VARIABILITY OF INFILTRATION CHARACTERISTICS AND WATER YIELD OF A SEMI ARID CATCHMENT

by

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ABSTRACT

Space-time variability in the hydrologic characteristics of four major soil series represented in the Silverbell validation site was investigated by sampling the infiltration characteristics, at randomly selected locations, under several vegetative covers within each series.

The experimental data was the time distribution of infiltration which, for each sampled location, was fitted by least squares to the Philip's infiltration equation. The parameters of this equation have physical interpretation and therefore were used as measures of the infiltration characteristics.

Analysis of variance was used to investigate the spatial variability in the parameters. The mean values of the parameters for selected soil-vegetation combinations were used to simulate runoff due to a rainfall event over a desert catchment "containing" the given combination.

Statistical tests show that there is no significant difference among the infiltration parameters of all the soil-vegetation combinations. However, the statistically insignificant variations in the parameters produce significant variations in simulated runoff volumes indicating the sensitivity of the runoff generating process to infiltration characteristics vis-a-vis the hydrologic properties of the soils.

INTRODUCTION

The high degree of water development in arid lands has created an even greater need for the efficient management of available water resources of desert catchments. In rural areas, it becomes necessary to determine, as a prelude to instituting watershed programs, the expected yield of the catchment so as to provide working estimates of within year storage and supply requirements for irrigation, watering of livestock and other uses. Unfortunately, the wide variability of rainfall and runoff volume from desert catchments and the fact that little information is available on water yield of these catchments in general makes such determinations a difficult task.

One of the major hydrologic processes determining the water yield of a semi arid catchment is the infiltration of water at the soil surface during and after a rainfall event. This is because the rate of infiltration determines the amount of water penetrating the subsurface soil and also the amount of overland flow which will form over the surface. The rate of infiltration depends on the rainfall intensity and duration, vegetation characteristics and near surface soil properties. Previous studies have shown that these biotic and soil properties vary widely under natural conditions.

The objectives are to sample the infiltration characteristics of the major soil series found in a typical Sonoran desert environment as exemplified by the Silverbell validation site near Tucson, Arizona, to investigate the variability of these characteristics under various vegetative cover and to observe the manner in which such variability affect the water yield of desert catchments.

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Previous studies. Studies pertaining to the desert ecosystem, that are germane to the present study, have been carried out at the Silverbell site and elsewhere under the auspices of the Desert Biome, U.S. International Biological program. Principal among these was the delineation of the soils at the Silverbell site into soil series as reported by Thames (1973). The resulting soil map provided a natural basis for establishing the sampling units for infiltration measurements performed in the current study. The report also contains a rather extensive description of the types, distribution and density of the vegetation found on the site. Mehuys et al. (1973) have measured hydraulic conductivity and soil water diffusivity for desert soils from the Santa Rita experimental range near Tucson, Arizona, the Silverbell site near Tucson and from the Rock Valley site in Nevada. In these studies, measurements were carried out in the laboratory over a wide range (0 to -50 bars) of water pressure using a transient outflow method.

In other studies, Lyford and Qashu (1969) used a double ring infiltrometer at the Santa Rita experimental site to evaluate the influence of two desert plants (Palo Verde and Creosote) on infiltration rates of two desert soils (Rillito gravelly-sandy loam and Continental sandy loam) at radial distances from the plant centers. They found that the final infiltration capacities near the base of the plant were, on the average, nearly three times those in the interplant areas. No significant difference in rates was found between the two vegetation types.

Kincaid, Gardner and Schreiber (1964), using an F-type infiltrometer on plots in southern Arizona, showed how certain soil and vegetation characteristics affect infiltration. They concluded that the crown spread (coverage) of shrubs was the most important vegetative parameter affecting infiltration for a catchment.

Sampled soil series. A detailed description of the soils within the Silverbell site has been documented by Thames (1973). A common characteristic of these soil series is that they are gravelly-sandy loams with moderately coarse to very coarse textured surfaces. For example, about 70% of the surface of the Rillito gravelly-sandy loam is covered by gravel.

The soil series sampled are shown in Table 1, which also contains the abbreviations used to designate these soils in this paper as well as those used by Thames.

Table 1: Sampled Soil Series

Soil Series	Representation	
	This report	Thames
Anthony-Tres Hermanos Complex	ANTTHC	A-TH
Rillito Gravelly Sandy Loam	RILGSL	R
Tres Hermanos Gravelly Sandy Loam	TRHGSL	TH1/TH2
Tubac Gravelly Sandy Loam	TUBGSL	Tu1/Tu2

METHODS

Sampling plan. A variety of sampling plans exist by which infiltration run locations may be selected. In choosing a plan for this study, we were guided by the prevailing experimental conditions within the project area. The soils of and the vegetation on the site are heterogeneous. This heterogenity motivated our adoption of a stratified sampling plan. Stratification was based on the four soil series identified in Table 1. Thus, each series corresponded to a sampling unit. The sampled variables are the soil sorptivity and the final infiltration capacity, as appear in the infiltration equation presented by Philips (1969).

Burr Sage (Franseria deltoida) is the most abundant plant species on the Silverbell site with an average density of about 6000 plants/ha. It is followed by the Creosote (Larrea divaricata) plant which has a density of about 190 plants/ha. However, in terms of plant cover,

which Kincaid et al. (1964) have described as the most important vegetative characteristic affecting infiltration, the Creosote covers almost twice as much area as does the Burr Sage bush. Estimates given by Thames (1973) show that 87% of the total area has no vegetative cover, about 4.6% is under creosote and about 2.6% is under Burr Sage. Given that infiltration measurements are to be made within each unit at randomly selected locations, the sampling urn should contain ballots with markings of no-cover, Creosote and Burr Sage in a proportion of 33:2:1. Sampling was not done as described above since it is most probable that not enough Creosote and Burr Sage marked ballots would be sampled to make comparisons among the three covers.

The approach followed was to sample from urns each of which contained ballots of the same type (i.e., vegetative cover). On each ballot was marked a number corresponding to a potential sampling location. Sampling from each urn was done at random and without replacement. The sample size was determined more by manpower and time limitations than by any sampling theoretic methods. Nevertheless, we consider the above procedure to be practical in the sense that it was possible to carry through according to specifications. A precision level, ρ, of 30% of the mean of the sampled variables was considered sufficient, considering the field conditions.

In order to be consistent and to compensate for the selected manner in which the sample size was arrived at, significant levels, α, were computed from ρ, the sample mean, y, the standard deviation, s, and the sample size, n, for each soil-vegetation combination sampled using equation 1 below.

$$T_\alpha = (\rho y\sqrt{n})/s \qquad \text{and} \qquad \alpha = 2(1 - P_\alpha) \qquad [1]$$

where T_α is statistic for the student-T distribution and P_α is the corresponding probability that the sampled variable will lie within ρ of the mean. The values of α obtained (given in Table 2) were used as guidelines for selecting a level of significance for subsequent statistical tests.

Collection of data. A rainfall simulator of the sprinkler-type was used to apply a steady rate (0.4 cm/min) of artificial rainfall over a 1000 cm^2 delimiter placed over each sampling location. The rainfall was applied through a grid of 0.1 cm diameter nozzles covering a total area of 45 x 45 cm. Nozzle spacing was 2 cm. The uniformity of the application depth over the area was determined by placing 5 collection cans under the simulator and was expressed in terms of Christiansen's uniformity coefficient, C_u defined below:

$$C_u = [1 - \{\sum_{i=1}^{5} |X_i - \bar{X}|\}/\bar{X}] \qquad [2]$$

where X_i is the depth observed in the i^{th} collection can, $\bar{X}$ is the mean depth of water for all cans. C_u was computed for the first run and at random intervals; the nozzles of the simulator being flushed after each determination. C_u varied between 89% and 95% for all determinations, which was considered acceptable.

It was originally planned that the rainfall simulator should stand at a height of 3.05 meters above the soil surface. At this height, however, the simulator was unstable due to wind effects. The simulator was placed at 1.53 meters above the surface for all runs. The 1.53 meter height was obtained by trial and error as the height at which the wind effects were not significant.

Uninfiltrated water was pumped out from within the delimiter into a container sitting on a transducer (strain gage) weighing balance. The pump was a variable discharge pump. The strain gage was connected to an automatic chart recorder through a voltmeter. The voltage from the gage varied between 0 and 1.5 mv. and was amplified to between 0 and 10 mv. to give a sensitivity of 0.03 liter.

The difference between the cumulative application and the corresponding pumpage is the cumulative infiltration up to that time which was the experimental data collected at each sampled location. Duration of test runs varied between 20 and 55 minutes with an average of

Table 2: Infiltration Characteristics at Sampled Locations

Soil Series \ Cover	No Cover		Creosote		Burr Sage	
	A	B	A	B	A	B
ANTTHL	.90	.14	1.13	.07	1.28	.10
	.99	.08	1.84	.08	.88	.06
	1.28	.08	1.14	.15	1.08	.11
	.96	.08	1.51	.07	1.44	.08
	1.01	.08	.66	.15		
	1.22	.08	.81	.14		
	1.01	.11	1.05	.06		
	1.22	.06	1.13	.02		
Mean	1.07	.09	1.20	.09	1.17	.09
Standard Deviation	.14	.03	.37	.05	.24	.02
Level of Significance	**	**	**	.10	**	**
RILGSL	1.15	.09	1.36	.05	1.19	.09
	.68	.15	1.24	.05	1.02	.04
	.73	.06	.66	.11	1.05	.09
	1.35	.11	1.17	.13	1.41	.08
	.92	.07	1.74	.04	1.45	.01
	.90	.15	1.72	.05	1.20	.06
	1.04	.02				
	1.56	.01				
	1.12	.03				
Mean	1.05	.08	1.32	.07	1.22	.06
Standard Deviation	.28	.05	.40	.04	.18	.03
Level of Significance	**	.20	**	.24	**	.24
TRHGSL	.60	.09	1.21	.10	1.17	.09
	.99	.27	.70	.17	.97	.08
	.42	.15	1.31	.02	.89	.02
	1.18	.06	.42	.13	1.13	.03
	1.05	.06	.81	.11		
	1.26	.04				
	1.40	.01				
Mean	.99	.10	.89	.11	1.04	.06
Standard Deviation	.36	.08	.37	.06	.13	.04
Level of Significance	**	.38	.10	.20	**	.34
TUBGSL	1.37	--	1.48	.06	1.46	.07
	.43	.04	.97	.03	1.43	.12
	.26	.01	1.37	.03	.91	.13
	1.18	.07	.63	.12	1.19	.04
	1.19	.05	.97	.10	1.18	--
	.45	.06	.92	.10		
			1.06	.11		
Mean	.81	.05	1.06	.08	1.23	.09
Standard Deviation	.48	.02	.29	.04	.22	.04
Level of Significance	.22	.10	**	.10	**	.10

** Significance level α, less than 0.02.

35 minutes. A run was terminated when the infiltration rate appeared to reach a constant value which may be observed from when the cumulative infiltration curve became approximately linear.

Collation of data. The experimental data as obtained from the continuous recording chart was extracted, in 15 second intervals, for the purposes of analysis. Data edition was made to correct for reading errors or instrument malfunction and to delete erroneous data.

The time distribution of infiltration obtained for each sampling location was fitted, by least squares, to the Philip infiltration equation:

$$F = At^{0.5} + Bt \qquad [3]$$

where F = cumulative infiltration in centimeters, t is time in minutes, A is soil sorptivity and B is the final infiltration capacity of the soil. The values of B from the least squares fit were, in some cases, unrealistic (negative) even though the experimental data showed a positive constant slope at later times in a run. In these cases, which were relatively few, the value of B determined from the plotted curve was used. In most cases, however, the values of B from the curves and that obtained by least squares fit were within 10%. Table 2 shows the values of the parameters as obtained for each sampled location. The mean values and the corresponding standard deviation are also shown for each cell (soil-vegetation combination) as well as the α-values.

RESULTS AND DISCUSSION

Analysis of variance. The analysis of variance technique was used to determine if the different soil-vegetation combinations have significantly different infiltration characteristics. In the process a two-way analysis of variance was performed on the response variables, soil sorptivity (A) and final infiltration capacity (B). The two factors were the vegetative cover (3 types) and the soil series (4 of them). The sample size of the soil-vegetation combinations (cells) were not necessarily equal. It was assumed that both the vegetative covers and the soil series had random effects sampled from infinite populations whose variances were not necessarily equal. The sources of variance were identified as the cover, C, the soil type, S, and the interaction between these two, CS. Since it was not assumed that the individual cell contents were drawn from populations with the same variance, Fisher's approximation was used to compute the degree of freedom, f, for each cell pair.

Based on the α-values obtained and given in Table 2, a significance level of 10% was used for tests involving the soil sorptivity, A, and 20% for tests involving the soil final infiltration capacity, B. Tests of significance were performed using the empirical F-statistics (variance ratios) given in the last column of Table 3 for both sources of variance C and S. For response variable, A, the theoretical F-statistics are 3.46 for C and 3.29 for S while the corresponding empirical values as given in Table 3 are 3.01 and 2.52, respectively. For B, the theoretical F-statistics are 2.10 for C and 2.10 for S while the empirical values are 0.54 and 0.80.

These results show that the gross effect of the different soil series and vegetative covers on the infiltration characteristics of the soil-vegetation combinations sampled are not significantly different. Also when considered pairwise and using the same α-levels as before, no pairs showed any statistically significant difference in soil sorptivity while only 3 of the 30 pairs showed such difference in final infiltration capacity.

Average infiltration characteristics. The mean values of the parameters shown in Table 2 were inserted into the Philips equation to generate infiltration rate curves for each cell. Selected curves are shown in Figures 1 and 2 to illustrate the spatial variability of the infiltration rate functions. Figure 1 shows the effect of the different vegetative cover on the infiltration characteristics while Figure 2 shows the effect of different soil series.

A visual inspection of the curves in Figure 1 would indicate some variations, albeit non-statistically significant. One may observe that Tubac gravelly-sandy loam (TUBGSL) shows a greater variability in the infiltration function due to vegetative cover, than the Anthony Tres

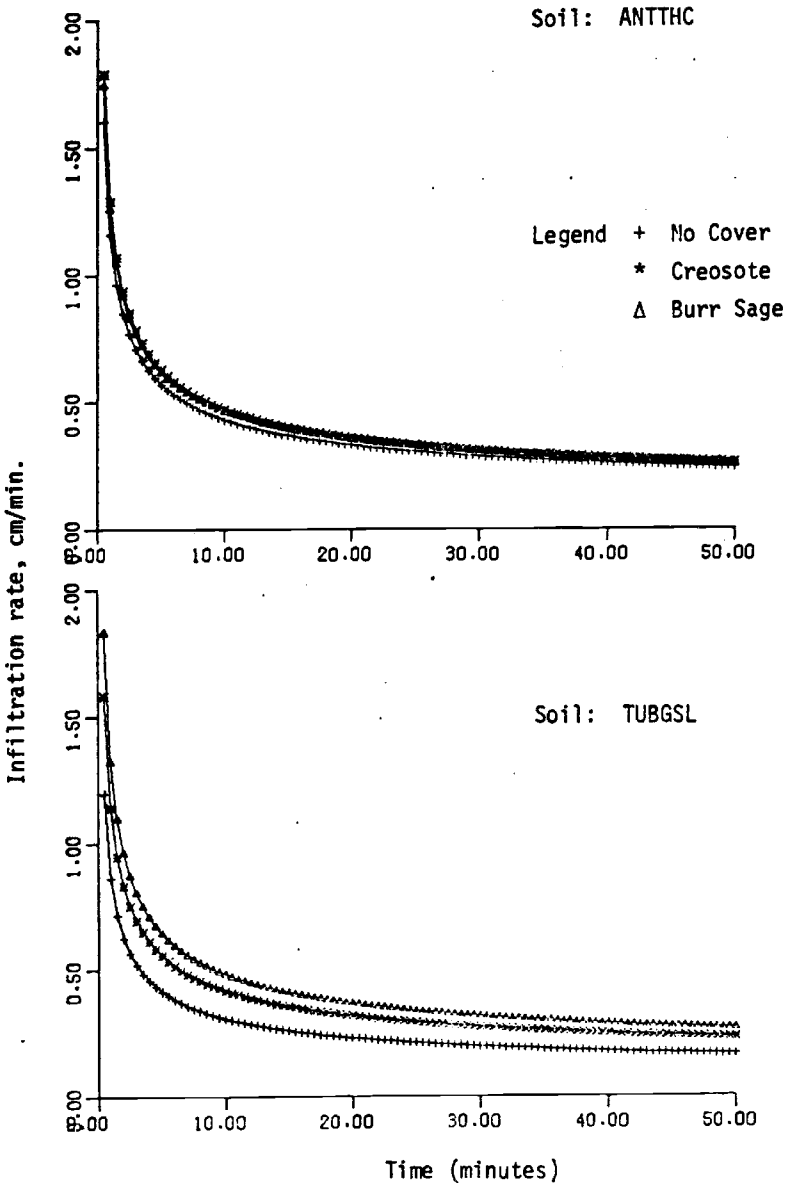

Figure 1. Effect of vegetative cover on the infiltration characteristics of two soils.

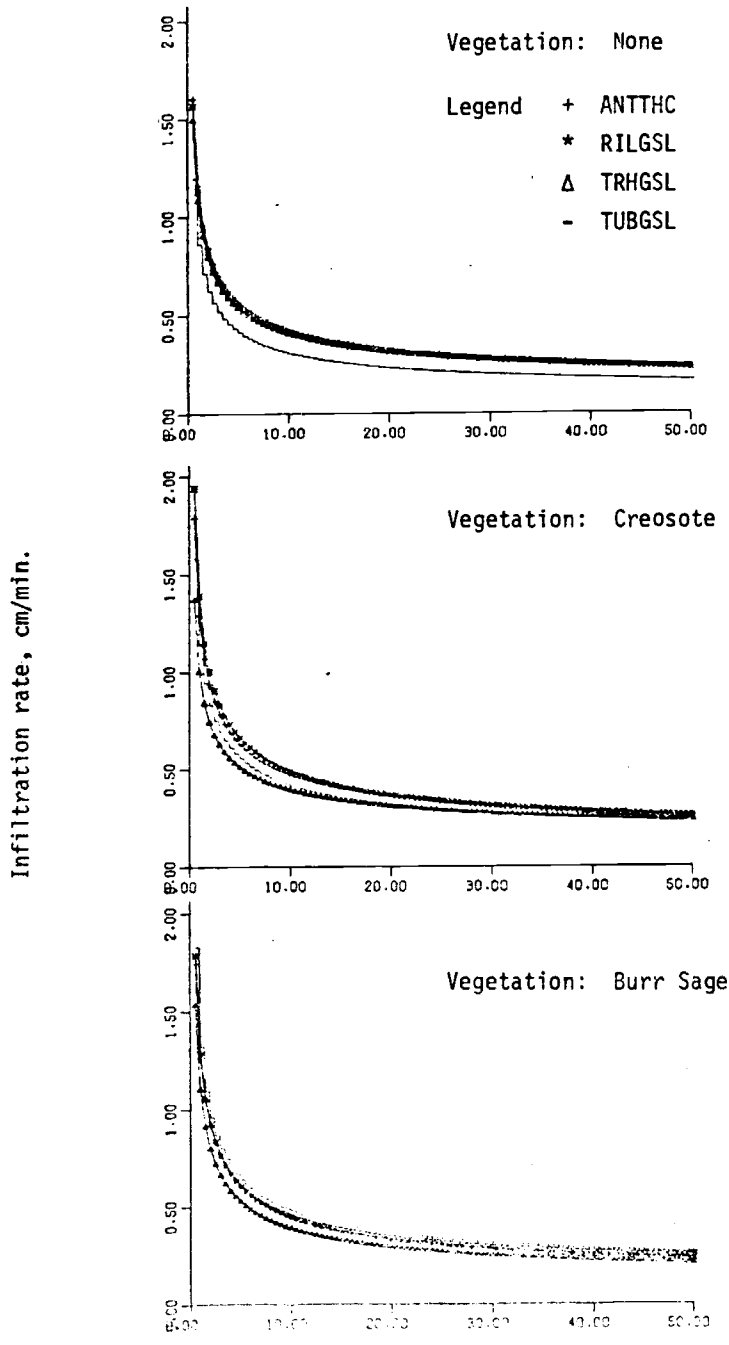

Figure 2. Effect of soil types on the infiltration characteristics under various cover.

Hermanos complex. On the same token, by comparing the curves in Figure 2, it appears that the variability is least in the different soils under no cover and greatest under the Burr Sage bush.

Table 3: Analysis of Variance for Soil-Vegetation Combinations

Response Variable	Source of Variance	Degree of Freedom	Mean Squares	Grand Mean	Variance Ratio
SOIL SORPTIVITY (A)	C	2	0.0357		3.01
	S	3	0.0298		2.52
	CS	6	0.0118		
	Total	11	0.0210	1.08	
FINAL INFILTRATION CAPACITY (B)	C	2	0.000199		0.54
	S	3	0.000295		0.80
	CS	6	0.000371		
	Total	11	0.000320	0.08	

Runoff simulation. In order to obtain a feel of the potential water yield of small catchments under natural desert conditions, the average values of the parameters in Table 2 were used to simulate runoff from a catchment 'containing' selected soil-vegetation combinations. The runoff simulation used was developed by Nnaji et al. (1974). The model simulates runoff on an event basis and has features that reflect the special hydrologic characteristics exhibited by semi arid environments.

The soil parameter values used in the simulation are given in Table 4. They represent, as an example, the mean values for no cover sampled locations only. The vegetation parameters used are shown in Table 5. Other parameters were estimated and kept constant for all runs.

The University of Arizona maintains a number of rainfall gages and a flume measuring runoff from a small catchment located within the Silverbell site. However, available data are poor and a topographical map of this catchment was not available. Under this condition, the Atterbury subwatershed (W2), an 0.47 square mile catchment located about 20 miles southeast of Tucson, Arizona was used for the purposes of providing a catchment boundary and topography only. All parameter estimates were obtained from data available from the Silverbell site.

The rainfall used was the storm of July 22, 1964, occurring over the Atterbury subwatershed as recorded in gage R-32 maintained by the Arizona Water Resources Research Center at the University of Arizona, Tucson.

The effect of the soil series on simulated hydrographs appears to be significant as can be seen from Figure 3. The runoff volume due to Tubac gravelly-sandy loam was 3.6 times and 8 times as large as those due to the Rillito gravelly-sandy loam and the Tres Hermanos gravelly-sandy loam, respectively. The hydrographs of Figure 3 were obtained for no vegetative cover.

CONCLUSION

The sampled variables (A and B) are highly dependent on the near surface properties (e.g., soil texture) of the soil. We have noted that the soil texture of all the soils sampled are gravelly loam, varying only in their degree of coarseness. The observation that there is no significant difference among the infiltration characteristics of the different soil-vegetation combinations is, therefore, attributed to the masking effect that the soil texture has on the

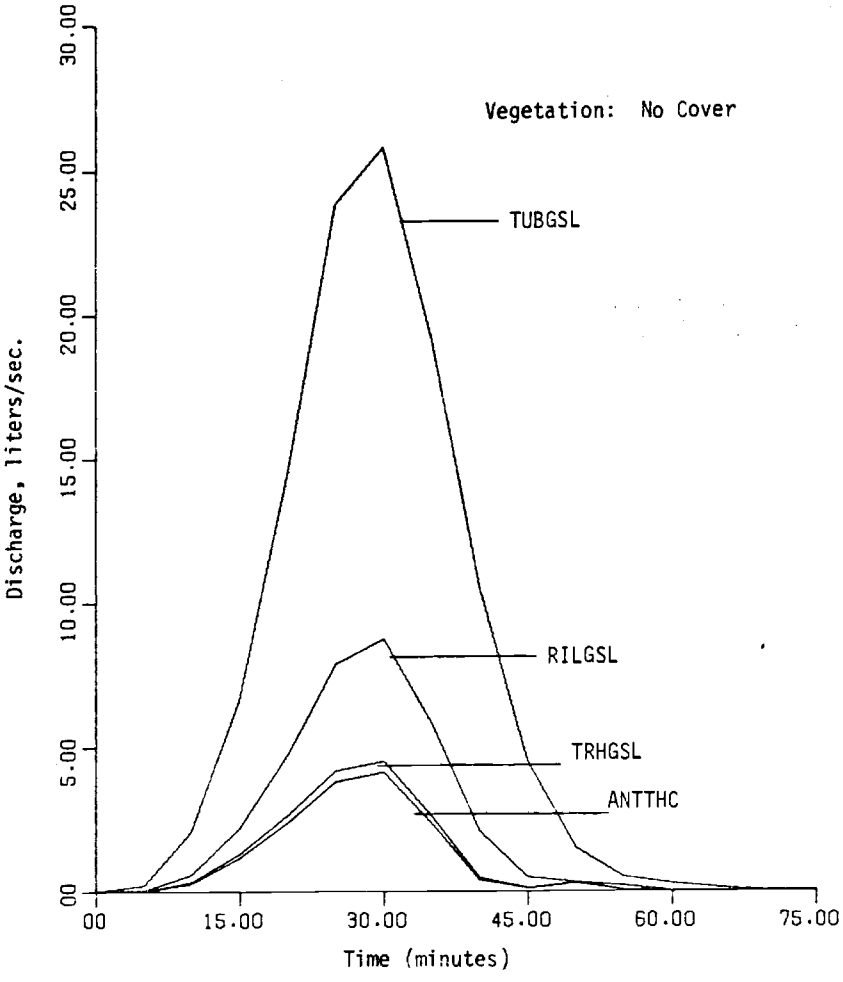

Figure 3. Soil series effect on simulated runoff.

other near surface properties. Further, our observation has the implication that a greater degree of parameter lumping might be permissible in the mathematical modeling of catchment behavior under natural desert conditions.

While statistical tests show that there is no significant difference among the infiltration characteristics of the different soil-vegetation combinations, the parameters from individual combinations tend to produce runoff volumes which vary signficantly. There was little variation in the duration of runoff from individual simulations. This indicates that the extent of opportunity time for natural recharge, during flow through the ephemeral stream channels, is about the same.

Table 4: Soil Parameter Values Used in Simulation

Soil	Parameter*		
	A	B	** Soil Moisture cm/cm
ANTTHL	1.07	0.09	0.18
RILGSL	1.05	0.08	0.14
TRHGSL	0.99	0.09	0.20
TUBGSL	0.81	0.05	0.14

* Mean values for no cover sampled locations only.
** Soil moisture near saturation, used as porosity.

Table 5: Vegetation Parameter Values Used in Simulation

Vegetative Cover	Parameter*		
	Coverage (m^2/ha)	Interception Capacity (cm)	Throughfall (fraction)
NO COVER	0.00	0.0	1.0
CREOSOTE	462	0.5	0.67
BURR SAGE	261	1.8	0.23

* Coverage data after Thames (1973).
* Interception and Throughfall estimated from two rainfall events over Silverbell (Evans and Sammis, 1975).

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NOTE

Information about the International Biological Program reports may be obtained from the Director, Ecology Center, Utah State University, Logan, Utah.