Modern Sediment Yield Compared to Geologic Rates of Sediment Generation in a Semi-arid Basin, New Mexico – Quantifying the human impact

Allen C. Gellis*
United States Geological Survey, Baltimore, MD 21237, USA
Milan J. Pavich
United States Geological Survey, Reston, VA 20192, USA
Paul Bierman
University of Vermont, Burlington, VT 05405, USA
Amy Ellwein
Foth & Van Dyke and Associates, Inc.
2900 Lone Oak Parkway, Suite 125
Eagan, MN 55121-1594
Scott Aby
P.O. Box 488, Dixon, N,M, 87527
Eric Clapp
University of Vermont, Burlington, VT 05405, USA

ABSTRACT

Modern short term sediment yields, averaged for geomorphic surfaces (mesa, steep colluvial slopes, gently sloping hillslopes, and the alluvial valley floor) with sediment traps and straw dams range from 0.2 to 1.8 $kg\cdot m^{-2}\cdot yr^{-1}$ and exceed long term sediment yield of 0.27 $kg\cdot m^{-2}\cdot yr^{-1}$ (^{10}Be-based) in a heavily studied semi-arid drainage basin. The differences between sediment production and yield were most noticeable for the alluvial valley floor, where individual sediment traps and dams ranged up to 3.3 $kg\cdot m^{-2}\cdot yr^{-1}$. The alluvial valley floor is grazed and has a gas pipeline running through it; thus, the sediment yields on the alluvial valley floor likely represent human influence. Sediment yield in contributing areas ranging from 8.0 x 10^{0} to 1.61 x 10^{10} m^2 showed considerable scatter and therefore, to determine the variance, sediment yield needs to be measured across a wide range of contributing areas. This study provides a model for contrasting human impact on sediment yield with background rates of sediment production.

INTRODUCTION

The distinction between background sediment production and erosion rates, determined by natural (geologic and climatic) factors, and human-accelerated sediment yields has important environmental and regulatory policy implications (U.S. Environmental Protection Agency, 1999). The need to understand how human activities influence sediment transport is essential in identifying and characterizing degraded landscapes. However, few studies describe a consistent, verifiable approach to comparing natural rates of erosion (Saunders and Young, 1983) to human-influenced rates (Hooke, 1994).

The measurement of erosion, sediment production, and sediment yield can be divided into time scales of modern (hours to years), historical (decades to centuries), and geologic (millennia). For each time scale, different approaches are used. Modern process geomorphic approaches, at the scale of hours to years, measure sediment yield using sediment traps (Gerlach, 1967; Bryan, 1991; Gellis, 1998) and streamflow-gaging sediment stations (Judson and Ritter, 1964; Walling, 1991), and measure surface lowering with erosion pins (Leopold et al., 1966). For the historical time scale of decades to hundreds of years, maps and surveys (Trimble and Lund, 1982; Kesel et al., 1992), and radionuclides such as, Cesium-137 (Walling et al., 1986) can be used to document erosion and sedimentation. From hundreds to thousands of years, archaeologic techniques can be used. For the geologic scale (>10^4 years), cosmogenic isotopes can be used to estimate rates of sediment production (Brown, et al., 1995; Bierman and Steig, 1996).

There is considerable uncertainty in extrapolating modern short term measurements to longer periods (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 normal 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 decreases (Schumm, 1977; Walling, 1983; Trimble, 1990). This paper examines and compares sediment yield measured in Arroyo Chavez, a subbasin of the Rio Puerco, at two different time scales, the modern and geologic, and examines the relation of sediment yield to scale.

Erosional Setting

The Rio Puerco is the largest tributary to the Rio Grande in New Mexico, draining more than 16,100 km^2 (fig. 1) and is one of the most sediment-laden streams on Earth. On the basis of 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 (fig. 2). The Rio Puerco has cut and filled three times in the past 3,000 years (Love and Young, 1983; Love, 1986), with the most recent period of incision occurred in the late 1800s (Bryan, 1928). Recent surveys indicate that the Rio Puerco is in a cycle of aggradation (Elliott et al., 1999; Gellis and Elliott, 2001).

The 2.28 km^2 Arroyo Chavez Basin, a subbasin in the Rio Puerco (fig. 1), was selected for detailed erosion studies (fig. 1) because its geology and land use are representative of the Rio Puerco. Arroyo Chavez Basin is semiarid, with average annual rainfall of 336 mm (data for the period 1941-1998, Cuba, New Mexico. located approximately 39 km from Arroyo Chavez) (U.S. Dept. of Commerce). Elevations in Arroyo Chavez range from 1,938 m to 2,021 m. The Arroyo Chavez Basin drains interbedded sandstones and shales. The surface soil textures range from silty-clay loam to sandy-clay loam, and both contain about 30% clay. The channel of Arroyo Chavez is incised 4 m below the alluvial valley floor with many tributaries actively headcutting (fig 3). Median grain size on the bed of Arroyo Chavez ranges from fine sand to gravel (0.15 to 3 mm). Land use is predominantly grazing with a gas pipeline running at shallow depths through the center of the basin.

Average rainfall at Cuba, N.M. during the study period was 325 mm, which is close to the long-term average (1942-98) of 331 mm. Rainfall for the study period at Arroyo Chavez averaged 289 mm/yr, which is less than the long-term average rainfall at Cuba (331 mm). Elevation at the Arroyo Chavez rain gage is approximately 150 m lower than the Cuba rain gage (2147 m), and therefore, lower rainfall totals are expected at Arroyo Chavez.

Figure 1. Location of U.S. Geological Survey streamflow-gaging and sediment stations in the Rio Puerco Basin, New Mexico.

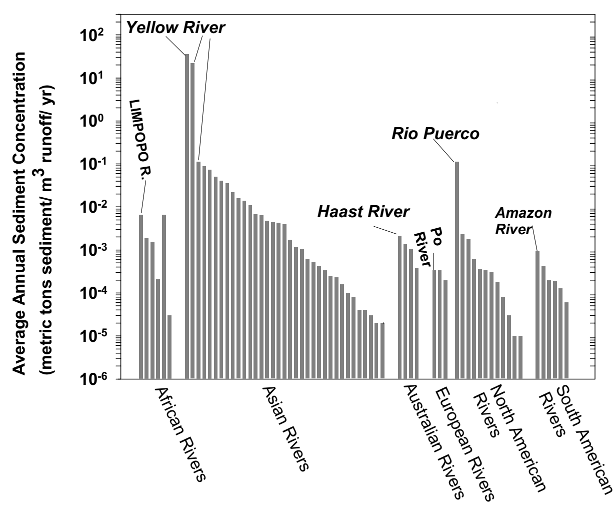


Figure 2. Sediment concentration in selected major world rivers after (Milliman and Meade, 1983; Zhao and others,1992; this study).

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

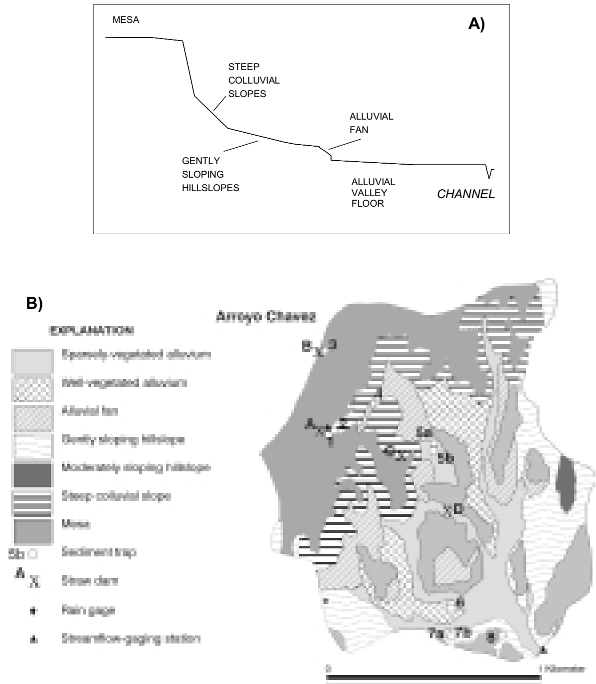


Figure 4. (a) Geomorphic elements defined for Arroyo Chavez. (b) Geomorphic map of Arroyo Chavez basin showing sediment traps, straw dams, rain gages, and streamflow-gaging station.

Measurement Methods

Modern rates of sediment yield were measured for five geomorphic elements: mesa, steep colluvial slopes, gently sloping hillslopes, alluvial fans, and alluvial valley floor (fig. 4a) from 1996 to 1998 using sediment traps and sediment deposition behind small straw dams (fig. 4b). Ten sediment traps based on a modified Gerlach Trough (Gerlach, 1967; Gellis, 1998), were installed in Arroyo Chavez. The contributing area of each trap was bounded with metal edging and ranged from 0.76 to 37 m^2. Sediment mass trapped in the troughs was measured after one or several closely spaced rainfall events during the 2-year period. 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. A notch approximately 1 m deep was dug in the channel and fitted with straw bales. The sediment pool on the upstream side of the dam was surveyed periodically to quantify sediment volume. Mass was determined by measuring the density of aggraded sediment. Contributing area of the straw dams ranged from 405 to 2,280 m^2.

An average sediment yield for each geomorphic surface was calculated by averaging sediment yield from the sediment traps and straw dams operating on each geomorphic surface. The percentage of vegetation cover in each trap was measured over time using 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 in the Arroyo Chavez Basin (fig. 4b), and operated during the study period. At the geologic time scale (10 to 20 x 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.

SEDIMENT YIELD RESULTS

Sediment traps sampled 29 to 58 rainfall and runoff events for which sediment concentration (ppm), calculated as mass of sediment (g) for the event divided by the runoff (g), and multiplied by 1 x 10^6, was highly variable (Table 1; fig. 5). Average modern sediment yields for each geomorphic element were: gently sloping hillslopes, 0.20 $kg \cdot m^{-2} \cdot yr^{-1}$; mesa, 0.38 $kg \cdot m^{-2} \cdot yr^{-1}$; steep colluvial slopes, 0.56 $kg \cdot m^{-2} \cdot yr^{-1}$; alluvial fan, 0.94 $kg \cdot m^{-2} \cdot yr^{-1}$; and the alluvial valley floor, 1.83 $kg \cdot m^{-2} \cdot yr^{-1}$ (fig. 6). The highest and lowest sediment yields were on the alluvial valley floor (table 1). The variation in sediment yield on the alluvial valley floor is related to vegetation cover. During the study period, well-vegetated areas covered 60% of the basin and sparsely vegetated areas covered 40%. The highest rate of sediment yield was 3.3 $kg \cdot m^{-2} \cdot yr^{-1}$, measured in a sparsely vegetated area on the alluvial valley floor, which had an average vegetative cover of 12%. The lowest erosion rate was 0.14 $kg \cdot m^{-2} \cdot yr^{-1}$, measured in a well-vegetated part of the alluvial valley floor, which had an average vegetative cover of 38%.

1. Summary of data from (a) sediment traps, (b) straw dams, and (c) sediment station for Arroyo Chavez.

(A)

Sediment trap	Geomorphic surface	Days in operation	Number of events sampled	Drainage Area (m^2)	Runoff volume (g)	Sediment load (g)	Rainfall (mm)	Sediment yield ($kg/m^2/yr$)
1	Mesa	841	46	37	692,390	19,230	688	0.23
2	Steep colluvial slopes	841	39	7.9	232,590	3,200	688	0.18
3	Mesa	841	47	35	487,880	28,730	701	0.35
4	Alluvial fan	841	52	27	726,130	59,130	688	0.94
5a	Alluvial valley floor	841	58	27	1,509,500	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	64,450	2,050	917	0.14
7a	Gently sloping hillslopes	841	46	28	807,660	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	286,380	7,280	1,016	0.14

(B)

Straw dam	Days in operation	Geomorphic surface	Drainage area (m^2)	Sediment deposition (kg)	Sediment yield ($kg/m^2/yr$)	Denudation (mm/yr)
A	1207	Steep colluvial slopes	2,280	3,471	0.46	0.36
B	1171	Mesa	1,420	2,511	0.55	0.45
C	1172	Steep colluvial slopes	541	1,791	1.03	0.89
D	931	Alluvial valley floor	405	2,849	2.76	2.78

(C)

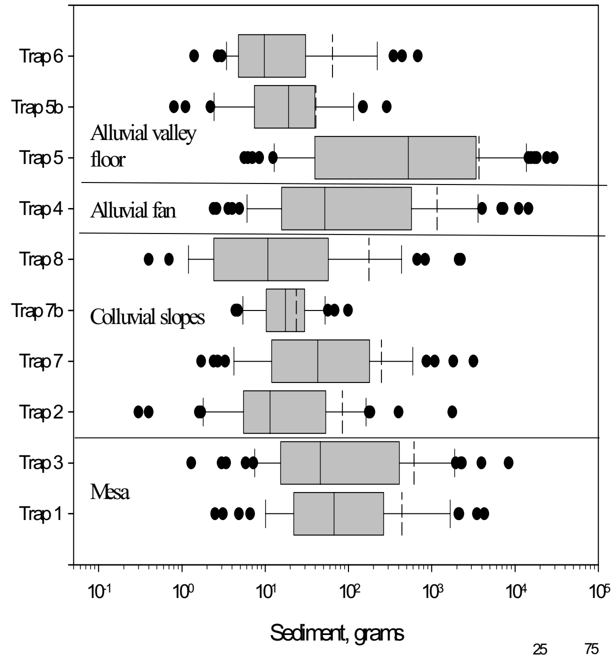
Water Year	Number of runoff events	Total rainfall (mm)	Runoff (m^3)	Suspended-sediment load, metric tons *	Rainfall at Cuba, New Mexico (mm)
1996	12	185	13,480	1,630	234
1997	12	410	27,860	1,880	400
1998	17	272	31,250	3,200	341

* *Average annual suspended-sediment load = 2,240 metric tons*

During the study period, 41 runoff events were recorded at the streamflow-gaging station (table 1). The average annual sediment yield measured at the Arroyo Chavez streamflow-gaging station was 1.0 $kg^{2\cdot}\ yr^{-2}$, which is close to the average of all sediment traps and straw dams (0.8 $kg{\cdot}m^{-2\cdot}\ yr^{-1}$). The average annual sediment yield data did not include bedload export out of the basin. Bedload in fine grained systems like the Rio Puerco is generally low (Meyer, 1989).

DISCUSSION

Sediment yields from the traps, dams, and streamflow-gaging station were compared to geologic rates of sediment production (Clapp et al., 2001)(fig. 6). The ^{10}Be data collected by Clapp et al. (2001) demonstrated that channel sediment nuclide concentrations collected on the arroyo bed are representative of basinwide sediment production. Clapp et al. (2001) used ^{10}Be to calculate a basinwide "bedrock equivalent" sediment production rate of 102 ± 24 m/Myr (0.10 ± 0.02 mm/yr). Using the density of bedrock (p = 2.7 g cm-^{3}) the basinwide sediment yield is 0.27 kg m^{-2} yr^{-1}. The geologic rates of sediment production are similar to the modern sediment yields for geomorphic elements: colluvial slopes, gently sloping hillslopes, and mesa (Table 1).



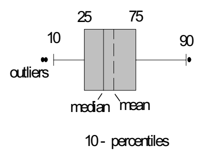


Figure 5. Storm event generated sediment measured in the sediment traps. Locations of traps shown in figure 4b.

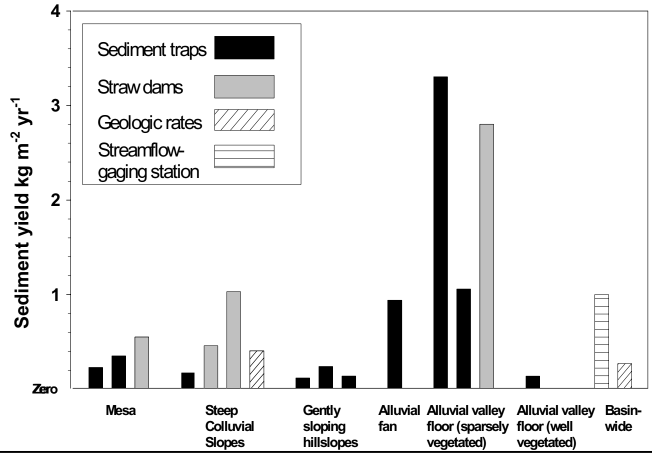


Figure 6. Sediment yield measured using sediment traps and straw dams on the geomorphic elements defined for Arroyo Chavez Basin, basinwide erosion using suspended-sediment loads measured at the streamflow-gaging station, and geologic rates of erosion using 10Be (Clapp et al., 2001).

Spatial Scale

Drainage area and average annual sediment load, measured over 10 orders of magnitude, are significantly well correlated ($r^2 = 0.98$) (fig. 7a). In contrast, drainage area and sediment yield show considerable variation (fig. 7b). This finding stands in stark contrast to those of Schumm (1977) and Walling (1983) who described decreasing sediment yield with increasing area as more sites in the basin become available for sediment storage. At the smaller scale, differences in sediment yields are related to vegetative cover and slope. At the intermediate and larger scale, variations in sediment yields are due to geology. Land use may be an important factor at all scales. 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.

Sediment Measurements and Grazing

A problem of short term studies is that short term climatic conditions may not be representative of long-term climatic conditions. The climatic conditions in Arroyo Chavez during the study were similar to or slightly drier than the long-term historical climatic record. Irrespective of climatic uncertainty, the short term rates of sediment yield were within an order of magnitude (many were within a factor of 2) of the geologic rates of basinwide sediment yield of $0.27\ kg \cdot m^{-2} \cdot yr^{-1}$ (Clapp et al., 2001). Kirchner et al. (2001) found that geologic rates of sediment yields in mountainous Idaho were 17 times higher that modern short term sediment yields. They attributed this difference in sediment yield to rare and extreme sediment delivery from large events, such as those from convective storms following a major wildfire, which may not be sampled in the short term. The similarity of geologic and short term rates of sediment yield in Arroyo Chavez may suggest several hypotheses related to climate, vegetation, sediment storage sites, and land use. Extreme climatic events in the Rio Puerco may not increase sediment yield significantly over average climate conditions. Vegetation density is low in Arroyo Chavez and wildfires may not be important factor in sediment generation. In addition, the lower vegetation density in Arroyo Chavez compared to mountainous Idaho, produces high sediment concentrations even during average rainfall events. Storage sites in mountainous Idaho are minimal and sediment delivery is high during extreme events; whereas, in Arroyo Chavez storage sites are widespread (alluvial fans, colluvial toe-slopes) and sediment yields are moderated during extreme events. Land use in Arroyo Chavez, such as grazing, may be increasing sediment yields measured in the short term.

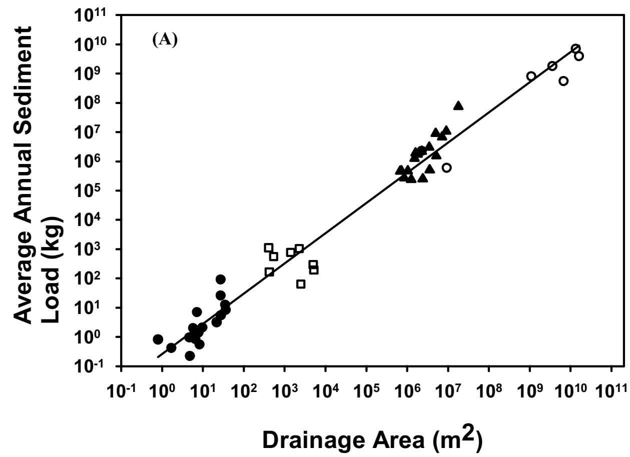
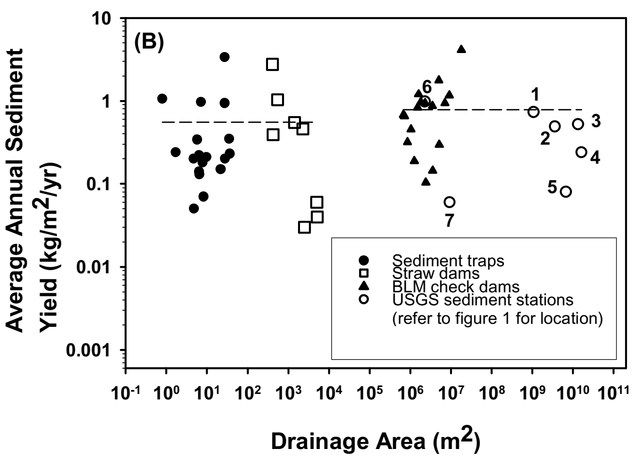


Figure 7. (A) Relation of drainage area and sediment load and (B) drainage area and sediment yield. Data was obtained from sediment traps and straw dams in this study and combined with sediment trap data from Volcano Hill, another subbasin of the Rio Puerco (Gellis et. al., 2001), stock pond surveys in the Rio Puerco, (Phippen, 2000), and data from USGS sediment stations in the Rio Puerco Basin (fig. 1). Average sediment yields for drainage areas 0.8 to 5,170 m^2 and $6.7x10^5$ to $1.61\ x10^{10}\ m^2$ are shown as dashed lines.



In Arroyo Chavez, the differences in erosion rates calculated by the two methods were greatest for the alluvial valley floor, where the modern rate of erosion ranged up to $3.3\ kg \cdot m^{-2} \cdot yr^{-1}$ (Table 1). Can this difference between the geologic-scale basinwide sediment yield ($0.27\ kg \cdot m^{-2} \cdot yr^{-1}$) and the short term average sediment yield on the alluvial valley floor ($1.83\ kg \cdot m^{-2} \cdot yr^{-1}$) be used to show that human influences have caused an order of magnitude increase in sediment yield on the alluvial valley floor in Arroyo Chavez?

Grazing increases sediment yield because it reduces vegetative cover, decreases infiltration, and increases surface runoff (Blackburn et al., 1982; Owens et al., 1996); although data are scarce. In a study of 4 grazed and 4 ungrazed basins in western Colorado, Lusby and others (1963) concluded that after 4 ½ years, sediment yield in grazed areas was 146 % higher ($8,950\ m^3 \cdot km^{-2} \cdot yr^{-1}$) than in ungrazed areas ($6,141\ m^3 \cdot km^{-2} \cdot yr^{-1}$). Owens et al. (1996) measured erosion rates and sediment concentration in a 26 ha unimproved pasture watershed near Coshocton, Ohio, that was grazed for 7 years and fenced out of the stream for the following 5 years. During the latter 5 years, the annual sediment concentration decreased by more than 50% and the amount of soil loss decreased by 40%. 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) and Fortier et al. (1980) found that grazing showed no significant effect on total watershed sediment loss.

The high sediment yields on the alluvial valley floor in Arroyo Chavez may be due to grazing. Gellis et al. (2001) compared sediment yields at Arroyo Chavez to a well-managed grazed subbasin of the Rio Puerco, Volcano Hill Wash, and found that the highest rates of sediment yield ($0.98\ kg\ m^{-2}\ yr^{-1}$) for Volcano Hill Wash also were found on the alluvial valley floor. However, 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 $kg \cdot km^{-2} yr^{-1}$) was more than twice the sediment yield at Volcano Hill Wash (0.4 $kg \cdot km^{-2} yr^{-1}$), and the sediment yield from all traps at Arroyo Chavez (0.68 $kg \cdot m^{-2} \cdot yr^{-1}$) was more than twice the average sediment yield for all traps at Volcano Hill Wash (0.27 $kg \cdot m^{-2} \cdot yr^{-1}$). 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 amount of disturbance and the watershed's recovery from this disturbance are not known. Because of this and other disturbance it is difficult to exactly define the additional sediment yield from grazing.

CONCLUSIONS

Results from this study provide a methodology using sediment traps and straw dams to determine short term sediment yields, comparable to geologic rates of sediment production determined using cosmogenic isotopes. Contrast of modern short term and geologic or natural rates of sediment yield allows assessment of possible human influences on erosion of the landscape. In this study, the differences in short term and geologic sediment yields were most noticeable for the alluvial valley floor, which is the portion of the basin most modified by human disturbance by grazing and gas pipeline activity, and may have caused sediment yields to be several orders of magnitude higher than the geologic rates of sediment production. Individual measurements of sediment concentration are highly variable and a small data set can lead to erroneous conclusions. Sediment yield varies significantly over a wide range of contributing areas. Reliance on a small number of similar contributing areas could yield a highly biased measurement. Therefore, to reduce the bias of measurements, erosion and sediment yield should be measured across a range of contributing areas.

ACKNOWLEDGEMENTS

We thank Steven Tillinghast, Andrew Dunne, Catherine Rehimaki, and Goeff Pociask for helping with sampling; Jeffrey Raffensperger, Helaine Markewich, and Gary Fisher for reviews. This study was supported by the U.S. Geological Survey Global Climate Change Program.

REFERENCES CITED

Bierman, P.R., and Steig, E., 1996, Estimating rates of denudation using cosmogenic isotope abundances in sediment: Earth Surface Processes, v. 21, p. 125-139.

Blackburn, W.H., Knight, R.W., and Wood, M.K., 1982, Impacts of grazing on watersheds: The Texas Agricultural Experiment Station, Report MP 1496, 32 p.

Brown, E., Stallard, R.F., Larsen, M.C., Raisbeck, G.M., and Yiou, F., 1995, Denudation rates determined from the accumulation of in situ produced ^{10}Be in the Luquillo Experimental Forest, Puerto Rico, Earth and Planetary Science Letters, v. 129, p. 193-202.

Bryan, K., 1928, Historic evidence on changes in the channel of the Rio Puerco, a tributary of the Rio Grande in New Mexico: Journal of Geology, v.36, p. 265-282.

Bryan, R.B., 1991, Surface Wash, *in* Slaymaker, O., ed., Field Experiments and Measurement Programs in Geomorphology: University of British Columbia Press, p. 107-168.

Clapp, E.M., Bierman, P.R., Pavich, M., Nichols, K.K., and Caffee, M.L., 2001, Rates of sediment supply to arroyos from upland erosion determined using in situ-produced cosmogenic ^{10}Be and ^{26}Al: Quaternary Research, v. 55, p. 235-245.

Elliott, J.G., Gellis, A.C., and Aby, S.B., 1999, Evolution of Arroyos--Incised Channels of the Southwestern United States: *In* Darby, S.E., and Simon, A., eds., Incised Channels--Processes, Forms, Engineering and Management, p. 153-185.

Fortier, D.H., Molnau, M., and Saxton, K.E., 1980, Sediment from a small grazed watershed: Symposium on Watershed Management 1980, Boise, Idaho, July 21-23, 1980, sponsored by the Committee on Watershed Management of the Irrigation and Drainage Division of the ASCE, v.2, p. 790-801.

Gellis, A.C., and Elliott, J.G., 2001, Arroyo changes in selected watersheds of New Mexico, United States: *In* Harvey, M., and Anthony, D., eds., Applying geomorphology to environmental management, a special publication honoring Stanley A. Schumm, Water Resources Publications, LLC Press, p. 225-240.

Gellis, A.C., 1998, Characterization and evaluation of channel and hillslope erosion on the Zuni Indian Reservation, New Mexico, 1992-95: U.S. Geological Survey Water Resources Investigations Report 97-4281, 60 p.

Gellis, A.C., Pavich, M. J., and Ellwein, A., 2001, erosion and sediment yields in two subbasins of contrasting land use, Rio Puerco, New Mexico: Sixth Federal Interagency Conference, Reno, NV., V83-V90.

Gerlach, T., 1967, Hillslope troughs for measuring sediment movement: Revue Geomorphologie Dynamique, v. 4, p. 173.

Hooke, R.L., 1994, On the efficacy of humans as geomorphic agents: GSA Today, v. 4, no. 9, p. 217, 224-225.

Hooke, R.L., 2000, On the history of humans as geomorphic agents: Geology, v. 28, p. 843-846.

Judson, S., and Ritter, D. F., 1964, Rates of regional denudation in the United States: Journal of Geophysical Research, v. 69, p. 3,395-3,401.

Kesel, R.H., Yodis, E.G., and McCraw, D.J., 1992, An approximation of the sediment budget of the lower Mississippi River prior to major human modification: Earth Surface Processes and Landforms, v. 17, p. 711-722.

Kirchner, J. W., R. C. Finkel, C. S. Riebe, D. E. Granger, J. L. Clayton and W. F. Megahan, 2001, Episodic mountain erosion inferred from sediment yields over decades and millennia, Geology 29, 591-594.

Leopold, L.B., Emmett, W.W., and Myrick, R.M., 1966, Channel and hillslope processes in a semiarid area, New Mexico: U.S. Geological Survey Professional Paper 352G, 253 p.

Love, D.W., 1986, A geological perspective of sediment storage and delivery along the Rio Puerco: *In*, Drainage basin sediment delivery, International Association of Hydrological Sciences Publication 159, Hadley, R.F., ed., p. 305-322.

Love, D.W., and Young, J.D., 1983, Progress report in the Late Cenozoic geologic evolution of the lower Rio Puerco: New Mexico Geological Society Guidebook, 34th Field Conference, Socorro Region 11, p. 277-284.

Lusby, G.C., Turner, G.T., Thompson, J.R., and Reid, V.H., 1963, Hydrologic and biotic characteristics of grazed and ungrazed watersheds of the Badger Wash Basin in Western Colorado, 1953-58: U.S. Geological Survey Water-Supply Paper 1532-B, 73 p.

Meyer, D.F., 1989, The significance of sediment transport in arroyo development: U.S. Geological Survey Water-Supply Paper 2349, 61 p.

Milliman, J.D. and Meade, R.H., 1983, World-wide delivery of river sediment to the oceans: Journal of Geology, v. 91, p. 1-21.

Owens, L.B., Edwards, W.M., and Van Keuren, R.W., 1996, Sediment losses from a pastured watershed before and after stream fencing: Journal of Soil and Water Conservation, v. 51, p. 90-94.

Phippen, S., 2000, An assessment of land uses and other factors that affect sediment yields in the Rio Puerco basin, Sandoval County, New Mexico: Unpublished Master's thesis, Colorado State University, Fort Collins, Co.

Rich, L.R., and Reynolds, H.G., 1963, Grazing in relation to runoff and erosion on some chaparral watersheds of central Arizona: Journal of Range Management, v. 16, p. 322-326.

Saunders, I., and Young, A., 1983, Rates of surface processes on slopes, slope retreat, and denudation: Earth Surface Processes and Landforms, v. 8, p. 473-501.

Schumm, S.A., 1977, The fluvial system: New York, Wiley, 338 p.

Trimble, S.W., 1990, Geomorphic effects of vegetation cover and management--Some time and space considerations in prediction of erosion and sediment yield: *In* Thornes, J.B., ed., Vegetation and Erosion: John Wiley and Sons, p. 55-65.

Trimble, S.W., and Lund., S.W., 1982, Soil conservation and the reduction of erosion and sedimentation in the Coon Creek basin, Wisconsin: U.S. Geological Survey Professional Paper 1234, 35 p.

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, 1941, 1941-98, Monthly climatological data reports for New Mexico.

U.S. Environmental Protection Agency, 1999, Protocol for developing sediment TMDLs: Office of Water, United States Environmental Protection Agency, EPA 841-B-99-004, 132 p.

Walling, D.E., 1983, The sediment delivery problem: Journal of Hydrology, v. 65, p. 209-237.

Walling, D.E, 1991, Drainage basin studies, *in* Slaymaker, O., ed., Field experiments and measurement programs in geomorphology: University of British Columbia Press, p. 17-60.

Walling, D.E., Bradley, S.B., and Wilkinson, C.J., 1986, A cesium-137 budget approach to the investigation of sediment delivery from a small agricultural drainage basin in Devon, UK, *in* Drainage Basin Sediment Delivery: International Association of Hydrological Sciences Publication 159, p. 423-435.

Zhao, W., Jiao, E., Wang, M G., and Meng, X., 1992, Analysis of the variation of sediment yield in Sanchuanhe River basin in the1980's: International Journal of Sediment Research, v. 7, p. 1-20.