Reprinted from *Journal of Range Management*
Vol. 41, No. 3, May 1988

Factors influencing infiltrability of semiarid mountain slopes

BRADFORD P. WILCOX, M. KARL WOOD, AND JOHN M. TROMBLE

Abstract

The objective of this research was to determine the effects of selected vegetation, soil, rock, and slope variables on infiltration of semiarid rangelands with slope gradients ranging from 0–70%. Analyses were made on 2 sets of data collected a year apart in the Guadalupe Mountains of New Mexico and consisted of Pearson and partial correlation analysis of the dependent infiltration variables and independent site variables. In addition, infiltration was regressed against uncorrelated factors produced by factor analysis. Vegetal cover and biomass strongly influenced infiltration. The relative importance of grasses, shrubs or litter was dependent on their respective abundance, especially grass. Soil depth also limited infiltration especially as soil water storage became satisfied. Infiltrability was negatively correlated with rock cover and the smallest rock size fragments were the most negatively related. When the effects of vegetal cover and slope were removed (using partial correlation analysis) however, the median sized rock fragments (26–150 mm) were positively related to infiltrability, and the smallest rock fragements (2–12 mm) were negatively related. Partial correlation analysis also suggested a positive correlation between infiltrability and slope gradient.

Key Words: soil water, infiltration, rangeland hydrology

An understanding of basic hydrologic processes on rangeland is critical for effective range watershed management. The infiltration process fundamentally influences rangeland hydrology; thus, knowledge of factors that influence infiltration is important. Many studies have assessed the influence of soil and vegetation factors on rangeland infiltration. Few, however, have evaluated semiarid rangelands and none to our knowledge have included very steep slopes in their study. Results of these studies have been variable depending on the characteristics of the study area (Branson et al. 1981).

Hillel (1971, 1982) has pointed out the shortcomings of the term "infiltration capacity" and has proposed the term "infiltrability" in its place to "designate the infiltration flux resulting when water at atmospheric pressure is made freely available at the soil surface" (Hillel 1982 p. 212). We concur that "infiltrability" is a more appropriate term and have used it throughout this article.

Smith and Leopold (1941) concluded that vegetal cover and initial soil moisture had the greatest influence on infiltrability in the Pecos River watershed in New Mexico. The importance of vegetal cover has been shown by many others (Woodward 1943, Dyksterhuis and Schmutz 1947, Duley and Domingo 1949, Rauzi 1960, Johnson 1962). In western Colorado infiltrability was more highly correlated with bare soil than it was with plant cover (Branson and Owen 1970). Blackburn (1975) reported that soil morphological characteristics (organic matter, clay content) had the greatest influence on infiltrability in Nevada. Tromble et al. (1974) evaluated infiltrability on 3 range sites in Arizona and found vegetal cover and litter biomass to be most positively related, whereas gravel cover was negatively related. Meeuwig (1970) and Dortignac and Love (1961) also found litter cover to be important. In the Rolling Plains of Texas, infiltrability was most strongly correlated with aggregate stability (Wood and Blackburn 1981). Generally, as the size of the bare ground area increases, influence of plant cover decreases (Wright et al. 1982). Soil macroporosity can also have a tremendous influence on infiltrability (Beven and Germann 1982). A complete review of the influence of soil and vegetation factors to rangeland infiltration is given by Branson et al. (1981).

The influence of slope on infiltrability has received less attention. Agronomic studies have shown little relationship between slope and infiltrability, especially on slope gradients greater than 4% (Duley and Hays 1932, Neal 1938, Duley and Kelley 1939). Slope gradients in these studies did not exceed 20%. Few rangeland studies have addressed the influence of slope gradient on infiltration. Meeuwig (1970) found little correlation between slope gradient and infiltrability of Utah rangelands. The range of slope gradients included in his study was not reported. Mean slope gradient was 20%. In northern Utah, runoff from sagebrush-grass covered plots (22.1 × 1.8 m) was the same for 10 and 32% gradients

---

Authors are assistant professor, Department of Earth Resources, Colorado State University, Fort Collins 80523; associate professor, Department of Animal and Range Sciences, New Mexico State University, Las Cruces, New Mexico 88003; range hydrologist, USDA/ARS Jornada Experiment Station, New Mexico State University, Las Cruces 88003.

This is journal article 1264 of the Agricultural Experiment Station, New Mexico State University, Las Cruces 88003.
Manuscript accepted 5 January 1988.

(Hart 1984). Assuming comparable evaporation losses, infiltrability on both slope gradients should have been the same as well. Others have found infiltrability to be positively related to slope angle (Wilcock and Essery 1984, McCord 1985).

The objectives of this study were two fold. One was to determine the effects of selected site variables on infiltrability of semiarid slopes with slope gradients ranging from 0–70%. This study is unique in that steep slope gradients have been sampled as well as the more gentle ones. The second objective was to determine when in the infiltration process each variable was most important. In other words, does the correlation between infiltrability and the respective variable increase, decrease, or stay the same with time?

Study Area

The study was conducted in the northern Guadalupe Mountains of southeastern New Mexico. The Guadalupe Mountains are a dissected plateau of moderate to high relief (King 1948, Hayes 1964). The plateau runs northwestwardly, and is about 64 km long and 5 to 19 km wide. Plateau width increases towards the south. The western edge is defined by a great fault scarp known as the Guadalupe Rim. Field work was conducted on and adjacent to the Guadalupe Rim. Elevation of the study area ranges from about 1,200 to 2,000 m. The climate is semiarid and is characterized by relatively mild winters and warm temperatures throughout the year. Average annual precipitation is about 50 cm per year. Approximately 80% of the precipitation comes from May to October (Gehlbach 1967).

Most soils in the study area developed from limestone or dolomite residuum and are shallow. Underlying bedrock begins at depths of 10 to 50 cm. Textures are gravelly loams and gravelly clay loams. Soils are classified as loamy-skeletal, carbonatic, mesic Lithic Calciustolls (Deama series) or clayey, mixed mesic Lithic Argiustolls (Encierro series). Deeper soils occur on alluvial valleys and fans. They are classified as Aridic Haplustalfs (Montecito series). Soils are well drained with moderate permeability (USDA 1981). Rock outcrops are common on steep slopes.

Succulent desert and evergreen woodland formations are present in the study area (Gehlbach 1967). Common shrub and tree species are one-seed juniper (*Juniperus monosperma* [Engelm.] Sarg.), three-leaf sumac (*Rhus aromatica* Ait. var. *flabelliformis* Shinners), mountain mahogany (*Cercocarpus montanus* Raf.), skeleton-leaf goldeneye (*Viguiera stenoloba* Blake), and wavy-leaf oak (*Quercus undulata* Torr.). Smooth-leaf sotol (*Dasylirion leiophyllum* Engelm.), lechuguilla agave (*Agave lechugilla* Torr.), and walkingstick cholla (*Opuntia imbricata* [Haworth] DC.) are common succulents. Major grasses are blue grama *(Bouteloua gracilis)*, sideoats grama (*Bouteloua curtipendula* [Michx.] Torrey), slim tridens (*Tridens muticus* [Torr.] Nash), curlyleaf muhly (*Muhlenbergia setifolia* Vasey), needle and thread (*Stipa comata* Trin. and Rupr.), and cliff muhly (*Muhlenbergia polycaulis* Schrilon). The area is seasonally grazed by sheep and cattle at moderate stocking levels (up to 2 ha per animal unit). Mule deer are also abundant in the area.

Methods

A hand-portable rainfall simulator (Wilcox et al. 1986) was used to apply rainfall to flexible plots about 1 m^2 in size. The rainfall simulator employed a single stationary nozzle that was placed 2.0 m above the plot. Rainfall application rate was 10.3 cm hr^{-1}. Drops varied from 0.8 to 2.0 mm in size. Median drop size was 1.2 mm. Plots constructed from sheet metal strips 10 cm wide and 355 cm long were lightly tamped into the soil. The lower inside borders were sealed with soil to prevent leakage. The soil seal was covered with a mulch layer to protect it from raindrop impact and subsequent soil particle detachment. Plot area was measured at each location using a grid construction from 1.27 cm wire mesh.

Water was applied twice at each plot location. Application times were separated by about 16–24 h. Water was applied for 45 minutes during the first application (dry run) and 35 minutes during the second (wet run). These times were selected to attain steady state infiltrability. Dry and wet runs were included in the analysis to increase the range in soil moisture conditions and to approximate field capacity conditions as well as dry or antecedent conditions. Immediately after the dry run the plot was covered with a plastic sheet to prevent evaporation loss.

Infiltrability was considered to be application rate minus runoff rate from the plot. Other components of the water budget (surface water storage, interception storage, evaporation) were not accounted for in determining infiltration since they represented minor losses to the system and would have been difficult to determine for each plot. Runoff was determined at 5-min intervals.

Data were collected for 2 consecutive field seasons (June–August). In year 1 (1983) infiltrability was determined at 72 locations on the face of the Guadalupe Rim. Plot slope gradients varied from 16–70%. In year 2 (1984) infiltrability was determined on 80 plots of which 34 were located on lower slope gradients (<10%) above the Guadalupe Rim and 46 were located on steep slopes of the Guadalupe Rim. Soils on and above the Guadalupe Rim were similar to one another (shallow, silty clay loams) with the exception of the deep soils on the alluvial valley bottoms (Montecito series). Six plots were located on alluvial soils in year 2 but not year 1. A productive grass community dominated by *Stipa comata* and *Bouteloua gracilis* was sampled (16 plots) in year 1 but not year 2. Plant communities sampled appear in Table 1.

Standing biomass (g m^{-2}) was determined for shrubs, grasses, and forbs by clipping to a 1.5 cm height. Plant litter was also collected. All plant material was dried for 48 h at 60–70° C before weighing.

Aerial and basal cover were estimated by species using a point sampling method (Pieper 1978). One-hundred points were read per plot for both aerial and basal cover estimates using a 100 cm wide 20-pin point frame. Aerial cover was estimated before the plot was clipped, and basal cover was estimated afterward. Bare ground and rock cover was also noted. Rocky were recorded by size classes (2-12, 13-25, 26-75, 76-150, >150 mm) in year 2. Rock cover was estimated before the vegetation was removed by clipping.

Antecedent soil moisture was estimated for the surface 5 cm by the gravimetric method. Samples were collected adjacent to the runoff plot before the first rain application. Soils were assumed to be at or near field capacity before the wet run. After the wet run, soil samples were taken within the plot at a depth of 0–5 cm for particle size and organic carbon analysis. Particle size distribution

Table 1. Steady state infiltrability and associated standard deviations of the plant communities sampled.

		Infiltrability (cm/hr)			
		Year 1		Year 2	
Vegetation types labelled by dominant Species	Slope	Dry	Wet	Dry	Wet
Muhlenbergia setifolia-Bouteloua curtipendula	Steep	6.9 (2.1)	4.1 (2.0)	7.4 (1.9)	5.5 (2.2)
Muhlenbergia palycaulis-Quercus undulata	Steep	9.1 (1.0)	7.6 (1.8)	6.8 (2.4)	5.7 (2.8)
Bouteloua gracilis-Juniperous monosperma	Low			6.3 (2.7)	4.3 (2.5)
Muhlenbergia richardsonis-Opuntia imbricata	Low			9.4 (0.8)	7.3 (2.1)
Stipa comata-Bouteloua gracilis	Steep	9.1 (1.2)	7.6 (2.7)		

was estimated using the hydrometer method (Bouyoucos 1962). Organic carbon percentage was determined by the Walkly-Black method (Allison 1965). Surface bulk density was determined for each plot by the core method (Blake 1965). In some cases, soil was too rocky within the plot, so samples were taken adjacent to the plots where the core sample could be tamped into the soil. Depth to bedrock was determined 3 times in each plot by probing with an iron bar. Slope gradient was determined in each plot as the maximum difference in elevation of a given length (0.9 m) divided by that length.

Pearson and partial correlation coefficients were computed between independent variables (soil, vegetation, rock slope) and the dependent infiltration variables (infiltrability at 5-minute increments). Partial correlation analysis was employed to reduce multicollinearity among the independent variables. This analysis allows the linear effect of one or more variables to be removed when examining the relationship between another pair of variables (Thorndike 1976).

Factor analysis was also used to reduce or account for multicollinearity. Principal component analysis (PCA) with a Varimax rotation extracted new uncorrelated factors from the independent variables. These factors were then regressed against the dependent variables (Afifi and Clark 1984). Analyses were performed separately on the 2 sets of data. Principal component analysis can be used to effectively overcome multicollinearity of the data by transforming the original independent variables into new uncorrelated variables or principal components (Afifi and Clark 1984). As many factors are produced as the number of original variables but the new factors are arranged in order of decreasing variance. Thus, most of the variance of the original data is accounted for by fewer variables. Interpretability of the principal components is often difficult and can be simplified by using a rotation technique. The most accepted method and the one used here is the Varimax rotation (Thorndike 1976). The new factors are easier to interpret than the principal components and are still uncorrelated with one another.

Results and Discussion

Correlation Analysis

Vegetation

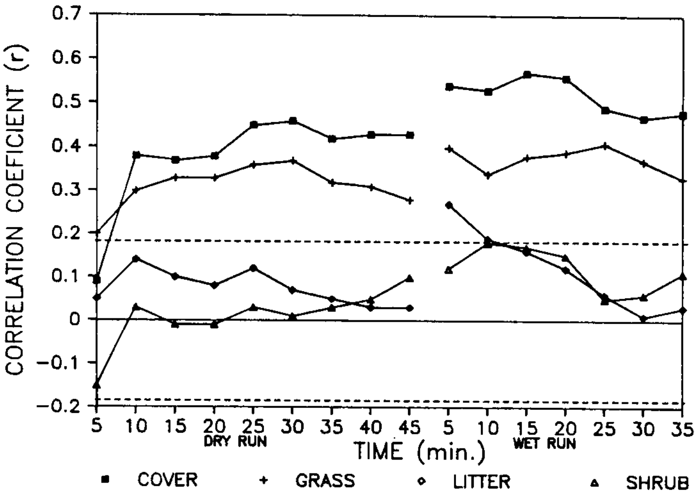

Fig. 1. *Year 1 correlations between vegetal cover and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

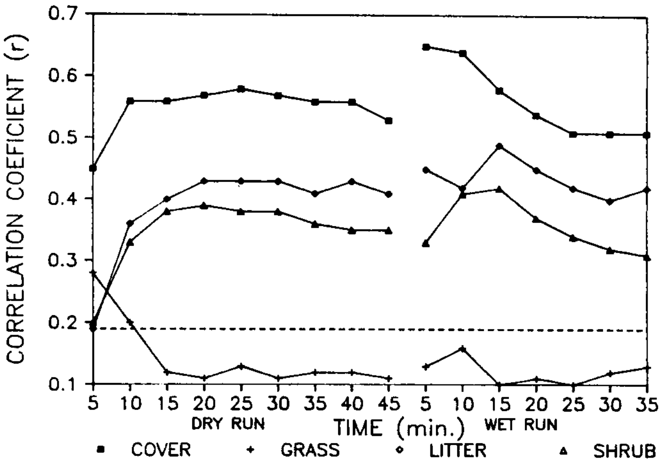

Fig. 2. *Year 2 correlations between vegetal cover and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value the which correlations are significant (p≤0.05).*

Both years of data indicate a strong relationship between infiltrability and total vegetal cover (Figs. 1 and 2). Coefficients were generally higher for year 2 than year 1. After the first 5 minutes coefficients remained steady throughout the dry run and increased slightly during the wet run. In year 2 (Fig. 2) wet run coefficients between total vegetal cover and infiltrability decreased with time. Correlation coefficients were also computed between the components of vegetal cover (grasses, forbs, shrubs, litter) and infiltrability. In year 1 grass cover was the dominant factor while shrub and litter cover were nonsignificant. In year 2 shrub and litter cover were dominant and grass cover was nonsignificant. Site differences account for some of this incongruity. Recall that the productive *Stipa comata-Bouteloua gracilis* community (high grass cover and production, low shrub-litter cover and production) were sampled in year 1 but not year 2. When these plots were removed and the data analyzed again correlations between infiltrability and shrub, litter, and grass cover were about the same for both years.

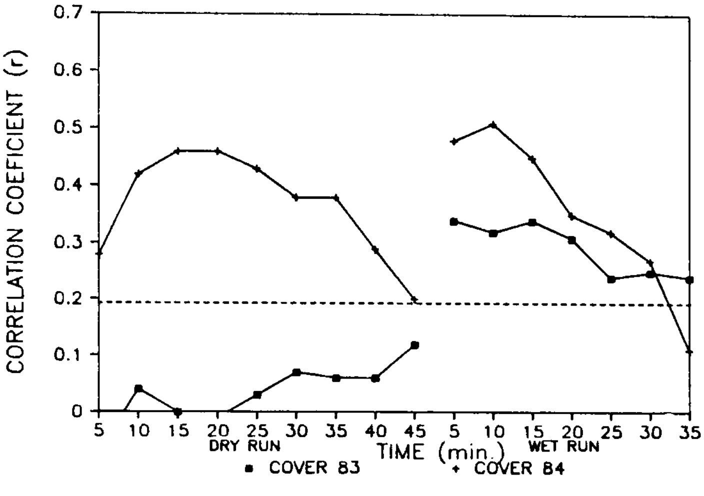

Fig. 3. *Partial correlations (effect of rock cover and slope gradient removed) between total vegetal cover and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

Partial correlation analysis was used to examine the relationship between infiltrability and vegetal cover with the effect of slope gradient and rock cover removed (Fig. 3). Both variables (slope gradient, rock cover) were highly correlated with vegetal cover. The resulting correlation coefficients were much reduced, especially in year 1. In year 2 a marked decline with time was evident in both the dry and wet run. These graphs also indicate that in year 1 (1983) infiltrability was more correlated with vegetal cover during the wet run. In year 2, however, little difference existed between coefficients of the dry and wet runs. The removal of only slope gradient had little effect on the correlation between infiltrability and vegetal cover. When only rock cover was removed, the resulting coefficients were very similar to Figure 3, suggesting that rock cover has a positive impact on infiltrability. In a semiarid environment rock cover should increase as vegetal cover decreases (assuming rocks are in the soil) because with lower vegetal cover raindrop impact and overland flow remove the finer particles, leaving the coarse particles behind (Cooke and Warren 1973). The effect of rock cover will be discussed in more detail later.

Basal vegetal cover was a poorer indicator of site infiltrability than aerial cover. In general, correlations between infiltrability and basal cover were nonsignificant. Kincaid et al. (1964) also found basal cover a poor indicator of infiltrability.

Results of the correlation analysis of infiltrability and vegetal biomass to some extent mirrors the results of the correlation between infiltrability and vegetal cover. Both cover and biomass are a reflection of vegetation abundance. Coefficients were higher during the wet run for both years. In year 1 (Fig. 4) grass was the only biomass component significantly correlated with infiltrability. Even total vegetal biomass (which is most heavily weighted by shrub biomass) was nonsignificant. In year 2 results were quite the opposite with significant correlations between infiltrability and total, shrub and litter biomass and low correlation for grass biomass (Fig. 5). Again it was thought that site differences caused these observed differences between year 1 and year 2. However, when the *Stipa comata-Bouteloua gracilis* plots were removed from the year 1 data, results were not much different. Grass biomass was higher in year 1 than in year 2 (Table 2) even when the productive grass stands were removed. These data suggest a threshold value of grass biomass must be surpassed before grass biomass has a large impact on infiltrability. Blackburn et al. (1980) noted that infiltration is higher under bunch grasses (high biomass) than sod-forming grass (low biomass) with all other conditions being equal. Most research however (Lyford and Qashu 1969, Tromble et al. 1974, Wood and Blackburn 1981, Brock et al. 1982, Thurow et al. 1986), with the exception of Box (1961), has demonstrated higher infiltrability under shrub canopy than in the interspace zone. Box (1961) measured higher infiltrability on some grassland communities than under mesquite canopies. Shrubs usually enhance infiltrability by providing protection from raindrop impact and preventing formation of a soil crust. The copious litter supply, besides reducing raindrop impact, also adds organic matter to the soil. Organic matter increases soil porosity by encouraging aggragation and reducing soil bulk densities.

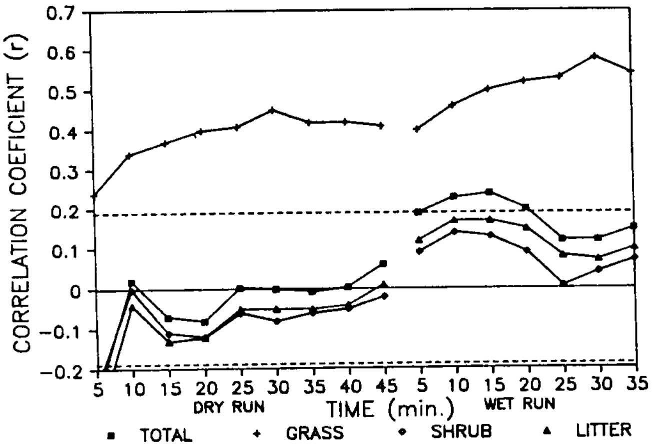

Fig. 4. *Year 1 correlation between vegetal biomass and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

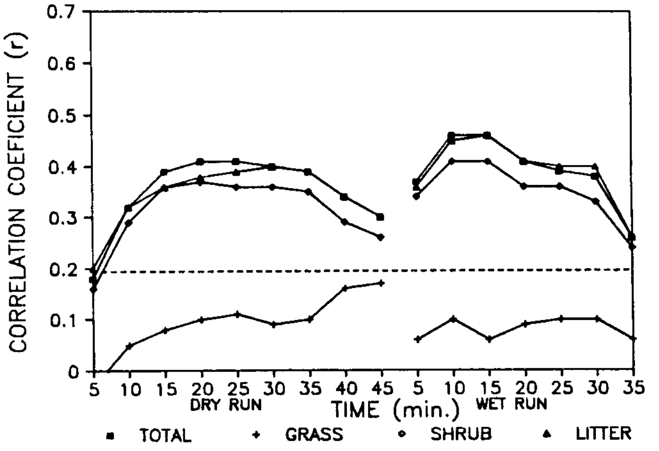

Fig. 5. *Year 2 correlations between vegetal biomass and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

The positive impact of vegetation on infiltrability is borne out by these data. Vegetation, in general, influences surface hydrological properties by decreasing velocity of overland flow, increasing surface roughness, enhancing soil infiltrability by root activity and addition of organic matter (Selby 1982). Vegetal cover also reduces impact energy of raindrops (Osborn 1954, Smith and Wischmeier 1957), substantially reducing rain splash erosion and formation of less permeable soil crusts.

Soil

Of all the soil variables measured infiltrability was most correlated with soil depth (depth to bedrock) (Fig. 6). Soils in the study area tended to be very shallow (underlain by limestone or dolomite bedrock) with the exception of the alluvial soils. Note that soil depth became more correlated with time. Soil depth limits soil water storage capacity and as storage capacity is reached, infiltrability slows. Others have also noted that infiltrability is limited by soil storage capacity (Dunne and Leopold 1978).

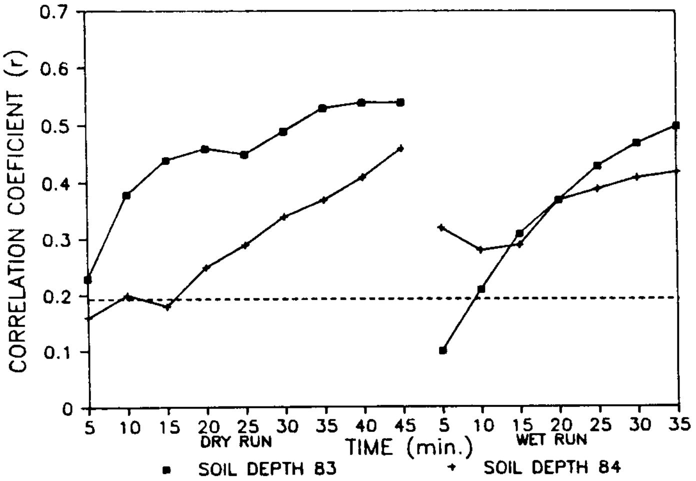

Fig. 6. *Correlations between soil depth and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

Infiltrability was slightly correlated with soil texture in both years (Fig. 7). It was positively related to percentage of clay sized particles and negatively related to sand and silt sized particles. Blackburn (1975) reported a significant relationship between infiltrability and soil texture in semiarid watersheds of Nevada. He found however, that clay and silt were negatively correlated while sand was positively correlated, just the opposites of these results.

Table 2. Mean values and associated standard deviations for measured plot characteristics.

	Year 1		Year 2			
	Steep Slopes		Flat Slopes		Steep Slopes	
Variable	$\bar{x}$	sd	$\bar{x}$	sd	$\bar{x}$	sd
Aerial vegetal cover (%)	38.5	16.0	63.5	18.7	42.3	17.5
Basal vegetal cover (%)	11.5	7.8	30.7	9.8	15.1	8.1
Aerial forb cover (%)	2.3	2.7	1.8	2.5	1.4	1.6
Aerial grass cover (%)	26.9	17.1	38.8	15.1	24.0	13.4
Aerial shrub cover (%)	9.0	14.4	10.0	17.1	10.7	16.9
Litter cover (%)	11.6	11.0	12.9	10.2	6.2	4.7
Bare ground (%)	16.6	10.9	21.8	12.3	20.6	8.6
Basal forb cover (%)	0.2	0.4	0.2	0.6	0.3	0.6
Basal grass cover (%)	11.0	8.0	29.8	10.2	13.7	8.7
Basal shrub cover (%)	0.4	1.0	0.7	1.1	1.2	2.3
Rock cover (%)	33.2	16.8	14.0	14.3	34.5	14.4
Rock 2-12 mm (%)			4.2	4.5	6.5	4.8
Rock 13-25 mm (%)			4.1	4.6	7.8	4.4
Rock 26-75 mm (%)			4.1	4.9	12.2	6.9
Rock 76-150 mm (%)			1.4	1.8	6.1	4.6
Rock 151+ mm (%)			0.1	0.6	1.9	2.7
Grass biomass (g)	132.5	110.5	75.8	43.1	87.5	34.3
Litter biomass (g)	237.0	232.8	133.7	238.6	64.7	106.7
Shrub biomass (g)	185.5	382.8	164.8	413.9	284.4	575.2
Forb biomass (g)	11.2	13.2	7.7	12.8	6.7	7.5
Organic carbon 0-5 cm (%)	6.0	1.7	5.3	2.0	5.3	1.4
Bulk density (g/cm^3)			0.98	0.2	0.98	0.1
Sand 0-5 cm (%)	25.7	5.3	22.0	3.7	23.1	4.0
Clay 0-5 cm (%)	33.9	5.6	33.5	6.5	35.3	4.8
Slope gradient (%)	41.0	13.1	5.7	4.5	51.1	8.0
Soil depth (cm)	23.1	13.6	34.9	21.3	26.5	7.5
Steady state dry run infiltrability (cm/hr)	8.0	2.0	6.8	2.7	7.3	2.0
Steady state wet run infiltrability (cm/hr)	6.0	2.5	4.8	2.6	5.6	2.3

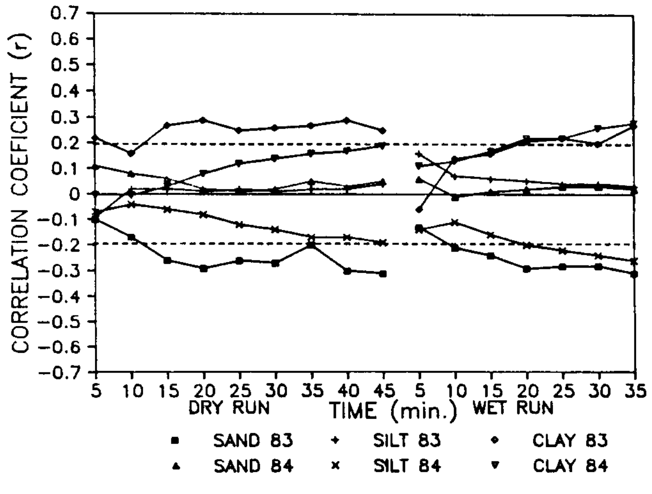

Fig. 7. *Correlations between soil texture and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

Indeed one would expect coarse size particles to enhance infiltrability rather than inhibit it. The surface soil textural range however was quite narrow (clay loam-silty clay loam). In this range it is conceivable that clay increases could increase infiltrability since clay enhances soil aggregation (Baver et al. 1972).

Bulk density was measured only in year 2. As expected, infiltrability was negatively correlated with bulk density (Fig. 8). Highest coefficients were observed in the middle of the infiltration event. The shape of the bulk density correlation curve was quite similar to the bare ground correlation curve of year 2. Both variables influence soil porosity. As more bare ground becomes exposed, raindrop impact has a greater compacting effect. The more extreme microenvironment of exposed soil also contributes to soil compaction (Satterlund 1972). Infiltrability however, was poorly correlated with bare ground in year 1. Significant negative correlations occurred only in the beginning of the wet run. Average bareground was lower in year 1 than year 2 (Table 1).

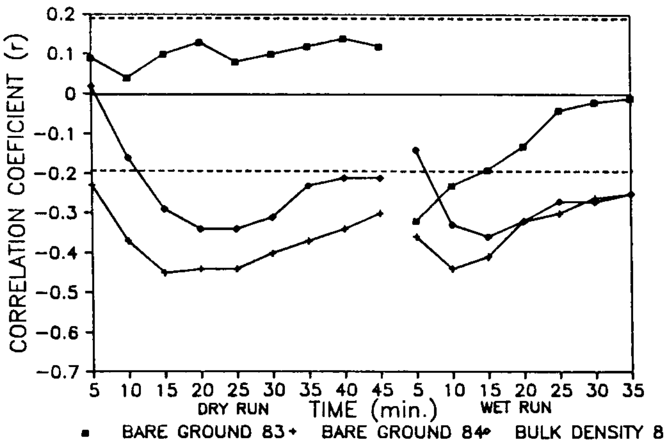

Fig. 8. *Correlations between bulk density and bare ground and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

The positive influence of organic matter on infiltrability is well established. Organic matter encourages soil aggregation and increases water holding capacity of the soil (Brady 1974). The year 2 data reflects this but the year 1 data do not (Fig. 9). In fact there was actually a negative relationship for the 1983 data set. One reason for this was that organic carbon was negatively correlated

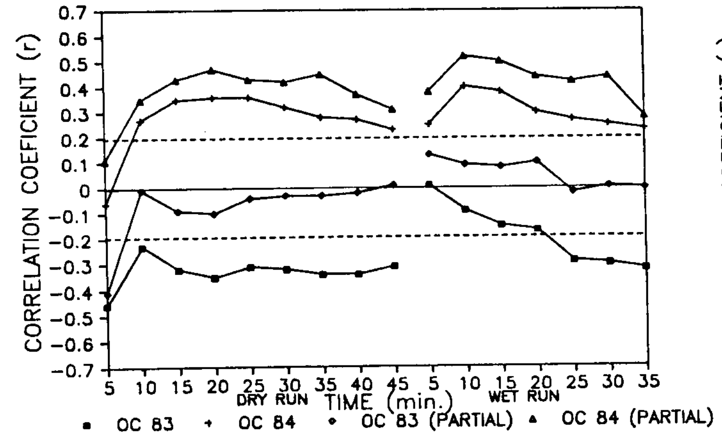

Fig. 9. *Correlations and partial correlations (effect of soil depth removed) between organic carbon and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

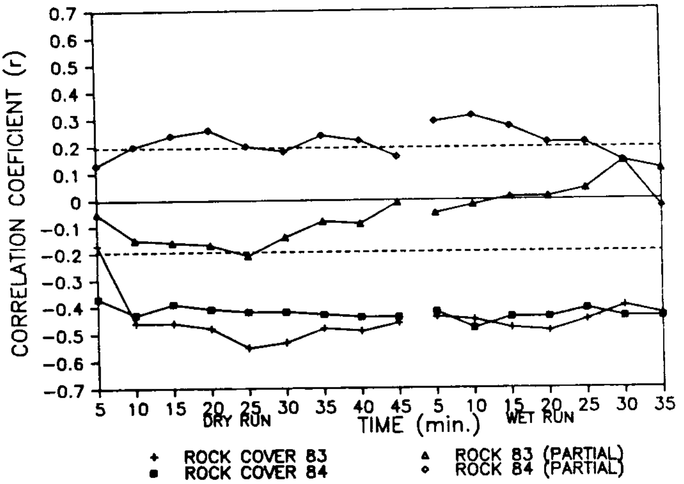

Fig. 10. *Correlations and partial correlations (effect of vegetation and slope removed) between rock cover and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

with soil depth. Very shallow soils had the highest amounts of organic carbon. When the effect of soil depth was removed, the relationship was nonsignificant in year 1 and made more positive for year 2. Another reason for the weak correlation in year 1 was that organic carbon was lower in the *Stipa comata* - *Bouteloua gracilis* community soils, which had high infiltrabilities.

Rock Cover

Infiltrability was negatively correlated with rock cover for both sets of data (Fig. 10). The key question is does rock cover on semiarid mountain slopes contribute to lower infiltrability and increased runoff or is it simply an indicator of low infiltrability? Thornes (1980, p. 162) states that "development of a stone carapace while protecting the soil from raindrop impact tends to inhibit infiltration and increase surface runoff though it may occasionally have the reverse effect." Research by Yair and Lavee (1976) on talus mantled slopes in Israel showed that rock cover contributed to runoff by concentrating and delivering water. Tromble et al. (1974) also found infiltrability to be negatively correlated with gravel (<10 mm) cover in semiarid rangeland of Arizona. Conversely, others have noted that under laboratory conditions a stone cover enhances infiltration by protecting the soil from raindrop impact and subsequent surface crusting (Grant and Struchtemeyer

Table 3. Communalities and factor loadings produced by the PCA with Varimax rotation on the 1983 data set.

Factor	Variable	Communality	Factor Loadings 1	2	3	4	5	6	7
1	Shrub biomass	.85	.88	0	-.23	.16	-.03	-.03	.04
	Shrub cover	.89	.86	.03	-.32	.17	.04	-.07	.09
	Total biomass	.92	.85	.21	-.19	.34	-.07	-.01	0
	Basal shrub cover	.74	.77	-.18	.10	-.06	.15	.19	-.19
	Litter biomass	.84	.73	.15	-.10	.52	-.03	.03	-.09
2	Rock cover	.85	-.31	-.80	-.19	-.18	-.10	.15	.07
	Total cover	.89	.42	.78	.14	.15	-.11	.22	.07
	Grass biomass	.66	-.14	.73	.04	-.04	-.28	.10	.16
	Grass cover	.90	-.29	.71	.45	.01	-.24	.23	-.03
	Soil depth	.82	-.12	.58	-.28	-.41	.26	-.33	-.18
3	Total basal cover	.87	-.20	.41	.81	-.03	-.04	.06	-.04
	Basal grass cover	.88	-.28	.43	.78	-.05	-.05	.03	-.03
	Slope gradient	.65	.16	.21	-.69	.07	.28	-.09	-.10
4	Litter cover	.83	.15	.17	-.04	.85	.06	-.18	-.11
	Bareground	.72	-.29	-.01	.08	-.69	.22	-.33	-.07
	Organic carbon (0-5 cm)	.78	.37	-.31	.01	.52	.06	.47	-.23
5	Forb cover	.83	-.22	-.19	-.19	.02	.84	.04	.07
	Forb biomass	.76	.11	-.10	-.35	-.04	.73	-.15	.25
	Ante. Moisture	.62	.35	.02	.40	-.08	.56	.10	.01
6	Silt (0-5 cm)	.84	0	.13	.12	-.02	-.02	.90	-.06
7	Clay (0-5 cm)	.91	-.12	0	-.01	-.14	.13	-.43	.82
	Sand (0-5 cm)	.90	.10	-.16	-.11	.06	-.11	-.48	-.78
	Basal forb cover	.29	.13	-.05	-.06	.34	.07	-.07	.36
	Eigenvalue		5.7	4.3	2.5	1.8	1.5	1.2	1.2
	% variance		25	19	11	8	7	5	5
	Cumulative %		25	44	55	63	70	75	80

1959, Jung 1960, Dadkhah and Gifford 1981). In Arizona, Simanton et al. (1984) demonstrated that if the erosion pavement is removed, erosion will increase, presumably because the soil surface is less protected. After root plowing and pitting semiarid rangeland, Tromble (1976) found that infiltrability was positively related to rock and gravel cover.

The apparent conflict in the literature can be readily explained. Under laboratory or even cultivated conditions, surface rock cover represents additional protection to the otherwise bare soil surface and will reduce raindrop impact and soil crusting. Under natural conditions in an arid or semiarid environment, a stone pavement has evolved and exists because of the lack of vegetal cover (Cooke and Warren 1973). In areas not protected by vegetation, more erosion will occur, resulting in removal of fine soil particles and organic matter and a lowering of the surface, leaving coarse fragments or a stone pavement behind. Exposure of the soil surface accelerates decomposition of organic matter and compaction of the soil by raindrop impact (Satterlund 1972) resulting in a more impermeable surface. Infiltrability of stone pavements is low, therefore, not because of the rock cover per se, but because of the soil crusting and compaction that has resulted from raindrop impact. This is supported by partial correlation analysis (Fig. 10) showing that when the effects of vegetal cover and slope are removed, rock cover was much less significant in year 1 and was positively related to infiltrability in year 2. This supports the laboratory research showing that rock cover enhances infiltrability.

A very interesting feature of the data was the relationship between the rock size classes and infiltrability (Fig. 11). The smaller the rock size the more significant and negative the relationship. Each succeedingly smaller rock size class became more strongly correlated with infiltrability. Yair and Lavee (1976) found the opposite relationship between rock size and infiltrability on talus mantled slopes in arid Israel. They concluded that runoff was positively correlated with rock size class. In their study area, however, rocks were larger and covered a greater surface area. In general, conditions were quite different from those in the Guadalupe mountains. The questions remains as to why low infiltrability was associated with cover by small rocks rather than larger ones? The most obvious answer is that the erosion pavement (from which sediment production was high) was composed mostly of the smaller sized rock fragments incorporated in the soil. The larger rock fragments mostly originated from weathered limestone cliffs faces which commonly protrude from the Guadalupe Rim, and do not represent erosional pavement.

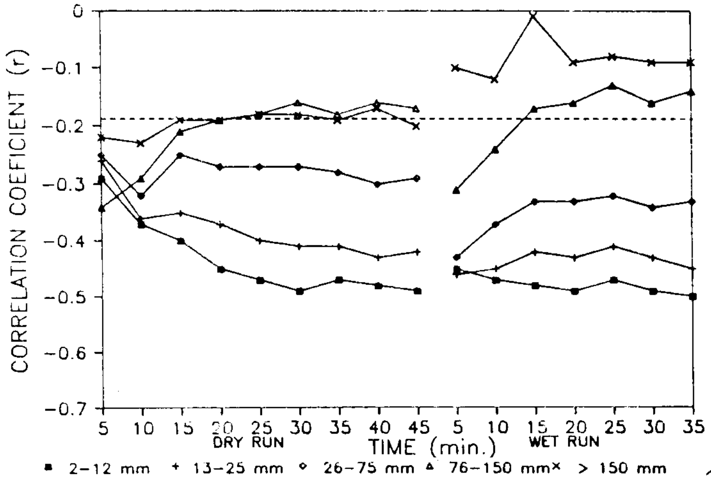

Fig. 11. *Year 2 correlations between rock cover by size class and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant ($p \leq 0.05$).*

When the effects of vegetal cover and slope gradient were removed, infiltrability was only negatively correlated with the very smallest size class of rocks and was positively correlated with the intermediate size classes (26–75 mm, 76–150 mm) (Fig. 12). Correlations were nonsignificant for the 13–25 mm and >150 mm size classes. These data indicate that if rock cover inhibits infiltration, it is most likely when smallest rocks dominate. Infiltration is encouraged by larger sized rock cover. Perhaps soil coverage by small rocks does not afford the same degree of protection as an equal coverage by larger sized rock fragments. The largest rock class was nonsignificant because of its low overall cover (Table 2). Similarly, Tromble et al. (1974) found that infiltrability was negatively correlated with gravel (<10 mm), but was positively correlated (not significantly) to the larger rock size fragments.

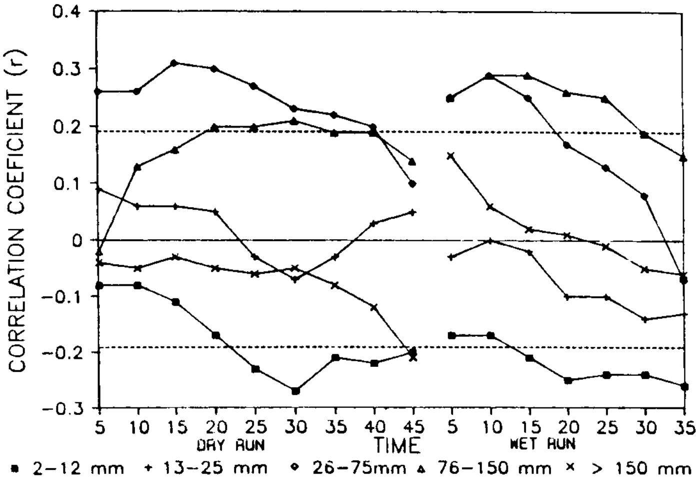

Fig. 12. *Year 2 partial correlations (effect of vegetal cover and slope removed) between rock cover by size class and infiltrability. Dashed lines represent the value at which correlations are significant. ($p \leq 0.05$).*

Slope Gradient

Infiltrability was positively related to slope gradient in year 1, although not significantly (Fig. 13). It was negatively related in year 2, with significant coefficients occurring at the beginning of the rainfall event. In other words in year 2, on the steep slopes infiltrability was initially lower than on the low ones, but after a

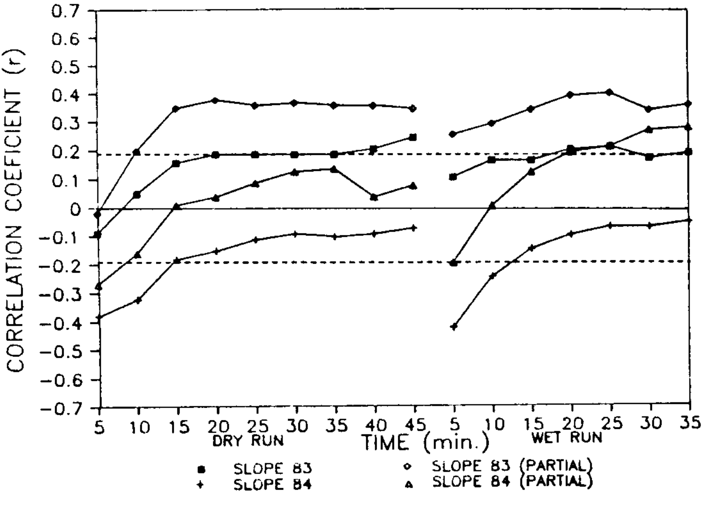

Fig. 13. *Correlations between slope and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant ($p \leq 0.05$).*

few minutes differences were minimal. Rock and vegetal cover were significantly correlated with slope and when the effect of these variables were removed (by partial correlation analysis), the correlation was mostly positive. Partial correlation coefficients were most significant for year 1. These data support the work of Wilcock and Essery (1984), who found a strongly positive correlation (r = .78) between infiltrability and slope, and McCord (1985), who argued that slope positively influences infiltrability because of its influence on subsurface flow. One possible reason for the positive correlation between slope gradient and infiltrability is that interflow rates are increased with slope gradient, particularly if a shallow subsurface impeding horizon is present (Whipkey and Kirkby 1978).

Factor Analysis

Factor analyses were performed on each set of data. Seven factors were produced from year 1 (Table 3) and 6 from year 2 (Table 4). Each factor has an eigenvalue >1, and thus accounted for more variation than an individual, original variable. Factor loadings and communalities appear in Tables 3 and 4. Communalities are assigned to each variable and are the percentage of the respective variable variance accounted for by the factors. For example, the 7 factors retained for year 1 accounted for 85% of the variance of shrub biomass (Table 3). The factor loadings are the correlation between the respective variables and factors.

The factors produced from both sets of data were quite similar and interpretation was straight forward. In each set there was a factor representing (1) vegetal and rock cover (2) vegetal biomass (3) forb cover and biomass (4) soil texture (each data set has 2 factors representing soil texture) and (5) soil surface condition (bare ground organic carbon, litter cover).

The factors produced were satisfactory but not ideal. The basal cover-slope gradient factor (year 1) was generally uninformative because slope gradient and basal cover counteracted one another. Basal cover was negatively correlated with slope gradient (r = –.44); thus as slope increased, basal cover tended to decrease. Pearson and partial correlation analysis has indicated that both are positively related to infiltrability. In year 2, slope was buried in the cover factor. The year 1 cover factor was heavily weighted by grass biomass and grass biomass contributed little to the biomass factor. The 2 soil textural factors produced from each data set also differ. In year 1, clay and sand were combined and silt occurred as a single factor, while in year 2 clay and silt were combined and sand accounted for an individual factor. Vegetal cover was positively related and rock cover was negatively related to the year 1 cover factor. The opposite relationship occurred for year 2.

The cover factor easily accounted for the most variation in year 1 (Fig. 14 and 15). Rock cover and total vegetal cover were the major variables loaded into this factor, but grass biomass was included as well (Table 3). The cover factor curves for the dry and wet run were quite similar. Infiltrability was generally poorly correlated to the biomass factor (minus grass biomass) in year 1. The only other factor with which infiltrability was significantly correlated was the clay/sand factor (Fig. 14). Note the gradual increase in correlation with time during both the dry and wet runs. This factor was positively weighted by clay and negatively weighted by sand (Table 3). The silt factor was nonsignificant. The soil surface factor and forb factor were nonsignificant.

In year 2 the cover, biomass and soil surface factors (Figs. 16 and 17) were most significant. Infiltrability was most correlated with

Table 4. Communalities and factor loadings produced by the PCA with Varimax rotation on the 1984 data set.

Factor	Variable	Communality	Factor Loadings 1	2	3	4	5	6
	Total rock cover	.97	.91	–.28	.19	.09	–.01	.10
	Total cover	.94	–.85	.36	–.09	.30	–.02	–.02
	Rock cover 26-75mm	.78	.84	–.20	.13	.11	.01	–.03
	Slope gradient	.84	.76	.37	–.30	.18	–.08	–.04
1	Rock cover 76-150mm	.97	.72	–.07	.04	.05	–.11	–.20
	Rock cover 13-25mm	.72	.71	–.32	.23	.03	0	.26
	Litter cover	.70	–.69	.20	.06	.33	–.06	–.27
	Basal grass cover	.82	–.66	–.51	.12	.18	–.04	.28
	Rock cover 2-12mm	.72	.51	–.37	.24	.09	.04	.37
	Shrub cover	.93	–.21	.93	.13	.06	.04	.02
	Shrub biomass	.88	–.16	.90	.01	.22	.03	.06
2	Total biomass	.88	–.24	.86	.03	.28	0	.05
	Basal shrub cover	.62	–.03	.78	.02	–.06	–.09	.02
	Litter biomass	.63	–.42	.57	.16	.30	–.05	.01
	Clay (0-5 cm)	.80	–.10	–.05	–.87	.09	0	–.16
	Silt (0-5 cm)	.84	.03	.02	.84	–.03	.06	–.37
3	Silt (5-10 cm)	.82	.08	.02	.72	.35	–.17	–.39
	Clay (5-10 cm)	.65	–.06	–.07	–.67	–.34	.24	.11
	Organic carbon (5-10 cm)	.71	.12	.05	.52	.49	.43	–.06
	Bare ground	.70	0	–.26	–.17	–.76	.08	–.13
	Organic carbon (0-5 cm)	.75	–.08	.35	.42	.55	.27	–.26
4	Bulk density	.46	.02	–.21	–.09	–.50	–.11	.37
	Grass biomass	.55	.03	–.25	–.33	.48	–.36	–.14
	Forb cover	.77	–.10	.06	–.02	–.03	.86	–.16
5	Forb biomass	.75	–.11	.06	–.11	.03	.85	–.02
	Basal forb cover	.43	.14	–.19	.01	–.01	.61	–.04
	Sand (0-5 cm)	.72	.10	.04	–.12	–.08	–.09	.82
6	Sand (5-10 cm)	.51	–.08	.10	–.19	–.06	–.12	.66
	Soil depth	.76	–.46	–.10	–.43	–.30	–.23	–.46
	Eigenvalue		7.0	5.0	3.1	2.4	2.0	1.5
	% variance		24	17	11	8	7	5
	Cumulative %		24	41	52	60	67	72

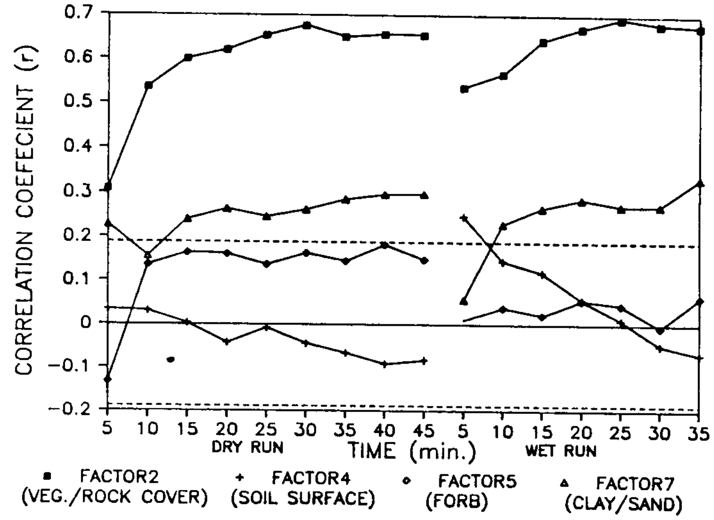

Fig. 14. *Positive correlations between the year 1 PCA factors and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

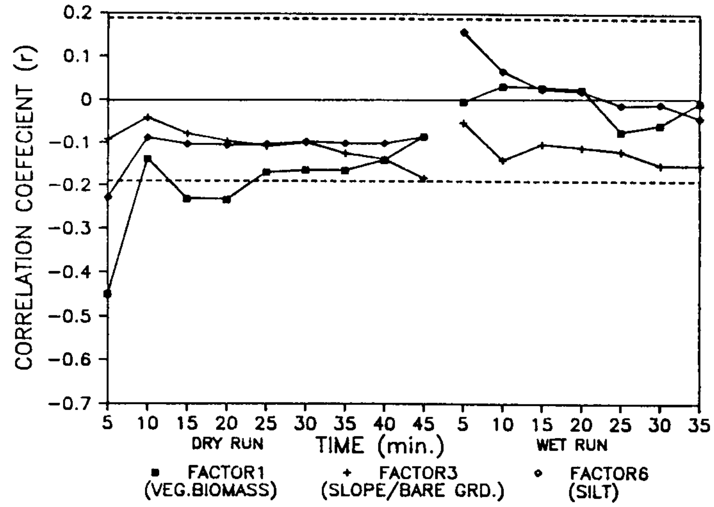

Fig. 15. *Negative correlations between the year 1 PCS factors and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

the cover factor, however, the coefficient decreased (absolute value) with time. (Infiltrability was negatively correlated with the cover factor because the factor was negatively weighted by vegetal cover and positively weighted by rock cover (Table 4)). Recall that vegetal cover (year 2) also decreased in significance in the wet run (Fig. 2). Similar phenomena were not observed in year 1 (Fig. 14). The soil surface and biomass factors correlation curves (Fig. 16) were very similar in shape (highest correlations occurred in the middle of the infiltration runs). This is the same general shape of the vegetal biomass, organic carbon, bareground and bulk density correlation curves produced for year 2 (Figs. 5, 8, and 9). This relationship to infiltrability was not evident for any of these variables or factors for year 1.

Conclusions

Analysis of 2 years of infiltration data collected with a small plot rainfall simulator on semiarid slopes indicated the following.

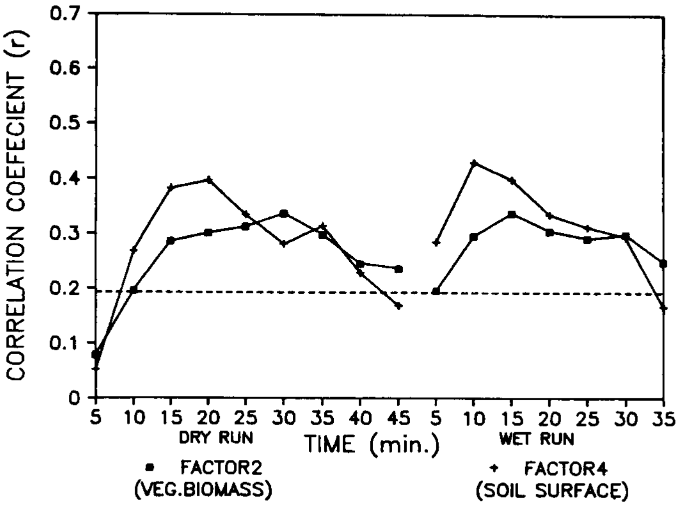

Fig. 16. *Positive correlations between the year 2 PCA factors and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

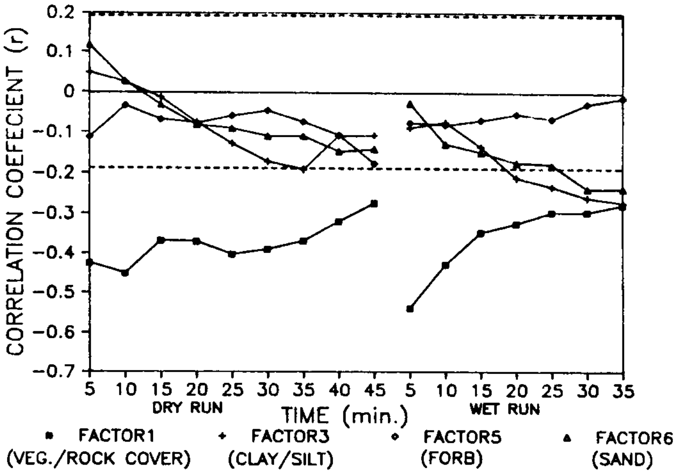

Fig. 17. *Negative correlations between the year 2 PCA factors and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

(1) Vegetation has a major effect on soil infiltrability. This conclusion is nothing new and has been shown by numerous previous research. Previous research, however, has generally ignored steep slopes. The relative importance of grasses, shrubs, and litter is dependent on their respective productivity, especially of grasses. Infiltrability was generally better correlated with vegetal cover than biomass. Aerial cover was a much better indicator of infiltrability than was basal cover.

(2) For shallow soils small changes in soil depth have a large impact on infiltrability. The impacts of soil depth to infiltrability become more acute as infiltration progresses.

(3) Increases in clay within the clay loam-silty clay loam textural classes increases infiltrability; possibly because of increased aggregation.

(4) Rock cover is negatively associated with infiltrability because generally low vegetal cover accompanies high rock cover. Some protection however is offered by rock cover, especially if fragments

are larger than 25 mm in length. In other words, infiltrability is higher if rock cover is protecting the soil surface than if the soil surface is bare.

(5) Infiltrability is positively related to slope gradient; possibly because interflow increases with increases in slope.

Factor analysis supported the conclusions drawn from the Pearson correlation analysis. Partial correlation analysis proved especially valuable in separating out the effects of one or more variables from another variable. Results of the 2 years of data were not always in complete agreement, sometimes making it more difficult to draw general conclusions, but well illustrating the potential danger of interpreting relationships based upon 1 year of data.

Literature Cited

Afifi, A.A., and V. Clark. 1984. Computer-aided multivariate analysis. Lifetime learning publications, Belmont.

Allison, L.E. 1965. Organic carbon. P. 1367-1378. *In:* C.A. Black (Ed.). Methods of Soil Analysis. Monogr. Ser. Part I, No. 9, Amer. Soc. Agron., Madison, Wisc.

Baver, L.D., W.H. Gardner, and W.R. Gardner. 1972. Soil physics. John Wiley and Sons, Inc., New York.

Beven, K. and P. Germann. 1982. Macropores and water flow in soils. Water Resour. Res. 18:1311-1325.

Blackburn, W.H. 1975. Factors influencing infiltration and sediment production of semiarid rangelands in Nevada. Water Resour. Res. 11:929-937.

Blackburn, W.H., R.W. Knight, M.K. Wood, and L.B. Merrill. 1980. Watershed parameters as influenced by grazing. Proc. of Symposium on Watershed Management, ASCE, p. 552-572, Boise.

Blake, G.R. 1965. Bulk density. P. 274-390. *In:* C.A. Black (Ed.). Methods of Soil Analysis. Monogr. Ser. Part I, No. 9. Amer. Soc. Agron., Madison, Wisc.

Bouyoucos, G.J. 1962. Hydrometer method improved for making particle size analysis of soil. Agron. J. 54:464-465.

Box, T.W. 1961. Relationships between plants and soils of 4 range plant communities in south Texas. Ecology 42:794-810.

Brady, N.C. 1974. The nature and property of soils, 8th Ed. MacMillan Publishing Co., New York.

Branson, F.A., F.F. Gifford, K.G. Renard, and R.F. Hadley. 1981. Rangeland Hydrology. Soc. Range Manage. Denver, Colo.

Branson, F.A. and J.B. Owen. 1970. Plant cover, runoff and sediment yield relationships on Mancos Shale in western Colorado. Water Resour. Res. 6:783-790.

Brock, J.H., W.H. Blackburn, and R.H. Haas. 1982. Infiltration and sediment production on a deep hardland range site in North central Texas. J. Range Manage. 35:195-198.

Cooke, R.V. and A. Warren. 1973. Geomorphology in deserts. Univ. California Press, Berkeley.

Dadkhah, M. and G.F. Gifford. 1980. Influence of vegetation, rock cover, and trampling on infiltration rates and sediment production. Water Resour. Bull. 16:979-986.

Dortignac, E.J. and L.D. Love. 1961. Infiltration studies on ponderosa pine ranges of Colorado. USDA Rocky Mtn. Forest and Range Exp. Sta. Pap. 59.

Duley, F.L. and C.E. Domingo. 1949. Effect of grass on intake of water. Neb. Res. Bull. 159.

Duley, F.L. and O.E. Hays. 1932. The effect of the degree of slope on runoff and soil erosion. J. Agr. Res. 45:349-360.

Duley, F.L. and L.L. Kelley. 1939. Effect of soil type, slope, and surface conditions on intake of water. Neb. Res. Bull. 112.

Dunne, T. and L.B. Leopold. 1978. Water in environmental planning. W.H. Freeman, San Francisco.

Dyksterhuis, E.J. and E.M. Schmutz. 1947. Natural mulches or litter of grasslands: with kinds and amounts on a southern prairie. Ecology 28:163-179.

Gehlbach, F.R. 1967. Vegetation of the Guadalupe Escarpment, New Mexico-Texas. Ecology 49:404-419.

Grant, J.W. and R.A. Struchtemeyer. 1959. Influence of coarse fraction in two main potato soils on infiltration, runoff and erosion. Soil Sci. Soc. Amer. Proc. 23:391-394.

Hart, G.E. 1984. Erosion from simulated rainfall on mountain rangeland in Utah. J. Soil and Water Conserv. 39:330-334.

Hayes, P.T. 1964. Geology of the Guadalupe Mountains, New Mexico. USGS Prof. Pap.446.

Hillel, D. 1971. Soil and water: physical principles and processes. Academic Press, New York.

Hillel, D. 1982. Introduction to soil physics. Academic Press, New York.

Johnson, A. 1962. Effects of grazing intensity and cover on the water intake rate of *Fescue* grassland. J. Range Manage. 15:79-82.

Jung, L. 1960. The influence of the stone cover on runoff and erosion on slate soil. Int. Ass. Sci. Hydrol. 53:143-153.

Kincaid, D.R., J.L. Gardner and H.A. Schrieber. 1964. Soil and vegetation parameters affecting infiltration under semiarid conditions. Int. Ass. Sci. Hydrol. 65:440-453.

King, P.B. 1948. Geology of the southern Guadalupe Mountains, Texas. USGS. Prof. Pap. 215.

Lyford, F.P. and K.H. Qashu. 1969. Infiltration rates as affected by desert vegetation. Water Resour. Res. 5:1373-1376.

McCord, J.T. 1985. Review and field study of lateral flow on unsaturated hillslopes, p. 1-11. *In:* H.J. Morel-Seytoux and D.O. Doehring (Eds.). Proc. AGU Front Range Branch Hydrology Days.

Meeuwig, R.O. 1970. Infiltration and soil erosion as influenced by vegetation and soil in northern Utah. J. Range Manage. 23:185-188.

Neal, J.H. 1938. The effect of the degree of slope on rainfall characteristics of runoff and soil erosion. Missouri Agr. Exp. Sta. Bull. 280.

Osborn, B. 1954. Effectiveness of cover in reducing soil splash by raindrop impact. J. Soil and Water Conserv. 9:70-76.

Pieper, R.D. 1978. Measurement techniques for herbaceous and shrubby vegetation. New Mexico State Univ., Las Cruces.

Rauzi, F. 1960. Water intake studies on range soils at 3 locations in the Northern Plains. J. Range Manage. 13:179-184.

Satterlund, D.R. 1972. Wildland watershed management. Ronald Press Co., New York.

Selby, M.J. 1982. Hillslope materials and processes. Oxford, University Press, Oxford.

Simanton, J.R., E. Rawitz, and E.D. Shirley. 1984. Effects of rock fragments on erosion of semiarid rangeland soils. p. 65-72 *In:* Erosion and Productivity of Soils Containing Rock Fragments. Soil Sci. Soc. Amer. Special Pub. 13.

Smith, D.D., and W.H. Wischmeier. 1957. Factors affecting sheet and rill erosion. Trans. Amer. Geophy. Un. 38:889-907.

Smith, H.L. and L.B. Leopold. 1941. Infiltration studies in the Pecos River watershed, New Mexico and Texas. Soil Sci. 53:195-204.

Thorndike, R.M. 1976. Correlational procedures for research. Gardner Press Inc., New York.

Thornes, J.B. 1980. Erosional processes of running water and their spatial and temporal controls: A theoretical viewpoint. p. 129-182. *In:* M.J. Kirby and R.P.C. Morgan (Eds.). Soil Erosion. John Wiley and Sons, New York.

Thurow, T.L., W.H. Blackburn, and C.A. Taylor, Jr. 1986. Hydrologic characteristics of vegetation types as affected by livestock grazing systems, Edwards Plateau, Texas. J. Range Manage. 39:505-509.

Tromble, J.M. 1976. Semiarid rangeland treatment and surface runoff. J. Range Manage. 29:251-255.

Tromble, J.M., K.G. Renard, and A.P. Thatcher. 1974. Infiltration for 3 rangeland soil-vegetation complexes. J. Range Manage. 27:318-321.

USDA. 1981. Soil survey of Otero area, New Mexico, parts of Otero, Eddy and Chaves Counties. USDA Soils Cons. Serv., Forest Serv. and New Mexico Agr. Exp. Sta.

Whipkey, R.Z. and M.J. Kirkby. 1978. Flow within the soil. p. 121-144. *In:* M.J. Kirbky (Ed.) Hillslope Hydrology. John Wiley and Sons, New York.

Wilcock, D.N., and C.I. Essery. 1984. Infiltration measurements in a small lowland catchment. J. Hydrol. 74:191-205.

Wilcox, B.P., M.K. Wood, J.T. Tromble, and T.J. Ward. 1986. A hand-portable single nozzle rainfall simulator designed for use on steep slopes. J. Range Manage. 39:375-377.

Wood, M.K. and W.H. Blackburn. 1981. Grazing systems: their influence on infiltration rates in the Rolling Plains of Texas. J. Range Manage. 34:331-335.

Woodward, L. 1943. Infiltration capacities of some plant-soil complexes on Utah range watershed-lands. Trans. Amer. Geophy. Un. 24:468-473.

Wright, H.A., F.M. Churchill, and W.C. Stevens. 1982. Soil loss, runoff and water quality of seeded and unseeded steep watersheds following prescribed burning. J. Range Manage. 35:382-385.

Yair, A., and H. Lavee. 1976. Runoff generation processes and runoff yield from arid talus mantled slopes. Earth Surf. Proc. 1:285-287.