from the watershed was calculated based on the slot sampler measurements as discussed above, with separate values reported for load particle sizes captured by the slot and the unsampled coarser load. Channel erosion was calculated as the difference between sediment export and the sum of hillslope erosion and deposition.

For the 40 ha area of watershed 223 below LH103, hillslope erosion and landscape deposition were calculated similarly as for LH103. Deposition in the pond and in the approach to the pond, as well as outflow in spills was calculated as discussed above. Again, channel erosion was estimated based on the difference between outflow and combined hillslope erosion and landscape deposition. A sediment density of 1.23 Mg m^{-3} was used to convert masses to volumes of sediment, based on previous measurements (Nichols, 2006).

4. Results and discussion

4.1. Rainfall and runoff characteristics

During the 44 year period from 1963 to 2006, 3% of the annual rainfall events were runoff producing at LH103. All runoff occurred in the months July–October, and 29% of the precipitation events during these months produced runoff. Average annual precipitation from 1963 to 2006 during July–October was 214 mm measured at rain gage 83 in the upper end of watershed 223. The annual monsoon season number of precipitation events ranged from 20 to 66.

4.2. Sediment budget

The overall sediment budget for the 44-year period of record is presented in Table 3. Because the outlet dam and pond control water and sediment outflow from the watershed, the sediment budget can be balanced. The sediment delivery ratio for the 44-year period of measurement, in the presence of the dam, was $0.4 \text{ t ha}^{-1} \text{ yr}^{-1}/6.6 \text{ t ha}^{-1} \text{ yr}^{-1}$, or 6%. However, considering the sediment delivery to the pond, including deposition in and directly above the pond along with the sediment overflow from the pond, the sediment delivery ratio was 98%, since only 194.6 m^3 or $0.13 \text{ t ha}^{-1} \text{ yr}^{-1}$ of material was deposited on the landscape and did not reach the pond or pond reach area. This result is consistent with that reported by Nearing et al. (2005) for watershed LH103 based on the ^{137}Cs measurements. In that paper Nearing et al. (2005) contrasted the efficiency of sediment delivery between LH103 and a nearby well-vegetated, grassed watershed of similar size (Kendall 112). They reported a sediment delivery ratio of 89% for LH103 and nearly zero for the grassed watershed, attributing the very low sediment delivery ratio for the Kendall watershed to a large swale at the toeslopes of that watershed. In our study we basically show that the pond of watershed 223 acts in a similar manner to the naturally occurring swale of the well-vegetated watershed in trapping a large amount of the sediment eroded within the watershed, even though otherwise watershed 223 acts as a highly efficient transport vehicle for sediment with a well developed channel system.

The sediment delivery ratio of 89% reported by Nearing et al. (2005) was based only on numbers for hillslope erosion rates and sediment delivery as measured by the flume, not including the coarse fractions considered here. They used an areal analysis of erosion and deposition distribution which differs from the method used here. In fact, the more complete value for the sediment delivery ratio for LH103, based on the current analysis, including consideration of channel erosion and the coarse load, would also be approximately 90% (727 m^3 sediment delivered vs. $580.9 + 231.2 \text{ m}^3$ of sediment generated by hillslope and channel erosion). Clearly, the similarity between the two reported sediment delivery ratio numbers is somewhat serendipitous.

4.3. Hillslope processes

Hillslopes were the dominant source of sediment, contributing 72% of the total sediment in the upper 3.7 ha of the watershed and 86% of the total below the measurement site at LH103, for an area weighted total of 85% overall. These calculated values are consistent with field observations that indicate relatively high rates of hillslope erosion by way of exposed root crowns (e.g. Fig. 2) and pedestaled rocks, as well as a developed erosion pavement on the hillslope surfaces that indicate a depletion of fines. Other visual evidence also suggests that the sparsely vegetated, steep hillslopes within the study watershed are eroding. A well developed layer of coarse surface armor is evidence of active surface erosion resulting from rain splash and the subsequent removal of fines by hydrodynamic processes (Parsons et al., 1992). Surface armoring has been shown to vary with slope aspect (Canfield et al., 2001) and the correlation between particle size on the surface layer and within the underlying sediment suggests that the armor developed in situ on the watershed. A detailed tracer study using rare earth elements conducted adjacent to the study watershed (Polyakov et al., 2009) identified efficient sediment transport through sheet flow and diffusive erosion processes on the upper slopes and where channels and hillslopes begin to decouple.

4.4. Channel processes and storage

A longitudinal pattern of changing channel morphology is visually apparent in watershed 223, and supports the numbers generated in this study. The upper portion of the channel, particularly above the flume at LH103, is characterized by eroding channel banks

Table 3

Summaries of watersheds 103 and 223 sediment budget. Rates of local erosion or deposition are those averaged over the area where the processes are active. Sediment yield contribution is averaged over entire watershed area considered (LH103, watershed 223 downstream of LH103, or total watershed 223 area). Sediment contribution and fate are reported as percentages within the respective areas of LH103 or 223 downstream of LH103. Sediment fate includes both deposition and discharge. The conversion factor for volume to mass is 1.23 Mg m^3 .

Area	Source/sink	Area (ha)	Local erosion or deposition rate ($\text{t ha}^{-1} \text{ yr}^{-1}$)	Total erosion or deposition (t yr^{-1})	Sediment yield contribution (t)	Sediment yield contribution ($\text{t ha}^{-1} \text{ yr}^{-1}$)	Sediment yield contribution (m^3)	Sediment contribution (%)	Sediment fate (%)
LH103	Hillslopes	2.9	5.6	16.2	715	4.4	581	72%	
	Channels	0.1	64.6	6.5	284	1.7	231	28%	
	Landscape deposition	0.7	-3.4	-2.4	-105	-0.6	-85		10%
	Measured discharge from LH103	3.7	5.0	18.5	813	5.0	661		81%
	Coarse load discharge from LH103	3.7	0.5	1.8	81	0.5	66		8%
	Total load discharge from LH103 (sum of measured and coarse loads)	3.7	5.5	20.3	894	5.5	727		
Watershed 223 downstream from LH103	Hillslopes	36.8	5.6	205.8	9056	5.1	7363	86%	
	Channels	1.0	33.7	33.7	1483	0.8	1206	14%	
	Landscape deposition	0.9	-3.4	-3.1	-135	-0.1	-109		1%
	Deposited in pond	0.005	NR	NR	-5007	-2.8	-4071		44%
Watershed 223 totals	Deposited in pond approach reach	0.34	NR	NR	-5597	-3.2	-4550		49%
	Sediment discharge by pond overflow	NA	NA	NA	695	0.4	565		6%
	Total erosion				11,538	6.6	9381		
	Total deposition				-10,843	-6.2	-8816		
	Total sediment discharge				695	0.4	565		

NR: not reported, NA: not applicable.

(e.g. Fig. 3), followed downstream by a transition region where signs of degradation are much lessened (e.g., Fig. 4), to aggradation immediately above and at the outlet pond (e.g., Fig. 5). The pattern follows the general concept of Schumm's (1977) source, transport, and sink zone (Lane et al., 1997). Channel cross section measurements

indicate that since 1975, bank erosion has been occurring in the upper reaches, and the contribution to the overall sediment budget is much greater in the headwaters of the watershed above LH103 (Figs. 3 and 6, and Table 3).

Channel cross section measurements in the transition region between the flume at LH103 and the watershed outlet pond covering a 10 year period indicate that the contribution of sediment bed and banks is not substantial in this reach (Fig. 4). However, channel banks contain large clasts and are the likely source of larger particles on the channel bed. Through the middle of watershed 223 cross section measurements indicate little change in channel bed elevation during the measurement period. In addition, a dirt road located 600 m above the outlet pond that crosses perpendicular to the main channel has been observed to have neither degraded nor aggraded during the period of study.

These measurements and observations are consistent with results of a channel scour study conducted by Powell et al. (2005) to investigate scour and fill patterns within the main channel on watershed 223. Although the channel bed was found to be highly mobile, with scour and fill depths ranging from 2 to 15 cm across a range of flow sizes during each event measured, compensating fill returned the channel bed to pre-flow elevation (Powell et al., 2005). The results of the scour study showed that sediment transfers are in approximate steady state, and sediment accumulation was not a factor through the study reach.

The channel reach immediately upstream from the pond has been aggrading (Fig. 5). Aggradation and hydraulic sorting in the lower watershed are the result of reduced transport capacity in response to reduced channel slope induced by the presence of the outlet dam. Sediment storage and a distinct variation in the channel profile are evident in the pond approach reach for at least 200 m upstream from the elevation of the outlet weir. The elevation of the outlet weir defines the maximum elevation of topographic surveys conducted to compute pond sediment accumulation. The computed volume of sediment stored in the approach reach based on topographic surveys of current channel geometry and reconstruction of the pre-dam longitudinal channel profile was 4550 m^3 , which is approximately the cumulative volume of sediment measured in the outlet pond. The trap efficiency of the pond is relatively high (90.8%), indicating that sediment accumulation measurements can be used to close the sediment budget with a high degree of confidence.



Fig. 2. Exposed root crown indicating surface soil erosion.



Fig. 3. Photo of typical incision within LH103 located at the upper end of watershed 223.

However, sediment accumulation in the approach reach above the spillway level would typically not be included in a measurement of watershed sediment yield based on measurements of pond volumes below the spillway level.

4.5. Sediment at the outlet pond

The long-term pond 223 records reveal that from 1963 to 2006 the annual average sediment accumulation in the pond was $92.5 \text{ m}^3 \text{ yr}^{-1}$ ($3.2 \text{ t ha}^{-1} \text{ yr}^{-1}$ averaged on the watershed area). These measurements

represent integrated measures of sediment transported and deposited during individual runoff events that occurred between surveys. As such, it is not possible to specifically determine the sediment contributed in association with particular events. However, it is likely that the largest sediment loads and geomorphic work were accomplished during the largest magnitude runoff events, because a relatively few individual events dominate the annual runoff records. Average annual runoff was 6900 m^3 , and ranged from 170 to $37,730 \text{ m}^3$. In 17 out of the 44 years of record, more than half of the annual runoff volume at the pond was attributable to a single runoff event during the year.



Fig. 4. Photo of the transport zone located between the flume at LH103 and the approach to the pond in watershed 223.



Fig. 5. Photo of the deposition zone located upstream of the pond in watershed 223.

4.6. Internal watershed redistribution

The upper end of watershed 223 (LH103) is considered a unit sources watershed that is, “a natural drainage area that has relatively homogeneous soil and vegetation cover, that is subject to essentially uniform precipitation” (Kincaid et al., 1966). In semi-arid regions most of the sediment moved from hillslopes occurs during infrequent, high intensity, rainfall events (Polyakov et al., 2010) that also generate runoff. However, runoff characteristics are variable.

On average, 10 runoff events per year are recorded at LH103 ranging from 1 (in 2004) to a high of 20 (in 1983 and 1984). Cumulative sediment re-distribution is generally greater during wet years than during dry years; however, within any given year, runoff and associated sediment redistribution can be highly variable. A wet year may result from many relatively small runoff events (e.g. in 2000 19 runoff

events produced 56.6 mm of runoff) or a few larger runoff events (e.g. in 1975 eight runoff events produced a record high 60 mm of runoff). Monsoon season rainfall was 250 mm in 1975, slightly higher than the long term average of 214 mm, but a single storm that produced 72.6 mm of rain generated a single runoff event at the pond that contributed 68% of the annual runoff. This variability can also be found during dry years. Although periods of both higher than average precipitation and droughts characterize the southwestern US, geomorphically influential high magnitude, low frequency, flash floods can and do occur under both conditions.

In-stream infiltration and associated downstream loss of flow is very important in this environment (Goodrich et al., 1997), and results in the fact that not all of the runoff generated on the upper end of the watershed reaches the pond at the outlet of watershed 223. At the spatial scale of watershed 223, precipitation and runoff

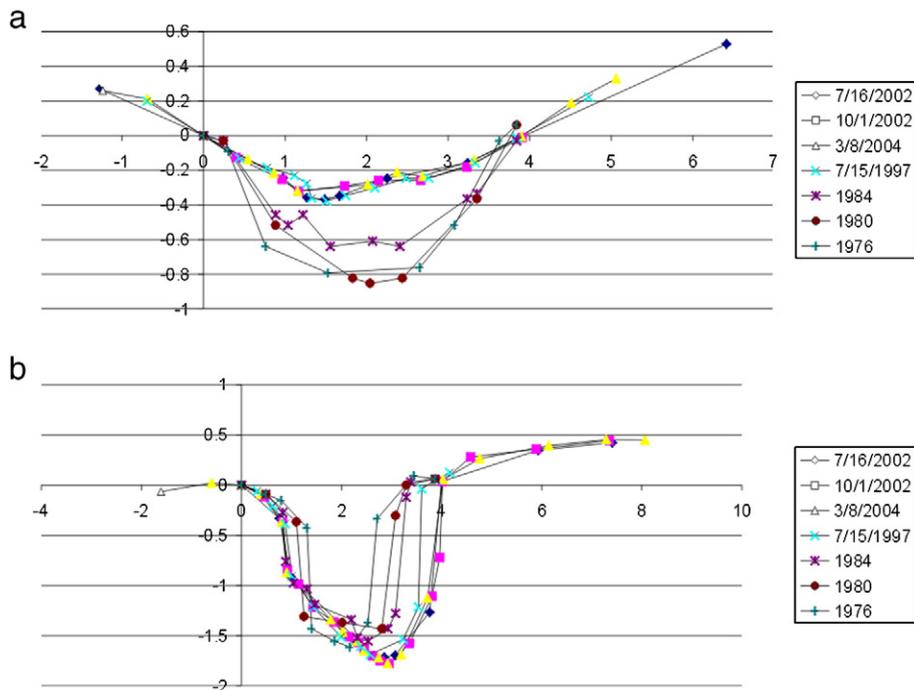


Fig. 6. Channel cross section evolution measured a) at 130 m upstream from watershed LH103 flume and b) in the approach reach 4 m above the watershed LH103 flume.

generation are spatially variable (Goodrich et al., 1997) and partial area response in runoff results in spatially variable sediment redistribution. The annual number of runoff events recorded at LH103 that did not have a corresponding measurement at the pond ranged from none to 10. All of these runoff events had less than the 2 year return period peak discharge, and 65% of them were less than the 1 year discharge (Table 4). Sediment transported during fully abstracted flows was re-deposited within the watershed and stored thus becoming a source of sediment supply during subsequent events with sufficient transport capacity to re-entrain and mobilize the sediment.

4.7. Uncertainty

Because the study watershed is small (43.7 ha) and has been the site of intensive field data collection during the past 5 decades by researchers at the U-ARA Southwest Watershed Research Center who have personal knowledge of watershed conditions, geomorphic changes in channel bed and banks, rainfall and runoff characteristics, and instrumentation, the primary sources of uncertainty are associated errors inherent in field measurement, and in the extrapolation of measured values. The coupled runoff and sediment measurements at LH103 are among the best available. The flume was designed specifically to measure runoff in sediment laden flow and the slot type samplers are considered to be most accurate among other devices in representing particle sizes in the sample relative to that in the flow (Barnes and Frevert, 1954).

Soil erosion and deposition estimates based on the ^{137}Cs study have a moderately high degree of confidence. The analysis was conducted based on a high number of samples (68) and the resultant values were compared to measurements of sediment export made during concurrent time period at the watershed outlet. Because calculated mean erosion rates corresponded closely with watershed outlet measurements, we have a relatively high degree of confidence in the numbers. In addition, the ^{137}Cs method was applied to a proximal watershed (Kendall 112) with comparable results (Nearing et al., 2005). Extensive field reconnaissance looking at variations in soils, vegetation, and slope gradients through watershed 223 suggests that extrapolation of the erosion and deposition rates computed for the upper end of the watershed was appropriate.

The sediment budget was closed by attributing the difference between hillslope erosion and sediment deposited in the pond and the approach reach into the pond. This difference is relatively small and is attributable to unmeasured channel processes including bank sloughing and erosion, especially within the lower order channels. Because these channel processes represent a relatively small contribution to the total calculated change in sediment within the watershed, there is a relatively high degree of confidence in the overall computed sediment budget.

4.8. Comparison to other sediment budgets in semi-arid regions

Sediment budgets provide a useful framework for understanding dominant erosion and sedimentation processes, and with sufficient

Table 4
Flood frequency summary based on measured runoff at LH103.

Return period	Exceedance probability	Peak discharge (m^3/s)
100	1%	0.926
50	2%	0.824
25	4%	0.719
10	10%	0.569
5	20%	0.447
2	50%	0.262
1.25	80%	0.140
1.05	95%	0.070
1	100%	0.007

detail can provide insight to internal watershed sediment dynamics across a range of scales. This study is unique because it is based on an extensive and intensive field campaign that has taken place over the last four decades (Nichols, 2006; Nichols et al., 2008).

Graf (1983) conducted an analysis of the sediment budget for the entire 150 km² Walnut Gulch Experimental Watershed, within which our study area is located, by looking at channel cross section data from early and recent surveys. He was working on the hypothesis that a significant period of erosion occurred in the 15 year period from 1930 to 1945 that resulted in stream entrenchment and massive channel scour, including the removal of large cienegas (wide grassy meadows) within the basin. Based on the limited data, he estimated the total volume of sediment removal from Strahler stream orders ranked 1 to 7, with the largest volumes by far being generated in the largest, highest order stream channel. While details are not precisely known as to the actual timing, quantification, and process characteristics of the erosion episode described by Graf (1983) and others (Nearing et al., 2007; Rieke-Zapp and Nichols, 2011), it is generally recognized that downcutting and entrenchment of Walnut Gulch have taken place since the late 1800s and that the channels contain large volumes of eroded sediment from the intervening period of time.

Graf (1983) did not attempt to make any estimates of hillslope erosion in his analysis; however, he did note that based on measurements and calculations of sediment exported from the watershed, as reported by Renard (1972) and Renard and Laursen (1975), and estimates of hillslope erosion rates within the watershed, as reported by Simanton et al. (1977, 1980) and Renard (1980), rates of hillslope erosion are essentially equal to sediment export rates for the entire 150 km² watershed (ca. 20,000 to 25,000 m³ yr⁻¹, or 1.6 to 2 t ha⁻¹ yr⁻¹). The results of our detailed analysis for watershed 223 in this study are in general agreement with the concept that most of the sediment generated in the watershed is currently being generated from the hillslopes, but the numbers used in the current study are more complete and undoubtedly more accurate.

Knowledge of physiographic setting and climatic conditions are not always sufficient to identify dominant sediment sources. Bartley et al. (2007) reported results for a sediment budget for a 13.5 km² grazed, semi-arid watershed in Queensland, Australia. Long-term annual rainfall in the Weenie Creek watershed was reported as ~584 mm, and average annual rainfall during the three year study period was 263 mm. Bartley et al. (2007) reported the major contributor of the primary erosion processes as gully erosion, with hillslope erosion contributing approximately one-fourth the amount of sediment as the gullies (592 vs. 2047 t yr⁻¹, respectively). The reason for the differences between Weenie Creek and watershed 223 at Walnut Gulch was due to lower reported hillslope erosion at Weenie Creek (0.44 vs. 5.6 t ha⁻¹ yr⁻¹) and active gully erosion at Weenie Creek. Channel cutting, gully sloughing, and headcutting in the first order streams in the Lucky Hills area of Walnut Gulch have largely stabilized because they have generally already eroded to near the watershed boundaries. Nonetheless, a commonality of the sediment dynamics at Weenie Creek and Walnut Gulch is that high rates of historical erosion within the past century at both locations have resulted in large amounts or sediment stored in the higher order streams of the system. In both cases, in the absence of structural controls, one can expect that it may take tens to hundreds of years for this stored sediment to move through these ephemeral systems to the watershed outlets.

5. Conclusions

This paper presents a sediment budget computed from data collected as part of an ongoing, long-term, semiarid rangeland watershed monitoring program in combination with results of short term field experiments. Sediment budgets based on such an extensive

and intensive, long-term field campaigns are rare. The data indicate that although spatially and temporally variable hydrologic drivers control erosion and sediment redistribution, hillslopes are the dominant sediment source. Identification of primary sediment sources has implications for management to reduce erosion.

Sediment redistribution on the watershed is controlled by hydrology, vegetation, and topography. Of these three dominant controls, the only one that can be controlled through management is vegetation. Land use and management during the 4-decade period of study have been stable; however, it is likely that regional land use patterns during the late 1800s and early 1900s altered the historic vegetative cover conditions (Nearing et al., 2007). The current scarcity of vegetative cover in combination with relatively steep topography and a dense channel network creates geomorphic conditions that support high rates of erosion and efficient sediment transport in response to discontinuous rainfall and runoff. We can speculate that the dominant contribution of hillslope sediment to the overall sediment budget suggests that restoration to reestablish grasses on the site offers the greatest potential for reducing sediment yield from the watershed. However, on this site, low soil organic matter content and poor soil structure offer significant challenges, and restoration will likely be expensive, time consuming, and subject to the variability inherent in rainfall.

The sediment budget highlights the influence of the outlet pond as a geomorphic control. If the pond were removed, conditions for sediment deposition and channel aggradation would be eliminated and the channel network would continue to evolve through downcutting. Because earthen dams are ubiquitous throughout the semiarid US, they may exert much more influence on larger watershed sediment transfers than currently accounted.

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