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MODERN SEDIMENT YIELD COMPARED TO GEOLOGIC RATES OF SEDIMENT PRODUCTION IN A SEMI-ARID BASIN, NEW MEXICO: ASSESSING THE HUMAN IMPACT

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ABSTRACT

In the semi-arid Arroyo Chavez basin of New Mexico, a 2·28 km^2 sub-basin of the Rio Puerco, we contrasted short-term rates (3 years) of sediment yield measured with sediment traps and dams with long-term, geologic rates (~10 000 years) of sediment production measured using ^{10}Be. Examination of erosion rates at different time-scales provides the opportunity to contrast the human impact on erosion with background or geologic rates of sediment production. Arroyo Chavez is grazed and we were interested in whether differences in erosion rates observed at the two time-scales are due to grazing.

The geologic rate of sediment production, 0·27 kg m^{-2} a^{-1} is similar to the modern sediment yields measured for geomorphic surfaces including colluvial slopes, gently sloping hillslopes, and the mesa top which ranged from 0·12 to 1·03 kg m^{-2} a^{-1}. The differences between modern sediment yield and geologic rates of sediment production were most noticeable for the alluvial valley floor, which had modern sediment yields as high as 3·35 kg m^{-2} a^{-1}. The hydraulic state of the arroyo determines whether the alluvial valley floor is aggrading or degrading. Arroyo Chavez is incised and the alluvial valley floor is gullied and piped and is a source of sediment. The alluvial valley floor is also the portion of the basin most modified by human disturbance including grazing and gas pipeline activity, both of which serve to increase erosion rates.

KEY WORDS: erosion; sediment; arroya; grazing; cosmogenic radionuclides

INTRODUCTION

The impact of human activities on river systems is often assessed by contrasting data collected in the river of concern to a natural, background, or reference condition (US Environmental Protection Agency, 1999). Over the last 5000 years, a large percentage of the earth's surface has been disturbed by human activity (Hooke, 1994) and finding undisturbed areas, where natural rates can be assessed, is extremely difficult. Sediment is currently listed as one of the major pollutants in the United States (US Environmental Protection Agency, 1999) and thus measuring and contrasting erosion and sediment yields between disturbed and undisturbed conditions is extremely important. However, few studies describe a consistent, verifiable approach for comparing natural rates of erosion (Saunders and Young, 1983) to human-influenced rates (Hooke, 1994).

Research in the Rio Puerco of New Mexico provided the opportunity to compare methods of quantifying modern and geologic rates of erosion. Since the interpretation of the relative magnitude of modern erosion requires defining background rates, we focused this effort in the semi-arid Arroyo Chavez sub-basin of the Rio Puerco, New Mexico, where studies were conducted on erosion rates at the geologic time-scale using cosmogenic radionculides (Clapp *et al*., 2001) and in the short term using geomorphic process techniques (Gellis *et al*., 2001).

In this paper, we use the cosmogenic radionuclide ^{10}Be as surrogate for natural or background rates of sediment production and compare ^{10}Be-determined rates to short-term or modern rates of sediment yield in a

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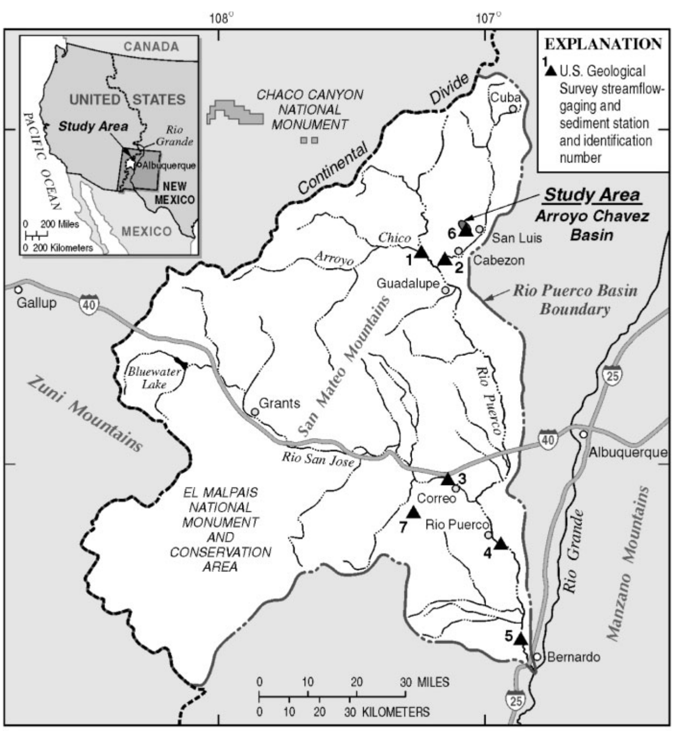
semi-arid setting: Arroyo Chavez. Cosmogenic nuclides have been used to measure erosion and sediment production at geologic time-scales (>10 000 years, Brown *et al*., 1995; Clapp *et al*., 1997, 2001; Schaller *et al*., 2001, 2002). Measuring erosion rates over geologic time-scales is important because it provides information on rates of sediment production and the dynamic equilibrium of basins over time-scales of thousands of years (Clapp *et al*., 2001). At the modern time-scale, erosion on the landscape is measured using process geomorphic approaches including sediment traps (Gerlach, 1967; Bryan, 1991; Gellis, 1998; Larsen *et al*., 1999), erosion pins (Leopold *et al*., 1966), streamflow sediment monitoring stations (Walling, 1991), and cesium-137 (Walling *et al*., 1986). Measuring sediment yield in the short term is important because it can be used to contrast erosion over different land uses or land cover classes (Gellis *et al*., 1999, 2001). In this paper we use the term 'sediment production' to describe geologic rates of erosion and 'sediment yield' for modern rates of sediment delivery.

There is considerable uncertainty in extrapolating modern short-term measurements to longer periods (Trimble, 1977; Kirchner *et al*., 2001). For example, at the geologic time-scale, it is assumed that wet and dry climatic cycles are combined into an integrated erosion rate, whereas at the modern time-scale measurements may be taken in either a wet, dry, or average part of the climate cycle. Spatial scale is also an important parameter. As drainage area increases, more sites in the basin are available for sediment storage and thus sediment yield (tonnes km^{-2} a^{-1}) has been reported to decrease (Schumm, 1977; Walling, 1983; Trimble, 1990).

Erosional setting

The Rio Puerco basin (Figure 1) is the largest tributary to the Rio Grande in New Mexico, draining more than 16 100 km^2 of the Continental Divide to the Rio Grande from the Zuni Acoma subsection of the Colorado Plateau and the Nacimiento Mountains of the Southern Rocky Mountains (Figure 1). The main channel and many of its tributaries are deeply incised in the landscape, eroded 6–18 m below the level of the former alluvial valley floor. The Rio Puerco contributes only 4 per cent of the Rio Grande's average annual run-off at San



Streamflow-gaging stations

1. Arroyo Chico near Guadalupe, NM
2. Rio Puerco above Arroyo Chico near Guadalupe, NM
3. Rio San Jose near Correo, NM
4. Rio Puerco at Rio Puerco, NM
5. Rio Puerco near Bernardo, NM
6. Arroyo Chavez near San Luis, NM
7. Volcano Hill Wash near Correo, NM

Figure 1. Location of US Geological Survey streamflow-gaging and sediment stations (black triangles) in the Rio Puerco Basin, New Mexico. Basin is outlined in white

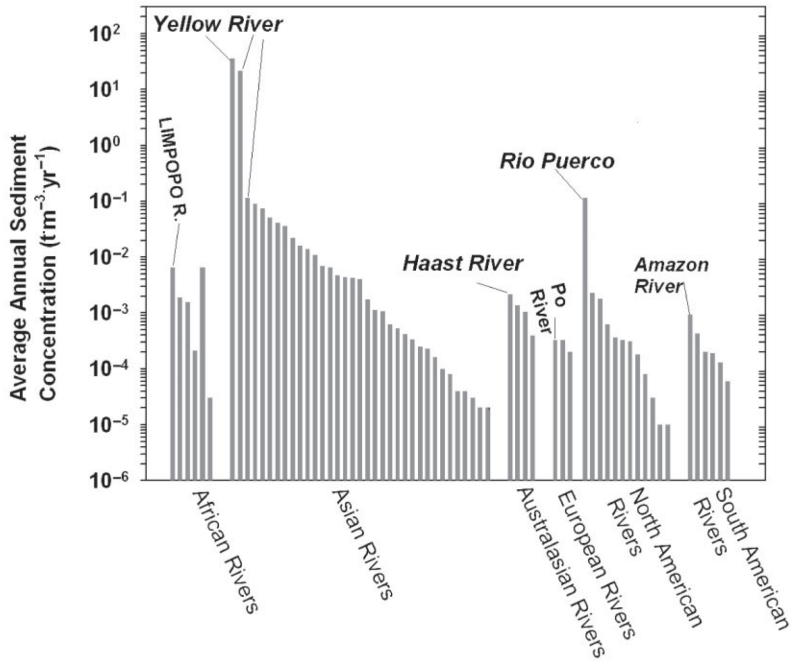


Figure 2. Sediment concentration in selected major world rivers, after Milliman and Meade (1983) and Zhao *et al*. (1992)

Marcial but over 70 per cent of the Rio Grande's average annual suspended-sediment load. Suspended-sediment concentrations of more than 600 000 parts per million (60 per cent) recorded at the US Geological Survey (USGS) gaging station near Bernardo at the river's lower end (Figure 1) make the Rio Puerco one of the most sediment-laden streams on earth. Using data compiled for world rivers by Milliman and Meade (1983) and Zhao *et al*. (1992), the Rio Puerco has the fourth highest average annual suspended-sediment concentration (Figure 2). The average annual suspended-sediment load of the Rio Puerco near Bernardo, measured from 1948 through 1998, is $3{\cdot}91 \times 10^6$ tonnes and the average annual run-off for the same period is $34{\cdot}6 \times 10^6$ m^3.

The Rio Puerco of New Mexico with its spectacular incised channels (arroyos) and high sediment concentrations has long been an area of interest to geologists, geographers, hydrologists, and engineers (Bryan, 1928; Widdison, 1959; Nordin, 1963; Heath, 1983; Gorbach *et al*., 1996; Love, 1997; Elliott *et al*., 1999; Gellis and Elliott, 2001). Similar to other southwestern arroyos, the Rio Puerco has a history of cutting and filling. Three major channels have cut and filled the Rio Puerco valley in the past 3000 years (Love and Young, 1983; Love, 1986). An interesting aspect of these cut-and-fill cycles is that the Rio Puerco channel filled to the same level in the valley it occupied prior to each cutting event. For example, by 1880 AD, the Rio Puerco occupied the same level in the valley it had before its incision around 600 BP (Love, 1986); the Rio Puerco then incised beginning in 1885 (Bryan, 1928). Recent surveys indicate that the Rio Puerco is in a cycle of aggradation (Elliott *et al*., 1999; Gellis and Elliott, 2001). The process of a channel repeatedly filling raises questions about the specific sediment source(s) for this filling: is channel filling the result of redistribution of sediment stored in alluvial valleys or from upland erosion of recently generated regolith?

The $2{\cdot}28$ km^2 Arroyo Chavez sub-basin of the Rio Puerco was selected for detailed erosion studies (Figure 1). The climate in the Arroyo Chavez basin is semi-arid with average annual rainfall of 329 mm recorded at Cuba, New Mexico (1942–1998) located approximately 39 km from Arroyo Chavez. Elevations in Arroyo Chavez range from 1938 m to 2021 m. The Arroyo Chavez basin drains interbedded sandstones and shales of the Paleozoic Menefee Formation (Gellis *et al*., 2001). Soils in the Arroyo Chavez basin are derived from these underlying sandstones and shales, as well as from eolian silt. The surface soil textures vary from silty clay loam to sandy clay loam, both containing about 30 per cent clay. The channel of Arroyo Chavez is incised 4 m below the alluvial valley floor with many tributaries actively headcutting (Figure 3). Median grain size on the bed of

Figure 3. View of the incised Arroyo Chavez channel looking downstream. Person on right bank for scale

Arroyo Chavez varies between fine sand to gravel (0·15–3 mm). Land use is predominantly grazing with a gas pipeline running at shallow depths through the center of the basin.

Measurement methods

The Arroyo Chavez basin was subdivided into five geomorphic units (mesa top, steep colluvial slopes, gently sloping hillslopes, alluvial fans, and alluvial valley floor, Figure 4A), based on slope and soil textures. Modern rates of sediment yield were measured on these five geomorphic units from 1996 to 1998 using sediment traps and straw dams. Ten sediment traps based on a modified Gerlach Trough (Gerlach, 1967; Gellis, 1998) were installed in Arroyo Chavez. All traps were 85 cm long and 13 cm deep with the exception of traps 5b and 7b, which were 65 cm long and 13 cm deep. To prevent precipitation from entering the trap directly, a lid made of sheet metal was fitted with a hinge to the back of the trap. One to three 1·27 cm diameter holes were drilled into the side of the trap, and were connected by tubing to 18·9-liter collection buckets. Lids were placed on the buckets to provide a seal. The traps were installed flush to the ground surface with the opening parallel to the slope contour. The contributing area was bounded with metal edging and ranged from 0·76 to 37 m^2 (Table I).

Sediment was collected in the buckets after one or more rainfall events during the two-year period. Some of the sediment settled out in the trough and was transferred into one of the buckets. Each bucket was weighed in the lab to determine total run-off (sediment and water). Total run-off was converted to a volume (liters) by assuming the density of the sediment–water mixture was 1·0 g cm^{-3}. In the laboratory, the samples were left sitting for a month to allow the suspended sediment to settle. Water was decanted from the buckets and the sediment

Table I. Summary of data from sediment traps for Arroyo Chavez

Sediment trap	Geomorphic surface	Days in operation	Number of events sampled	Drainage area (m^2)[a]	Total run-off (liters)	Total sediment load (g)	Rainfall (mm)[b]	Average sediment yield (kg m^{-2} a^{-1})
1	Mesa top	841	46	37	692	19 230	688	0·23
2	Steep colluvial slopes	841	39	7·9	233	3 200	688	0·18
3	Mesa top	841	47	35	488	28 730	701	0·35
4	Alluvial fan	841	52	27	726	59 130	688	0·94
5a	Alluvial valley floor	841	58	27	1510	210 730	790	3·35
5b	Alluvial valley floor	576	34	0·76	Not collected	1 280	602	1·06
6	Alluvial valley floor	841	31	6·4	64	2 050	917	0·14
7a	Gently sloping hillslopes	841	46	28	808	12 560	894	0·12
7b	Gently sloping hillslopes	576	29	1·7	Not collected	660	790	0·24
8	Gently sloping hillslopes	841	43	22	286	7 280	1 016	0·14

[a] The contributing area of each trap was bounded with metal edging and surveyed with a total station to define the contributing area.
[b] Rainfall was collected at various raingages in the Arroyo Chavez basin shown in Figure 4.

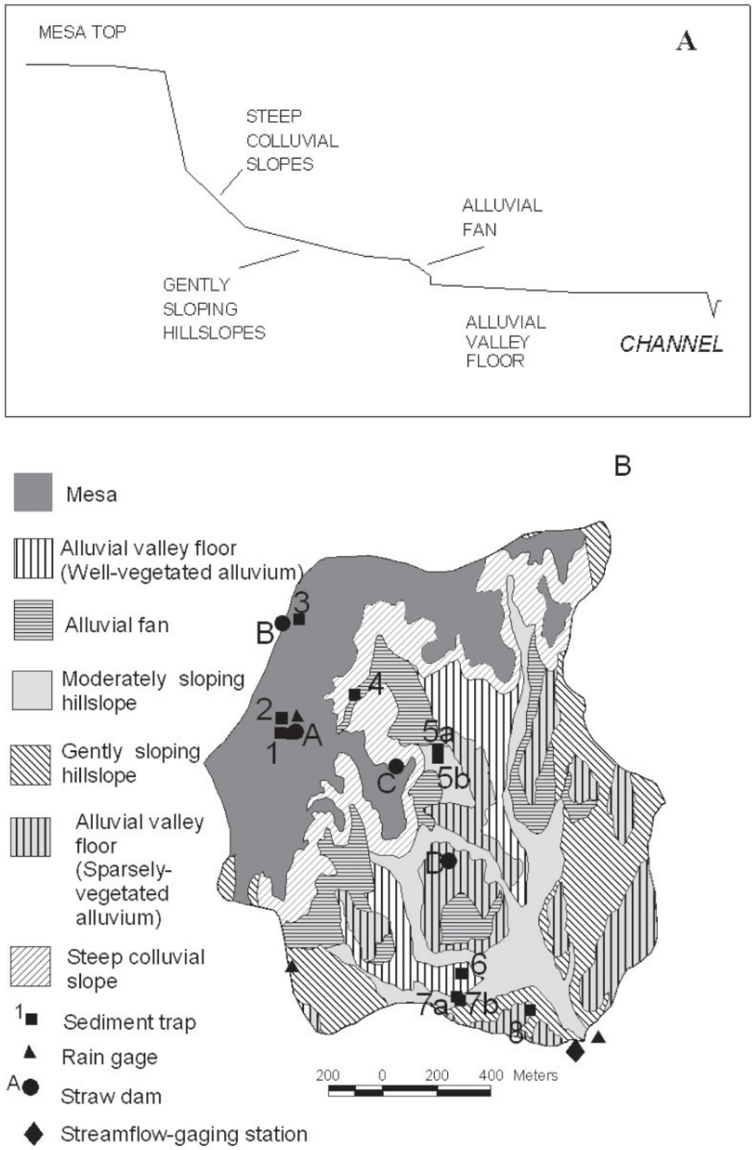


Figure 4. (A) Geomorphic units defined for Arroyo Chavez. (B) Geomorphic map of Arroyo Chavez Basin showing sediment traps, straw dams, rain gages, and streamflow-gaging station

was oven dried for 24 h at 98 °C. Samples of the water were taken, dried in a bowl, and weighed to determine the amount of sediment still remaining in suspension. This amount was added to the total mass of sediment. The total mass of sediment for each trap was divided by the contributing area to quantify the sediment yield.

Errors in measuring sheetwash erosion may result from the installation of boundaries used to define the contributing area to a trap. The boundaries eliminate any upslope supply of sediment. The geomorphic surfaces in Figure 4A receive sediment from upgradient sources, are mantled with varying thickness of fine-grained soil, are subject to rainsplash erosion, and are undergoing sheetwash erosion. The likelihood of changing a surface from depositional to erosional as a result of installing boundaries is unlikely. In the short time-scale of this study (three years), erosion was not affected by cutting off any upslope supply of sediment. In addition, we tried to eliminate creating an unnatural drainage divide by using the natural topography of each slope so that each trap collected run-off and sediment from an existing micro-catchment.

To quantify sediment yields over larger contributing areas than the sediment traps, four straw dams in each basin were constructed in first- and second-order channels (Figure 4B). A notch approximately 1 m deep was dug in the channel and fitted with straw bales. The bales were secured into the ground with steel rebar, and large rocks were piled on the downstream side of the straw bales to prevent the bales from toppling. The sediment pool on the upstream side of the straw bales was dug out, and four to six cross-sections were monumented in the pool using steel rebar on either end. The cross-sections were surveyed periodically to quantify sediment deposition. Using the measured density of deposited sediment multiplied by the volume of deposited sediment allowed the mass of sediment to be quantified and dividing by contributing area, the sediment yield can be determined. Contributing area upstream of the straw dams ranged from 405 to 2280 m^2 (Table I). The straw dams proved to be a reliable technique because they are simple to install, easy to maintain, require surveys only after several rainfall events, and capture virtually all the sediment.

Average sediment yield for each geomorphic unit was calculated from the sediment traps and straw dams operating on that surface. The total number of days the sediment traps and straw dams operated varied. To calculate an annual sediment yield, the total mass of sediment was normalized by the number of days each site operated and multiplied by 365. The percentage of vegetation cover in each trap was measured over time with a hoop at two or more permanent locations in the trap, and at random locations. A streamflow-gaging station and automatic suspended-sediment sampler were installed downstream in the Arroyo Chavez Basin (Figure 4B), and operated during the study period. Streamflow, sediment data collection, and computation followed US Geological Survey guidelines (Carter and Davidian, 1968; Porterfield, 1972; Edwards and Glysson, 1988). Suspended-sediment loads were computed using the subdivision method (Porterfield, 1972).

At the geologic time-scale (10 to 20×10^3 years), sediment production rates for Arroyo Chavez were estimated by Clapp *et al.* (2001) using the *in situ*-produced cosmogenic radionuclide ^{10}Be. ^{10}Be is produced in quartz from the interaction of secondary cosmic rays (primarily high-energy neutrons) with Si and O (Lal, 1988). These cosmogenic radionuclides accumulate most rapidly in sediment and bedrock residing at or near the earth's surface (<3 m depth); accumulation or 'production' rates decrease exponentially with depth (Lal, 1988). Cosmogenic radionuclide abundances in near-surface (<1 m) quartz provide an estimate of the rate at which sediment is produced within a drainage basin (Brown *et al.*, 1995; Bierman and Steig, 1996; Granger *et al.*, 1996).

In areas where erosion is low, sediment at the earth's surface accumulates many cosmogenic radionuclides. Conversely, in rapidly eroding areas, the abundance of radionuclides in the sediment is low. Sediment particles travel from the initial bedrock source to the basin outlet and may reside for a period of time in storage. Storage areas can be thought of as a series of reservoirs through which sediment flows before it exits via the main channel. If a basin is in 'dynamic equilibrium' over geologic time, there will be neither an increase or decrease in cosmogenic abundances in these storage reservoirs. Clapp *et al.* (2001) showed that Arroyo Chavez is in dynamic equilibrium over geologic time where the drainage network of the basin is an integrator of sediment from throughout the basin, and thus interpreted the ^{10}Be concentrations in the stream channel sediments to represent basin-wide average concentrations. The measurements made by Clapp *et al.* (2001) presented an opportunity to contrast modern rates of erosion and sediment yield to geologic rates of sediment production.

SEDIMENT YIELD RESULTS

In Arroyo Chavez, between June 1996 to October 1998, 29–58 rainfall/run-off events were sampled by the sediment traps (Table I). Storm-event produced sediment concentration measured in the traps was highly variable reflecting differences in vegetative, geomorphic, and land use characteristics (Table I; Figure 5). Average modern sediment yields for each geomorphic unit were (Figure 6): gently sloping hillslopes ($0{\cdot}20$ kg m^{-2} a^{-1}), mesa top ($0{\cdot}38$ kg m^{-2} a^{-1}), steep colluvial slopes ($0{\cdot}56$ kg m^{-2} a^{-1}), alluvial fan ($0{\cdot}94$ kg m^{-2} a^{-1}), and the alluvial valley floor ($1{\cdot}83$ kg m^{-2} a^{-1}).

The highest and lowest sediment yields were on the alluvial valley floor (Tables I and II). The variation in sediment yield on the alluvial valley floor is partly related to vegetation cover. During the study period, well-vegetated areas covered 60 per cent of the basin and sparsely vegetated areas covered 40 per cent. The highest rate of sediment yield was $3{\cdot}35$ kg m^{-2} a^{-1}, measured in a sparsely vegetated area on the alluvial valley floor,

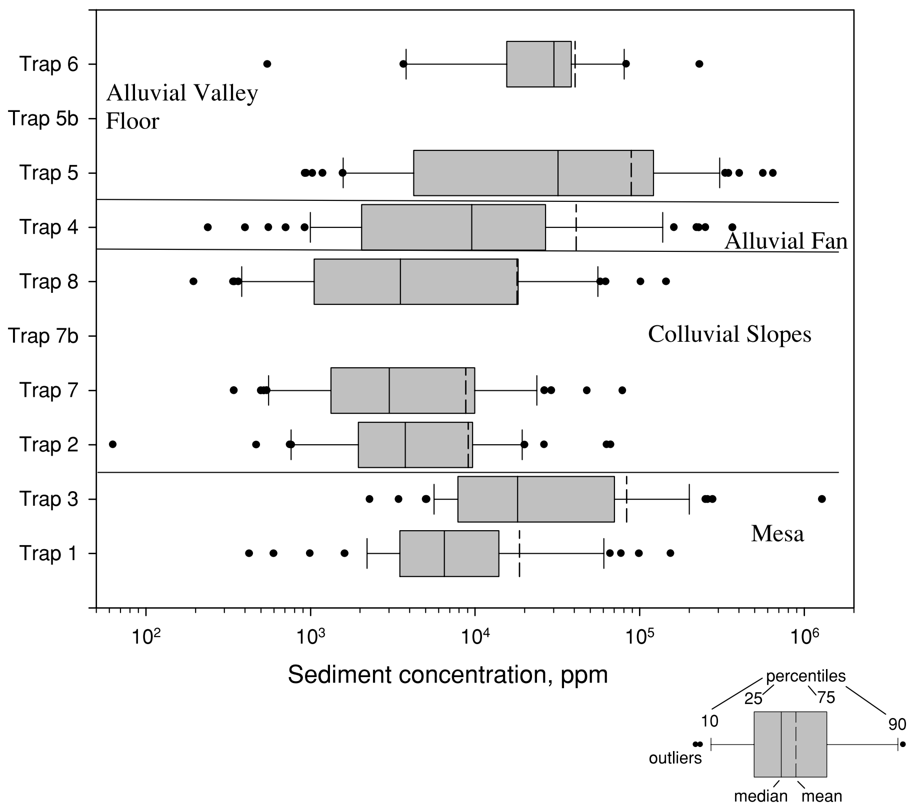


Figure 5. Sediment concentrations measured during storm events at the sediment traps in Arroyo Chavez Basin, June 13, 1996 to October 2, 1998

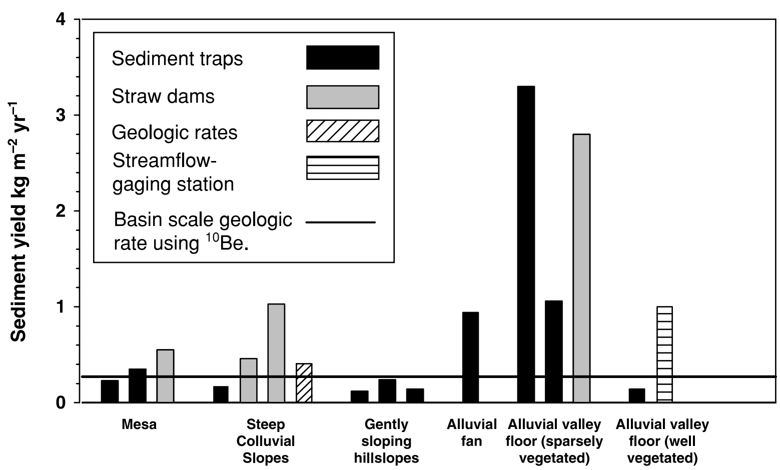


Figure 6. Sediment yield measured using sediment traps and straw dams on the geomorphic units defined for Arroyo Chavez Basin. Basinwide erosion estimated using suspended-sediment loads measured at the streamflow-gaging station. Geologic rates of sediment generation estimated using ^{10}Be (Clapp *et al*., 2001)

Table II. Summary of data from straw dams for Arroyo Chavez

Straw dam	Days in operation	Geomorphic surface	Drainage area (m^2)[a]	Sediment deposition (kg)	Average sediment yield (kg m^{-2} a^{-1})
A	1207	Steep colluvial slopes	2280	3471	0·46
B	1171	Mesa top	1420	2511	0·55
C	1172	Steep colluvial slopes	541	1791	1·03
D	931	Alluvial valley floor	405	2849	2·76

[a] The contributing area of each straw dam was traversed and surveyed with a total station.

Table III. Summary of data from streamflow gaging station at Arroyo Chavez

Water Year	Number of run-off events	Rainfall Arroyo Chavez basin (mm)[a]	Total run-off (m^3)	Suspended-sediment load (tonnes)	Rainfall at Cuba, New Mexico (mm)
1996	12	185	13 480	1630	234
1997	12	410	27 860	1880	400
1998	17	272	31 250	3200	341

[a] Rainfall amounts were averaged from rain gages shown in Figure 4.

which had an average vegetative cover of 12 per cent. The lowest sediment yield was 0·14 kg m^{-2} a^{-1}, measured in a well-vegetated part of the alluvial valley floor, which had an average vegetative cover of 38 per cent.

During large rainfall-run-off events, a few traps and collection buckets were completely filled and some run-off and sediment was lost. This rarely occurred for the mesa top, steep colluvial slopes, and gently sloping hillslope sediment traps. For traps installed on the alluvial fan and alluvial valley floor, some run-off and sediment was lost during the largest storm events. In addition, the traps on the alluvial-valley floor were occasionally trampled by livestock. Putting precise error values on the trap data is difficult, but the sediment yield data obtained from traps on the alluvial fan and alluvial valley floor should be regarded as minimum values. Although large rainfall-run-off events may cause the straw dams to be overtopped, this did not appear to happen during the study period.

During the study period, 41 run-off events were recorded at the streamflow-gaging station (Table III). The average annual sediment yield measured at the Arroyo Chavez streamflow-gaging station was 1·0 kg m^{-2} a^{-1}, which is close to the average of all sediment traps and straw dams (0·8 kg m^{-2} a^{-1}). The average annual sediment yield data does not include bedload export out of the basin. Bedload in fine-grained systems like Arroyo Chavez is generally low (Meyer, 1989).

DISCUSSION

Temporal scale comparison

Sediment yields from the traps, dams, and streamflow-gaging station were compared to geologic rates of sediment production (Clapp *et al*., 2001, Figure 6); Clapp *et al*. used ^{10}Be to calculate a basinwide sediment production rate of 0·27 kg m^{-2} a^{-1}, equivalent to bedrock lowering at ~100 m / Ma. The geologic rate of sediment production is similar to the modern sediment yields for most geomorphic units including colluvial slopes, gently sloping hillslopes, and mesa tops (Figure 6). The geologic rate of sediment production is dissimilar to the sparsely vegetated portions of the alluvial valley floor. The similarity of modern and geologic rates estimated by these independent methods is striking. This similarity indicates that we can make short-term measurements that are comparable to long-term rates of sediment production. Of the modern methods used to quantify sediment yields, if information on individual rainfall-runoff events is not needed, the straw dams, because of their low cost, simple construction, and low maintenance, proved to the most useful and reliable method for measuring sediment yield.

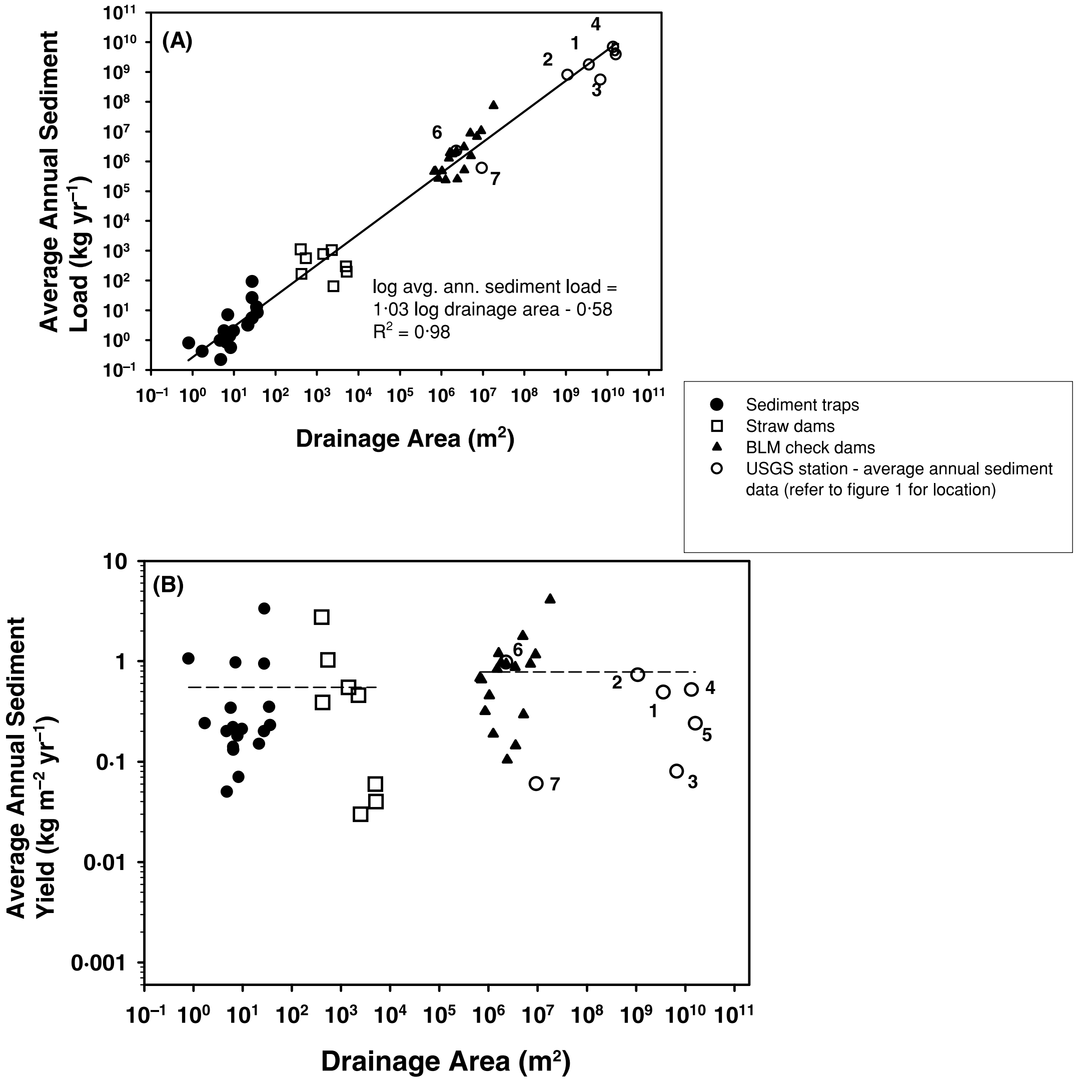


Figure 7. (A) Relation of drainage area and sediment load and (B) drainage area and sediment yield. Data obtained from sediment traps and straw dams in this study were combined with sediment trap data from Volcano Hill, another subbasin of the Rio Puerco (Gellis *et al.*, 2001), stock pond surveys in the Rio Puerco (Phippen, 2000), and data from USGS sediment stations in the Rio Puerco Basin (Figure 1). Average sediment yields for drainage areas 0·8 to 5170 m^2 and $6{\cdot}7 \times 10^5$ to $1{\cdot}61 \times 10^{10}$ m^2 are shown as dashed lines

Spatial scale

Drainage area and average annual sediment load, measured over 10 orders of magnitude, are well correlated ($r^2 = 0{\cdot}98$, Figure 7A). The strong relation between sediment load and drainage area is related to the power relation between discharge and contributing area (Strahler, 1964). Using sediment yield values from the sediment traps and straw dams in this study, combined with sediment trap data from Volcano Hill, another sub-basin of the Rio Puerco (Gellis *et al.*, 2001), stock pond surveys in the Rio Puerco (Phippen, 2000), and USGS sediment stations in the Rio Puerco basin (Figure 1), which range in drainage area from 0·8 to $1{\cdot}61 \times 10^{10}$ m^2, a plot of drainage area versus sediment yield shows that there is a considerable variation of sediment yield with contributing area and no trend (Figure 7B).

Schumm (1977) and Walling (1983) described decreasing sediment yield with increasing basin area as more sites in the basin become available for sediment storage. Figure 7B shows that the variation in sediment yield

Table IV. Average annual rainfall and daily rainfall intensity for the period of record and for the study period at the Cuba, New mexico rain gage

	Period of record (1948–98)[a]	Study period (1996–98)
Average annual rainfall	329	348
Average number of days of rainfall, 0·01 < 12·7 mm	60	45
Average number of days of rainfall, 12·7 < 25·4 mm	5·8	5·3
≥25·4 mm	1·0	2·0

[a] Years with missing data: 1964, 1973, 1977, 1982, 1983, 1996, 1997.

is not just a function of contributing area but other factors are important. At the intermediate and larger scale, variations in sediment yields are due to geology. Sediment yields measured at USGS streamflow-gaging stations are typically lowest in the Rio San Jose drainage, an area of extensive Cenozoic volcanic deposits, and the highest sediment yields are found draining the Mesozoic sandstone and shale. Because of the variation of sediment yield at a given drainage area, Figure 7B illustrates the importance of measuring erosion rates at different spatial scales. Land use may be an important factor at all scales. The dominant land use in the basin is grazing, so we consider the possible effects of grazing on erosion below.

Influence of climate

A problem with short-term sediment studies is that climate conditions may not be representative of long-term climate conditions. Average annual rainfall at Cuba, New Mexico during the study period (1996–98) was 348 mm, which is close to the long-term average annual rainfall of 329 mm during 1942–98 (Department of Commerce) (Table IV). Rainfall intensity may affect erosion more than annual rainfall (Leopold, 1951; Leopold *et al*., 1966). Following Leopold's (1951) classification of rainfall intensity, daily rainfall at Cuba, New Mexico was separated into three classes (0·01 to <12·7 mm per day, 12·7 to <25·4 mm per day, and ≥25·4 mm per day) for the period of record and the study period (Table IV). Daily rainfall totals greater than 0 mm but less than 12·7 mm per day represent low-intensity storms; daily totals between 12·7 and 25·4 mm per day represent moderate-intensity storms, and totals greater than 25·4 mm per day represent high-intensity storms. Moderate-intensity and high-intensity storms affect erosion and low-intensity storms affect vegetation (Leopold *et al*., 1966). A similar average number of days of moderate-intensity rainfall occurred during the study period and the period of record, and on average one more day of high-intensity rainfall occurred during the study period (Table IV). Therefore, the climatic conditions in Arroyo Chavez during the study period were similar to the long-term historical climatic record.

Sediment yields

The short-term sediment yields for Arroyo Chavez (closed circles in Figure 7) were within an order of magnitude (many were within a factor of 2) of the geologic rates of basinwide sediment production (0·27 kg m^{-2} a^{-1}; Clapp *et al*., 2001). This is in contrast to Kirchner *et al*. (2001), who found that sediment production rates on geologic time-scales in mountainous Idaho were up to 17 times higher than modern short-term sediment yields. They attributed this difference to extreme episodic sediment delivery from large events, such as those triggered by convective storms following major wildfires, a phenomenon not accounted for by short-term sampling.

The similarity of geologic and short-term rates of sediment yield in Arroyo Chavez suggests that extreme climatic events occurring over geologic time in Arroyo Chavez do not increase sediment yield significantly over yield during average climate conditions. The Rio Puerco drainage is transport rather than supply limited and wildfires are likely not an important factor in controlling rates of sediment production. Arroyo Chavez and the Rio Puerco, in general, produce high sediment concentrations even during average rainfall events. Sediment storage sites are widespread (alluvial fans, colluvial toe-slopes) and sediment yields are moderated during extreme events.

In Arroyo Chavez, the differences between modern and geologic rates were greatest for the alluvial valley floor, where the average modern rate of sediment yield (1·83 kg m^{-2} a^{-1}) was an order of magnitude greater than the geologic rate (0·27 kg m^{-2} a^{-1}) (Table I). Since the alluvial valley floor by definition is a constructional feature, then how is it now a source of sediment? The answer may be related both intrinsic properties and land use. Intrinsic properties involve the dynamic changes in channel geometry that occur in arroyos and the current hydraulic state of the channel. Land use includes grazing activity on the alluvial valley floor.

Arroyo Chavez channel

The modern Arroyo Chavez probably responded to the base-level lowering caused by incision of the Rio Puerco in the late 1800s by headcut erosion. In the model of arroyo evolution depicted by Gellis *et al.* (1991), following incision, the arroyo proceeds through sequential stages of channel incision, channel widening, inner flood-plain formation, and aggradation. Channel geometry in each of these stages determines its hydraulic state (eroding versus aggrading). Thus the channel bed, banks, and floodplain are sediment sources when the channel is incising and widening.

The present Arroyo Chavez channel is deeply incised, with widening occurring as an active process. The channel is so deeply incised that overbank flooding on the alluvial valley floor is extremely unlikely. Because Arroyo Chavez is so deeply incised, piping and gullying are common on select portions of the alluvial valley floor and the alluvial valley floor is now a sediment source. Most of the upper surfaces (mesa tops, colluvial slopes, gently sloping hillslopes) are not graded to the main channel and thus are not affected by the incised state of the Arroyo Chavez channel. Areas on the alluvial-valley floor where sediment traps were installed were not near gullies or piping holes and thus the incised state of the channel did not affect these measurements. Straw dam D was placed in a gully on the alluvial-valley floor and its erosion rates over time will be influenced by the arroyo cycle (Table II).

Effects of grazing

Grazing increases sediment yield because it reduces vegetative cover, decreases infiltration, and increases surface run-off (Blackburn *et al.*, 1982; Owens *et al.*, 1996), although the relation of grazing effects on infiltration and run-off is highly variable across the landscape (Trimble and Mendel, 1995). In a study of four grazed (0·06–0·43 km^2) and four ungrazed (0·05–0·41 km^2) basins in western Colorado, Lusby *et al.* (1963) concluded that after $4^1/_2$ years sediment yield in grazed areas was 46 per cet higher (8950 m^3 km^{-2} a^{-1}) than in ungrazed areas (6140 m^3 km^{-2} a^{-1}). Owens *et al.* (1996) measured erosion rates and sediment concentration in a 0·26 km^2 unimproved pasture watershed near Coshocton, Ohio, that was grazed for 7 years and had grazing excluded near the stream for the following 5 years. During the latter 5 years, the annual sediment concentration decreased by more than 50 per cent and the amount of soil loss decreased by 40 per cent. Average annual soil losses were reduced from 2·5 to 1·4 Mg/ha, while average annual precipitation remained similar. In contrast, Rich and Reynolds (1963), in four watersheds (0·04–0·08 km^2) in central Arizona, and Fortier *et al.* (1980), in a 0·22 km^2 watershed in northern Idaho, found that grazing showed no significant effect on total watershed sediment yield.

Although grazing can occur in any portion of the Arroyo Chavez basin, livestock favor the alluvial valley floor, where the water sources are located. Therefore, the high sediment yields on the alluvial valley floor could be attributed to grazing activity. Gellis *et al.* (2001) compared sediment yields at Arroyo Chavez to a well-managed, grazed sub-basin of the Rio Puerco, Volcano Hill Wash. The stocking densities at Arroyo Chavez (7·3 animals per 100 ha) were 7 times higher than Volcano Hill Wash (1·0 animal per 100 ha), the average annual sediment yield at Arroyo Chavez streamflow-gaging station (1·0 kg km^{-2} a^{-1}) was more than twice the average annual sediment yield at Volcano Hill Wash (0·4 kg km^{-2} a^{-1}). The highest sediment yields for Volcano Hill Wash also were found on the alluvial valley floor, ranging up to 0·98 kg m^{-2} a^{-1} and averaging 0·42 kg m^{-2} a^{-1}, and indicate that even under lower grazing pressures the alluvial valley floor is a major source of sediment. However, the average sediment yield for the alluvial valley floor at Volcano Hill Wash is within a factor of 2 of geologic sediment production for Arroyo Chavez and supports the view that grazing at Arroyo Chavez augmented erosion on the alluvial valley floor.

Grazing is not the only human disturbance in Arroyo Chavez. Other human activity on the alluvial valley floor includes a gas pipeline. During construction of the gas pipeline several decades ago, the alluvial valley was trenched and therefore disturbed. The lingering influence of this disturbance and the watershed's recovery are not known. However, at the plot scale, the sediment traps installed on the alluvial valley floor were not affected by the gas pipeline but were affected by grazing.

CONCLUSIONS

This study compares modern short-term sediment yields measured using sediment traps and dams to geologic rates of sediment production estimated using cosmogenic nuclides. Contrasting modern, short-term rates of sediment yield with long-term geologic or natural rates of sediment production allows assessment of human influences on erosion rates. Individual measurements of sediment concentration using sediment traps are highly variable. Sediment yield varies significantly over a wide range of contributing areas and reliance on a small number of similar contributing areas could yield a highly biased measurement. Therefore, to adequately describe the range in sediment yield, multiple erosion and sediment yield measurements were made at the same and different scales. Of the modern methods used to quantify sediment yields, if information on individual rainfall-runoff events is not needed, the straw dams, because of their low cost, simple construction, and low maintenance, proved to the most useful and reliable method for measuring sediment yield.

In this study, the differences in short-term and geologic sediment yields were most noticeable for the alluvial valley floor. The relation of the alluvial valley floor to the hydraulic state of the arroyo appears to be extremely important in determining whether the alluvial valley floor is aggrading or eroding. Currently, Arroyo Chavez is incised and the alluvial valley floor is eroding. The alluvial valley floor is also the portion of the basin most modified by human disturbance including grazing and gas pipeline activity, which may be increasing erosion rates. We find that alluvial valley floor sediment yields in areas of sparse vegetation are an order of magnitude higher than the geologic rates of sediment production. In the well-managed grazed basin Volcano Hill Wash, the highest average sediment yield also was found on the alluvial valley floor but were similar to the geologic rates of sediment production. At Arroyo Chavez, we conclude that grazing is the likely cause for higher sediment yields on the alluvial valley floor.

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