Rainfall Simulation to Estimate Potential Sediment Loadings to the Albuquerque North Diversion Channel

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DISCLAIMER

ABSTRACT

Runoff from high-intensity short-duration thunderstorms is a major hydrologic phenomenon in the southwestern United States. If the runoff is excessive, flooding with concurrent damages may result. Exacerbating the flood hazard is simultaneous sediment transport with the runoff water. When the sediment-laden flow enters a constructed channel it may exceed the water-only design capacity or the sediment in the flow may deposit to such an extent that the channel no longer can contain the water-only flow adequately. Either situation reduces the frequency or return period design flow which the constructed facilities can accommodate.

Estimating the amount and characteristics of the sediment being transported in the channels requires an understanding of the material reaching the channels from upslope sources. In this study, rainfall simulation was used to measure runoff and sediment yields from three sites in the drainage basin of the Albuquerque North Diversion Channel. Nine 1m x 3m plots were studied and simulated rainfall was applied under "dry" and "wet" antecedent soil moisture conditions for a total of 18 plot-runs. One plot was scraped bare at each of the three sites to simulate disturbance caused by clearing and construction activities. The other plots were sampled with the natural vegetation at the site intact.

Steady-state infiltration or loss rates ranged between 3 and 69 mm/hr (0.12 and 2.72 in/hr) for the dry runs and between 18 and 42 mm/hr (0.71 and 1.65 in/hr) for the wet run experiments. Sediment yield per area per unit of runoff can be used to estimate sediment loading to a channel once runoff is modeled. Study results indicate that a value of 50 kg/ha/mm of runoff (0.52 tons/acre/in of runoff) is reasonable for undisturbed plots and that 300 kg/ha/mm (3.12 tons/acre/in) is reasonable for plots which were scraped bare of vegetation. The deposited sediments had median grain diameters comparable to the surface soils at the sites, but the gradation coefficients were lower for the sediments indicating that the finer particles were eroded preferentially from the plots. The ratio of deposited sediment yield to total sediment yield averaged 61%, with a wide range from 20% to 94%. Manning's n values, as determined from hydrograph analyses, averaged 0.453 $m^{1/3}/s$ (geometric mean of 0.231 $m^{1/3}/s$) with a very wide range. Study results should be very useful for hydrologists and erosion and sediment-transport modelers conducting drainage analyses in the Albuquerque area and other southwestern cities.

Keywords: simulated rainfall, soil erosion, sediment transport, infiltration, runoff plot

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INTRODUCTION

Runoff from high-intensity short-duration thunderstorms is a major hydrologic phenomenon in the southwestern United States. Many southwestern cities like Albuquerque, New Mexico, have developed structural responses to flood hazards by constructing various artificial channels and detention facilities. If the runoff is excessive, flooding with concurrent damages may result. Exacerbating the flood hazard is the simultaneous transport of sediment with the runoff water. When the sediment-laden flow enters a constructed channel, the "bulked" flow may exceed the "water only" design capacity or the sediment in the flow may deposit to such an extent that the channel can no longer contain the "water only" flow adequately. Either situation reduces the frequency or return period design storm which the constructed facilities can accommodate.

In steep, highly erosive areas, such as much of New Mexico, the sediment load can reach 10% of the water-flow volume (Ward 1986). The Albuquerque area is no exception as sediment may enter the constructed facilities from upland watershed or channel sources. To fully understand the sources of sediment inflow, one must obtain measurements from the watershed surfaces which contribute to the channel system.

Many approaches for obtaining such information are possible. The most controlled, flexible, and rapid approach is through rainfall simulation on runoff plots. This study was conducted using rainfall simulation on upland watershed plots to determine the potential sediment loading to the channel system. Study results will aid U.S. Army Corps of Engineers (COE) personnel in the analysis of the Albuquerque North Diversion Channel (ANDC).

Purpose

The purpose of this study is to determine the potential sediment loading abilities of the upland watershed surfaces as sources of sediment inflow to the ANDC. The study used rainfall simulation at three sites selected by COE personnel in conjunction with personnel from the Albuquerque Metropolitan Arroyo Flood Control Authority (AMAFCA).

Objectives

The study objectives are to:

1) determine erosion and sediment transport characteristics of three selected soils/sites in the ANDC drainage area,

2) determine infiltration and overland flow resistance for the same data, and

3) analyze and present the collected data in a data summary report and a final report.

Scope of report

This is the final report as required in the objectives. A brief summary report regarding data which had been collected and analyzed to date was presented on October 2, 1992. This report contains complete data analyses.

METHODOLOGY

Data were collected from three plots at each of three field sites in the Albuquerque, New Mexico, area between September 15 and 18, 1992. The three sites were, in order of data collection: 1) Albuquerque Academy property north of Academy Boulevard, west of Ventura Boulevard and east of Wyoming Boulevard; 2) Lopez property north of Eagle Rock, west of Wyoming Boulevard and east of Louisiana Boulevard, and; 3) Embudo Park Open Space Area east of Monte Largo along Embudo Arroyo. The soil series at the three sites were, respectively, 1) Embudo (gravelly fine sandy loam and gravelly sandy loam), 2) Embudo, and 3) Embudo and Tesajo (very gravelly loam to very gravelly loamy sand) (USDA 1977). In general, the soils were sandy to stoney loams typically of the Embudo series with a Unified Soil Classification of SM (silty sand).

At each of the three sites--Academy, Eagle Rock, and Embudo Park--three 1m x 3m plots were installed. In order to simulate a disturbed site, one of the three plots was selected by the project principal investigator and scraped bare down to the mineral soil. Slopes for all the plots were measured with a level and stadia rod. Vegetation and rock cover were estimated visually.

The simulator was installed and experiments were conducted following the approach of Ward and Bolin (1989a, b) which was devised for 1m x 1m square plots. In this study, only one plot was sampled at a time. Two simulations were conducted on each plot. The first was in an initial "dry" antecedent moisture condition, in the afternoon of one day, then in a "wet" condition (from the previous rainfall simulation) the next morning. Because there had been significant rainfall in the area on the evening on September 14 and morning of September 15, the "dry" conditions had higher antecedent moisture contents than would be expected for a typical dry situation (2%-5% water on a dry weight basis).

Two types of sediment were sampled from the runoff experiments. The first was suspended material which was pumped with the runoff water into the collection tank. At the end of the run, the water in the tank was agitated and dip samples were taken. One sample was sent to the Soil, Water and Air Testing Laboratory at New Mexico State University (NMSU). This sample was subsampled and passed through a micropore filter under suction. The filter and sediment were dried and weighed, then ignited to determine the volatile portion (primarily organic) of the suspended material. A second sample was collected in 500 ml plastic bottles, weighed, dried (all water evaporated), reweighed, and the bottles tared. This dried sample technique is comparable to the general procedures established in the Water Erosion Prediction Project (WEPP) (Laflen et al. 1991, for example). Ward and Bolin (1989a, b) and Ward and Bolton (1991) compared the above two methods of analysis with a third. A modification to the WEPP procedure was made wherein the supernatant liquid (water) in the bottle was tested for dissolved solids. This was done so that the dried residue weight could be corrected to reflect only suspended sediment and not suspended and dissolved materials. The average concentration of the dissolved material in the water was about 283 mg/l with a standard deviation of 17 mg/l based on the 18 samples measured. These two analyses techniques, filtration and drying, formed the basis for estimating suspended load from the plots [See ASCE (1977) for further details on both methods]. Sediment which settled out or deposited in or on the water collection device at the end of the plot was removed and bagged, then dried and weighed. Samples having total dry weights in excess of 300 grams were passed through a stack of six U.S. standard mesh sieves. Those samples with less than 300 grams (dry weight) were sieved with #4 (4.75 mm), #10 (2.00 mm) and #200 (0.075 mm) sieves. Fewer sieves were used so that detectable weights would be caught. Plots of sieve size and percent weight retained were developed, and the partial sieve stack results (small sample weight) were compared with the complete sieve stack (large sample weight) results. In addition, material passing through the #200 sieve from the large samples was analyzed with a hydrometer test to determine the silt and clay percentages. The small samples were not analyzed with a hydrometer because of the lack of material. Sediment data were analyzed for yields per unit area for suspended and deposited loads and for yields per unit area per unit depth of runoff (a concentration term) for the same two components.

Three bulk soil samples were collected also from each site, The soil samples were sieved and the portion passing the #200 sieve was further analyzed with a hydrometer. Plots of sieve size and percent retained were prepared in order to compare the samples.

Rainfall and runoff data were analyzed following the procedures described in detail by Ward and Bolton (1991) for the small plot experiments. These analyses include calculation of steady-state infiltration or loss rate, ratios of runoff to rainfall, and estimates of the Green and Ampt infiltration parameters. For this study, the data were further analyzed to determine appropriate values for the initial abstraction-constant loss rate model used by the City of Albuquerque. The method used for estimating the appropriate initial abstraction and constant loss rates was developed from a conservation-of-mass equation and a regression relationship. Applying a conservation-of-mass equation to a constant rainfall rate simulation application on a unit area gives:

$$D_{RO}=D_{RF}-D_{ABS}-D_{CL} \tag{1}$$

where D_{RO} is depth of runoff, D_{RF} is total depth of applied rainfall, D_{ABS} is depth of rainfall lost to initial abstractions, and D_{CL} is depth of rainfall lost to constant rate infiltration. The initial abstractions are assumed to be satisfied by rainfall occuring at the beginning of the storm (simulation) and it is assumed to be satisfied at a rate equal to the rainfall rate, i. The time necessary to satisfy the initial abstractions T_1 is then:

$$T_1=\frac{D_{ABS}}{i} \tag{2}$$

The time remaining in the event (simulation), T_2, is the duration of constant loss and is given by:

$$T_2=T_T-T_1 \tag{3}$$

where T_T is total duration of the event.

If the constant loss rate is defined as f_c, then combining equations (1), (2), and (3) yields

$$D_{RO}=i\,T_T-D_{ABS}-f_c\,[\,T_T-(\frac{D_{ABS}}{i})\,] \tag{4}$$

Equation (4) has two unknowns, D_{ABS} and f_c, and cannot be solved unless one of the two unkowns is assumed. Instead, a linear relationship was developed between initial abstraction and constant loss rate values provided by AMAFCA [D.P.M. Drainage Design Criteria Committee (D.P.M.D.D.C.C.), 1991]. The resultant regression equation, based on four pairs of initial abstraction and constant loss rate values was:

$$D_{ABS}=2.05+0.337f_c \tag{5}$$

where D_{ABS} is in mm, f_c is in mm/hr and the simple linear correlation coefficient is 0.99943. Both regression parameters in equation (5) are significant at $p=0.02$ levels.

Substitution of equation (5) into equation (4) followed by rearrangement gives a quadratic equation in f_c of

$$a(f_c^2)+b(f_c)+c=0 \tag{6}$$

where

$$a=\frac{0.337}{i} \tag{7}$$

$$b=-[0.337+T_T-(\frac{2.05}{i})] \tag{8}$$

and

$$c=i\cdot T_T-D_{RO}-2.05 \tag{9}$$

The solution of equation (6) is then

$$f_c=\frac{-b\pm(b^2-4ac)^{1/2}}{2a} \tag{10}$$

where a, b, and c are given by equations (7), (8), and (9), respectively. Note that depths are in millimeters, rates are in mm/hr and times are in hours for the above equations. Equation (10) could then be applied to each experiment to determine f_c and corresponding D_{ABS} [by equation (5)]. In addition, equations (4) and (5) could be used to find an optimal value of f_c which would minimize:

$$F_{obj}=\sum_{i=1}^{n} (D_{ROp_i}-D_{ROm_i})^2 \tag{11}$$

where F_{obj} is a least square objective function, D_{ROp} and D_{ROm} are predicted (from equation (4) using equation (5) and measured depths of runoff) and the squared differences are various values of f_c. The value of f_c which causes F_{obj} to be a minimum is the optimal answer for the data set analyzed.

The runoff data also were used to estimate values of overland flow resistance following the procedures presented by Jorat (1991). Overland flow resistance is an important, although difficult to measure, parameter used in mathematical modeling of runoff and erosion.

RESULTS AND DISCUSSION

Site Characteristics

The data are best presented in tabular form for easier comparison within and between sites. The characteristics of the plots are listed in Table 1. As the table indicates, a diverse set of cover and slope conditions was sampled with the plot selection. The steepest slopes were at the Embudo Park site and the lowest were at the Eagle Rock site. One plot was scraped bare at each site, and plots were selected to sample a difference in cover of 20 percent or more. The water contents for the dry runs at the Academy site reflect the antecedent rainfall mentioned above. As the soils drained and dried, the subsequent dry runs at the other sites exhibited lower water contents. The 9.3 % water content for the dry run at AND9 appears to be in error, but the reasons for the error cannot be determined from the test data. A better estimate for the dry run antecedent water content would be about 5%. Soil porosities are difficult to calculate from field data because of the soils' heterogeneous nature and the effects of slight variations in sample quality. The average porosity was about 34% with a standard deviation of 4%.

Table 1 Site Characteristics of the Experimental Plots

Site	Plot ID	Slope (%)	Cover (%)[2]	Water Content (%)[3]		Porosity (%)[4]
				Dry	Wet	
Academy	AND1[1]	10.3	40	7.2	8.6	25.8
	AND2	9.9	60	8.2	9.9	35.5
	AND3	13.5	Bare	6.3	9.6	32.2
Eagle Rock	AND4	7.2	20	6.2	12.7	34.0
	AND5	6.9	Bare	5.3	11.7	40.3
	AND6	6.7	40	5.9	9.6	32.9
Embudo Park	AND7	20.4	50	5.4	12.8	35.9
	AND8	22.0	65	4.8	9.4	33.1
	AND9	23.7	Bare	9.3	9.8	36.5

[1] AND = Albuquerque North Diversion channel
[2] Cover includes vegetation and rock as estimated visually, all plots had small gravel cover
[3] Water content, dry weight basis, at beginning of the simulation run
[4] Volume of voids/volume of core sample

Rainfall and Runoff

The measured rainfall and runoff rates were used to calculate the steady-state loss or infiltration rates (as a difference between steady-state rainfall and runoff rates) and the infiltration parameters for a plot. As the results presented in Table 2 indicate, there is a marked difference in runoff between sites and antecedent moisture conditions. The data in Table 2 show that the dry runs exhibit higher infiltration rates and lower runoffs than do the wet runs. This is a typical result because the increased soil moisture stemming from the dry run rainfall application creates a spatially diverse saturation and produces an air-water flow situation which retards loss rate. However, this typical situation does not always hold as evidenced by higher losses for the wet run experiment on AND9, which was a bare plot. Observations of the plot during the experiment indicated that the bared surface "roughened" as the fine particles were eroded and the coarser particles remained on the plot. This coarser surface and lack of fine particles during the wet run may be the reason for the higher loss rate. The coarser surface was not as noticeable on the

Table 2 Rainfall and Runoff Data from the Experimental Plots

Plot ID	Rainfall				Runoff Depth, mm		Steady-state Loss Rate, mm/hr		Runoff-Rainfall Ratio	
	Rate, mm/hr		Depth, mm							
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
AND1	76	78	38	39	12	18	49	33	.32	.47
AND2	76	77	38	38.5	17	22	41	23	.45	.57
AND3	76	77	38	38.5	22	28	23	18	.58	.73
AND4	76	78	38	39	3.6	22	69	31	.09	.56
AND5	79	77	39.5	38.5	9.1	22	47	25	.23	.57
AND6	78	79	38	39.5	7.0	16	59	38	.18	.41
AND7	77	78	40	39	4.8	14	63	42	.12	.36
AND8	77	77	38.5	38.5	7.8	15	58	38	.20	.39
AND9	77	77	38.5	38.5	28	20	3	38	.73	.52

All experimental runs had 30 minutes of applied rainfall except AND7 dry with 31 minutes other bare plots primarily because of the smaller sized soil particles. Note that AND9 wet is comparable to AND7 and AND8 wet runs. This further supports the observation that the AND9 wet surface was coming into equilibrium with respect to hydrologic response. The AND9 dry run also exhibited noticeably lower AMC which may have created a hydrophobic condition in the soil. The data used by Bolton et al. (1990) indicate that in some cases hydrophobic behavior can be observed in dry desert soils. There was substantial variation in runoff among the plots for the dry run conditions. The wet run conditions were such that the variation was reduced, but was still present. It is difficult to attribute the observed differences to the other site characteristics such as slope and vegetative cover because the soils were somewhat different at each site. The location of the vegetation on the plot can also have as much of an effect as the extent of the cover. For example, vegetation near the runoff collection end of the plot may act as a buffer strip to trap water and sediment before they can be sampled. A much larger number of plots would need to be sampled before meaningful statistical differences could be inferred from the data.

Table 3 contains a listing of the steady-state loss rates from Table 2 and the best estimates of Green and Ampt infiltration parameters for each experiment. The steady-state loss rates and the Green and Ampt conductivities compare very well with one another in most cases. Those times when the two measures did not compare could be attributed to fluctuations in the data and the method by which the Green and Ampt conductivity was estimated. In general, the Green and Ampt conductivity was lower than the steady-state loss rate. The Green and Ampt capillary suction head is inversely related to the conductivity due to the soil's physical characteristics and the method used to estimate it from the data. The wide variation in the calculated capillary suction values and the inherent errors in their estimation results in capillary suctions being viewed as an interesting parameter without much confidence in use. Fortunately, for most design storm events, the effect of capillary suction values on infiltration losses are insignificant relative to rainfall depth.

Sabol et al. (1982) used a rainfall simulation on the Albuquerque Academy property and at other sites in the Albuquerque area. A reanalysis of their data indicates that the steady-state infiltration rate at the Albuquerque Academy site was about 50 mm/hr. Heggen (1987) used a split-ring infiltrometer at

Table 3 Infiltration Parameters for the Experimental Plots

Plot ID	Steady-state loss rate, mm/hr	Green-Ampt conductivity mm/hr	Capillary suction, mm	Constant loss rate mm/hr	Initial abstraction, mm
AND1-D	49	50	0*	31	15
AND1-W	33	37	7	27	11
AND2-D	41	39	0	28	11
AND2-W	23	14	44	20	9
AND3-D	23	20	9	20	9
AND3-W	18	14	9	11	6
AND4-D	69	70	0	59	22
AND4-W	31	29	2	21	9
AND5-D	47	34	18	46	18
AND5-W	25	16	34	20	9
AND6-D	59	56	4	51	19
AND6-W	38	32	19	32	13
AND7-D	63	62	3	57	21
AND7-W	42	37	24	35	14
AND8-D	58	58	1	48	18
AND8-W	38	35	15	32	13
AND9-D	3	3	75	11	6
AND9-W	38	39	0	23	10

* Values less than 1 mm are listed as zeros.

various sites in the Albuquerque area including the Albuquerque Academy property and the Embudo Arroyo Open Space. Although the report did not include data for individual sites, Heggen's conclusions contained the recommendations that for the first 30 minutes of rainfall, a steady (uniform) loss rate of 50 mm/hr be used for uncompacted soils and a steady loss rate of 25 mm/hr be used for compacted soils, and that for 30 to 60 minutes, 65 percent of those values be applied.

Also included in Table 3 are estimates of initial abstraction and constant loss rate values. These were determined from the data as discussed in the Methodology section. The variation in the constant loss rates mirrors that of the Green and Ampt conductivity. Both measures are derived from the same data base and they should also be physically related. The average constant loss rate was 32 mm/hr which was the value given for land treatment B in the Development Process Manual (D.P.M.D.D.C.C. 1991). However, the variation in rates ranged across the A, B, and C treatments in the Manual. The optimized loss rate, as a comparison, was 31 mm/hr (essentially the same) with the average initial abstraction being 13 mm. In contrast, the COE uses an initial abstraction of 13 mm and a constant loss rate of 21 mm/hr (Bruce Beach personnel communication) for modeling rainfall-runoff. These values correspond to land treatment B for initial abstractions and land treatment C for constant loss rates. When the COE values were used to estimate runoff from each of the experiments, the depth of runoff was about 19 mm for each run. This corresponds to an average overestimation of about 59% with a range of -32% to +350%, depending on the plot and soil moisture condition. However, the average overestimation for the wet runs was only about 1% with a range of about -32% to +36%. It is apparent that the COE values may be more appropriate for wet conditions.

Erosion and Sediment Transport

Table 4 lists the important gradation characteristics for the surface soils at each site. As Table 4 shows, the soil at the Embudo Park site was coarser than at Academy and both were coarser than at Eagle Rock. These data are in agreement with field observations. The gradation coefficients, G, are comparable between sites and in the range one might expect for upland soils. More complete grain size descriptions for the soils are presented in Appendix A.

The on-site soil gradations in Table 4 can be compared with the deposited sediment gradations listed in Table 5. Table 5 shows that the sediment deposits from the Academy and Embudo Park sites were a bit coarser than those at the Eagle Rock site. This is due to the fact that: 1) the on-site soil was finer at the Eagle Rock Site; and, 2) that the steeper slopes at the other two sites enhances movement of larger particles. A comparison of the data in the two tables also indicates that the D_{50} and D_{16} of the soil and sediment are about the same, but that the D_{84} of the soil was coarser. This suggests that there is a preferential erosion and transport of the soil particles which favors the finer sizes. This coarsening was

Table 4 On-Site Soil Gradation Characteristics

Site	Sample	Size of Material, mm			
		D_{84}[1]	D_{50}	D_{16}	G[2]
Academy	AND1	2.57	.52	.05	7.17
	AND2	3.30	.54	.06	7.42
	AND3	3.46	.54	.06	7.59
Eagle Rock	AND4	4.06	.29	.05	9.01
	AND5	1.42	.18	.05	5.33
	AND6	3.43	.25	.05	8.28
Embudo Park	AND7	4.14	.76	.06	8.31
	AND8	8.34	2.03	.18	6.81
	AND9	4.69	1.02	.08	7.66

[1] D_x is equivalent diameter D for which x percent of the sieved material was finer, dry weight basis.

[2] G is a gradation coefficient calculated as $G=(D_{84}/D_{16})^{1/2}$

observed on all the bare plots, and it was especially noticeable on the AND9 wet run plot. More complete grain size descriptions for the deposited sediments are presented in Appendix B.

The sediment yield data of Table 6 indicate that the bare plots usually produced the most sediment per unit area, wet runs produced more sediment than dry runs for the same plot, and that cover, slope, and soil characteristics combine in a complex fashion to help control sediment yield. Small plot experiments generally produce less sediment during the wet run because the supply of soil material has been depleted during the dry run (Ward and Bolton 1991). Experiments utilizing the longer plots allow overland flow to become more effective at moving sediment from higher on the plot to the outlet if enough time is allowed. The lower runoff experienced during the AND9 wet run created a lower sediment yield for that experiment relative to the dry run.

A technique by which to normalize unit area yields is to divide by the water yield expressed as millimeters of runoff depth. The resulting units of kg/ha/mm of runoff is, in effect, a concentration term equivalent to 1/100 of a mg/l, or 1 mg/l = 100 kg/ha/mm. Ward (1986) found this parameter to be a reasonable way to compare sediment yield results from different rainfall simulators. Data from Table 2

Table 5 Deposited Sediment Gradation Characteristics

Site	Sample[1]	Size of material[2], mm				Sample size[4]
		D_{84}	D_{50}	D_{16}	G[3]	
Academy	AND1-D	2.07	.38	.07	5.44	S
	AND1-W	2.44	.69	.09	5.21	L
	AND2-D	2.34	.42	.07	5.78	S
	AND2-W	3.79	1.42	.12	5.62	S
	AND3-D	1.28	.28	.06	4.62	L
	AND3-W	1.51	.36	.06	5.02	L
Eagle Rock	AND4-D	1.44	.30	.06	4.90	S
	AND4-W	1.47	.29	.06	4.95	S
	AND5-D	1.05	.25	.06	4.18	S
	AND5-W	1.03	.24	.06	4.54	S
	AND5-P[5]	.87	.37	.09	3.11	L
	AND6-D	1.15	.27	.06	4.38	S
	AND6-W	1.04	.22	.05	4.56	L
Embudo Park	AND7-D	1.33	.33	.08	4.08	S
	AND7-W	4.35	1.84	.19	4.78	S
	AND8-D	2.76	.60	.12	4.80	S
	AND8-W	3.87	1.26	.14	5.26	S
	AND9-D	1.31	.31	.07	4.33	L
	AND9-W	1.63	.41	.06	5.21	L

[1] Sample designation-example AND1-D is plot 1, dry antecedent moisture condition and AND1-W is plot 1, wet condition

[2] D_x is equivalent diameter D for which x percent of the sieved material was finer by dry weight basis

[3] G is a gradation coefficient calculated as $G = (D_{84}/D_{16})^{1/2}$, when D_{16} values were less than 0.075 mm for the small sample sites, the values were extrapolated

[4] Designates whether the sample was large (L) (complete sieve stack) or small (S) (partial sieve stack)

[5] Sample taken from deposit on plot after both experiments completed

combined with data in Table 6 were used to produce Table 7. This table reverses some of the observations made using information contained in Table 6. The data in Table 7 indicate that the dry and wet run concentrations are relatively close to one another for the same plot and that the wet runs do not consistently have higher values. The data in Table 7 imply that the sediment yield is hydraulically controlled in that a unit increase in runoff produces about the same increase in sediment yield for both dry and wet antecedent conditions. This observation may help persons attempting to model sideslope sediment contributions to the arroyo system in that once water yield is modeled, the sediment yield may be estimated by simply multiplying by an appropriate value from Table 7. The choice of an appropriate value is a difficult one, however. The data presented in Table 7 suggest that a value of 50 kg/ha/mm of runoff be used for natural plots and a (conservative) value of 300 kg/ha/mm of runoff be used for disturbed plots.

Table 6 Sediment Yield in kg/ha for Each Site

Site	Sample[1]	Sediment Yield kg/ha [2]			
		Susp 1	Susp 2	Deposits[3]	Total[4]
Academy	AND1-D	228	221	648	873
	AND1-W	282	379	1090	1421
	AND2-D	234	282	63	321
	AND2-W	203	285	234	478
	AND3-D	500	524	6209	6721
	AND3-W	499	517	8707	9215
Eagle Rock	AND4-D	36	53	46	91
	AND4-W	202	313	275	533
	AND5-D	87	115	62	163
	AND5-W	--[5]	276	87	363
	AND6-D	26	48	407	444
	AND6-W	112	162	1060	1197
Embudo Park	AND7-D	20	31	47	73
	AND7-W	105	166	40	176
	AND8-D	198	208	213	416
	AND8-W	218	241	410	640
	AND9-D	--[6]	2459	3726	6185
	AND9-W	--[5]	638	2358	2996

[1] Sample designation-example AND1-D is plot 1, dry antecedent moisture condition and AND1-W is plot 1, wet condition

[2] Susp 1 is the filtered sample of the suspended sediments and Susp 2 is the dried sample

[3] Material which settled out onto and into the collection device

[4] Sum of deposits and average of two suspended sediment measurements, if available

[5] Sample not collected

[6] Sample bottle damaged

Samples AND3, AND5, and AND9 are from bare plots.

Serrag (1987) examined eight data sets collected with rainfall simulators (261 pairs of dry and wet

Table 7 Sediment Production in kg/ha/mm of Runoff for Each Site

Site	Sample[1]	Sediment Production[2] kg/ha/mm			
		Susp 1	Susp 2	Deposits[3]	Total[4]
Academy	AND1-D	18.86	18.27	53.61	72.18
	AND1-W	15.25	20.51	59.01	76.89
	AND2-D	13.97	16.83	3.76	19.16
	AND2-W	9.24	12.96	10.66	21.76
	AND3-D	23.18	24.30	287.73	311.47
	AND3-W	17.76	18.43	310.13	328.23
Eagle Rock	AND4-D	9.77	14.49	12.65	24.78
	AND4-W	9.39	14.55	12.77	24.74
	AND5-D	9.55	12.62	6.80	17.89
	AND5-W	--[5]	12.69	3.99	16.68
	AND6-D	3.75	6.87	57.97	63.28
	AND6-W	7.03	10.13	66.31	74.89
Embudo Park	AND7-D	4.17	6.55	9.86	15.22
	AND7-W	7.63	12.10	2.92	12.79
	AND8-D	25.33	26.60	27.73	53.20
	AND8-W	14.70	16.29	27.70	43.20
	AND9-D	--[6]	87.65	132.83	220.48
	AND9-W	--[5]	31.97	118.14	150.11

[1] Sample designation-example AND1-D is plot 1, dry antecedent moisture condition and AND1-W is plot 1, wet condition

[2] Susp 1 is the filtered sample of the suspended sediments and Susp 2 is the dried sample

[3] Material which settled out on and into the collection device

[4] Sum of deposits and average of two suspended sediment measurements, if available

[5] Sample not collected

[6] Sample bottle damaged

Samples AND3, AND5, and AND9 are from bare plots.

run values) and found that dry run total sediment yields averaged 1800 kg/ha (not kg/ha/mm units) with a standard deviation of about 3000 kg/ha and that wet run total sediment yields averaged about 1500 kg/ha with a standard deviation of about 2300 kg/ha. Ward and Bolin (1989a) report values of between about 3 and 200 kg/ha/mm from simulations on a variety of soil-vegetation complexes throughout New Mexico and Arizona. Ward and Bolin (1989b) report values of between 7 and 190 kg/ha/mm of runoff from experiments in the pinon-juniper rangelands of Arizona and New Mexico. Ward and Bolton (1991) report values of between 1 and 760 kg/ha/mm of runoff for the same sites as the 1989b studies plus additional, more erosive, sites on degraded in New Mexico rangelands.

On average, the ratio of deposited sediment yield to total sediment yield was 61% with a range of 20% to 94%. The suspended sediment was almost all 100% finer than 0.075 mm equivalent grain size, whereas the deposited sediments contained between 3% and 25% material less than 0.075 mm in size depending on the plot.

One important aspect to consider in using sediment yield information collected with a rainfall simulator is the effects of scale. Scale effects arise as the area of interest increases from a small plot to a hillslope and then to a watershed. As the area of interest becomes larger, the spatial variability of the associated soils, vegetation, land use and other surface conditions increases, thus changing the mix of hydrologic and hydraulic processes which control runoff and sediment yield. Ward (1986) found that sediment yields per unit area from 1m x 1m simulation plots were about 2.7 times higher than those from plots of about 186 square meters in area. Ward and Bolin (1989a) reported a factor of about 4 times higher sediment yields from 1m-by-1m plots compared to standard size WEPP plots (3m x 10m). In that study, some of the difference may be attributed to the types of simulators utilized. A general observation is that as an area grows larger, the total sediment yield increases, but the yield per unit area decreases. The only accurate way to determine the yield from a hillslope is to measure the runoff and sediment outflow from the entire slope. Because that approach is not practical except in ideal situations, extrapolations from simulator plot data, either directly or through parameterization of hillslope erosion models, are the best way to estimate yields.

Overland Flow Resistance

Each of the 18 runoff hydrographs was analyzed following the approach used by Jorat (1991) in his study of overland flow resistance on small simulator plots. As noted by Jorat (1991), Engman (1986) and Weltz 1992), results from field studies of overland flow resistance have a large range and high degree of variation, much of which cannot be easily explained by site characteristics. Like these previous studies, the results from the experiments on the simulator plots were extremely varied. Nevertheless, values of

Manning's n were calculated for each of the plots. The average value was 0.453 $m^{1/3}/s$ and the geometric mean was 0.231 $m^{1/3}/s$. These values are comparable with those presented by Weltz (1992) (a range of 0.09 to 0.56 $m^{1/3}/s$ for similar rangeland conditions) and are therefore acceptable as indicators of the overland flow resistance.

SUMMARY AND CONCLUSIONS

Estimating sediment loading to arroyos can be aided by rainfall simulation on upslope areas. In this study, plots 1m x 3m were utilized to collect rainfall and runoff data. The collected data provided information on infiltration rates, erosion and sediment transport, and overland flow resistance. Steady-state infiltration rates ranged between a low of 3 mm/hr up to a high of 69 mm/hr depending on the site characteristics of the plot. Constant loss rates were calculated from the runoff data and were found to coincide very well with values currently being employed in the Albuquerque area. Sediment yield data indicated that a value of 50 kg/ha/mm of runoff for undisturbed surfaces and a value of 300 kg/ha/mm of runoff for disturbed surfaces would provide reasonable estimates of the sediment loading to the channels. The sediment would average about 50% finer than 0.075 mm and 50% larger than this size. Note, however, that there are large variations in all the measured values indicating the natural spatial and temporal variability found in upland watersheds.

Scale effects may be important if these values of 50 and 300 kg/ha/mm of runoff are extrapolated to very large areas. In general, though, the values are probably conservative when used to estimate yields from larger hillslope areas. The sediment yield values do not apply to gullys or areas which have been extensively rilled. In those cases, channel flow processes rather than sheet flow and raindrop splash are controlling the sediment yield.

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CONVERSION FACTORS

The following factors may be helpful in converting the units in this paper into common English units.

1 millimeter = 0.0394 feet

1 hectare = 2.47 acres

1 kilogram (weight) = 2.205 pounds

1 kilogram/hectare (kg/ha) = 0.8924 lbs/acre

1 mg/l = 100 kg/ha /mm of runoff = 20.77 lbs/acre/in of runoff

APPENDIX A

Table 1A On-site soil gradations

Sieve Size (mm)	Percent Finer								
	AND1	AND2	AND3	AND4	AND5	AND6	AND7	AND8	AND9
50.000	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
25.000	100.0	100.0	96.6	100.0	100.0	100.0	100.0	93.6	100.0
19.000	100.0	97.2	95.3	100.0	100.0	100.0	100.0	88.1	99.2
12.500	100.0	97.2	95.0	98.7	100.0	97.2	99.2	87.6	96.9
6.300	98.2	93.4	91.5	89.9	98.6	93.0	93.5	81.5	90.4
4.750	96.6	89.7	89.2	86.0	96.8	88.5	87.2	75.3	84.3
2.000	78.8	76.2	75.0	74.9	88.6	76.5	66.9	49.5	64.3
0.850	57.8	56.7	56.5	64.1	77.2	64.7	51.6	32.2	46.2
0.420	46.5	46.1	46.2	55.2	66.6	56.3	41.9	23.3	36.0
0.149	33.2	33.3	30.9	40.5	46.0	43.3	29.3	14.3	23.7
0.075	23.1	21.1	20.3	27.0	29.5	29.7	19.6	9.3	15.9
0.045	11.9	10.6	10.4	13.4	14.9	15.6	12.0	5.6	9.0
0.034	7.8	6.8	6.6	8.3	9.3	9.7	9.1	4.4	6.8
0.025	5.0	4.5	4.2	5.4	5.3	5.9	6.6	3.5	5.2
0.018	3.7	3.0	3.2	3.7	4.1	4.7	5.6	2.8	4.4

APPENDIX B

Table 1B Gradations for Composited On-Site Soils and Individual Sediment Deposits AND 1-3

	DRY DEPOSITS				WET DEPOSITS		
Size (mm)	AND1 (%)	AND2 (%)	AND3 (%)	ONSITE 1-3 (%)	AND1 (%)	AND2 (%)	AND3 (%)
50.000				100.0			
25.000				98.9			
19.000				97.5			
12.500				97.4	100.0		
6.300			100.0	94.4	99.7		100.0
4.750	99.3	100.0	99.9	91.8	97.1	94.4	99.9
2.000	83.3	80.4	94.8	76.7	80.1	54.7	91.8
0.850	--	--	74.1	57.0	54.1	--	67.8
0.420	--	--	57.5	46.3	40.0	--	52.9
0.149	--	--	38.6	32.5	25.8	--	36.2
0.075	17.8	16.8	22.6	21.5	13.3	9.8	23.1
0.045			11.2	11.0	6.1		11.4
0.034			6.3	7.1	3.2		6.9
0.025			3.6	4.6	1.9		4.1
0.018			2.2	3.3	16.8		3.0

Table 2B Gradations for Composited On-Site Soils and Individual Sediment Deposits AND 4-6

	DRY DEPOSITS				WET DEPOSITS		
Size (mm)	AND4 (%)	AND5 (%)	AND6 (%)	ONSITE 4-6 (%)	AND4 (%)	AND5 (%)	AND6 (%)
50.000				100.0			
25.000				100.0			
19.000				100.0			
12.500				98.6			100.0
6.300				93.8			99.7
4.750	100.0	100.0	99.8	90.4	98.7	100.0	99.2
2.000	91.1	80.4	96.9	80.0	90.4	99.2	94.8
0.850	--	--	--	68.7	--	--	80.6
0.420	--	--	--	59.4	--	--	63.5
0.149	--	--	--	43.3	--	--	41.1
0.075	20.0	21.2	19.9	28.7	21.8	23.6	24.8
0.045				14.6			12.3
0.034				9.1			7.4
0.025				5.5			3.9
0.018				4.2			3.2

Table 3B Gradations for Composited On-Site Soils and Individual Sediment Deposits AND 7-9

	DRY DEPOSITS				WET DEPOSITS		
Size (mm)	AND7 (%)	AND8 (%)	AND9 (%)	ONSITE 7-9 (%)	AND7 (%)	AND8 (%)	AND9 (%)
50.000				100.0			
25.000				97.9			
19.000				95.8			
12.500				94.6			
6.300			100.0	88.5			100.0
4.750	100.0	98.2	99.9	82.3	87.7	92.3	99.9
2.000	94.1	75.6	93.4	60.2	51.2	57.2	89.6
0.850	--	--	74.4	43.3	--	--	66.1
0.420	--	--	56.7	33.7	--	--	50.5
0.149	--	--	33.6	22.4	--	--	31.9
0.075	13.2	5.8	17.4	14.9	2.6	5.9	18.3
0.045			9.3	8.9			10.0
0.034			6.6	6.8			6.9
0.025			5.0	5.1			5.1
0.018			4.3	4.3			4.0