A STUDY OF RUNOFF AND EROSION PROCESSES USING LARGE AND SMALL AREA RAINFALL SIMULATORS

by

Timothy J. Ward
Professor
Department of Civil Engineering
New Mexico State University
Las Cruces, New Mexico

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ABSTRACT

Estimation of runoff and sediment yield from small, ungaged watersheds is a difficult hydrologic task. Process oriented mathematical models can be an important part in the solution of this task. Models, however, require some information which is directly related to the hydrologic processes occurring on the watershed. Rainfall simulation is an important experimental technique for gathering such information.

This technical report contains the results of a pilot study on the utility of using rainfall simulation in southwestern watersheds. Two different simulators were compared on three sites in New Mexico. A small area simulator, 10 square feet, and a large area simulator, approximately 2000 square feet, were operated for a total of 60 plot experiments. The large simulator was modified and operated with variable intensity rainfall and with overland flow without rainfall for some of the experiments.

Analysis of the data indicates that the simulators provide similar results for hydrologic processes, and that sediment yields averaged about 2.7 times higher for the small simulator. Addition of the variable intensity and overland flow capabilities to the large simulator have provided a means for isolating and studying those two important processes.

Keywords: computer models*, data collection*, hydrologic models, hydrologic processes, infiltration, parametric hydrology, runoff plot, sediment yield, simulated rainfall, soil erosion*, watersheds.

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CONSERVE NEW MEXICO'S WATER AND SOIL

INTRODUCTION

Three small abandoned USDA-ARS watersheds located north and west of Albuquerque, New Mexico, have been designated as target watersheds for further study of rainfall-runoff modeling. Personnel of the Region 3 office of the USDA Forest Service requested assistance in characterizing the infiltration and erosion parameters for these watersheds. Most current watershed models neglect the importance of channel infiltration in the runoff cycle of arid and semiarid watersheds. Therefore, channel losses are lumped into infiltration or routing parameters. If more information is known about upland infiltration, then it becomes easier to delineate the influence of channel losses when models are used to simulate measured rainfall-runoff events. The technique of rainfall simulation is available for deriving infiltration parameters, and lends itself to studying soil erosion. In this study, infiltration and erosion parameters were derived from data collected with rainfall simulation techniques. The derived parameters will be useful in further attempts to test models on the target watersheds.

This pilot study also tested the applicability of the rainfall simulation technique for data collection. Data were used to demonstrate and evaluate the use of simulated rainfall and to help characterize the hydrologic processes on the target watersheds. Two types of simulators were used, a large area simulator (up to 370 square meters) and a small area simulator (1 square meter). Infiltration and erosion parameters and characteristics were derived from both types of simulators and compared to study differences between runoff and erosion data collected with the simulators. In addition, modifications to the large simulator were tested on an area of the NMSU campus.

Goals and Objectives

Two goals were identified for this study. These were to:

A. Use data and observations collected with the simulators to help characterize infiltration, runoff, and erosion processes for the target watersheds; and

B. Demonstrate the applicability of rainfall simulation for studying runoff processes in a southwestern environment.

These two major goals were subdivided into seven objectives related to the simulation device or the field studies. These objectives were to:

A. Site Studies

1. Characterize infiltration parameters on at least two soils,
2. Characterize soil erosion parameters on the same soils,
3. Collect water and sediment chemistry samples for chemical analyses by the USDA Forest Service, and
4. Relate site and soil characteristics to the infiltration and erosion parameters derived in objectives 1 and 2 above.

B. <u>Testing of Large Simulator</u>

1. Modify and test variable intensity capabilities of the larger rainfall simulator,
2. Develop and test an overland flow generating device, and
3. Compare infiltration and erosion measurements collected using the large simulator with those collected using the small simulator.

Scope of Report

This report is a summary and analysis of rainfall-runoff and erosion data collected from two target watersheds and from a site on the New Mexico State University (NMSU) campus using large and small simulators. Data collection methods and techniques were previously presented in the study plan and are reiterated in this report. This final report includes analyses of the data as related to the goals and objectives of the study.

Literature Review

Considerable advances have been made in recent years in our understanding of the generation of storm runoff. A number of models are now available to describe mechanisms that produce runoff from precipitation. Briefly, these mechanisms include: (1) Hortonian overland flow, where rainfall rate exceeds the infiltration rate of the soil and the excess precipitation flows over the ground surface; (2) saturated overland flow from "partial source area," in which high water tables cause saturation of small areas of a watershed, often near stream channels, and generate overland flow; (3) subsurface flow of infiltrated water moving laterally through the soil mantle toward the channel system; and (4) expansion of the channel system during storms to tap subsurface flow systems and permit overland flow from "variable source areas." Dunne (1978) has provided a review of these mechanisms.

In the study area, Hortonian overland flow is the primary mechanism because infiltration rates are low and rainfall rates are high. With this constraint, infiltration parameters were the primary factors considered. Of particular interest to Watershed Specialists assigned to the Southwest Region (R-3), United States Forest Service, are those parameters used in the RAIN model (Solomon 1983), specifically those parameters that are used in the Horton (1940), Philip (Jaynes and Gifford 1981) and Green and Ampt (Mein and Larson 1973) infiltration equations. This information can be derived from rainfall-runoff experiments (for example, see USDA-ARS 1979) conducted in this study.

A benefit of using rainfall simulation to determine infiltration parameters is that measurements can be taken for estimating soil erosion parameters. Erosion parameters can be subdivided as those related to raindrop splash and to overland flow (e.g., Knisel 1980). The specific parameters in this study were those used in models developed at Colorado State University (e.g., Simons, Li and Ward 1977). Techniques for derivation of these parameters have been discussed by Ward and Seiger (1983 and 1985) for data collected with the small simulator.

A question arises, however, as to whether or not parameters derived from different rainfall simulation devices are the same. Such a comparison has not been published to this writer's knowledge. This study makes such a comparison.

METHODOLOGY

Location of Sites

The two watersheds selected for tests are located in the Bernabee M. Montano Grant of the Laguna Indian Reservation. They are located at about 35 11' 23" north latitude and 107 01' 30" west longitude on the Herrera, New Mexico, USGS 7.5 minute quadrangle (see figure 1). The watersheds lie at elevations between 5900 and 6100 feet. Watershed II(2) covers an area of 40.5 acres and Watershed III(3) is larger at 176 acres. Soils in both watersheds are predominantly fine sandy loams (>60 percent) with clay loams occurring near channels and as residual soils on shaley bedrock. Because of the predominance and accessibility of the fine sandy loams, these soils were selected for study. Field observations indicate that these soils are typically less than 18 inches deep and overlay interlayered sandstone, shale and gypsum.

Because the soils composing both watersheds were similar, a different soil was included for testing at a site on the NMSU campus in Las Cruces. The site is west of Interstate 25, east of the football stadium and south of University Avenue. The elevation at the site is about 4000 feet. The soil is old alluvium composed primarily of sands and gravels.

Samples

One large simulator plot and 8 to 10 small simulator plots were subjected to simulated rainfall and/or overland flow at each

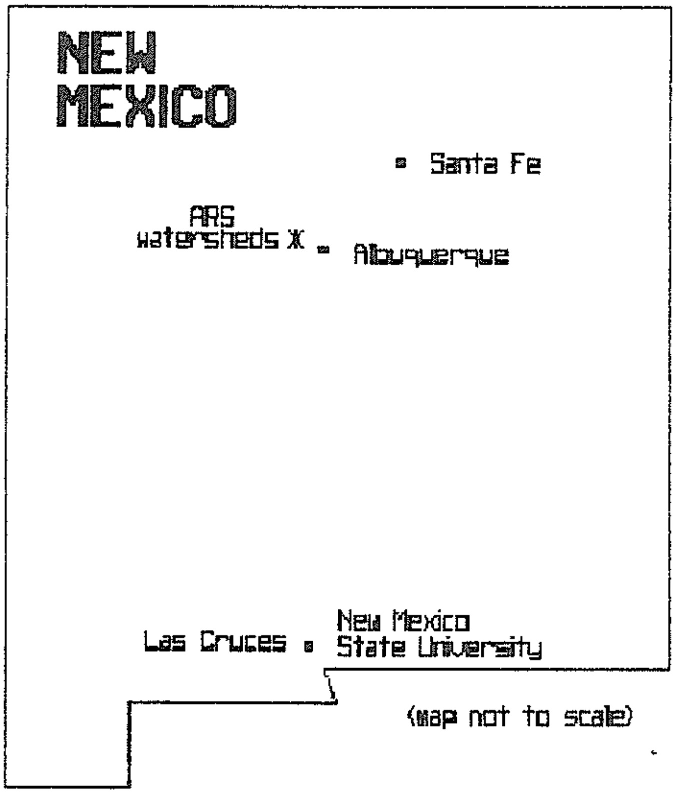


Figure 1. Location map of ARS watersheds and NMSU site

of the three sites. The small plots on the watersheds were sampled during August 7-10, 1984. Subsequently, between August 19 and 22 the large plots were sampled. For the NMSU site, the small plots were sampled between October 8 and 13, and the large plot on October 29 and 30. Time constraints and the cost of hauling water prevented testing of variable intensity rainfall and the overland flow device at the remote sites. These tests were conducted at the NMSU site on May 19, 1985. The two variable intensity rainfall simulations and two overland flow simulation experiments were conducted.

Simulator Experiments

Large Simulator

General. The large plots, were approximately 60 feet long by 30 feet wide with an iron plot frame penetrating the soil approximately four inches deep to form a boundary. Surface flow was directed off the plot with a sheet metal trough. Overland flow was measured with cut-throat flume and water level recorder. Suspended sediment in samples of runoff water were collected during the flow for determination of soil erosion. Additional samples of runoff were collected for chemical analyses by the USDA Forest Service. Site conditions such as surface soil characteristics, soil texture, topography, and vegetation cover were also measured. Site selection was important as it is necessary to have reasonable access for the water truck.

Two simulations per plot were conducted with two others applied at the NMSU site.

The two primary simulations were:

1. Dry run - single intensity rainfall, and
2. Wet run - single intensity rainfall.

The two secondary simulations were:

3. Variable intensity rainfall - dry and wet run, and
4. Saturated run - overland flow water discharge only.

Simulations 3 and 4 required modifications to the simulator equipment.

Artificial rainfall. The large rainfall simulator consists of Rainjet 78 C sprinklers mounted on top of 10 foot tall standpipes so that the individual water drops will attain near terminal velocities. Water is supplied from a tank truck via a 215 gpm pump powered by a 30 HP engine. Flow is regulated by in-line flow valves on each standpipe. A valve (or flow regulator) will deliver seven gpm to the sprinkler head when water enters with a pressure of between about 30 to 100 psi. The standpipes are placed in five parallel rows and arranged in equilateral triangles to produce overlapping systems of approximately one- and two-inch per hour intensities. By controlling the one-inch per hour system, it was possible to create a variable intensity rainfall. Maximum total coverage for the system is about 4,000 square feet.

The large rainfall simulator has been modified from one originally built at Colorado State University (Holland 1969). Flow regulators have been substituted for the pressure regulators in the original design to allow for less system adjustment and more reliability. The original design was determined to deliver approximately 40 percent of the kinetic energy that would occur from a natural rainfall of the same intensity (based on the relationship used by Wischmeier and Smith (1978)). This percentage of natural energy may not be appropriate for Southwestern rainfall. The present system was tested, using flour pan sampling and measurements of the height of drop fall, to determine the energy delivered. Results indicate a 55 percent delivery of energy and not 40 percent as found for the original design. The reason for this large difference is not clear, however, it may be related to outflow pressure-drop size characteristics and interference effects from the arrangement of several sprinklers. Ward (1985) compared sediment yields generated with this simulator with natural rainfall and a simulator that delivers about 56 percent of the energy. No significant differences in sediment (or water) yield were found between the application methods. Even if the energy is not the same, there are appropriate correction methods available to adjust yields.

The fourth type of simulation involved overland water flow only. The pump and pipe system was modified to measure inflow rates, with an in-line flow meter, to a 30-foot-long perforated (3/8 inch holes) diffusing pipe that was located at the top edge of the plot. Water entering the diffusing pipe was distributed across the plot and then flowed downslope to the collection point. This simulation allowed easier viewing of overland flow and was used to investigate overland flow conditions.

Topography. Topography of each site was surveyed on approximately 3-by-3 foot grid system. Maps of each site were prepared showing the location of the rain gages and sprinkler standpipes. The topographic maps were digitized and plotted using computer aided graphics.

Runoff measurements. Runoff water was collected at the lower end of each runoff plot. A plot frame placed to a depth of approximately four inches was installed at each site to help define the boundary.

All data are referenced to the initiation of the artificial rainfall or overland flow. The runoff rate was measured with a water level recorder on a cut-throat flume.

Sediment and water quality samples. Water samples were collected for analysis of the suspended sediment concentration at intervals of 30 seconds to two minutes. The sediment samples were filtered and the filters dried and weighed to determine the amount of sediment. Bed load sediment was minimal but was collected after the flow ceased from depositions in the approach flume, dried and weighted. Water samples collected at the beginning, middle, and end of runoff were supplied to the Tempe work unit for chemical analyses.

Vegetation and ground cover. Two techniques were used to estimate vegetation and ground cover on the large plots. First, the vegetation and ground cover were estimated by visual inspection and by the field crew members (checked in the office with photographs). Second, a minimum of 10 transect lines perpendicular to the flow direction were sampled using a line intercept method. At these intercepts, the surface cover type, grass, brush, rock, or bare soil, was noted. If a rill was at the point, that too was recorded. The observations and measurements provided reasonable estimates of actual cover.

Soil samples. Surface soil cores were collected from the outside edge of the large plots immediately before and after a run. These were measured for soil moisture content. A minimum of four cores were collected each time. Three bulk samples, each approximately 2.2 pounds (1 kilogram) in weight were randomly sampled from the plot after the final simulation. One sample was collected in each third, top middle and bottom, of the plot. In addition, other samples were collected from the small simulator and were used to check on spatial homogeneity of the plot samples. The bulk samples were taken from the top 5 inches (12.5 cm) of the soil for sieve analysis.

Overland flow velocity. Determination of overland flow velocities on natural surfaces under simulated (and actual) rainfalls is a difficult task. On forest roads, a colored dye has been used, but is difficult to trace because of dispersion and dilution (Eric Sundberg, U.S. Forest Service, Moscow, Idaho personal communication). Earl Neff (personal communication, retired from the USDA-ARS in Sydney, Montana) has used salt slug tracers and electrical conductivity measurements of the outflow water to determine the travel times of the overland flow. In this study, a "time-of-concentration" technique was investigated whereby the average overland flow rate was calculated with the time elapsed from introduction of the water via the diffusing pipe to hydrograph equilibrium.

Flow visualization. Dye was introduced as a line or point source at various places in each plot. Because concentrated flow advances downslope more rapidly than the general sheet of water, the stringers of dye left behind could be photographed. The dye was reintroduced as needed to detect new concentrations as they form downslope.

Laboratory measurements. Once the data sheets and field samples were returned to NMSU, they were measured and analyzed for several basic data including:

1. Rainfall depth and duration,
2. Total runoff and runoff hydrograph,
3. Suspended sediment yield and sediment sedigraph,
4. Bed load sediment yield,
5. Final infiltration rate,
6. Infiltration parameters,
7. Soil moisture and porosity,
8. Depth to wetted front,
9. Soil particle size distribution,
10. Percent and type of cover, and
11. Erosion parameter(s).

Suspended sediment was filtered following procedures for fine sediments as discussed in USGS (1977). Bed load was dried and weighed. Cover was estimated by two methods and was checked from photographs. Soil moisture was measured as found in USGS

(1977). Soil gradation is determiend on a split sample following ASTM specifications D421-58 and D422-63. Bulk density was found from oven dried weights of measured cores. Rainfall rates were determined by the gage readings. Runoff rate was determined from the water level recordings. Infiltration and erosion parameters were derived from the measured and the processed data as discussed in following sections.

Small Simulator

Field sampling. Data were collected using a modified Purdue simulator (Bertrand and Parr 1961) mounted on a 16-foot-long trailer. A pair of nozzles is mounted on two separate booms, one boom on either side of the trailer. At each parking spot it is possible to simultaneously collect two samples from the one square meter target shape with one side drive flush with the soil surface. That side is where runoff exits the plot, enters a collection trough and is sampled. This simulator delivers an average intensity of approximately 3.5 in/hr rainfall intensity to the plot with 2.5 psi inlet pressure to the nozzle. Pressure variations change the intensity. Applied energy to the plot is approximately 56 percent of that expected from natural rainfall (Wischmeier and Smith 1978), as determined by flour pan studies conducted by Andy Seiger (unpublished data). Water is delivered simultaneously to both booms by a pump and water tank mounted on the trailer. First a dry run, then a wet run, was conducted as described by the following sequence.

DRY RUN

1. Select site and fill in general information on sample (data) sheet.
2. Initially position one square meter plot frames.
3. Position trailer carrying rainfall simulator so that it covers the plots as desired.
4. Install plot frames with trench for collection trough.
5. Seal disturbed edges of soil with bentonite.
6. Take pictures of the plots and estimate cover.
7. Connect suction pumps to troughs.
8. Collect soil moisture and density samples from top ten cm of surface in the 1" I.D. sampling tube. Collect on outside edge of plot frame. Put in soil cans, label and seal.
9. Place impervious rainfall collection cover on plot.
10. Install raingages.
11. Install wind screens as needed.
12. Begin rainfall.
13. Sample rainfall rate using runoff from impervious cover.
14. Remove cover.
15. Note times of ponding and runoff into the trough.
16. Pump troughs as necessary (every three to five minutes).
17. Record pumped volume and save sample in barrel.
18. Rain for approximately 30 to 45 minutes to assure a steady-state runoff.

19. Replace cover and again sample rainfall rate.

20. Stop rain and pump trough a final time.

21. Measure depths in barrels.

22. Agitate barrels and collect two samples of about 500 ml of water and sediment, one for USDA Forest Service analyses. Preserve one with 10 ml of chlorine bleach in a one quart glass jar, labelled and sealed.

23. Remove deposited material (bed load) from runoff collection trough and from runoff tray (metal flume between plot and trough). Bag material in plastic ziploc bags and label.

24. Record raingage depths in inches and millimeters.

25. Measure depth to wetted front on outside edge of plot.

26. Cover plot with plastic sheet, plywood, and dirt until wet run.

WET RUN (12 to 24 hours later)

27. Repeat steps 6 to 25 above except rain for a minimum of 20 minutes or until steady runoff is observed.

28. Measure slope in plot with a Brunton compass.

29. Remove about 2.2 pounds (1 kilogram) of soil for sieve analyses from the center of the plot.

Samples of water, sediment, and soil are transferred along with sample sheets.

Laboratory measurements. Similar procedures as listed for the large simulator data were used with the small simulator data. Exceptions are that sediment load was analyzed using a composite runoff sample and hydrographs were not developed.

Derivation of Parameters

Selected parameters were derived from the data using statistical techniques. For infiltration, the key model parameters are steady-state infiltration rate and a soil water parameter such as capillary suction. These values can be determined from appropriate data analysis techniques using model components.

Erosion on overland flow surfaces comes about when there is sufficient energy to dislodge and move the soil materials. The two sources of energy present in simulator studies are from raindrop impact and overland flow. Raindrop impact does work by dislodging particles and transporting them relatively short distances in splash water. In the absence of overland flow, splash is an inefficient transport mechanism. Overland flow, particularly sheet and rill flow, typically has lower energy but is more efficient at transporting sediment. In combination the two energy inputs provide an effective method of soil erosion. It is usually difficult to precisely separate the two processes when analyzing soil erosion data (Kinnel 1985). Instead, a balance between the two is found by analyzing data from different rainfall intensity and overland flow rate experiments. This is a primary reason for conducting a series of experiments on a site.

For surface erosion, the key parameters are raindrop splash detachment and overland flow detachment coefficients. These parameters can also be determined using model components (Ward and Seiger 1983). However, they are not the only ones affecting the erosion processes. In addition, there are the smaller surface roughness elements, vegetative cover, soil particle size distribution, and the time of runoff concentration. These were quantified so as to provide numeric data for comparative purposes.

Simulator Tests and Comparisons

Data from the two simulators were compared to define the relationship between the two approaches with respect to depicting infiltration and erosion. Descriptive statistics were employed whenever possible. Derived information is used to depict site response in common terms that can be applied to future modeling efforts and to help in establishing future experimental designs.

An important part of this study was the demonstration of rainfall simulation in helping to define site/watershed response to water inputs. This technique of sampling rainfall-runoff-erosion is a more efficient and effective use of equipment and personnel for collecting data needed in studying watershed response to precipitation.

RESULTS AND ANALYSES

Data collected from the large and small simulator experiments were reduced, analyzed and summarized. The results of these efforts are presented in following sections. The results are then used to provide evidence for the applicability/usefulness of simulation and for extraction of model parameters. Note that for the following discussions the following conversions apply: one inch = 25.4 mm, one pound = 0.454 kilograms force = 454 grams force, one ton/acre = 2245.5 kilograms force/hectare, and one ton/acre-in. (one ton per acre per inch of runoff) = 88.4 kilograms force/hectare-mm.

Site Characteristics

Tables 1 and 2 list individual and summarized site measurements for the small simulator plots. Means and standard deviations of each measured variable were determined for the small plot experiments. Only one large simulator plot was used at each location. The summarized data for the large simulator are presented in table 3. Most information in these tables is self-explanatory. Gradation was determined from seiving the bulk soil samples. Gravel percent is the average percent by total sample weight of particles larger than 4.75 mm in diameter. Sand represents the size fraction between 4.75 mm and 0.075 mm, and fines are less than 0.075 mm in size. Wet and dry AMCs are the antecedent moisture contents on a dry weight basis sampled just prior to the rainfall application. For each large plot, topographic maps and 3-D projections were prepared as shown in

Table 1

Plot Characteristics for Small Area Simulator

				COVER		GRADATION		
PLOT ID	AMC (%)	SLOPE (%)	POROS (%)	ROCK (%)	VEG (%)	GRAVEL (%)	SAND (%)	FINE (%)
WS2 -L -D1	7.1	3.0	51.9	3.0	15.0	.5	61.2	38.3
WS2 -L -D2	6.3	5.2	51.0	.0	30.0	.0	65.2	34.8
WS2 -L -D3	6.9	6.2	55.0	3.0	20.0	.2	61.8	38.0
WS2 -L -D4	7.2	8.9	52.4	2.0	10.0	.4	60.4	39.2
WS2 -L -W1	14.3	3.0	51.9	3.0	15.0	.5	61.2	38.3
WS2 -L -W2	14.1	5.2	51.0	.0	30.0	.0	65.2	34.8
WS2 -L -W3	16.2	6.2	55.0	3.0	20.0	.2	61.8	38.0
WS2 -L -W4	18.6	8.9	52.4	2.0	10.0	.4	60.4	39.2
WS2 -U -D1	8.0	10.8	58.2	2.0	20.0	.0	42.2	57.8
WS2 -U -D2	6.4	13.3	56.3	1.0	40.0	.0	64.8	35.2
WS2 -U -D3	7.9	10.7	55.5	2.0	25.0	.0	43.1	56.9
WS2 -U -D4	8.3	8.6	60.3	1.0	25.0	.0	59.9	40.1
WS2 -U -W1	18.3	10.8	58.2	2.0	20.0	.0	42.2	57.8
WS2 -U -W2	13.5	13.3	56.3	1.0	40.0	.0	64.8	35.2
WS2 -U -W3	19.3	10.7	55.5	2.0	25.0	.0	43.1	56.9
WS2 -U -W4	15.2	8.6	60.3	1.0	25.0	.0	59.9	40.1
WS3 -L -D1	8.6	5.6	54.4	.0	25.0	.0	51.1	48.9
WS3 -L -D2	11.8	8.5	61.8	.0	20.0	.0	34.0	66.0
WS3 -L -D3	11.0	5.7	60.1	.0	13.0	1.8	43.8	54.4
WS3 -L -D4	7.5	3.9	56.4	.0	10.0	.3	52.5	47.2
WS3 -L -W1	14.9	5.6	54.4	.0	25.0	.0	51.1	48.9
WS3 -L -W2	27.8	8.5	61.8	.0	20.0	.0	34.0	66.0
WS3 -L -W3	21.6	5.7	60.1	.0	13.0	1.8	43.8	54.4
WS3 -L -W4	17.1	3.9	56.4	.0	10.0	.3	52.5	47.2
WS3 -U -D1	16.2	9.1	67.9	.0	7.0	.0	8.8	91.2
WS3 -U -D2	15.0	10.7	62.0	.0	1.0	1.7	22.4	75.9
WS3 -U -D5	10.5	9.1	54.8	1.0	12.0	11.1	26.9	62.0
WS3 -U -D6	13.5	21.1	62.3	.0	20.0	.0	11.5	88.5
WS3 -U -W1	24.1	9.1	67.9	.0	7.0	.0	8.8	91.2
WS3 -U -W2	22.2	10.7	62.0	.0	1.0	1.7	22.4	75.9
WS3 -U -W3	22.0	15.3	60.1	.0	.0	.0	21.2	78.8
WS3 -U -W4	22.4	15.9	56.4	.0	5.0	.0	13.5	86.5

Table 1 continued

NMSU-N -D1	3.2	2.6	37.2	40.0	3.0	13.3	65.0	21.7
NMSU-N -D2	2.6	4.4	46.1	40.0	3.0	13.0	65.5	21.5
NMSU-N -W1	8.7	2.6	37.2	40.0	3.0	13.3	65.0	21.7
NMSU-N -W2	9.2	4.4	46.1	40.0	3.0	13.0	65.5	21.5
NMSU-S -D1	2.6	4.4	53.7	40.0	3.0	21.8	67.2	11.0
NMSU-S -D2	3.4	4.1	43.1	30.0	8.0	20.1	64.1	15.8
NMSU-S -W1	8.2	4.4	53.7	40.0	3.0	21.8	67.2	11.0
NMSU-S -W2	8.3	4.1	43.1	30.0	8.0	20.1	64.1	15.8
NMSU-E -D1	2.3	4.4	46.8	30.0	1.0	9.6	69.7	20.7
NMSU-E -D2	2.4	3.9	45.3	35.0	16.0	12.7	64.9	22.4
NMSU-E -W1	7.5	4.4	46.8	30.0	1.0	9.6	69.7	20.7
NMSU-E -W2	10.7	3.9	45.3	35.0	16.0	12.7	64.9	22.4
NMSU-W -D1	1.2	5.5	40.0	30.0	3.0	19.8	54.8	25.4
NMSU-W -D2	2.0	4.5	42.6	30.0	7.0	19.7	63.3	17.0
NMSU-W -W1	8.2	5.5	40.0	30.0	3.0	19.8	54.8	25.4
NMSU-W -W2	10.1	4.5	42.6	30.0	7.0	19.7	63.3	17.0
NMSU-N2-D1	1.6	2.9	42.8	30.0	4.0	17.5	64.9	17.6
NMSU-N2-D2	2.6	3.5	40.1	60.0	1.0	23.1	59.5	17.4

Table 2

Means (M) and Standard Deviations (S) of Plot Characteristics for Small Area Rainfall Simulator

						COVER				GRADATION									
		POROSITY (%)		SLOPE (%)		ROCK (%)		VEG (%)		GRAVEL (%)		SAND (%)		FINES (%)		DRY AMC (%)		WET AMC (%)	
	N	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S
WS2	8	55.	3.	8.3	3.3	2.	1.	23.	9.	0.1	0.2	57.3	8.9	42.5	9.0	7.3	0.7	16.2	2.3
WS3	8	60.	4.	9.3	4.7	0.	0.	12.	8.	1.2	2.8	31.1	16.4	67.7	16.5	11.8	3.0	21.5	4.0
NMSU	9	44.	5.	4.1	0.8	36.	8.	5.	4.	16.7	4.5	64.1	4.1	19.2	4.2	2.4	0.7	8.9	1.1

Table 3

Plot Characteristics for Large Area Simulator
(The AMC values are for the constant rainfall experiments only)

	AREA (SQ.FT.)	POROSITY (%)	SLOPE (%)	VEG COVER (%)	GRAVEL (%)	SAND (%)	FINES (%)	DRY AMC (%)	WET AMC (%)
WS2	2173.	50.	7.56	25.67	0.00	55.73	44.27	3.35	17.91
WS3	1708.	49.	9.17	21.76	0.23	61.36	38.41	3.98	12.76
NMSU	2023.	45.	3.47	12.30	16.02	68.15	15.83	5.66	9.22

figures 2 and 3 for WS2, figures 4 and 5 for WS3, and figures 6 and 7 for the NMSU sites. These computer generated figures provide an overall feeling for the relative topography on the plots. Note that the computer drawn figures do not have precise locations for the plot borders.

Comparisons of the small and large simulator plot characteristics indicate no difference between the two for most site measures. Notable exceptions are found on the WS3 plots where measured porosity is signficantly higher on the small plots relative to the large plots. Vegetative cover was significantly lower on the small plots. There was a big difference between the sand and fine fractions. For the small plots there was twice as much fines as sand, but the ratio was reversed for the large plots. Re-examination of the data for the individual plots shows that differences are caused by a large variation in soil characteristics in the plot area. Both WS2 and WS3 have higher proportions of fines near the upper (U) end of the big simulator plots and lower proportions near the lower end (L). One of the three samples taken from the large simulator plot had a very low content of fines which tends to skew the composited sample somewhat. A subsequent field visit in April 1984, confirmed this suspicion. Therefore, it appears that the differences in the gradations is caused by natural variations in the soil coupled with the random selection of plots and samples. A complete wet sieving was performed on each sample, and selected samples were further analyzed with a hydrometer test. Sediment yield samples were not sieved.

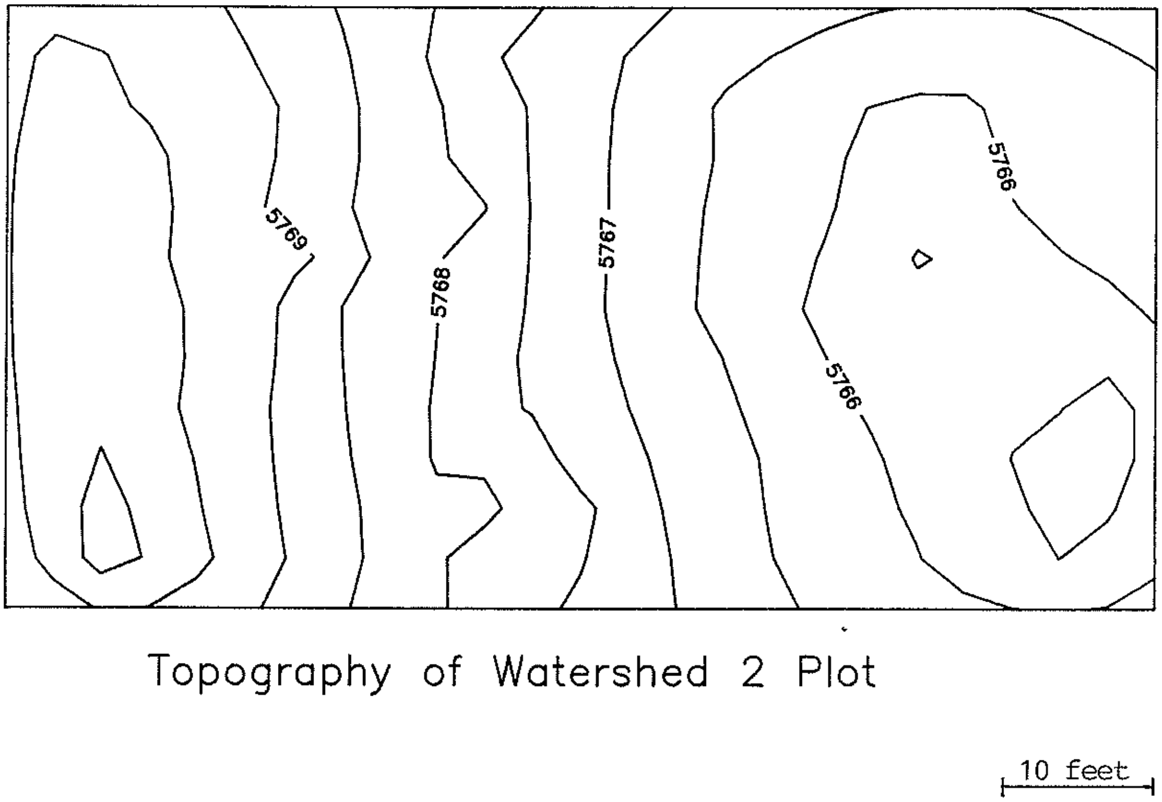


Figure 2. Topographic map of WS2

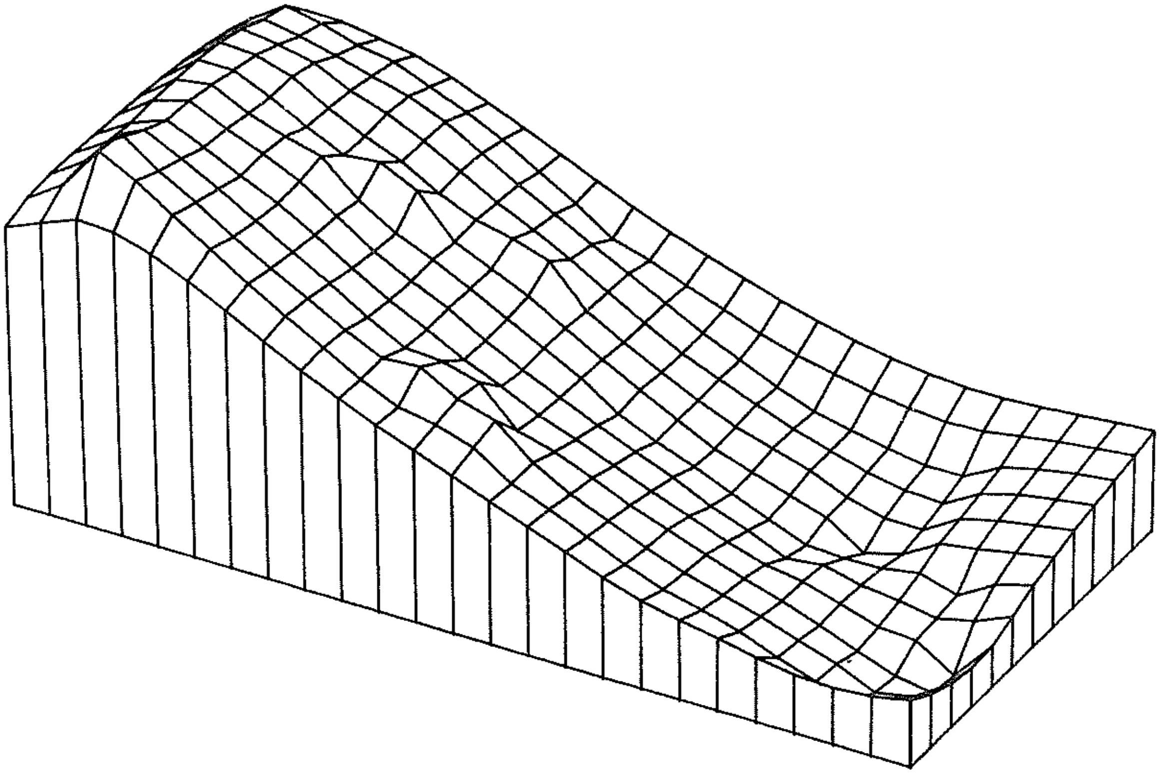


Figure 3. Relief projection of WS2

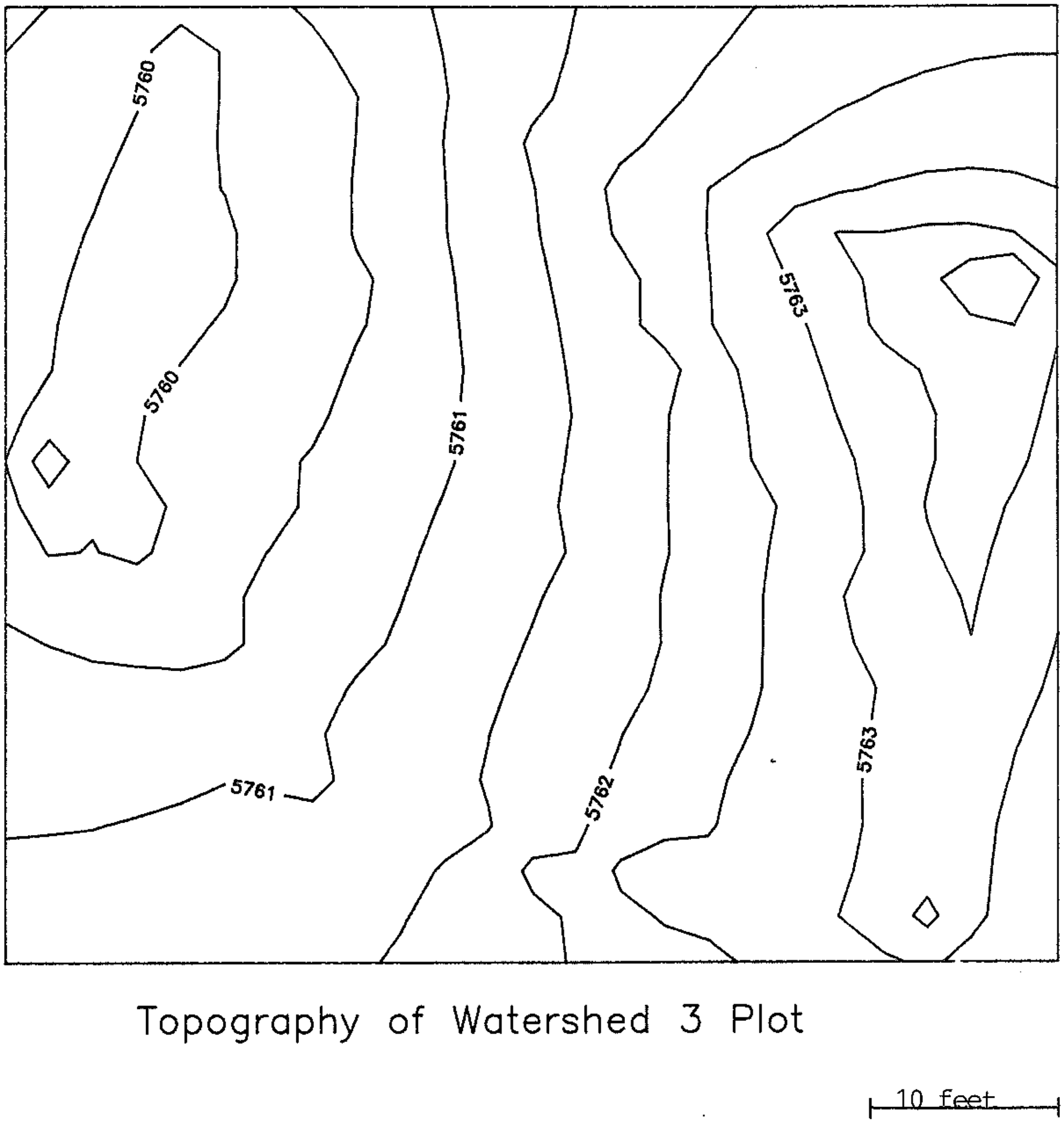
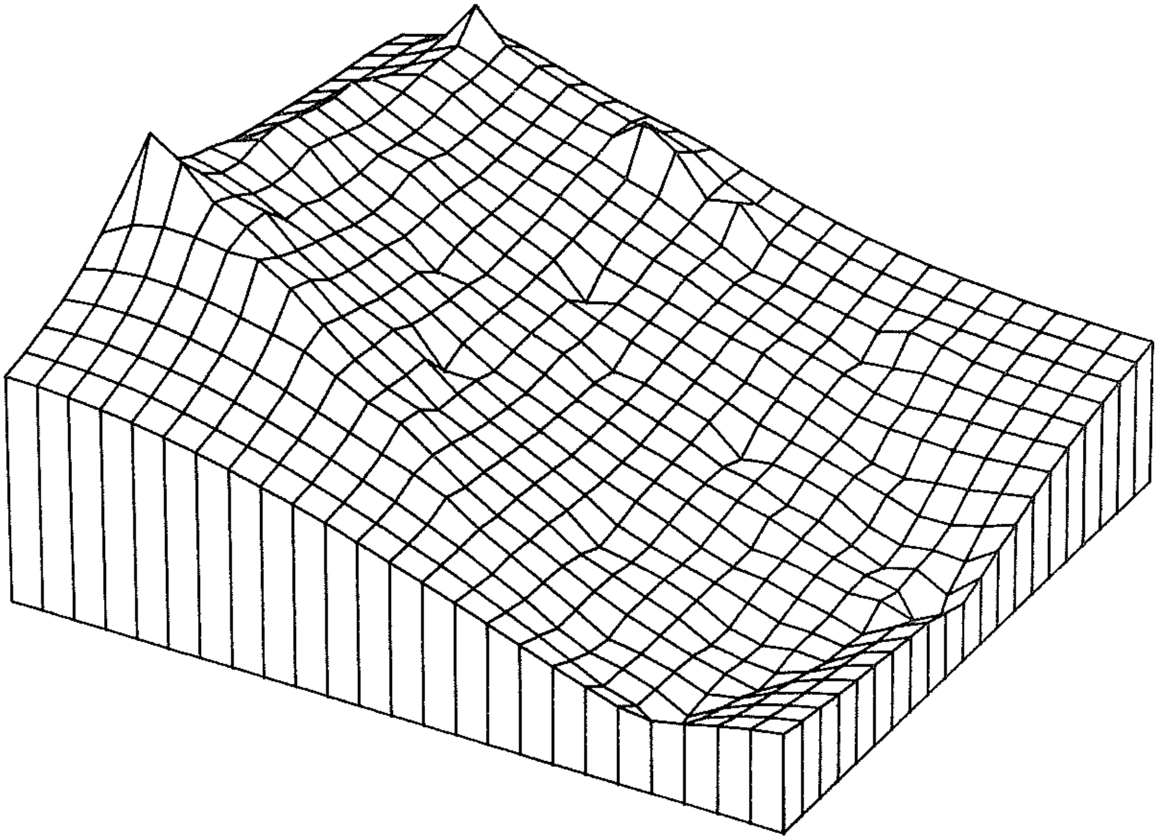


Figure 4. Topographic map of WS3



Topography of Watershed 3 Plot

Figure 5. Relief projection of WS3

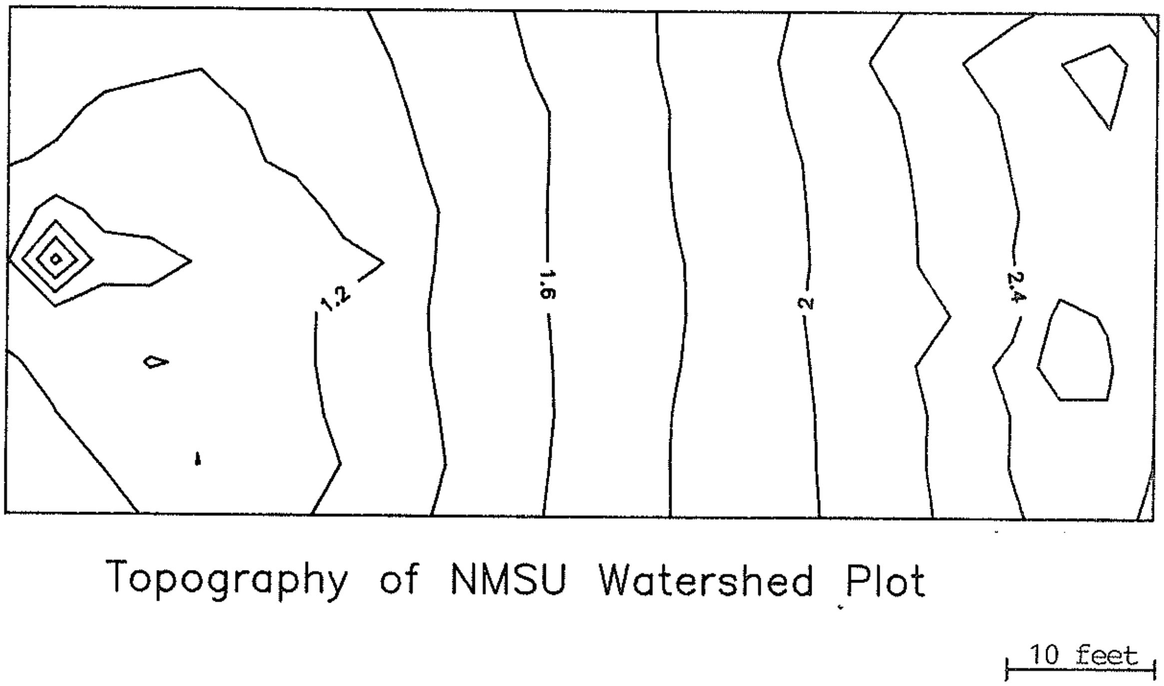
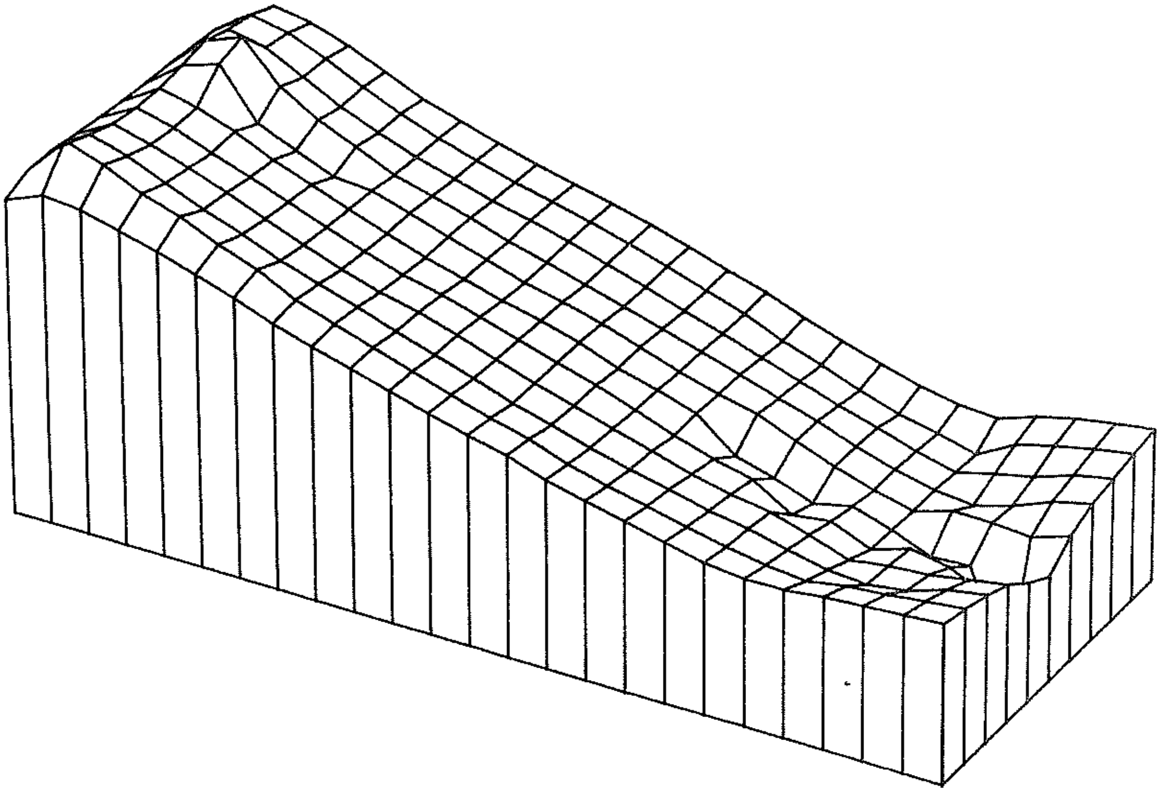


Figure 6. Topographic map of NMSU site



Topography of NMSU Watershed Plot

Figure 7. Relief projection of NMSU site

The differences in vegetation cover are attributable to an inherent tendency to place the small plots where vegetation is sparse (easier to install) and that the small plots are a point sample while the large plot was sampled by a line intercept. (Note that rock cover, although present, was not explicitly sampled along the line intercepts used for the large plots.) A more random method may overcome this sampling bias. The differences in porosity are more difficult to explain. It appears that the average small plot porosity is consistently higher for both WS2 and WS3. This diference may reflect a sampling/measurement error, but there is no confirmation of errors in the data books. Again this may be related to the natural soil variability as found in the gradation comparisons. Differences in plot characteristics, if they are not artifacts of the sampling/measurement system, should affect rainfall-runoff erosion processes. These comparisons are made in the following sections.

Constant Rate Rainfall

Individual plot measurements are presented in tables 4 and 5 for the three sites. Tables 6 and 7 list the summarized results of the simulated constant rate rainfall experiments. Notable differences between measurements for the two types of simulators are seen in rainfall rate, rainfall depth, runoff depth, and runoff to rainfall ratio (RO/RF). There are also differences between the sites for the same type of simulator, and, as expected, differences between dry and wet runs. Some of these

Table 4

Storm Characteristics for Small Area Simulator

PLOT ID	RAINFALL			RUNOFF		RO / RF
	RATE (IPH)	EVENT (MIN)	DEPTH (IN)	EVENT (MIN)	DEPTH (IN)	
WS2 -L -D1	4.62	27.0	2.08	25.8	1.40	.67
WS2 -L -D2	4.64	28.0	2.17	26.0	1.14	.53
WS2 -L -D3	5.30	23.0	2.03	22.4	1.23	.61
WS2 -L -D4	4.19	29.3	2.04	28.0	1.53	.75
WS2 -L -W1	5.26	24.0	2.11	23.6	1.60	.76
WS2 -L -W2	4.36	20.4	1.49	20.0	1.10	.74
WS2 -L -W3	5.32	20.5	1.82	20.2	1.43	.79
WS2 -L -W4	3.80	24.4	1.55	24.0	1.18	.76
WS2 -U -D1	5.06	34.0	2.87	32.5	1.97	.69
WS2 -U -D2	4.78	35.4	2.83	34.0	1.81	.64
WS2 -U -D3	4.88	34.0	2.77	33.0	1.98	.72
WS2 -U -D4	4.47	36.5	2.72	34.0	1.63	.60
WS2 -U -W1	5.53	25.5	2.35	25.3	1.90	.81
WS2 -U -W2	4.55	24.3	1.84	24.0	1.59	.86
WS2 -U -W3	4.59	22.0	1.68	21.6	1.37	.82
WS2 -U -W4	4.01	24.5	1.64	24.0	1.26	.77
WS3 -L -D1	3.56	30.0	1.78	27.7	.97	.55
WS3 -L -D2	3.25	36.0	1.95	33.9	1.20	.62
WS3 -L -D3	3.92	19.0	1.24	17.8	.68	.55
WS3 -L -D4	4.21	28.6	2.00	26.0	1.27	.63
WS3 -L -W1	4.65	20.0	1.55	18.9	1.26	.81
WS3 -L -W2	4.24	22.5	1.59	22.2	1.32	.83
WS3 -L -W3	5.41	25.0	2.25	24.4	1.71	.76
WS3 -L -W4	3.39	23.2	1.31	22.4	.93	.71
WS3 -U -D1	3.20	34.5	1.84	32.9	1.11	.61
WS3 -U -D2	3.82	35.2	2.24	33.8	1.52	.68
WS3 -U -D5	4.75	34.0	2.69	33.1	2.07	.77
WS3 -U -D6	4.57	31.3	2.38	30.0	1.62	.68
WS3 -U -W1	4.29	20.0	1.43	19.7	1.29	.90
WS3 -U -W2	4.45	22.3	1.66	22.0	1.31	.79
WS3 -U -W3	4.20	19.0	1.33	18.2	1.08	.81
WS3 -U -W4	4.04	22.7	1.53	22.0	1.14	.75

Table 4 continued

NMSU-N -D1	4.25	46.6	3.30	45.2	1.92	.58
NMSU-N -D2	3.38	51.4	2.90	48.2	1.51	.52
NMSU-N -W1	4.49	45.7	3.43	44.9	2.10	.61
NMSU-N -W2	4.45	30.0	2.23	29.3	1.76	.79
NMSU-S -D1	2.42	37.0	1.50	33.1	.73	.49
NMSU-S -D2	3.87	42.0	2.71	39.4	1.05	.39
NMSU-S -W1	3.76	34.0	2.13	32.6	1.47	.69
NMSU-S -W2	3.54	31.0	1.83	29.7	1.13	.62
NMSU-E -D1	3.85	43.0	2.76	40.2	1.23	.44
NMSU-E -D2	3.66	42.0	2.56	39.4	1.17	.46
NMSU-E -W1	3.24	26.0	1.40	25.4	.96	.69
NMSU-E -W2	3.39	24.5	1.39	23.6	.92	.67
NMSU-W -D1	3.46	37.5	2.16	36.2	1.02	.47
NMSU-W -D2	4.18	34.5	2.41	32.7	1.51	.63
NMSU-W -W1	3.92	40.0	2.61	39.4	1.79	.68
NMSU-W -W2	3.69	31.0	1.90	29.9	1.29	.68
NMSU-N2-D1	3.54	41.0	2.42	38.9	1.24	.51
NMSU-N2-D2	4.17	36.1	2.50	34.5	1.56	.62

Table 5

Infiltration and Erosion for Small Area Simulator

PLOT ID	INFILTRATION		EROSION		
	FINAL RATE (IPH)	FRONT DEPTH (IN)	SUSP YIELD (GMS)	BED YIELD (GMS)	TOTAL YIELD (T/A.IN)
WS2 -L -D1	1.11	4.7	106.8	194.0	1.02
WS2 -L -D2	1.49	9.1	60.9	261.0	1.33
WS2 -L -D3	1.55	3.9	168.1	514.0	2.62
WS2 -L -D4	.48	6.3	121.1	848.0	2.98
WS2 -L -W1	1.07	****	138.6	252.0	1.16
WS2 -L -W2	.86	****	60.7	281.0	1.47
WS2 -L -W3	.98	****	303.3	346.0	2.14
WS2 -L -W4	.22	****	76.2	461.0	2.15
WS2 -U -D1	.96	5.5	307.5	449.0	1.81
WS2 -U -D2	1.24	5.5	220.9	894.0	2.91
WS2 -U -D3	.79	4.3	288.5	840.0	2.70
WS2 -U -D4	1.00	5.1	117.4	139.0	.74
WS2 -U -W1	.93	4.3	262.5	587.0	2.12
WS2 -U -W2	.63	5.9	159.0	663.0	2.45
WS2 -U -W3	.68	****	119.8	424.0	1.87
WS2 -U -W4	.55	****	72.2	160.0	.87
WS3 -L -D1	1.15	7.3	83.6	119.0	.99
WS3 -L -D2	1.07	5.7	307.9	253.0	2.20
WS3 -L -D3	1.48	5.1	99.6	165.0	1.85
WS3 -L -D4	.79	5.3	161.3	23.0	.69
WS3 -L -W1	.36	5.9	174.5	.0	.66
WS3 -L -W2	.53	4.3	259.6	244.0	1.80
WS3 -L -W3	1.23	6.7	339.0	157.0	1.37
WS3 -L -W4	.49	7.9	104.2	32.0	.69
WS3 -U -D1	.82	4.3	277.8	745.0	4.34
WS3 -U -D2	.87	5.4	404.8	638.0	3.25
WS3 -U -D5	.62	5.5	1085.7	1008.0	4.78
WS3 -U -D6	.76	8.7	805.0	1028.0	5.35
WS3 -U -W1	.25	5.5	636.5	347.0	3.60
WS3 -U -W2	.70	5.5	143.9	555.0	2.53
WS3 -U -W3	.43	6.5	144.0	524.0	2.92
WS3 -U -W4	.64	6.5	201.5	640.0	3.47

Table 5 continued

NMSU-N -D1	1.41	13.0	41.8	82.0	.31
NMSU-N -D2	.48	13.0	36.5	11.0	.15
NMSU-N -W1	1.34	12.6	29.7	157.0	.42
NMSU-N -W2	.73	12.6	11.8	48.0	.16
NMSU-S -D1	1.02	5.5	130.6	51.0	1.17
NMSU-S -D2	1.94	11.0	16.3	10.0	.12
NMSU-S -W1	.85	11.0	18.3	15.0	.11
NMSU-S -W2	.91	12.6	18.1	15.0	.14
NMSU-E -D1	1.32	8.8	42.3	135.0	.68
NMSU-E -D2	1.45	7.3	34.5	123.0	.64
NMSU-E -W1	1.26	12.0	40.2	78.0	.58
NMSU-E -W2	1.24	11.0	191.1	89.0	1.43
NMSU-W -D1	1.65	4.9	10.5	115.0	.58
NMSU-W -D2	.96	9.0	21.8	152.0	.54
NMSU-W -W1	.93	9.4	16.3	161.0	.47
NMSU-W -W2	.89	11.0	11.7	94.0	.39
NMSU-N2-D1	1.15	11.9	11.3	44.0	.21
NMSU-N2-D2	.91	9.8	73.9	146.0	.67

**** wetting front depth not distinct

Table 6

Means (M) and Standard Deviations (S) of Simulated Storm Results for Small Area Rainfall Simulator

														DEPTH					
			FINAL INFILT (iph)		SUSP YIELD (gms)		BED YIELD (gms)		TOTAL YIELD (T/Ac.in)		RAIN RATE (iph)		RAIN (inch)		RUNOFF (inch)		RO/RF (dim)	
		N	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S
WS2	D	8	1.08	0.35	173.9	89.8	517.4	310.2	2.01	0.90	4.74	0.35	2.44	0.39	1.59	0.32	0.65	0.07
	W	8	0.74	0.28	149.0	90.0	396.8	171.1	1.78	0.55	4.68	0.63	1.81	0.29	1.43	0.26	0.79	0.04
WS3	D	8	0.95	0.28	403.2	359.0	497.4	407.4	2.93	1.77	3.91	0.57	2.01	0.44	1.30	0.43	0.64	0.07
	W	8	0.58	0.30	250.4	172.9	312.4	244.1	2.13	1.17	4.33	0.57	1.58	0.30	1.25	0.23	0.80	0.06
NMSU	D	10	1.28	0.45	41.9	36.5	86.9	54.7	0.51	0.32	3.68	0.54	2.52	0.48	1.29	0.34	0.51	0.08
	W	8	1.02	0.23	42.1	60.5	82.1	58.8	0.46	0.43	3.81	0.46	2.11	0.69	1.43	0.43	0.68	0.06

Table 7

Simulated Storm Results for Large Area Simulator
(Results for the constant rainfall experiments only)

		DURATION (mins)	APPROX. FINAL INFIL. (iph)	SUSP YIELD (lbs)	BED YIELD (lbs)	TOTAL YIELD (T/Ac.in.)	RAIN RATE (iph)	RAIN DEPTH (inch)	RUNOFF DEPTH (inch)	RO/RF (dim)
WS2	DRY	27.0	1.08	18.7	4.8	0.56	2.33	1.05	0.42	0.40
	WET	16.4	0.63	31.3	6.5	0.82	2.60	0.71	0.46	0.65
WS3	DRY	29.8	0.82	41.8	0.9	1.05	2.52	1.24	0.50	0.40
	WET	27.2	0.03*	147.5	5.0	1.80	2.85	1.29	1.08	0.82
NMSU	DRY	16.4	1.56	4.1	0.7	0.19	3.00	0.82	0.27	0.33
	WET	22.4	0.87	6.4	1.3	0.13	3.05	1.14	0.66	0.58

* This value is too low because of the derivation technique used.
An adjusted value of 0.28 iph may be more realistic.

differences are caused by operational characteristics of the simulators. However, there do seem to be some points of similarity. In most cases, the final infiltration rates of the small simulator plots compare very well to the rates found by analysis of the large plot runoff hydrographs.

Large Plot Hydrographs

All the stage recordings from the large plot simulations were digitized, converted to discharge, smoothed using a three-point (nearest neighbor) moving average and replotted with the corresponding sediment concentration values. The six hydrographs for the constant rainfall simulations are presented in figures 8,9,10,11,12 and 13 for the WS2 dry, WS2 wet, WS3 dry, WS3 wet, NMSU dry and NMSU wet experiments.

The hydrographs all have been plotted to the same time and discharge scales. Sediment concentration scales vary because concentration had extreme fluctuations that are important to visualize. The concentration scales for the NMSU experiments are the same, however.

Water discharge. The hydrographs reflect many effects of the natural and human controlled system. Although each hydrograph reaches, approximately, a steady rate of runoff, there are fluctuations and trends in the rate. Infiltration theory suggests that there should be a slow increase in the crest limb with time. This increase is apparent for the WS2 and WS3 experiments. The slowly increasing runoff rate is in response to the infiltration rate approaching a constant value, as suggested

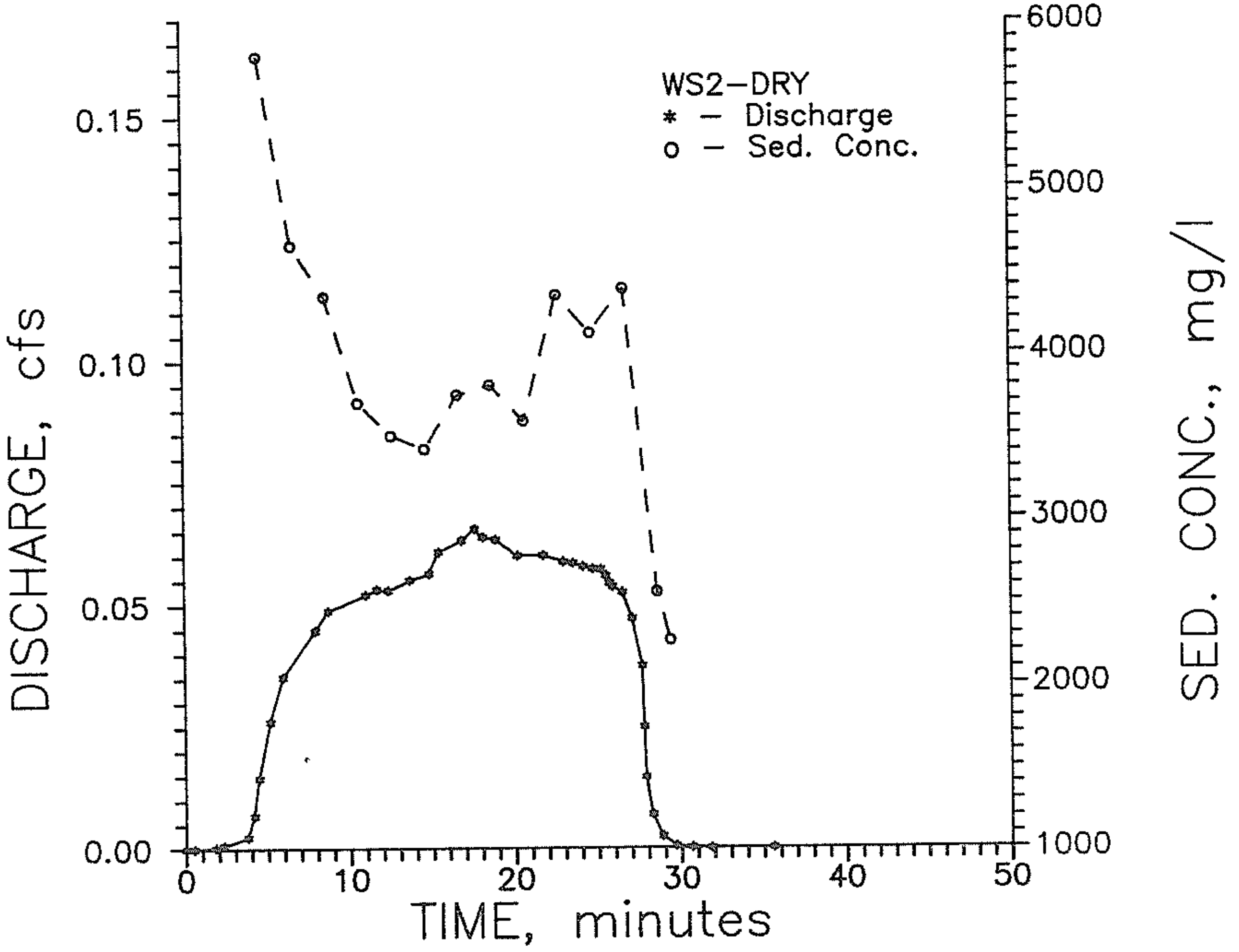


Figure 8. Discharge and sediment concentration for WS2 - Dry experiment

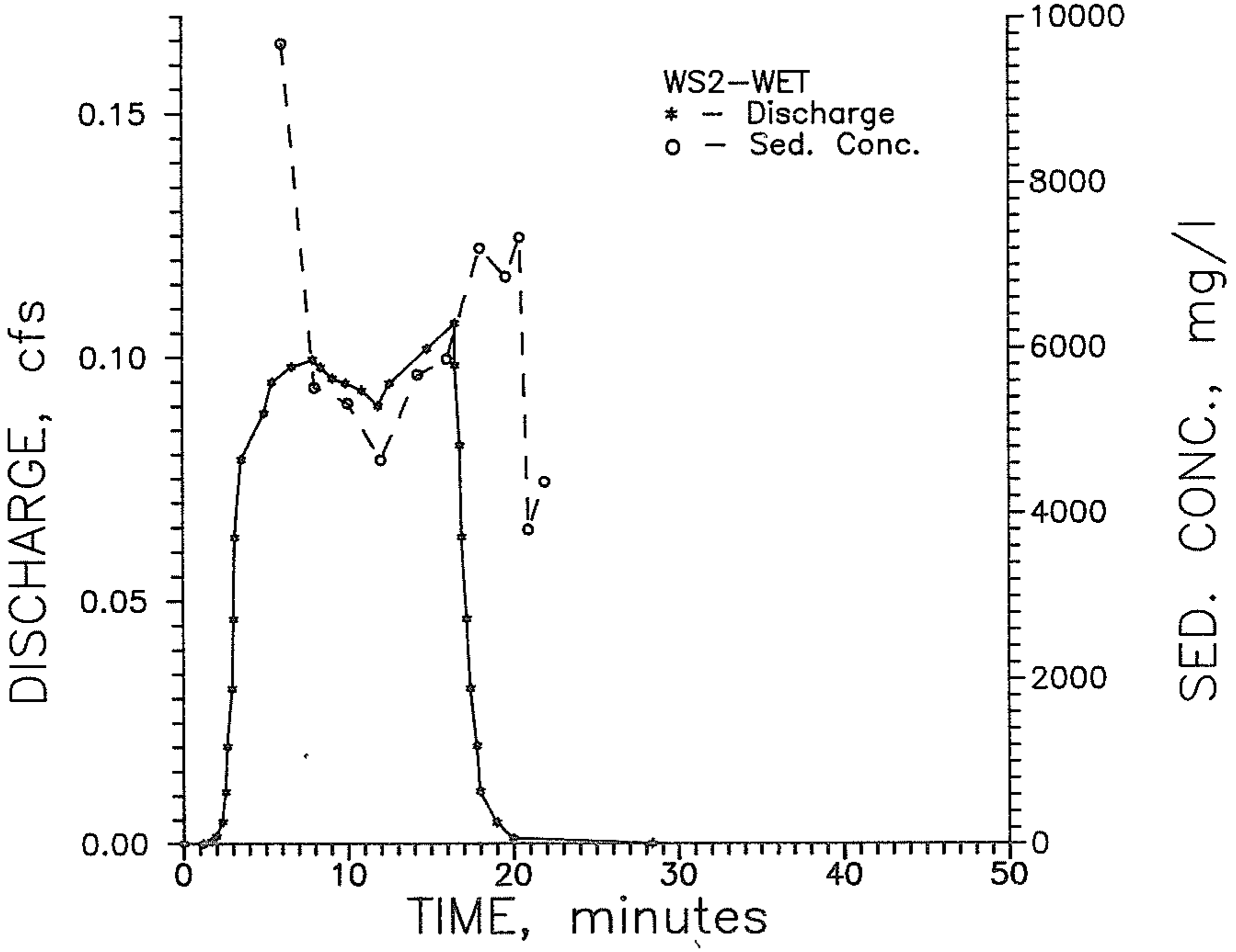


Figure 9. Discharge and sediment concentration for WS2 - Wet Experiment

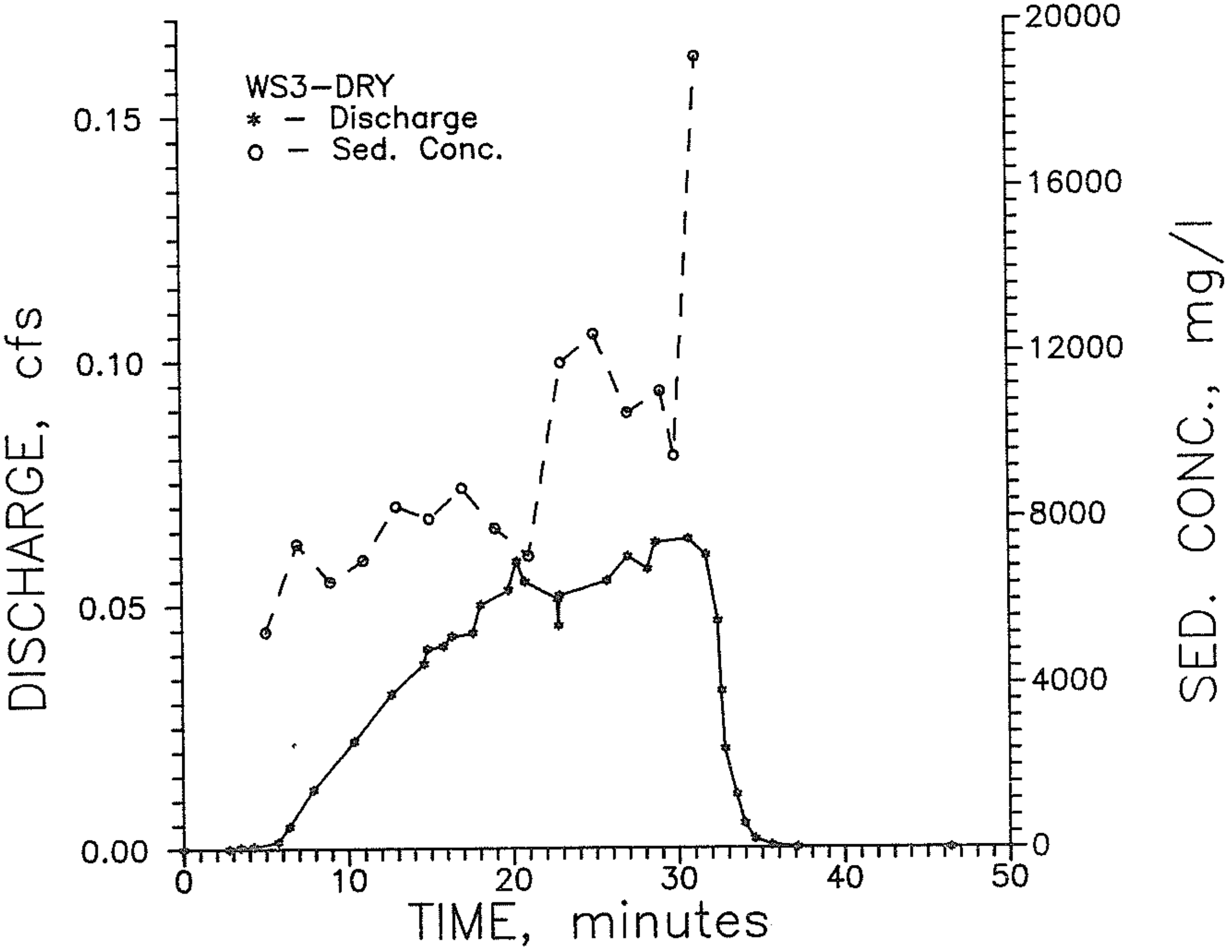


Figure 10. Discharge and sediment concentration for WS3 - Dry Experiment

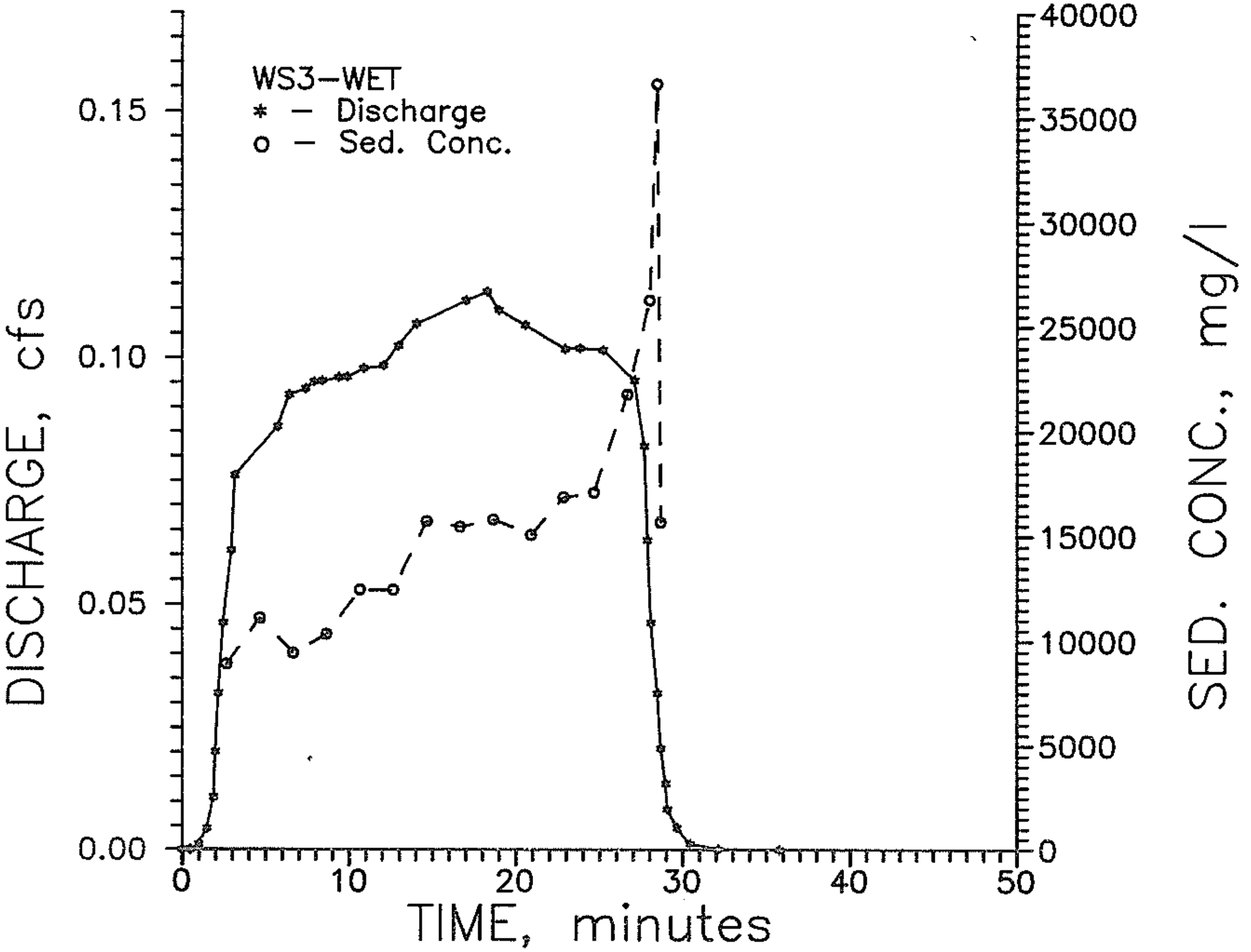


Figure 11. Discharge and sediment concentration for WS3 - Wet Experiment

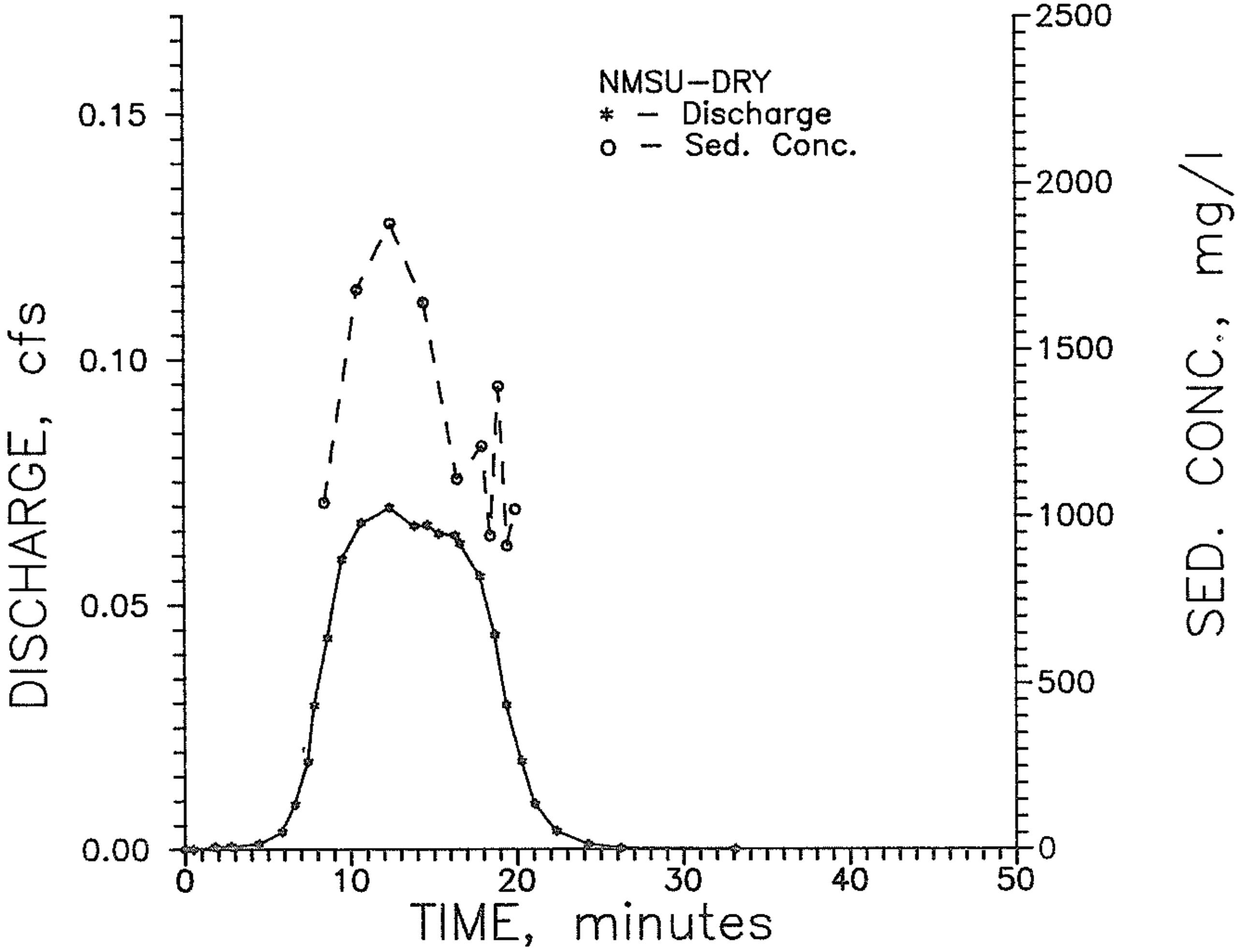


Figure 12. Discharge and sediment concentration for NMSU - Dry Experiment

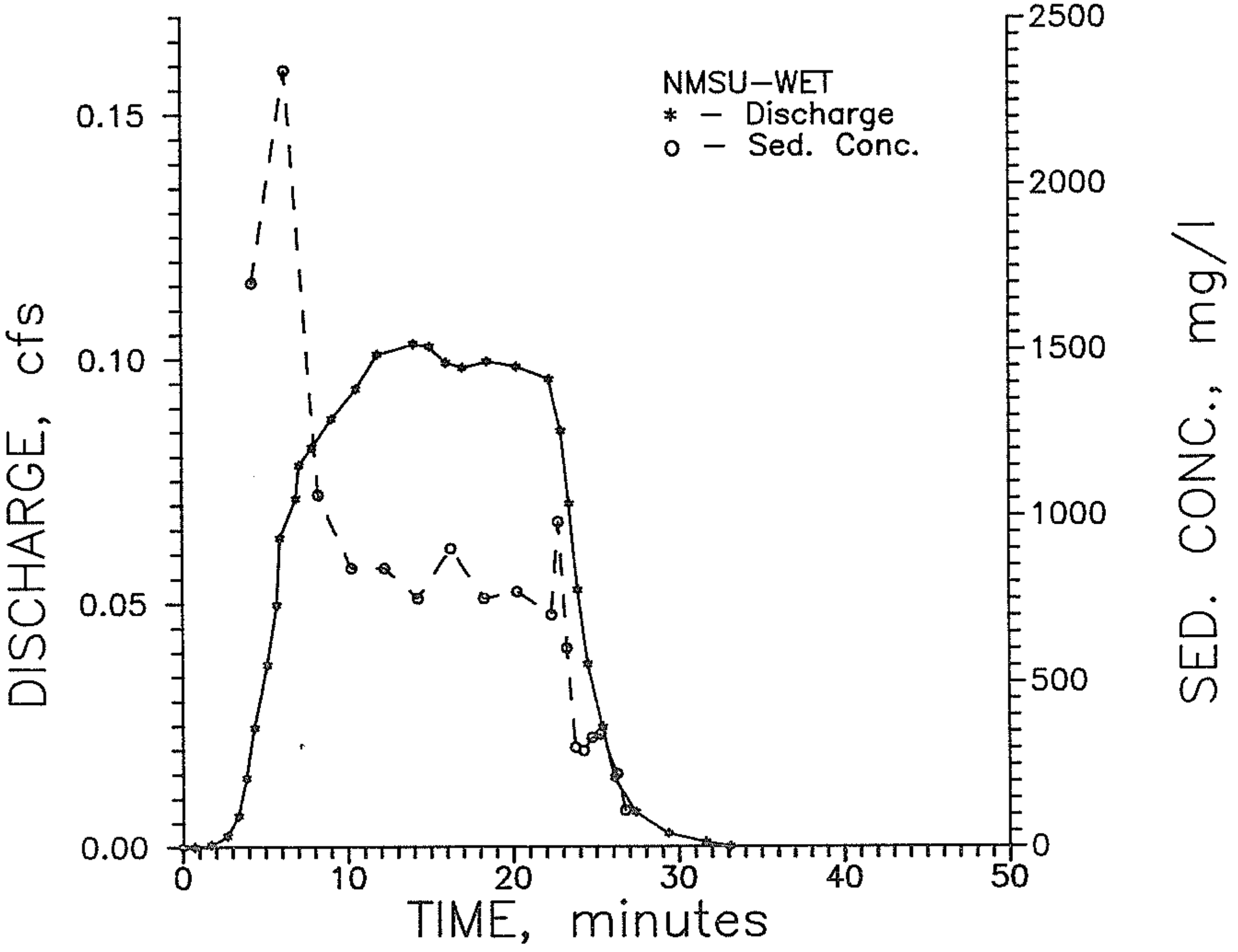


Figure 13. Discharge and sediment concentration for NMSU - Wet Experiment

by serveral rational algebraic approaches to modeling infiltration. Fluctuations on the crest limb are related to wind (WS2 wet (figure 9) is a good example of wind blowing rain off the plot.), equipment (The stage recorder is very good but very sensitive to changes in flow depth, and the constant rainfall rate does vary slightly as evidenced by rainfall weighing gage charts.), and natural processes (Infiltration fluctuates with time and location.). The hydrographs accurately represent the runoff and can be used for other analyses.

Infiltration rate. One analysis is to determine the steady state infiltration rate for the constant rainfall experiments. This analysis was done by averaging the three highest runoff rates on the crest limb (not the rising or recession limbs) then subtracting that average from the constant rainfall rate. The resultant infiltration rate is listed in table 7. Other methods can be used. However, this technique is one that the author has applied in rainfall-runoff modeling to provide a good, first estimate of the infiltration rate. It should be noted that this technique produces a very low rate for WS3-wet, which may be a result of rainfall, not infiltration, fluctuations. If the steady rate values occurring before the recession limb are used, a more reasonable infiltration rate can be calculated. Comparison of the rates with those from the small plots are made in another section.

Sediment concentration. Sediment concentration grab samples were periodically collected and subsequently analyzed. The concentration time plots (sedigraphs) are interesting in that they reflect different processes occuring on the different sites. WS2 shows the classic concentration decay with time, then an increase towards the end of the crest limb. The decay is caused by the finer materials quickly washing off the plot while the rise is hypothesized to be attrituted to coarser materials (or other source areas) reaching the outflow at a slower rate. The high concentration values on the recession limb of WS2-wet indicate this supposed wash off-lag effect. It appears that as the flow decreases, the total amount of material remains about the same because it is limited by supply and not by transport capacity of the flow. Therefore, sediment concentration increases. If the sediment yield were completely controlled by transport capacity, the sediment concentration would be expected to either remain the same or decrease as the flow decreased. Unfortuneately, sediment samples were not sieved so this hypothesis could not be tested. This increase during the recession limb also is evident on the other plots. The WS3 experiments do not exhibit the early decay as seen on WS2. Instead, an increase with time is evident as a larger amount of material reaches the flume. Concentrations for NMSU plots rise initially then decrease. This result is caused by an initial "flush off" of the fine materials at the NMSU site, then a decay as less and less material reaches the flume. It is obvious from the hydrographs and sedigraphs that each site responds differently from the others with respect to sediment production.

Sediment yield. Sediment yields were determined for each experiment. Suspended yield, that material in transport through the flume, was computed by three different methods, all of which produced equivalent answers. The values reported in table 7 were found by interpolating the hydrograph and concentration values on one-minute intervals, multiplying, and summing. The other methods were: a) to use a time averaged concentration for the entire sediment sampling period, and b) to use the instantaneous discharge at the time of sampling as a weighting factor. Applications of a conversion factor produced suspended yield in pounds. Sediment that was deposited in the approach trough, "bed load", was removed and weighed separately after the experiments. The amount of bed load at the WS2 and WS3 sites is some indication of the material that was moving through the system at a slower rate, as compared to the NMSU site. On average, the small plots produced sediment yields on a per-unit-area-and-per-unit-of-runoff basis of about 2.7 times higher than the large plots.

Comparison of Parameters

The site characteristics and runoff measurements most useful in modeling are infiltration parameters, sediment production parameters, soil porosity, and antecedent moisture content.

Infiltration Parameters

Infiltration parameters were derived from the small plot data for the Green-Ampt (G-A) infiltration equation. Four parameters are needed in this equation: soil porosity, initial soil moisture content, hydraulic conductivity in the wetting (infiltrating) front, and capillary (suction) head across the wetted front. Soil porosity and initial soil moisture have already been presented and are not repeated here. Instead, two sets of derived values for the hydraulic conductivity and suction head are presented. Conversion of the G-A parameters to those used in other equations is possible with the information provided here (Rawls and Brakensiek, 1985).

Two methods were used to derive the G-A parameters. The first method (used by Ward and Seiger 1983) involves fitting a straight line to the data pairs of instantaneous infiltration rate and the reciprocal of infiltrated water depth or:

$$f = a + \frac{b}{F} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where f is the instantaneous infiltration rate for a sample period, F is the depth of infiltrated water, and a,b are best fit parameters.

Equation 1 is a simple form of the G-A equation. The hydraulic conductivity (kw) is equal to a (as F gets large, f approaches kw), and the capillary (suction) head is:

$$Hc = \frac{b}{(a)\ (ds)\ (n)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where Hc is the capillary head
ds is the difference between initial soil saturation and final saturation (=1), and n is porosity.

An approximation to ds is

$$ds = (1-Si) = 1 - \frac{AMC\ (1 - n)\ 2.65}{n} \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

where Si is the initial soil saturation, AMC is the antecedent soil moisture (decimal fraction, table 1), and n is the soil porosity (table 1).

For the soil conditions encountered, dS varied between about 0.20 and 0.80, wet and dry, respectively.

The second technique was formally presented by Bach, Wierenga, and Ward (1985) in an application to the Phillip infiltration equation. Sometimes the data points do not contain values of F that are relatively large (as is the case in most simulator experiments). It is therefore possible to obtain negative values of a, hence Kw and Hc. To avoid this, the following technique was applied. The last three steady state runoff rates were averaged to find a steady or final infiltration rate (table 5) or fr. It is then assumed that Kw = fr, and using equation 1:

$$\frac{(f - 1)}{fr} = \frac{C}{F} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where C is now the "no-intercept" slope, and the other variables are defined previously. The best fit parameter C can be used to find Hc as

$$Hc = \frac{C}{(dS)\ (n)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

with all variables defined previously. The results of these techniques are summarized in table 8.

The approach using equation 1 fits the data better because it involves two coefficients (a and b) and not just one (C only). The infiltration rates, final and G-A, are similar at the WS2 plots, both dry and wet. They differ at the other plots. Capillary heads are inversely related to infiltration rates (mathematically and physically) and are usually quite variable.

Table 8

Means (M) and Standard Deviations (S)
for Selected Infiltration Parameters

	FINAL INFIL. (iph)		CAPIL. SUC. (inch)		G-A INFIL. (iph)		G-A SUCTION (inch)	
SITE ID	M	S	M	S	M	S	M	S
WS2-D	1.08	0.35	0.40	0.19	0.34	0.30	2.52	2.77
WS2-W	0.74	0.28	0.16	0.21	0.83	0.16	0.51	0.77
WS3-D	0.95	0.28	0.46	0.42	0.51	0.33	1.40	0.59
WS3-W	0.58	0.30	0.35	0.36	0.29	0.23	1.40	1.24
NMSU-D	1.28	0.45	0.92	1.54	0.91	0.50	2.31	1.78
NMSU-W	1.02	0.23	0.29	0.22	0.80	0.49	2.07	1.90

NOTE: Final infiltration is found from the last three steady state runoff measurements.

Capillary suction is derived from the runoff measurements using the final infiltration rate as the assumed Green-Ampt hydraulic conductivy (G-A infiltration) in the wetted front.

G-A infiltration and G-A suction are found by fitting a straight line to data pairs of instantaneous infiltration rate and the reciprical of cumulative infiltration.

The heads at the WS3 plots, dry and wet, are surprisingly close. In general, there should be a decrease in capillary head with increasing moisture content, which appears to occur. The NMSU plots tended to have a higher infiltration rate and higher capillary (suction) head. As a final comparison, information from Rawls, Brakensiek, and Miller (1983) was used. Their data indicate that the Kw values for the soils in the watershed (sandy loams and clay loams) should range between 0.08 and 0.86 inches per hour. The capillary heads should range between 4.33 and 8.22 inches. The Kw values in table 8 exceed those suggested while the Hc values are much lower. This is expected because the data used by Rawls, Brakensiek and Miller were primarily from laboratory tests, and not simulator experiments, but the laboratory test results were adjusted to other data to bring them closer to field values. Therefore, a precise match is not to be expected between the results in this study and the published tables of values.

Erosion Parameters

Erosion parameters can be divided into those related to rainfall detachment and those related to overland flow. For the smaller plots, overland flow erosion is minimal, but splash erosion is important. On the larger plots, overland flow detachment plays a larger part in the sediment production and there is a complex interaction between splash and flow detachment. No attempt was made to delineate between the two processes for the large simulator experiments. One important parameter is the splash detachment coefficient (Ward et al. 1983). This coefficient is found from

$$Yr = (SC)\ I^2 \qquad (6)$$

where Yr is the rate of erosion in tons/acre-hour (bare area),
I is rainfall intensity in inches per hour, and
(SC) is the splash coefficient.

The (SC) has units of ton-hr/Ac-sq. in. and is a derived parameter. Determination of this value permits calibration for overland flow erosion parameters in state-of-the-art mathematical models (e.g. Ward and Seiger 1985). The derived values are summarized in table 9 for suspended and bed load (sediment deposited in collection troughs) sediment yields. Note that because the yields are additive,the coefficients are also additive to find total yield coefficient. These values compare well with a compilation by Ward et al. (1983) where values (for the Southwest) ranged between about 0.10 and 0.50. Again it is obvious that WS3 produces sediment at a much higher rate than the other two sites.

The above comparisons of selected parameters (suspended and bed load splash detachment coefficients) indicate that the simulators can be used to differentiate between sites, derive parameters, and produce parameters that are comparable to other studies. The large simulator is capable of other functions in addition to constant rainfall rate experiments.

Variable Rainfall Rate and Overland Flow

Modifications were made to the large simulator equipment to produce variable intensity rainfall (VIR) and overland flow

Table 9

Means (M) and Standard Deviations (S) For Selected Sediment Yield Parameters

	SUSP. YIELD (tons/Ac.)		SUSP. COEF. *		BED YIELD (tons/Ac.)		BED COEF. *	
SITE ID	M	S	M	S	M	S	M	S
WS2-D	0.82	0.42	0.10	0.04	2.45	1.47	0.30	0.19
WS2-W	0.70	0.43	0.11	0.05	1.88	0.81	0.32	0.16
WS3-D	1.91	1.70	0.25	0.15	2.35	1.93	0.33	0.23
WS3-W	1.18	0.82	0.20	0.14	1.69	1.07	0.28	0.19
NMSU-D	0.20	0.18	0.06	0.11	0.40	0.26	0.08	0.05
NMSU-W	0.20	0.29	0.07	0.14	0.39	0.27	0.09	0.06

* - The coefficient values are derived from the yield and runoff data. The working equation is

$$Y = a I^2$$

where Y is yield rate in tons/Ac.(bare area)/runoff duration,
a is the coefficient as listed above, and
I is rainfall rate in inches per hour.

The derived units on the coefficients are tons-hr/Ac.-sq. in. (OLF). The VIR set up required that the piping system be valved with high quality, rapid open-close butterfly valves. The OLF set up required a 30 foot long - 4 inch diameter PVC pipe with 3/8 inch holes drilled on one foot centers. The pipe diffuser was connected directly to the pump with an inline flow meter. The diffuser pipe also had a piezometer tube which was calibrated in the lab over a range in flow rates.

In operation, the VIR set up could be rapidly changed (less than 10 seconds) between 1, 2, and 3 inch per hour sprinkler patterns. The OLF set up was placed at the top of the plot with the holes pointing directly up to minimize erosion. Pressure to the diffuser was regulated at the pump. These two modifications were tested on the NMSU site in May of 1984. Both performed quite well. The following sections present the results of the experiments using the VIR and OLF modification.

Runoff and Sediment Yield

The experiments were conducted in sequence as: VIR-Dry, OLF-dry, VIR-wet, and OLF-wet. Obviously after the VIR-dry experiment, everything was wet, however, there was a lapse of about five hours before the OLF-dry experiment was conducted. The VIR-wet was conducted about 90 minutes later, followed by the OLF-wet after one hour. Final clean up was done with flashlights. The VIR-dry was run in four rainfall intensity steps, 3-2-1-2 inches per hour (theoretical rates). The OLF-dry was run at a low flow rate then increased to a higher rate. The VIR-wet stepped at 3-2-1 inches per hours, and the OLF-wet also went from a low flow rate to a high flow rate. Sediment samples were taken for these experiments as they were for the constant rainfall rate experiments. The discharge-concentration-time plots are shown in figures 14, 15, 16 and 17 for the VIR-dry, OLF-dry, VIR-wet, and OLF-wet experiments. The discharge values have been smoothed using a 3-point moving average. Even after smoothing, there is still some variation inherent to the recording devices and digitizing procedures. Further smoothing is possible, but it would tend to obscure some of the timing aspects for the hydrographs. This is particularly true when examining the times at which the rainfall or overland flow rates were changed. (The vertical lines on the hydrographs in figures 14 through 17.) From the smoothed data, it would appear that the times of change do not seem to precisely match the corresponding changes in the hydrographs. These apparent time discrepencies are an artifact caused primarily by the smoothing procedure and secondarily by the inacccuracy between the differnt timing devices used in the experiments.

Water discharge. Discharge rates for the VIR experiments showed good response to changes in rainfall rate. The changes are apparent on the hydrographs, particularly on the VIR-wet graph (figure 16). The slowly rising crest limb is evident in all the hydrographs, as discussed earlier for the constant rainfall rate hydrographs. Note that the VIR and OLF hydrographs have longer durations than the constant rainfall rate hydrographs, reflecting the acquisition of a water truck between experiments. Perturbations on the hydrographs were minimal

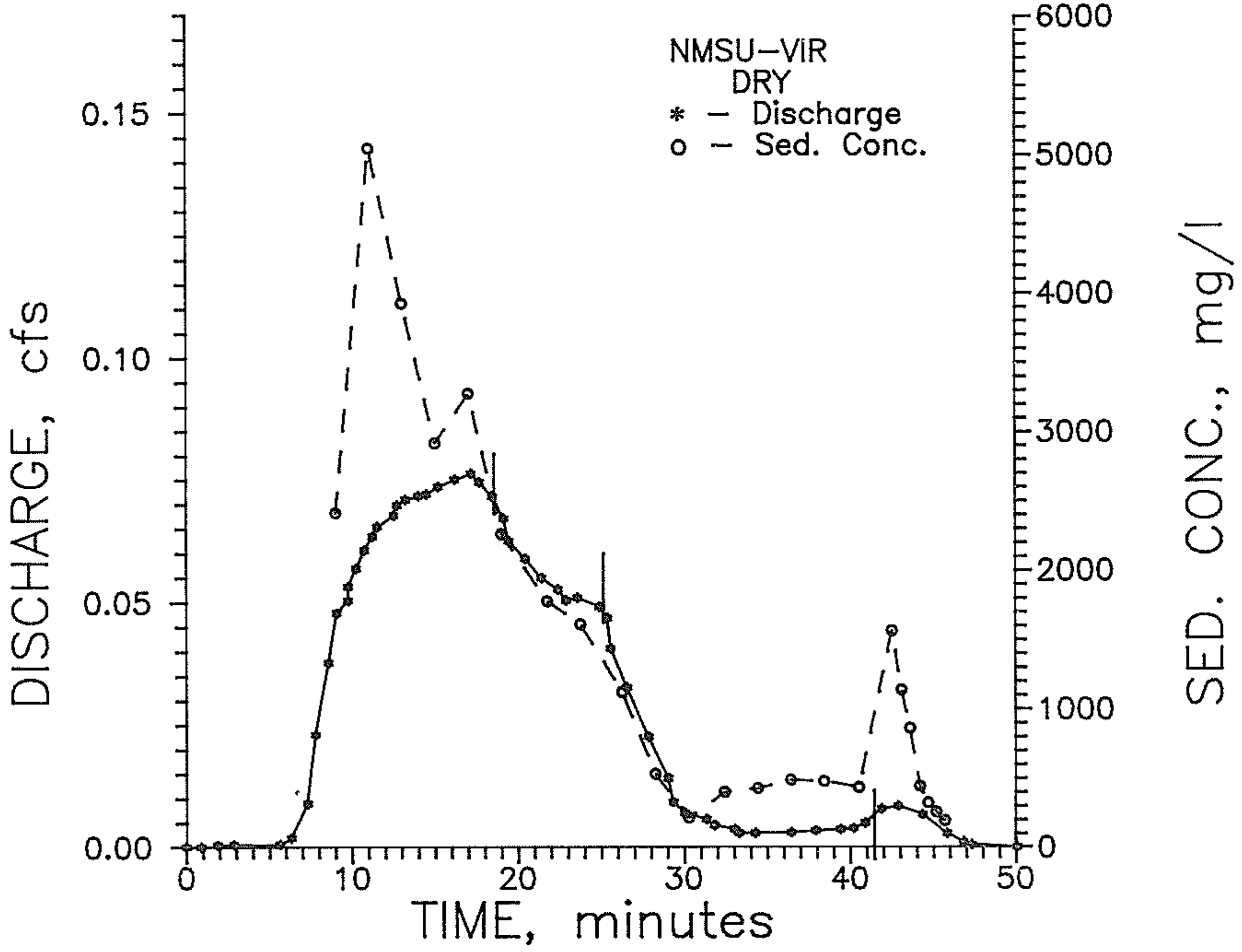


Figure 14. Discharge and sediment concentration for NMSU - Variable Intensity Rainfall (VIR) - Dry Experiment

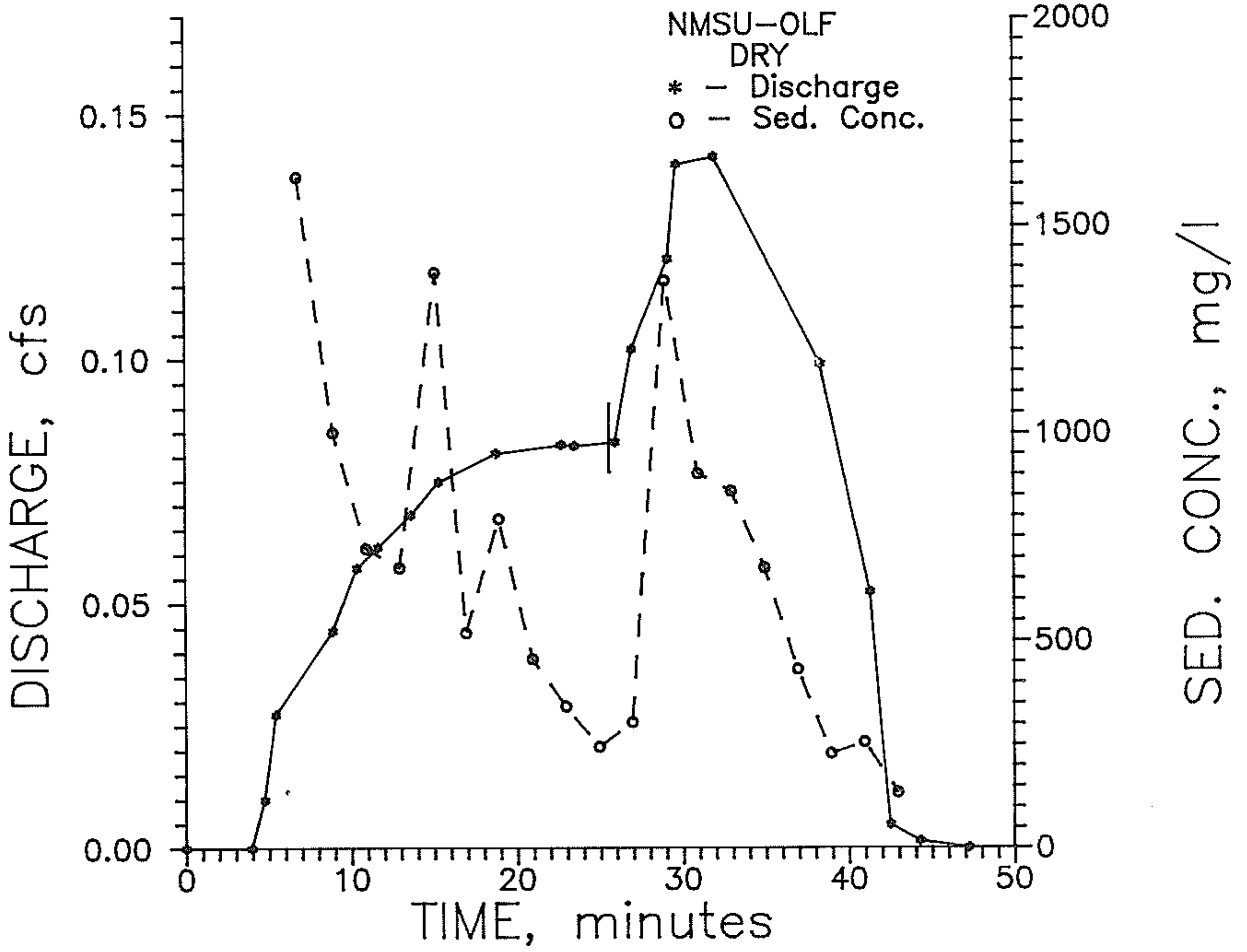


Figure 15. Discharge and sediment concentration for NMSU - Overland Flow (OLF) - Dry Experiment

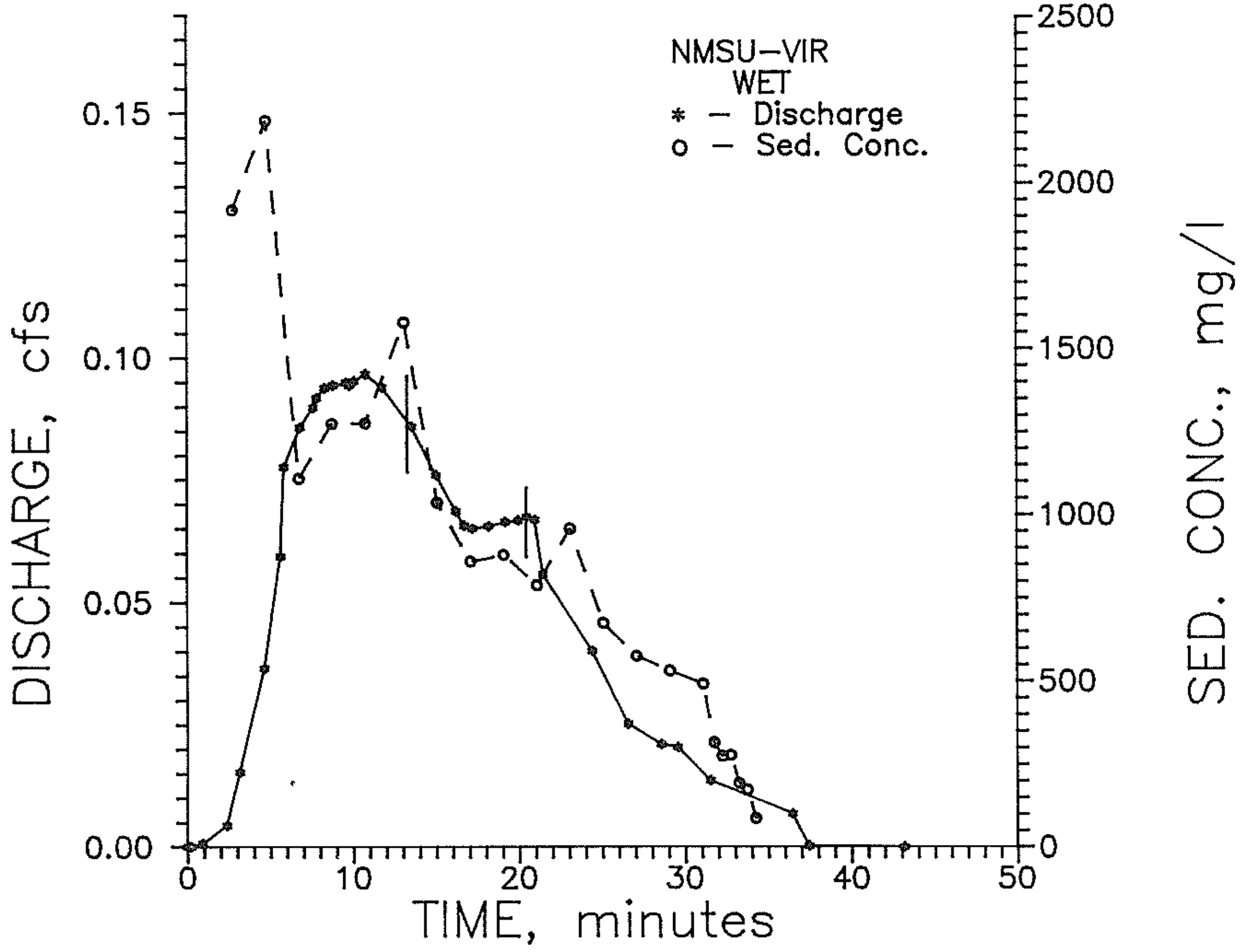


Figure 16. Discharge and sediment concentration for NMSU - Variable Intensity Rainfall (VIR) - Wet Experiment

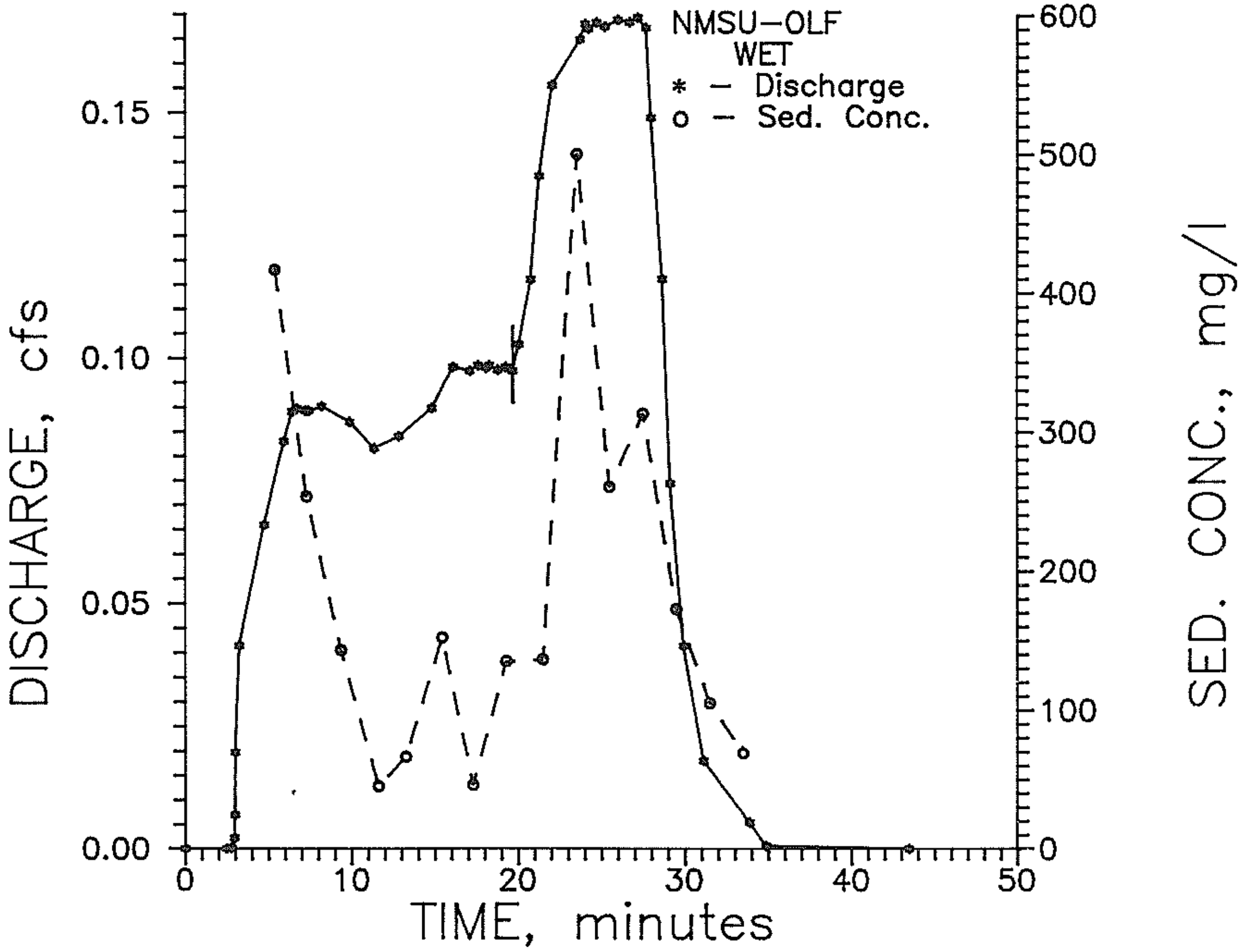


Figure 17. Discharge and sediment concentration for NMSU - Overland Flow (OLF) - Wet Experiment

thanks to a more experienced crew, only one equipment mishap (kinked hose) on the OLF-wet experiment, and cooperative weather. The hydrographs clearly reflect the input changes from the equipment.

Sediment concentrations. Sediment concentrations behaved as noted before in the constant rainfall rate experiments. There is a rise then decline in concentration for the VIR experiments. There is also an increase in the concentration on the falling limb (VIR-wet), and a big jump on VIR-dry when a 2-inch-per-hour burst is applied at the end of the experiment. Similar jumps can be seen on the OLF hydrographs when the flow rates are increased. Interestingly, the concentrations for the OLF experiments exhibit a decay during each constant rate, rather than an increase then decrease as seen in the VIR experiments.

Comparison of experiments

A distinct difference appears between the processes taking place in the VIR and OLF experiments. Summaries of the experiment results are listed in table 10. As with the constant rate rainfall experiments, the theoretical rain rates are not always achieved. However, the results are very consistent. The calculated final infiltration rates are in line with those presented in tables 6 and 7 for this site, confirming the contention that infiltration rate can consistently be measured with a rainfall simulator regardless of scale and application rate. It is also noteworthy to see that infiltration rate can be calculated from the overland flow experiments to provide

Table 10

Runoff Characteristics for the VIR and OLF Experiments

Experiment	Duration (mins)	Rain Rate (iph)	Runoff Rain Depth (inch)	Runoff Depth (RO) (inch)	Infilt Rate (iph)	Rate (iph)	RO/RF (dim)	AMC (%)
NMSU-VIR D	18.55	2.91			1.61	1.30		
	7.02	1.70			1.07	0.67		
	15.80	0.77			0.06	0.71		
	1.82	1.52			0.16	1.36*		
			1.35	0.54			0.40	4.4
NSMU-VIR W	13.25	3.00			2.04	0.96		
	7.33	1.96			1.43	0.56		
	10.50	0.96			0.44	0.52		
			1.07	0.62			0.58	10.2
NMSU-OLF D	25.58	2.39**			1.76	0.63		
	11.40	3.76			3.00	0.76		
			1.73	1.12			0.65	
NMSU-OLF W	19.67	2.68			2.09	0.59		
	7.60	4.26			3.59	0.67		
			1.42	1.05			0.74	

* Infiltration rate not accurate because runoff was not at a steady state.
** Converted from overland flow application rate of gallons per minute.

comparable results. The infiltration rates decrease with time and tend to reach a steady state.

Sediment yields are also comparable with the previous experiments. The yields are a bit higher because of the increased energy available from the rainfall and overland flow. The suggestion that raindrop splash in concert with overland flow are effective erosion agents is evidenced in table 11. The normalized yields, in the sequence of the experiments, are 0.24-0.08-0.13-0.02 tons per acre-in. This finding shows that the rainfall is an important erosion agent.

In general, the water discharge and sediment yield measurements taken during these experiments are of high quality and reflect the fact that the equipment performed as planned. The results further indicate that rainfall is an important part of the experiment, but it does not necessarily need to be of variable intensity as the results from the constant rate rainfall experiments were quite similar in most respects.

Overland Flow Rates

One purpose of the overland flow experiments (OLF) was to help determine overland flow characteristics related to hydraulic routing. The OLF hydrographs were analyzed to determine the time of concentration for the different flow rates. These "travel times" were then used in a simple equation to find a hydraulic

Table 11

Sediment Yields (suspended) from the VIR and OLF Experiments

Experiment	Total (lbs)	Yield (T/Ac.-in)
NMSU-VIR D	12.2*	0.24
NMSU-VIR W	7.2*	0.13
NMSU-OLF D	8.2	0.08
NMSU-OLF W	2.4	0.02

* Suspended load only. No deposits were left in the approach troughs to the flume.

roughness coefficient. The working equation is

$$Kr = C^{3} V^{-3} q^{2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

where Kr is an overland flow resistance,
V is average flow velocity
q is unit width discharge, and
C is a constant as determined by

$$C = (8\ (g/v)\ So)^{1/3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

where g is the acceleration of gravity,
So is the surface slope of the plot, and
v is the kinematic viscosity of water.

Equation 7 is a kinematic wave substituted into the classic Darcy-Weisbach formulation. The Kr parameter is dimensionless, and it should be a constant for a constant roughness surface.

Each OLF hydrograph was analyzed in four portions. In the first, the first discharge steady state data were used to find the travel time to a marked point on the plot. This first arrival time, with the steady discharge, should give a low resistance estimate, as the first arrival time really represents a discharge less than steady state. The second portion was a determination of time of concentration at the flume for the first discharge, with the subsequent travel velocity. The third portion was the time of concentration for the second discharge, and the fourth portion was the time of recession for the second discharge. A Kr value was computed at each portion for both hydrographs. The results are presented in table 12. Portion 1 Kr values are lower than the rest. This result reflects the fact that the assumed discharge is not precise. The portion 2 values cannot be compared between hydrographs because the resolution/timing on the OLF-dry graph yielded an unrealistically

Table 12

Flow Resistance Determined from Overland Flow Experiments

Portion of Flow*	Calculated Resistance Values, Kr for	
	OLF-Dry	OLF-Wet
1	652	271
2	**	1198
3	784	1110
4	1954	1922

* 1- Using travel time from the inflow to a point on the site.
2- Using the time of concentration from the first flow rate.
3- Using the time of concentration from the second flow rate.
4- Using the rescession time of the second flow rate.

** Time of concentration difficult to determine.

high value. The portion 3 values show a drop in Kr, which is an effect of relative roughness on the flow, while in portion 4 Kr increases as the flow decreases and the flow is attenuated by the roughness. In general, the Kr values computed from the two hydrographs, excluding the obviously erroneous measurements, are very close to one another. A value for Kr of about 1500 appears reasonable for this site. This value is in line with those presented by Woolhiser (1975), in which a range of 500-3000 was appropriate. The overland flow device appears to have a high potential for gathering data that can be used to estimate surface roughness conditions.

Summary

Fifty plot-runs using the small simulator and ten with the big simulator were conducted for this study. A tremendous amount of data was gathered and analyzed. Information was developed for rainfall rate, runoff ratre, types and percent of ground cover, size and slope of the sampled plots, soil particle size gradation, soil water content, soil porosity, sediment yield, infiltration parameters, erosion parameters, and overland flow resistance. The analyses presented here compare site characteristics, how the sites respond to simulated rainfall, how results from the two simulators compare, and demonstrate the potential of other uses for the large simulator. The data base developed in this study will provide information for further research and analyses.

CONCLUSIONS AND RECOMMENDATIONS

There were two goals and seven objectives for this study. The first goal was to collect data and use it to characterize the rainfall-runoff-erosion processes on target watersheds. Sixty plot-runs (number of plots times number of experiments on each plot) produced a large amount of data that was used to define site characteristics including slope, cover, soil type, infiltration parameters, and erosion measures. This type of information is essential for future hydrologic studies.

The second goal was to demonstrate the applicability of rainfall simulation for studying runoff processes. The volume and high quality of the data prove that simulation is a valuable, cost effective and efficient tool. However, there is a qualitative aspect that is not easily conveyed. When the simulator is operating on a large or small plot, one has the unique opportunity to watch the surface runoff and erosion processes up close, in comfort, and at will. These advantages are as important, if not more important than the numbers that are gathered. Dogmatic views on hydrology can quickly be changed by this experience.

Comparison of the large and small simulators indicated that infiltration parameters were similar, and that sediment yields on a per unit of runoff and area basis were higher for the small plots by an average of about 2.7 times. The higher yields are most likely related to the shorter distance the sediment must travel on the small plot before it is sampled.

The large simulator was modified for this study. It was tested for variable intensity rainfall and overland flow. Both modifications worked extremely well and provided data regarding the relative erosivity of overland flow and rainfall, the effects of changes in flow rate on sediment transport, and the resistance to overland flow on a natural surface.

Further improvements can be made in the equipment and field procedure. For future studies, it is recommended that:

1. A totalizing flow meter be placed in line downstream of the pump to help better quantify flow rates;
2. The clock gear rate on the weighing bucket raingage be increased up to provide better time resolution;
3. A strip of matting be placed beneath the diffuser pipe overland flow device to help prevent erosion;
4. An electronic data logger be added to the stage recorder apparatus;
5. Video taping be used to record the experiments;
6. Small plots be subjected to rainfall from the large simulator to examine scale effects under the same rainfall energy; and
7. A minimum crew of four be available for the large simulator at all times.

In conclusion, this study provided a tremendous amount of data and clearly demonstrated the utility of simulated rainfall in examining and measuring runoff and erosion processes.

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