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FLOOD CONTROL DISTRICT
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REMARKS
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4 September 1991

Mr. Joe Tram
Flood Control District of Maricopa County
3335 West Durango
Phoenix, Arizona 85009

Subject: Effect of gravel and stones in soil on infiltration rates

Dear Joe:

During my meeting with Davar Khalili and Steve Waters on 23 August 1991, they informed me that there has been a concern expressed by some users and reviewers of the Hydrologic Design Manual about the effect of gravel and stones in and on the soil in regard to infiltration rates. The effect of ground cover; that is, stones, vegetation and litter, was extensively researched during the preparation of the Manual. Dr. Leonard Lane helped with this effort. The results of that research were that 1) ground cover has a dramatic impact on infiltration rates, and 2) data are not presently available to develop reliable estimators on the effect of ground cover on the Green and Ampt parameters (mainly hydraulic conductivity). That research resulted in a simplified correction of hydraulic conductivity as a function of vegetation cover only (Figure 4.3). The results of the research by Dr. Lane and I are contained in the Documentation Manual, Part 2.

That research was directed at total ground cover and not just the effect of gravel and stones, and therefore there probably is the need to provide some additional documentation on the effect of gravel and stones so as to answer questions by users and reviewers of the Manual.

There is considerable information on this subject in the professional literature. Regrettably, as Dr. Lane and I discovered, very little conclusive results are available at this time.

I am providing copies of articles that I have compiled that address the effect of gravel and stones on hydraulic conductivity. The following are brief annotations of those articles (in chronological order):

Mehuys and others (1975) - This research was directed at unsaturated hydraulic conductivity and we are concerned with near saturated hydraulic conductivity. The results indicate that there is no appreciable difference in the unsaturated hydraulic conductivities whether the soil contains stones or the stones are excluded from the soil.

Brakensiek and others (1984) - This paper presents information that can be used to adjust or define SCS curve numbers (CN) for rangeland soils, however some of the information is relevant to our concern. On page 10 is referenced another study in which stone cover on the soil surface, from 0 to 20%, decreased CN by nearly 10%. Also on page 10, equation 6 indicates that CN decreases as a function of total cover, and therefore an increase in

infiltration rate. Total cover, presumably being vegetation, stone, litter, etc.

On page 9, equation 4 indicates that saturated hydraulic conductivity decreases linearly with an increase in stone content of the soil. This equation appears to be too simple and obviously does not apply in the limit that Z1 = 100% (clean gravel) for which the hydraulic conductivity would be 0.0! I would not place much confidence in this equation.

Devaurs and Gifford (1986) - The major conclusion is that use of the soil texture triangle developed for agricultural lands may need revision for use on rangelands. This is because the soil coarse fraction (gravel and stones), rangeland soil porosities, and percent organic matter may need to be considered. The Manual relies on parameter values based on the soil texture triangle classification, and therefore this conclusion should be noted. However, Figure 4 (2) of the article compares hydraulic conductivies from observed field data and from soil texture data. Those results indicate that the actual hydraulic conductivity is <u>greater</u> than that from soil texture classification. This indicates that use of the soil parameters from the Manual are probably conservative and that a correction for soil cover (such as Figure 4.3 of the Manual) is warranted.

Brakensiek and others (1986) - This is a review of methods to calculate the hydraulic conductivity of soil containing stones. These equations indicate that hydraulic conductivity decreases with an increase in stone content. This is the same as equation 4 of Brakensiek and others (1984).

Lane and others (1987) - The results of studies using experimental plots in rangelands and deserts in Arizona and Nevada are presented. Rainfall simulator data from these plots were used to investigate the influence of soil characteristics, vegetative cover, and surface stone and gravel cover (desert pavement) on runoff and infiltration rates. The studies indicate that infiltration rates decrease as vegetative canopy cover, and stone and gravel cover decrease.

All sites had a stone and gravel cover that averaged about 16% (range of 13 to 19%). The plots <u>always</u> had significantly lower infiltration rates after the stone and gravel cover had been removed. Removal of the vegetation cover resulted in a 39% decrease in the mean final infiltration rate, and also removing the stone and gravel resulted in an additional 34% decrease in final infiltration rate. The results of previous studies with similar results are discussed.

These results indicate that, if anything, the bare ground Green and Ampt parameters are conservative for flood estimation purposes and that reasonable corrections of hydraulic conductivity for ground cover are appropriate.

Wilcox and others (1988) - Although this paper is oriented towards semiarid

mountain slopes, it provides considerable information of value. One of the conclusions is that infiltration is higher if stone cover is protecting the soil surface than if the soil surface is bare. Several explanations for this are provided in the text; 1) stone cover enhances infiltration by protecting the soil from raindrop impact and subsequent surface crusting, and 2) exposure of the soil surface accelerates decomposition of organic matter and compaction of the soil by raindrop impact resulting in a more impermeable surface.

Rawls and others (1989) - Using a data base from rangeland infiltration experiments, a procedure incorporating the effects of soil properties, soil surface cover, and vegetative canopy cover on the Green and Ampt hydraulic conductivity was developed. Dr. Lane and I studied this procedure extensively. (Results and discussions are contained in the Documentation Manual, Part 2.) The results of our studies indicate that we should not adopt this procedure in the Manual because of some peculiar results that could be obtained for various soils and cover combinations. The authors state in the conclusions, "since the development and testing of data sets did not include high silt soils and grass-dominated vegetative cover, using the proposed procedure may yield questionable results."

In conclusion, I believe that the best data and results that are reported indicate that stone and gravel cover, and the presence of stones in the soil does <u>not</u> decrease the hydraulic conductivity that is reported based on the agricultural soil texture. The use of bare ground hydraulic conductivity is probably conservative. The use of a vegetation cover factor, such as Figure 4.3 of the Manual, is reasonable and should be applied when appropriate.

It may be appropriate to share this information with the users of the Manual at the District. This may be of value to them when addressing questions from consultants to the District and other users of the Manual.

I suggest that this letter and attachments be incorporated into the Documentation Manual, Part 2 since it is an important point that may be of value to the District in the future.

From my perspective, this topic of adjustments to the Green and Ampt parameters for conditions in Maricopa County (and throughout the Southwest) is an important one. Presently, the best researchers in this area have not been able to come to grips with a solution. Until such a solution is available, we should continue with our approach and refine it, when and if, such refinement is justified.

Sincerely yours,
George V. Sabol Consulting Engineers, Inc.

George V. Sabol

Effect of Stones on the Hydraulic Conductivity of Relatively Dry Desert Soils[1]

G. R. MEHUYS, L. H. STOLZY, J. LETEY, AND L. V. WEEKS[2]

ABSTRACT

The objective of this study was to determine whether moisture transmission properties of stony soils could be evaluated using samples of the same soil in which the stony fraction (> 2 mm) had been excluded. Experiments were conducted in the laboratory on soil columns with and without stones. Unsaturated hydraulic conductivity (K) was measured with a transient outflow method over the matric potential range of −0.05 to −50 bars using tensiometers and soil psychrometers. The soils studied were Rock Valley gravelly loamy sand (Mojave Desert, Nevada) and Tubac and Rillito gravelly sandy loams (Sonoran Desert, Arizona). On a weight basis, these soils contain up to 40% stones > 2 mm in diameter.

If expressed as a function of matric potential, hydraulic conductivity values were similar, with or without stones. Soil water potential as measured by tensiometers or by thermocouple psychrometers is not affected by stones because these instruments respond to moisture changes in the soil portion only. When K was expressed as a function of volumetric water content, the apparent conductivities were higher for a given water content when stones were present. A simple correction of water contents of stone-free samples, based on the stone volume of each soil, adequately accounted for differenecs observed when water contents were computed on a total volume basis.

Additional Index Words: unsaturated soil, transient flow, moisture desorption curves, coarse fragments.

MOST STUDIES on the movement of water through relatively dry soils have either been experimental verifications of the theory of unsaturated flow or aimed at separating the components of flow as the soil dries beyond a certain level (e.g. Hanks, 1958; John, 1962; Jackson, 1964; Rose, 1963). The soil is assumed to be homogeneous and only that part of the mineral soil which will pass a 2-mm sieve is considered.

A particular problem with desert soils is that they often contain appreciable amounts of coarse fragments (or stones as these will be referred to in this paper). Bulk density measurements in such soils are difficult because stones impose sampling problems and introduce errors in the determination (Curtis and Post, 1964; Reigner and Phillips, 1964; Shipp and Matelski, 1965; Cunningham and Matelski, 1968). When measuring soil moisture of a stony sample by the direct gravimetric method, adjustments must be made for the weight and moisture content of the stones (Coile, 1953). Further, stone volumes and bulk densities must be known to convert gravimetric water contents to soil moisture volumes (Reinhart, 1961).

There is no mention in the literature of the effect of stones on soil moisture movement in general and on hydraulic conductivity in particular.

Stones would tend to restrict moisture movement by reducing the area available for flow and by increasing the tortuosity of the medium. The increase in tortuosity is probably negligible, especially at low matric potentials because moisture movement takes place in small, tortuous pores. While the reduction in cross-sectional area available for flow is variable from place to place in a soil profile and would depend on the size, shape, and orientation of individual stones, it can be estimated by making it proportional to the volume of soil occupied by stones.

The purpose of this study was to determine whether unsaturated hydraulic conductivity of stony soils could be evaluated using samples of the same soils in which the stony fraction (>2 mm) had been excluded.

MATERIALS AND METHODS

The hydraulic conductivity of three desert soils was measured by the transient outflow method of Weeks and Richards (1967). This method was chosen because it is relatively fast, does not require much specialized equipment, and can be quite easily extended beyond the tensiometer range to cover relatively dry conditions.

The soil materials used in this study are described in Table 1. Samples were dug from the first 25- to 50-cm layer of the profiles and placed in 20-liter containers for shipment to the laboratory. Undisturbed samples were impossible to take owing to the stoniness of these soils. Field bulk density (ρ_T) was determined according to the procedure known as the rubber balloon method (Blake, 1965). The samples were dry sieved into separates <2 mm, 2 to 4 mm, 4 to 9.51 mm, and >9.51 mm in diameter. Size classes > 2 mm were chosen arbitrarily. Each size fraction was oven-dried, then weighed to determine its percentage on a total weight basis. The stone density (ρ_s) was determined by dividing weight by volume which was obtained by water displacement. The bulk density of the <2-mm fraction (ρ_b) was calculated from an equation based on the following reasoning.

Consider a unit volume of soil containing stones whose total weight is d grams. If the ratio of the weight of soil <2 mm in diameter to the total weight of the sample is W, then the unit volume of soil can be represented by the expression

$$\text{unit volume of soil} = \frac{d}{\rho_T} = \frac{Wd}{\rho_b} + \frac{(1-W)\,d}{\rho_s}. \qquad [1]$$

Solving the second and third terms of Eq. [1] for ρ_b yields

$$\rho_b = \frac{\rho_s \rho_T W}{\rho_s - \rho_T (1-W)}. \qquad [2]$$

Bulk density data are reported in Table 2.

Air-dry soil material was packed into acrylic plastic columns, 10 cm in diameter by 30 cm in length, with a piece of acrylic plastic taped at one end to form a soil container. To achieve a packing density similar to the field bulk density, a preweighed

[1] Contribution of the Department of Soil Sci. & Agr. Eng., Univ. of Calif., Riverside 92502. This work was supported in part by funds from the National Science Foundation under IBP Desert Biome, Utah State Univ., Ecology Center, Subcontract no. 539. Presented before Div. S-1, Soil Science Society of America meetings, 14 Nov. 1973, Las Vegas, Nev. Received 1 May 1974. Approved 18 Oct. 1974.

[2] Former Research Assistant, Professors of Soil Physics, and Staff Research Associate, respectively. Senior author is now Research Scientist, Canada Agriculture, 2560 Chemin Gomin, Ste-Foy, Quebec G1V 2J3, Canada.

Table 1—Fractionation analysis of fine and coarse fragments of the soils studied

Soil series (USDA Classification)	Sampling depth	Texture	Particle size analysis: Clay <2 μm	Silt 2-50 μm	Sand >50 μm	Coarse fragments: Fines <2 mm	Stones: 2-4 mm	4-9.5 mm	>9.5 mm
	cm		% of <2 mm fraction			% on total weight basis			
Rock Valley* (Entic Durorthid)	0-50	Gravelly loamy sand	4.2	18.4	77.4	61.9	4.8	9.8	23.5
Tubac† (Typic Paleargid)	2-25	Gravelly sandy loam	13.2	18.3	68.5	73.1	8.9	8.6	9.5
Rillito† (Typic Calciorthid)	2-30	Gravelly sandy loam	12.3	12.4	75.3	66.2	10.9	9.0	13.9

* Not a recognized soil series, name indicates neighborhood of samples (Nevada Test Site, Mojave Desert).
† Sonoran Desert, Silverbell, Arizona.

amount of material was added to fill one 2-cm section of the column at a time and was tapped level with markings on the outside wall of the column. This procedure insured uniform packing and very little migration of the fine material towards the bottom of each section. For those columns that were to contain stones, each increment was filled with the relative proportions of fine and coarse materials shown in Table 1. This permitted reconstitution of the field soil in a reproducible, although somewhat arbitrarily uniform manner. To facilitate later insertion of instrumentation, cavities were maintained behind the port holes in the plastic column by inserting tensiometer cups during the packing process. Once a column was filled, the cups were removed and the cavities filled with fine material before adding water.

The equipment and procedures used to measure hydraulic conductivity were similar to those described by Weeks and Richards (1967), except for some changes that were necessary to extend the method beyond the tensiometer range. A predetermined amount of tap water was added to the air-dry soil and each column was left to equilibrate for 2 days. A cell, consisting of a ceramic plate fitting the inside diameter of the column and glued to a hollowed piece of acrylic plastic, was pressed against the soil and held in place with silicone sealant. The column was then placed horizontally on a stand. Tensiometers were inserted at 2.5, 5, 10, and 20 cm from the porous cell wall. Additional water was added through a burette connected to the ceramic cell under a controlled suction of 30 cm of water until all tensiometers showed the same reading.

At a convenient time ($t = 0$), water was withdrawn through the ceramic cell by applying a constant suction of 0.7 bars. Volume of outflow was recorded at the burette, together with the tensiometer readings and time, every hour for the first 8 hours, at $t = 24$ hours, and once a day thereafter. As the soil dried out, the controlled suction was first increased to 0.9 bars, then the ceramic cell and attached burette were removed and replaced by a perforated copper disc to prevent rapid loss of water from the column. The latter was finally removed and the column was left to evaporate freely into the ambient atmosphere. After removal of the cell and burette, the volume of outflow was recorded by weighing the entire apparatus. Atmospheric pressure was maintained inside the column at all times through a small hole drilled at the opposite end of the column from which water was withdrawn.

The experiments were conducted in a room where the temperature was controlled at 23 ± 1C. Relative humidity was not controlled but remained at 50 ± 10%.

Table 2—Some physical properties of the soils studied

Soil series	Bulk densities: Field ρ_T	Stones ρ_s	Soil* ρ_b	EC_e
	g cm^{-3}			mmhos cm^{-1}
Rock Valley	1.79	2.59	1.50	0.66
Tubac	1.86	2.60	1.68	0.61
Rillito	1.88	2.56	1.66	0.34

* Calculated from Eq. [2].

As each tensiometer went off scale, it was replaced by a soil thermocouple psychrometer that had previously been calibrated in standard KCl solutions at 25C. Soil temperature was measured at the time of the psychrometric reading with a copper-constantan thermocouple built into the instrument. Psychrometer outputs were corrected to 25C from the relation (Brown, 1970)

$$\text{Corrected reading at 25C} = \text{Reading}/(0.027T + 0.325) \quad [3]$$

where T is the measured psychrometer temperature in degrees C. For these soils the osmotic pressure component, as measured by psychrometers, was negligible since the electrical conductivities of the saturated extracts were low (Table 2). The volumetric water content for these soils is approximately 40 and 6.5% at saturation and −50 bars matric potential, respectively. This represents a sixfold concentration of the soil solution. Considering all solutes to remain in solution, an EC_e of 0.6 mmhos cm^{-1} would result in only −1.3 bars osmotic potential for −50 bars total soil water potential measured by a soil psychrometer.

When the soil psychrometer closest to the drying end of the column went off scale (at −50 bars approximately), the soil column was cut into 2-cm sections. These were placed in cans, weighed, oven-dried, and reweighed to determine final water contents and bulk density. From the total water content (volume of water) of the column at the end of the run, total water contents for each time were calculated from the weight or burette records. It was not always possible to cut stony columns exactly into 2-cm sections. However, only the amount of water held in the soil column at the end of a run is required in subsequent calculations. In such cases, sectioning served merely to speed up oven-drying. The average time required to complete a run was 31 days excluding the time to prepare the soil columns.

Calculations of hydraulic conductivity were carried out on an IBM 360/50 Data Processing System using a program written in the Fortran IV language. Input data to this program include, for each time, the four matric potential values (in millibars or cm of water), the total water content of the column (cm^3), and time (hours). Hydraulic conductivity was calculated for each time and position by dividing the rate of flow past a given section of the column by the hydraulic head gradient at that point. For a detailed description of how these values were obtained, the reader is referred to Weeks and Richards (1967). [Their Eq. [6], p. 722, should read . . . $(1 + n_t b_j)$ instead of $(1 \times n_t b_j)$.]

The same calculations were performed for columns containing stones as for those that did not. Water contents were calculated on a total volume basis, including stones when present. Since stones hold less water per unit volume than the soil fraction, this procedure resulted in an underestimation of the actual water content in the soil portion of stony samples. Thus, water contents of stony and nonstony columns were not directly comparable. To correct water contents of nonstony samples as though stones were present, the data was rerun using a column volume increased in proportion to the volume of total soil occu-

pied by stones. The volume ratio of stones to total soil was computed from

$$\text{Volume ratio of stones} = (1 - W)\rho_T/\rho_s. \quad [4]$$

The required increase in column volume is achieved simply by dividing the actual volume by 1 − volume ratio of stones. In applying such a correction, the area available for flow is likewise increased. Thus, for an equivalent amount of water passing any plane in a nonstony column the flow velocity is reduced, which in turn results in decreased hydraulic conductivity values. This decrease is included in the calculation of hydraulic conductivity of a stony sample, because the total volume of the stony column is used.

Samples of the Rock Valley soil were run in triplicate without stones and in duplicate with stones. In addition, one column containing only the largest size fraction of stones (>9.51 mm) was also run. No replication was made for the Tubac and Rillito series.

RESULTS AND DISCUSSION

In considering replicated columns of a particular soil, it is essential that the bulk densities be as similar as possible. Furthermore, a valid comparison of results observed on samples containing all size fractions with those obtained on samples without stones is only possible if the packing densities of the < 2-mm fraction of the sample are in close agreement. The bulk densities found at the end of each run after sectioning the columns are reported in Table 3. The packing technique used to fill the soil containers resulted in fairly good replication of bulk densities. The ρ_T values for Rock Valley soil were slightly higher than the field values (Table 2), but slightly lower for the two other soils. With one exception, ρ_b values of stone-free columns were higher than calculated values in Table 2.

The volumetric water content–matric potential relationships for each soil as calculated from the transient outflow method during desorption are presented graphically as solid and dashed lines in Fig. 1. Data points correspond to water contents determined experimentally at the end of a run for which the matric potential was known. While different

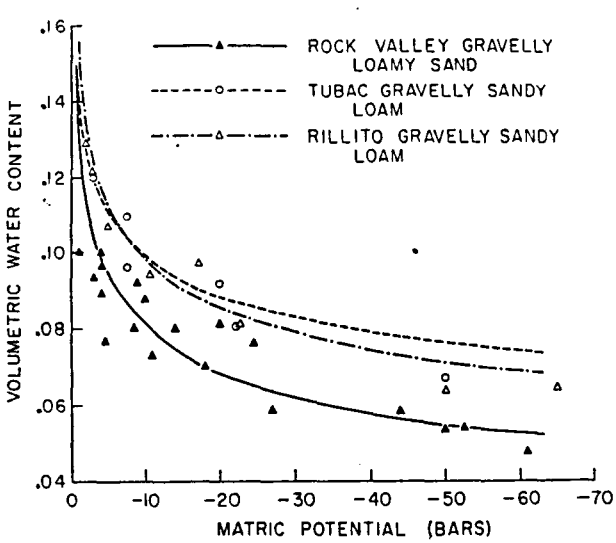

Fig. 1—Calculated moisture characteristic curves for three desert soils during desorption. Data points were obtained experimentally.

Table 3—Bulk densities achieved in laboratory soil columns

Soil series	Column no.	Weight ratio of stones >2 mm (1-W)	Bulk densities: Total* ρ_T	Stones† ρ_s	Soil‡ ρ_b
			g cm^{-3}		
Rock Valley	3	0			1.50
	6	0			1.56
	7	0			1.55
	4	0.235§	1.71	2.59	1.55
	5	0.381	1.83	2.59	1.55
	8	0.381	1.80	2.59	1.52
Tubac	9	0			1.72
	10	0.269	1.84	2.60	1.66
Rillito	11	0			1.69
	12	0.338	1.87	2.56	1.64

* Determined at end of each run.
† Measured.
‡ ρ_b for columns with stones calculated from Eq. [2].
§ >9.5-mm fraction only.

curves were calculated for Tubac and Rillito soils, there is little difference between the two as seen from the data points. The generally good agreement between experimental points and calculated curves leads to the conclusion that the transient outflow method can be readily extended to relatively dry soil systems. The assumption made by Weeks and Richards (1967) in developing their methodology that an exponential equation correctly describes the relationship between matric potential and volumetric water content appears to be valid over a much wider matric potential range than they initially investigated.

Unsaturated conductivity values (K) calculated for stony samples of Rock Valley and Tubac soils over the matric potential (h) range —0.05 to —50 bars are shown in Fig. 2. These are typical examples of the results obtained on these soils. Results for Rillito were very similar to those for Tubac. The experimental points for K as a function of h are given for three positions along the column corresponding to distances of 2.5, 5, and 10 cm from the drying end.

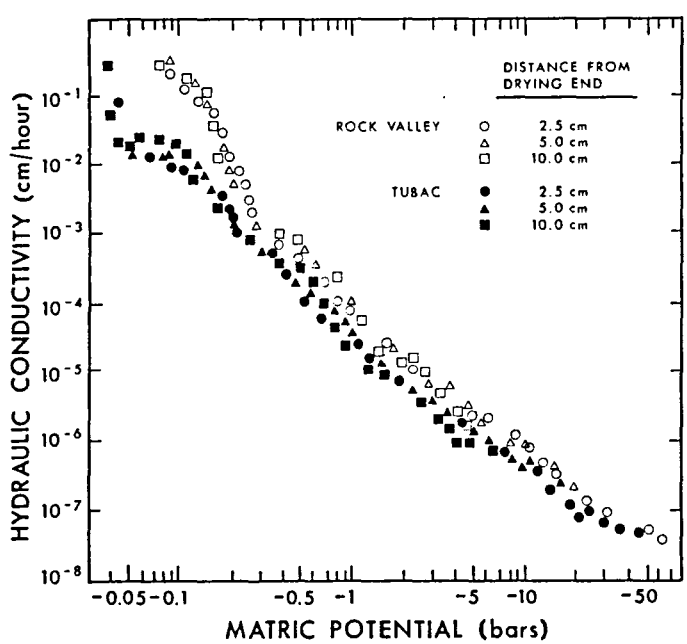

Fig. 2—Experimental points given for unsaturated hydraulic conductivity at three positions and plotted as a function of matric potential for stony samples of Rock Valley and Tubac soils.

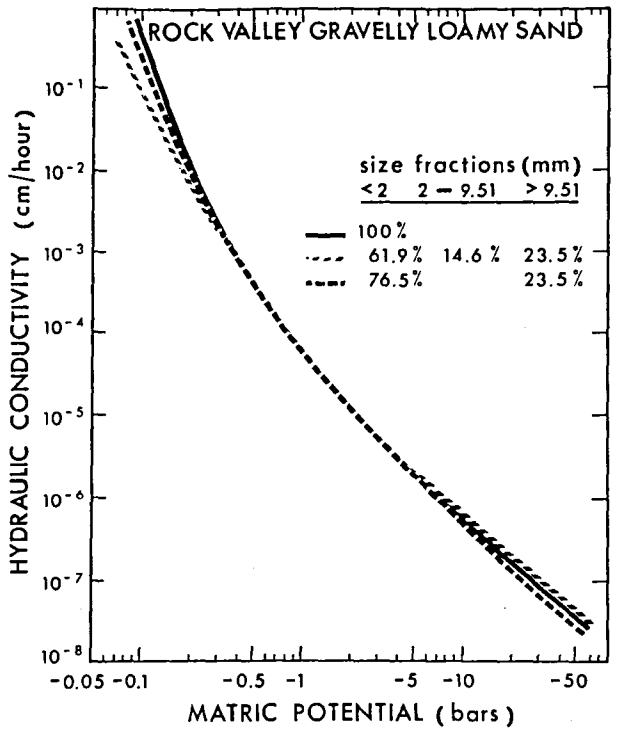

Fig. 3—Hydraulic conductivity as a function of matric potential for stony and non-stony samples of Rock Valley gravelly loamy sand, curves represent the average of replicates.

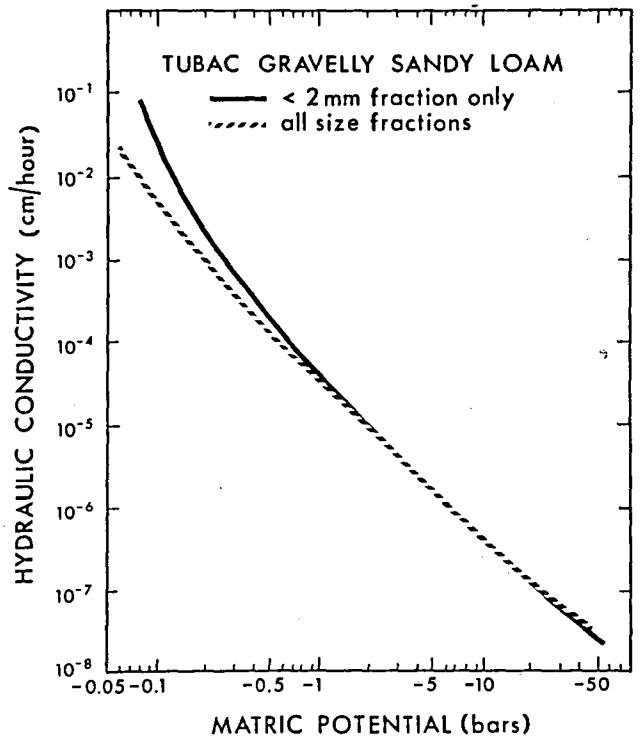

Fig. 4—Hydraulic conductivity as a function of matric potential for stony and non-stony samples of Tubac gravelly sandy loam.

Some replication is obtained with the transient outflow method because similar values of h occur at different positions along the column at different times. Since the experimental points for different positions but similar h values are in close agreement, the extension of the transient outflow method to matric potentials beyond the tensiometer range is further justified.

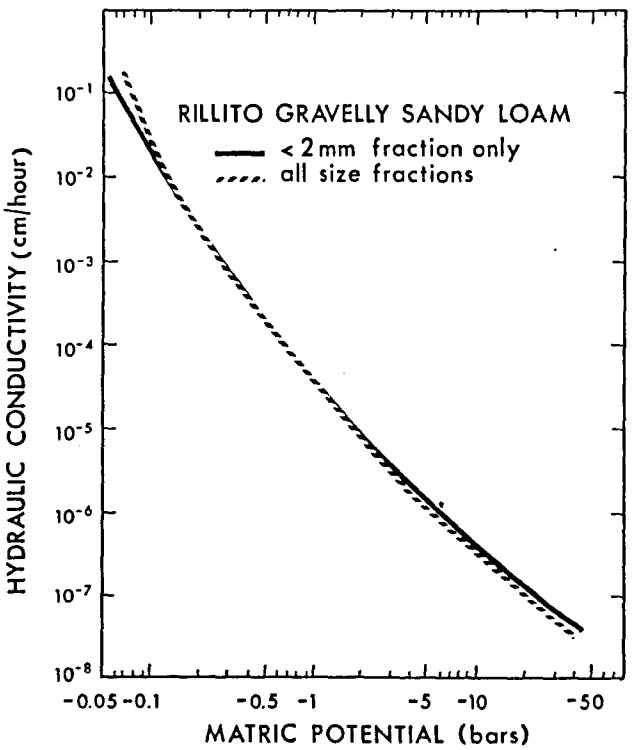

Fig. 5—Hydraulic conductivity as a function of matric potential for stony and non-stony samples of Rillito gravelly sandy loam.

Plots similar to those shown in Fig. 2 were obtained for each soil column. Distinguishing between nonstony and stony cases, "best-by-eye" fit curves were drawn through all data points. Replicates were averaged in the case of Rock Valley soil. As a measure of variability of K, the mean relative error between replicates and the average curve was 25% (max. = 56%) for stone-free columns and 10% (max. = 34%) for stony columns. There is little difference between stony and nonstony samples when hydraulic conductivity is expressed as a function of matric potential (Fig. 3, 4, and 5). As shown in Fig. 3, even varying the weight ratio of stones to total soil from as much as 38.1 to 23.5% has no effect on the relationship between K and h.

In the case of Tubac soil (Fig. 4), agreement between stony and nonstony samples is not so good, especially at matric potential values > —1 bar. In the dryer range, the curves tend to be quite similar. Tensiometers or thermocouple psychrometers measure the water potential of the soil fraction only since they do not come in contact with stones. The measured matric potentials should therefore not be affected by the presence of stones, as was indeed found with Rock Valley and Rillito (Fig. 3 and 5).

When unsaturated hydraulic conductivity is expressed as a function of volumetric water content, distinct curves are obtained for stony and nonstony samples (Fig. 6, 7, and 8). For the Rock Valley soil in Fig. 6, each line represents the average of replicates. For similar K values, water contents are always higher when stones are excluded be-

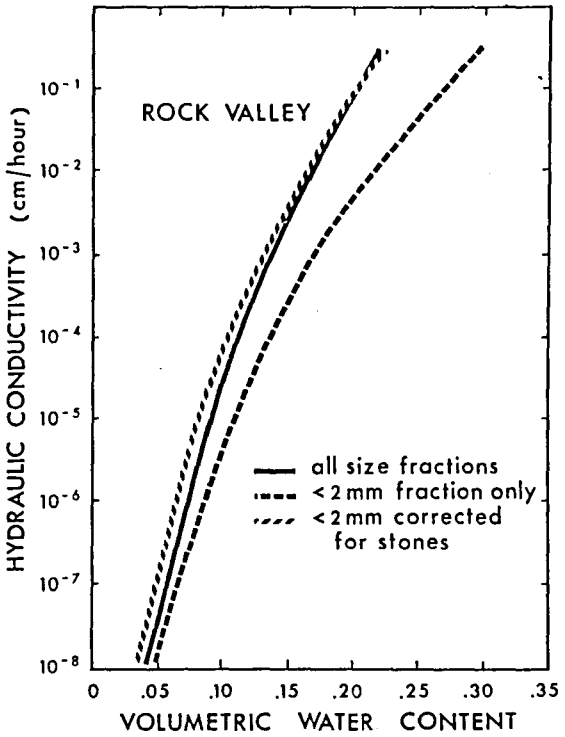

Fig. 6—Relation between hydraulic conductivity and volumetric water content for Rock Valley gravelly loamy sand with and without stones. Curves represent the average of replicates.

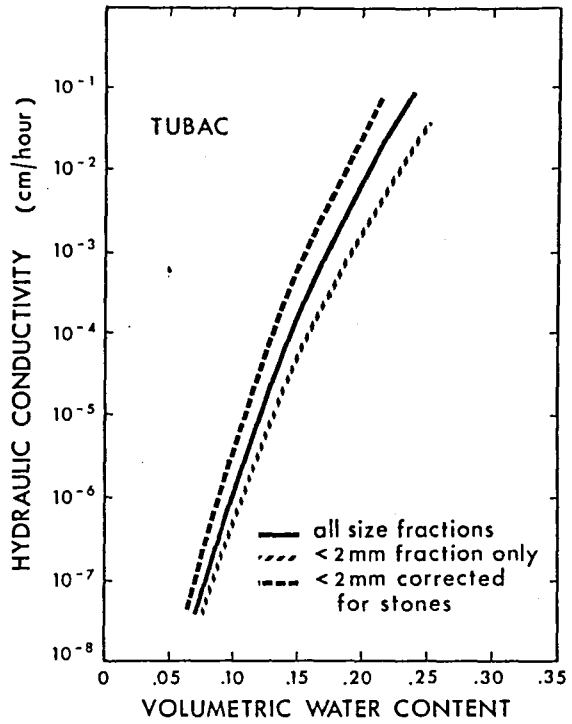

Fig. 7—Relation between hydraulic conductivity and volumetric water content for Tubac gravelly sandy loam with and without stones.

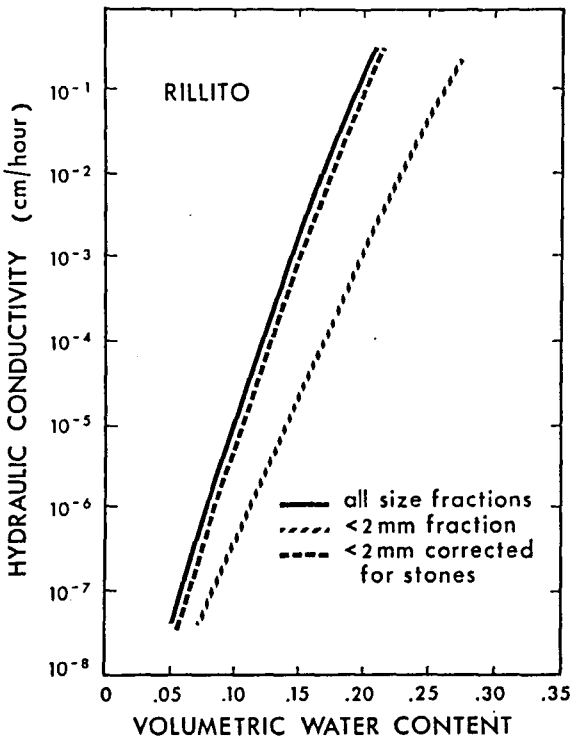

Fig. 8—Relation between hydraulic conductivity and volumetric water content for Rillito gravelly sandy loam with and without stones.

cause, in the transient outflow method, volumetric water contents are calculated on the basis of the total volume of the column. In other words, stones are considered to hold as much water as the soil portion does. But stones hold much less water than soil at comparable matric potentials, so that the water contents of the soil fraction computed for soil samples containing stones are underestimated. With increasing water content, the underestimation also increases.

It is not implied that water contents for stony soil based on total volume are erroneous. These are the values that a field worker would obtain by direct gravimetric sampling or from neutron probe readings. Therefore, on the assumption that the stony fraction did not absorb water, hydraulic conductivity curves for samples without stones were redrawn by correcting water contents as though stones were present. For Rock Valley and especially Rillito (Fig. 6 and 8), the correction appears to be appropriate. For Tubac (Fig. 7), the $K(\theta)$ curve was overcorrected.

It is difficult to explain the behavior of this latter soil. The fit between stone-free and stony samples of this soil was not good when K was expressed as a function of h. While there is good reason to believe it should have been better and therefore also K vs θ, the validity of the assumption that stones do not absorb water at all may be questionable. It is probably only correct for quartz gravel but is not necessarily true for rock composed of other minerals in various stages of weathering. For example, Reinhart (1961) estimated that stones in the Fernow Forest of West Virginia, which are derived from sandstone and shale, usually had a gravimetric water content of 6.5%. Furthermore, moisture content of stones may vary appreciably with soil water content and thus the correction used would be different at different moisture levels. Coile (1953) prepared a simple regression graph relating moisture content of stone to uncorrected soil water content for soils derived from

Table 4—Volumetric water content of stones at various soil matric potentials

Soil series	Soil matric potential			
	0	-1	-5	-15
	$cm^3 cm^{-3}$			
Rock Valley	0.041	0.039	0.029	0.028
Tubac	0.076	0.053	0.049	0.048
Rillito	0.090	0.060	0.044	0.043

various and differing parent materials. Unfortunately, his data are restricted to relatively wet moisture levels. His regression line indicates that at zero moisture content of total soil (stones included), stones would have a moisture content close to 4% by weight. Hence, Coile's correction is useless at the water contents encountered in this study.

In order to estimate what the magnitude of the correction would be, separate stone samples of each soil were equilibrated at various matric potentials to —15 bars in pressure plate apparatus (Table 4). As expected, the moisture content of stones is significantly less than in soil, but the shape of the water release curves from stones is similar to that of the finer soil material. After a rapid decrease in moisture content, from saturation to —5 bars, moisture release becomes very slow with a further decrease in matric potential.

Although examination of Fig. 7 reveals a greater overcorrection at high than at low water contents, the amount of water held by the stones is insufficient to account for the overcorrection. The lack of agreement found in Fig. 4 and 7 for Tubac could result from different bulk densities achieved in the stony and stone-free columns (Table 3). Had the two columns been packed at the same density of 1.66 g cm^{-3}, water contents in the stone-free column would have been higher. A lower bulk density increases the amount of large pores which are only filled with water at high water contents. Therefore, a larger increase in water content would be expected at high than at low moisture levels, which is confirmed by the data in Fig. 7. Similarly, matric potential would be reduced and the curves of Fig. 4, would come closer to each other. However, the differences observed with Tubac soil cannot be entirely explained on the basis of a bulk density effect as the difference in bulk density (ρ_b) between stone-free and stony columns of Rillito soil was nearly as large. Replication might have provided better agreement.

In conclusion, a simple correction of water contents and of the area available for flow would be sufficient in most cases to account for the presence of stones. If the amount of water held by stones was known as a function of soil water content, then a progressive correction could be applied to values obtained on columns without stones. But this refinement is probably not necessary in practice. On the other hand, if K is expressed as a function of h, unsaturated hydraulic conductivity values obtained by the transient outflow method on columns of soil with stones excluded provide a good estimate of the values that would be obtained if stones were present, without any special treatment of the data, providing care is taken to pack the laboratory columns to the same bulk density as the field soil.

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PAPER NO. PNR-84-203

MODIFYING SCS HYDROLOGIC SOIL GROUPS AND CURVE NUMBERS FOR RANGELAND SOILS

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For presentation at the 1984 Annual Meeting
AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS
PACIFIC NORTHWEST REGION

Cavanaugh's Motor Inn
Kennewick, WA
September 26-28, 1984

SUMMARY:

Procedures are proposed for determining SCS hydrologic soil groups and curve numbers for rangeland soils. The procedures utilize the SCS Soils-5 data base and previously developed infiltration research results. An example for the USDA-ARS Reynolds Creek research watershed in Idaho is presented.

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Modifying SCS Hydrologic Soil Groups and Curve Numbers for Rangeland Soils[1]

D. L. Brakensiek, W. J. Rawls, and G. R. Stephenson[2]

Alternative determinations of SCS hydrologic soil groups (HSG) and runoff curve numbers (CN) procedures are presented along with examples. The procedure utilizes the SCS Soils-5 data base. Use of this data base is facilitated by SIRS (Soils Information Retrieval Systems) facilites use of this data base.

SOILS DATA

The SCS Soils-5 file represents the largest and most available U.S. soils data bank. SIRS has now greatly facilitated access to Soils-5. Since the Soils-5 data file does not include certain soil water properties such as percent sand, R. B. Grossman of the National Soils Survey Laboratory, SCS, Lincoln, Nebraska, developed expressions for calculating these quantities from the Soils-5 data. He cautions that the exactness of the approximations may vary and that they should only be used if measurements for particular properties are unavailable.

Table 1 presents Soils-5 property entries from SIRS for the Searla soil series (found on the Reynolds Creek watershed in Idaho). We have added a letter code for reference to the following calculations. Necessary soil properties which we require but are not available on SOILS 5 are: Z1, the percent of fragments < 250 mm, > 2 mm by weight, and Z5, the percent sand.

These can be calculated from the Grossman expressions as,

$$Z1 = E + \left[\left(1 - \frac{E}{100}\right)(100 - G)\right], \qquad (1)$$

where

E = percent fraction greater than 3 inches (E),
G = percent material less than 3 inches passing sieve #10 (G),
and

---

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TABLE 1. SOILS-5 FILE FOR SEARLA SOIL SERIES

--*-*-*-*-*-*-*-*-*-*

searla (id0929)cool

mlra(s): 25
rev. th,ghl , 12-82
calcic argixerolls, loamy-skeletal, mixed, frigid

the searla series consists of very deep well drained soils that formed in colluvium from sedimentary rocks on mountains. elevation is 5500 to 6900 feet. aap is 14 to 16 ihes. mast is 42 to 45 f. ffs is 50 to 70 days. vegetation is mountain big sagebrush and bluebunch wheatgrass. typically the surface layer is brown gravelly loam 15 inches thick. the subsoil is yellowish brown very gravelly clay loam to 32 inches. the substratum is white very gravelly loam and very pale brown very gravelly sandy loam to 60 inches. slopes are 30 to 60 percent.

--*-*-*-*-*-*-*-*-*-*

searla (id0929)cool

A depth (in.)	B texture	C unified	D aashto	E fract > 3in (pct)	F percent of material less than 3 in passing sieve no. 4	G 10	H 40	I 200	J liquid limit	K plast'y index	M clay %<2mm	N moist bulk density (g/cm3)
0-15	gr-l	sm-sc,gm-gc	a-4	5-10	65-85	60-80	45-60	35-50	25-30	5-10	12-20	1.40-1.50
15-32	grv-cl	gc	a-2	5-15	45-60	35-50	25-40	20-35	30-40	10-15	27-35	1.40-1.50
32-60	grv-l,grv-sl	gm-gc	a-1,a-2	0-15	35-60	25-50	15-35	10-30	25-30	5-10	10-22	1.50-1.60

O permea- bility (in/hr)	P available water (in/in)	Q soil reaction (ph)	R salinity mmhos/cm	S shrink- swell	T erosion factors k	U t	V wind erod. group	W organic matter (pct)
0.6-2.0	0.13-0.16	6.6-7.3	-	low	.15	2	6	2-4
0.2-0.6	0.10-0.13	6.6-7.3	-	low	.10			
0.6-2.0	0.05-0.07	7.4-8.4	< 2	low	.05			

$$Z5 = 100 - \frac{100\ I}{G} \qquad (2)$$

where

I = percent material less than 3 inches passing sieve #200 (I).

PROPOSED HYDROLOGIC SOIL GROUP (HSG) PROCEDURES

Our procedure for determining the HSG is based on knowing the percent sand and clay, and soil porosity. If Soils-5 data are used, then the percent sand (Z5) is calculated by equation (2).

Calculation of the soil porosity from the moist bulk density (N), if not given in Soils-5, is computed as follows:

1 - Enter Fig. 1 with the percent sand (Z5) and clay (M) and read the mineral bulk density.

2 - Use the equation in Fig. 1 to calculate the Soil Bulk Density (SBD) with an appropriate percent of organic matter (OM) (W).

3 - Calculate the total porosity as,

Porosity = 1 - SBD/2.65.

If the Soils-5 data contains bulk density, then calculate the porosity from that value. With the inputs of percent sand and clay and porosity, enter the computer program shown in Table 2 to determine the fine earth fabric saturated conductivity, KS. Table 3 presents a sample output. For our purposes, only the KS from the output is needed.

With the saturated hydraulic conductivity (KS) known, determine the hydrologic soil group (HSG) from Table 4. Rangeland soils may require a modification due to conditions, such as stone or coarse fragment content, soil compaction, or frozen soils. These modifications are considered in the next section. The saturated conductivity limits for A, B, C, and D were taken from Musgrave (1955).

Wood and Blackburn (1984) indicated that the hydrologic soil groupings should be "greatly modified" for use in arid and semiarid rangelands, especially to make more use of surface soil properties.

RANGELAND SOIL MODIFICATIONS

Coarse Materials

Rangeland soils, such as those on the Reynolds Creek Watershed, contain significant amounts of coarse fragments. From work by Bouwer and Rice (1983) and unpublished SCS Soils-5 based equations, developed by Grossman (1983), a relationship was developed for calculating the soil porosity for the bulk soil containing coarse fragments,

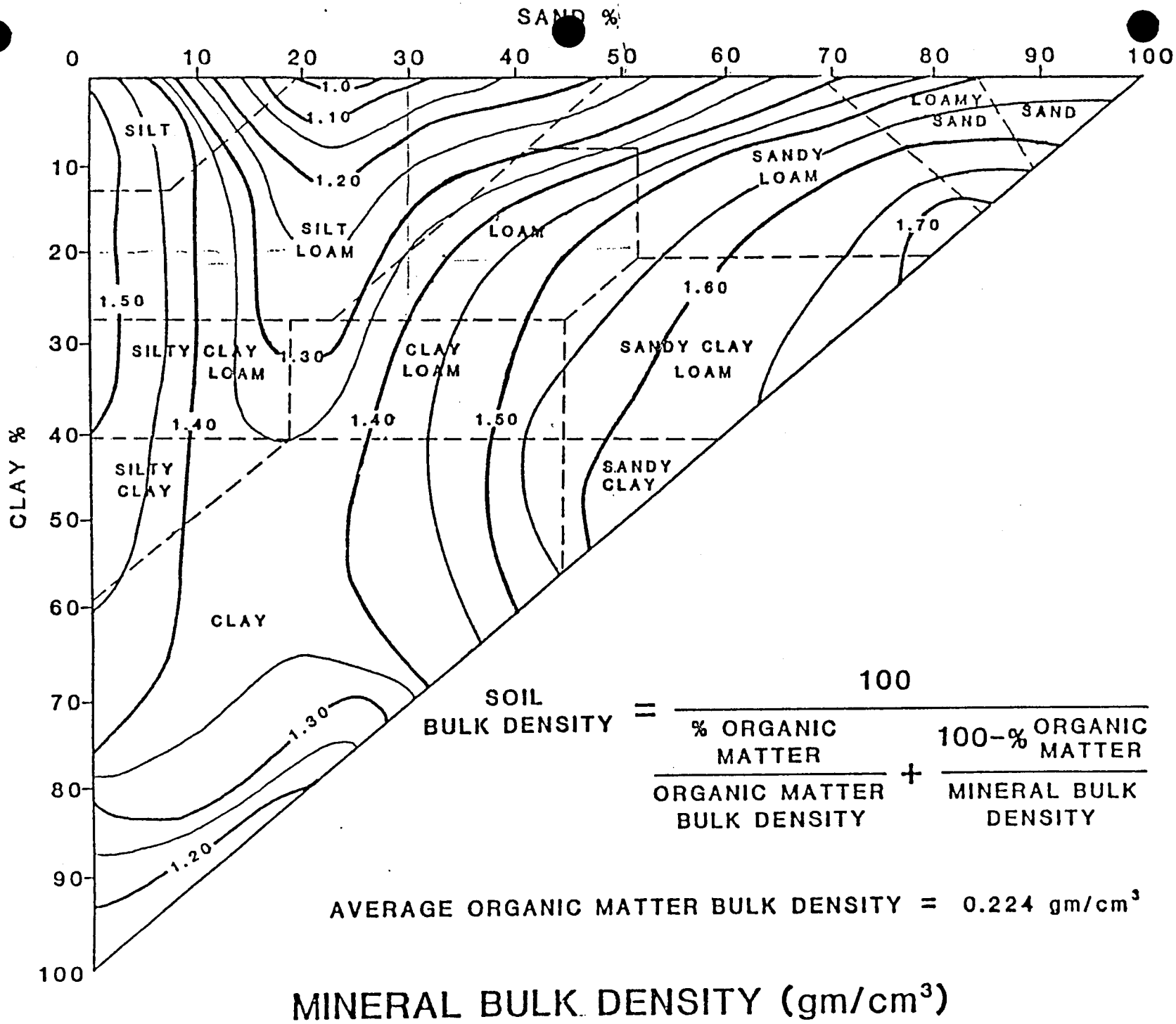

Fig. 1--Determination of soil bulk density.

TABLE 2. PROGRAM TO FIND SOIL PARAMETERS

POR = POROSITY PS = PERCENT SAND = % SAND PC = PERCENT CLAY = % CLAY

```
      REAL*4 Ks,Yf,Qe,Qr,Yb,LAM
      CHARACTER*1 ANS
10    WRITE(6,20)
20    FORMAT(/,/,5X,'$ ENTER THE POROSITY: ',$)
      ACCEPT*, POR
      IF(POR .LT. 0.0 .OR. POR .GT. 1.0) GO TO 150
30    WRITE(6,40)
40    FORMAT(/,5X,'$ ENTER THE % OF SAND: ',$)
      ACCEPT*, SAND
      IF(SAND .LT. 5.0 .OR. SAND .GT. 70.0) GO TO 170
50    WRITE(6,60)
60    FORMAT(/,5X,'$ ENTER THE % OF CLAY: ',$)
      ACCEPT*, CLAY
      IF(CLAY .LT. 5.0 .OR. CLAY .GT. 60.0) GO TO 190
      PS=SAND
      PC=CLAY

    EQUATIONS DESCRIBING GREEN-AMPT PARAMETER CHARTS

      Qe=0.01162-0.001473*PS-0.002236*PC+0.98402*POR+0.0000987*PC**2
     1+0.003616*PS*POR-0.010859*PC*POR-0.000096*PC**2*POR-0.002437*
     2POR**2*PS+0.0115395*POR**2*PC

      Yf=6.5309-7.32561*POR+0.001583*PC**2+3.809479*POR**2+0.000344*
     1PS*PC-0.049837*PS*POR+0.001608*PS**2*POR**2+0.001602*PC**2*
     2POR**2-0.0000136*PS**2*PC-0.003479*PC**2*POR-0.000799*PS**2*POR

      Yf = EXP(Yf)

      Ks=19.52348*POR-8.96847-0.028212*PC+0.00018107*PS**2-0.0094125*
     1PC**2-8.395215*POR**2+0.077718*PS*POR-0.00298*PS**2*POR**2-
     20.019492*PC**2*POR**2+0.0000173*PS**2*PC+0.02733*PC**2*POR+
     30.001434*PS**2*POR-0.0000035*PC**2*PS

      Ks = EXP(Ks)

      Qr=-0.0182482+0.00087269*PS+0.00513488*PC+0.02939286*POR
     1-0.00015395*PC**2-0.0010827*PS*POR-0.00018233*(PC**2)*
     2(POR**2)+0.00030703*(PC**2)*POR-0.0023584*(POR**2)*PC

      LAM=-0.7842831+0.0177544*PS-1.062498*POR-0.00005304*PS**2
     1-0.00273493*PC**2+1.11134946*POR**2-0.03088295*PS*POR
     2+0.00026587*(PS**2)*(POR**2)-0.00610522*(PC**2)*(POR**2)
     3-0.00000235*(PS**2)*PC+0.00798746*(PC**2)*POR-0.00674491
     4*(POR**2)*PC

      LAM = EXP(LAM)
```

TABLE 2. PROGRAM TO FIND SOIL PARAMETERS (CONT.)

```
      Yb=5.3396738+0.1845038*PC-2.48394546*POR-0.00213853*
      1PC**2-0.04356349*PS*POR-0.61745089*PC*POR+0.00143598
      2*(PS**2)*(POR**2)-0.00855375*(PC**2)*(POR**2)-0.00001282*
      3(PS**2)*PC+0.00895359*(PC**2)*POR-0.00072472*(PS**2)*POR
      4+0.0000054*(PC**2)*PS+0.50028060*(POR**2)*PC

      Yb = EXP(Yb)
---------------
      BARTHD=.1535-.0018*PS+.0039*PC+.1943*POR
      BAR15 =.0370-.0004*PS+.0044*PC+.0482*POR

    OUTPUT SECTION

      WRITE(6,70) POR,SAND,CLAY
 70   FORMAT(/,/,/,12X,'POROSITY',5X,'% SAND',5X,'% CLAY',/,
      112X,F7.5,6X,F6.2,5X,F6.2)
      WRITE(6,80) Qe
 80   FORMAT(/,/,5X,'EFFECTIVE POROSITY = ',F7.4)
      WRITE(6,85) LAM
 85   FORMAT(/,5X,'POROSITY INDEX      = ',F7.4)
      WRITE(6,90) Yf
 90   FORMAT(/,5X,'WETTING FRONT CAPILLARY PRESSURE = ',F10.4,' cm')
      WRITE(6,100) Ks
 100  FORMAT(/,5X,'SATURATED HYDRAULIC CONDUCTIVITY = ',F10.5,' cm/hr')
      WRITE(6,110) BARTHD
110   FORMAT(/,5X,'ONE THIRD BAR WATER CONTENT      = ',F10.4)
      WRITE(6,120) BAR15
120   FORMAT(/,5X,'15 BAR WATER CONTENT             = ',F10.4)
      WRITE(6,125) Qr
125   FORMAT(/,5X,'RESIDUAL WATER CONTENT           = ',F10.4)
      WRITE(6,126) Yb
126   FORMAT(/,5X,'BUBBLING PRESURE                 = ',F10.4,' cm')
      WRITE(6,130)
 130  FORMAT(/,/,/,5X,'$ WOULD YOU LIKE TO CALCULATE ANY MORE?(y/n) ',$)
      READ(5,140) ANS
 140  FORMAT(A1)
      IF(ANS .EQ. 'Y' .OR. ANS .EQ. 'y') GO TO 10
      STOP

    ERROR CHECKING

 150  WRITE(6,160)
 160  FORMAT(/,/,5X,'ERROR IN POROSITY,  value must be > 0 and < 1')
      GO TO 10
 170  WRITE(6,180)
 180  FORMAT(/,/,5X,'ERROR IN PERCENTAGE OF SAND, value must be > 5 and
      1 < 70')
      GO TO 30
 190  WRITE(6,200)
 200  FORMAT(/,/,5X,'ERROR IN PERCENTAGE OF CLAY, value must be > 5 and
      1 < 60')
      GO TO 50
      END
```

TABLE 3. SAMPLE OUTPUT

```
RUN SOILS

   $ ENTER THE POROSITY: 0.45

   $ ENTER THE % OF SAND: 39

   $ ENTER THE % OF CLAY: 16


         POROSITY      % SAND      % CLAY
         0.45000        39.00       16.00

   EFFECTIVE POROSITY =  0.3788

   POROSITY INDEX     =  0.3460 (GREEN AND AMPT λ)

   WETTING FRONT CAPILLARY PRESSURE =    21.1312 cm (GREEN AND AMPT ψf)

   SATURATED HYDRAULIC CONDUCTIVITY =    0.59637 cm/hr

   ONE THIRD BAR WATER CONTENT      =     0.2331

   15 BAR WATER CONTENT             =     0.1135

   RESIDUAL WATER CONTENT           =     0.0710 (GREEN AND AMPT Θr)

   BUBBLING PRESURE                 =    27.4790 cm


   $ WOULD YOU LIKE TO CALCULATE ANY MORE?(y/n) N

FORTRAN STOP
```

Table 4.--SCS hydrologic soil groups for saturated conductivity (KS) classes.

HSG (KS cm/hr)	Description
A (0.76-1.14)[1]	(Low runoff potential). Soils having high infiltration rates even when thoroughly wetted and consisting chiefly of deep, well to excessively drained sands or gravels. These soils have a high rate of water transmission.
B (0.38-0.76)	Soils having moderate infiltration rates when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.
C (0.13-0.38)	Soils having slow infiltration rates when thoroughly wetted and consisting chiefly of soils with a layer than impedes downward movement of water, or soils with moderately fine to fine texture. These soils have a slow rate of water transmission.
D (0.0-0.13)	(High runoff potential). Soils having very slow infiltration rates when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very slow rate of water transmission.

[1]It is assumed that a KS greater than 1.14 cm/hr is an "A" soil.

$$\phi_c = (1 - \frac{Z1}{100}) / (\frac{1}{\phi} - \frac{Z1}{100}) \quad (3)$$

where

ϕ_c = the bulk soil porosity (with coarse fragments),
ϕ = fine earth fabric, < 2 mm, porosity, and
Z1 = percent by weight of the soil material > 2 mm and < 250 mm,

where Z1 is calculated from Soils-5 data by equation (3). The value of ϕ is the porosity determined from Fig. 1 by the procedure described in the text or taken from the Soils-5 data file.

Equation (4) was also derived from the results of Bouwer and Rice (1983). The saturated conductivity can be calculated for the soil containing coarse fragments, K_c, from the conductivity of the fine earth fraction, KS, and the percent by weight of coarse fragments, Z1. If Z1 is not known it is calculated by equation (1).

$$K_c = (1 - \frac{Z1}{100}) KS \quad (4)$$

The value of K_c is entered in Table 4 and a hydrologic soil group is determined for the bulk soil. The computer program in Table 2 can be entered with ϕ_c to determine bulk soil properties other than the saturated hydraulic conductivity, which is determined by equation (4). Equation (4) is also similar to one derived by Peck and Watson[3]. Additional research on gravels in soils is presented by Dunn and Mehuys (1984).

Compacted Soils

Soil bulk densities can change as a function of land use which induce compaction. As the bulk density increases the bulk soil porosity will decrease, which may change the HSG. Our procedure is simply to change the original bulk density by the percent change and compute a new porosity. The program in Table 2 is entered with a new porosity, and the calculated KS value is used in Table 4 to determine the HSG.

FROZEN SOILS

Frozen soil conditions frequently occur on rangelands. The following procedure was developed by Lee (1983) from his study of a frozen soil. He related the ratio of the frozen soil saturated conductivity $(KS)_f$ to the unfrozen soil KS as a function of antecedent soil water content. We have expressed his

[3]Peck, A. J., and J. D. Watson. 1979. Hydraulic conductivity and flow in non-uniform soil. Unpublished paper, presented at the Workshop on Soil Physics and Field Heterogeneity, Canberra, Australia, p. 31-36.

antecedent soil water factor as a percent of field capacity. One-third bar water contents are also estimated in our computer program. Equations (5a,b) present Lee's relationships,

$$(KS)_f/KS = 1.89 - 0.023\ (\%\ \text{of FC}), \quad \%FC < 78 \tag{5a}$$

and

$$= 0.1 \quad , \quad \%F > 78. \tag{5b}$$

For example, if it is estimated that the antecedent soil water content when the ground is frozen was 50 percent of field capacity, then by equation (5a)

$$(KS)_f/KS = 0.74.$$

Thus, if the original hydrologic soil group was "B", KS = 0.45 cm/hr, then

$$(KS)_f = 0.33 \text{ cm/hr}$$

and the HSG determined from Table 4 would be reduced to a "C" soil. Equations (5a,b) should be used very cautiously, since they are based on laboratory tests of only one soil texture. However, they do indicate the hydrologic importance of frozen soils.

SURFACE ROCK COVER

A thesis study by Dadkhah (1979) indicated that rock cover on the soil surface, from 0 percent to 20 percent, decreased the SCS curve number by nearly 10 percent. Apparently surface rock cover is a signficant factor to consider on rangeland curve number hydrology, but more research is needed to quantify its effect. The same thesis study also investigated the interactions of rock cover, vegetation cover, and soil compaction.

RANGELAND RUNOFF CURVE NUMBERS

Standard SCS procedures for determining rangeland CN's are given in Tables 8.1, 8.2, and 9.1 of their Hydrology Guide (SCS 1972). Inputs are land use treatment or practice, hydrologic condition, and hydrologic soil group (HSG). The HSG can be estimated by our procedure.

We propose an alternative procedure which uses the KS parameter directly, rather than the hydrologic soil group. We developed Fig. 2 by combining Tables 8.1, 8.2, and 9.1, and our Table 4. Fig. 2 would be entered with the estimated KS value and with an estimated hydrologic condition (HC), i.e., cover class. We are suggesting that HC can be estimated from percent cover. Based on SCS Table 8.2, the cover classes were defined as shown in Fig. 2 for bare, poor, fair, and good cover. The lines in Fig. 2 were oriented with the four points in their Table 9.1 representing the curve numbers for a bare, poor, fair and good HC plotted versus the mid-point KS for each HSG. For interpretation between classes, we developed the following equation assuming the average cover percent shown in Fig. 2 for each class.

$$CN = 96.38 - 0.158C - 19.84K - 0.397KC \tag{6}$$

where

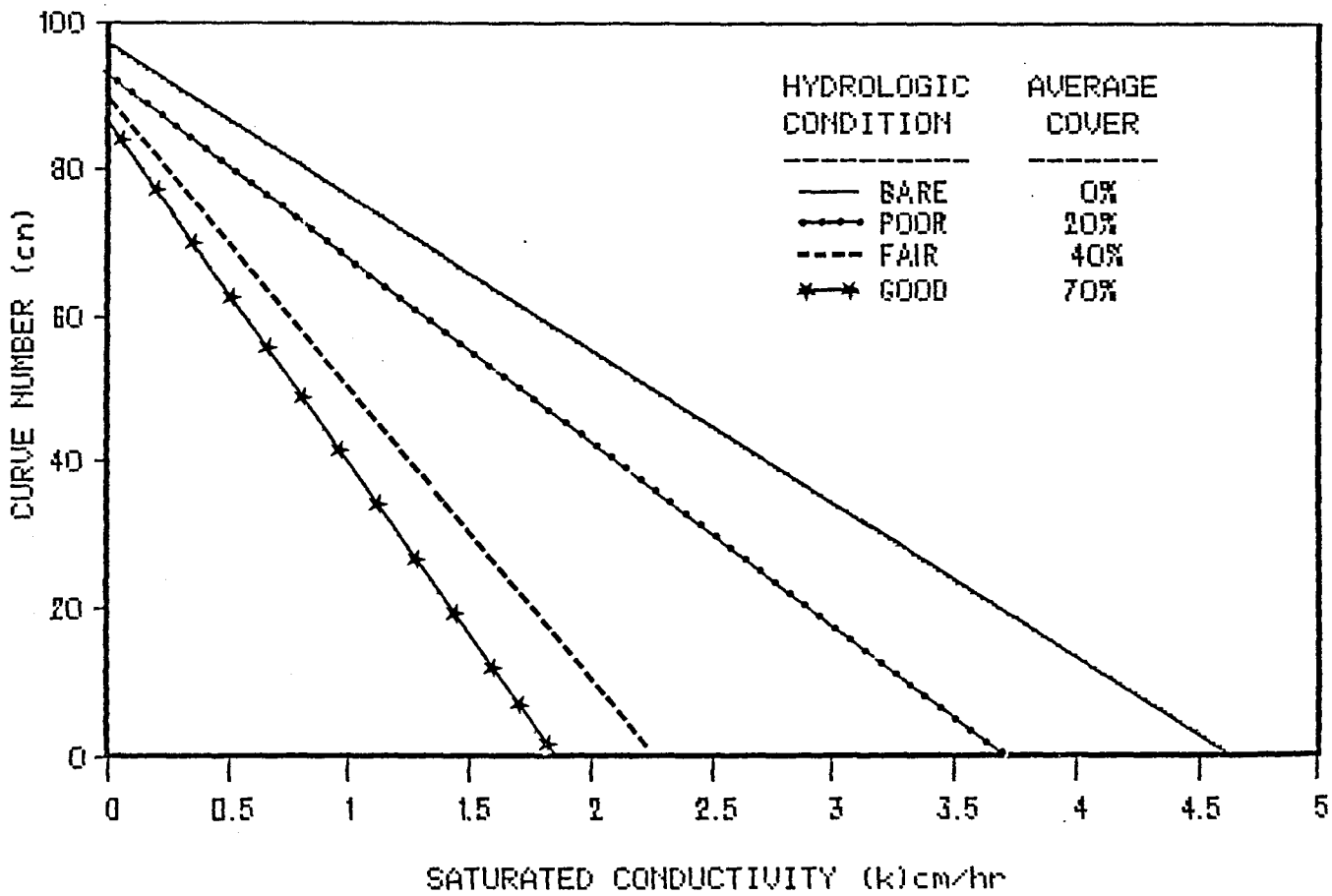

Fig. 2--Rangeland curve numbers as a function of saturated conductivity for cover classes.

CN = Curve Number,
C = total cover in percent, and
K = saturated conductivity, cm/hr.

EXAMPLES

Given: Reynolds Creek Soils-5 data for Searla (id0929) cool

(1) Find - percent sand

Sand (%) = Z5 = 100 - 100 I/G

I = percent material < 3" passing #200 sieve = 35 - 50 percent
G = percent material < 3" passing #10 sieve = 60 - 80 percent.

Using the midpoint value for I and G

Sand (%) = 100 - 100 (42.5/70)
= 39 percent.

(2) Find - percent by weight of material > 2 mm and < 250 mm = Z1

$$Z1 = E + \left[\left(1 - \frac{E}{100}\right)(100-G)\right]$$

E = percent fraction > 3 inches
G = percent material < 3 inches passing the #10 sieve.

From Soils-5

E = 5 - 10 percent
G = 60 - 80 percent

$$Z1 = 7.5 + \left[\left(1 - \frac{7.5}{100}\right)(100 - 70)\right]$$

Z1 = 35 percent.

(3) Find - Hydrologic Soil Group

From the Soils-5, the percent clay (M) is 12 - 20 with the mid-value of 16 percent and the percent of sand (Z5) is 39 percent.

The measured moist bulk density (N) is 1.4 - 1.5 with a mid-value of 1.45.

From our computer program

KS = 0.60 cm/hr.

Referring to Table 4, this soil is Hydrologic Soil Group B.

If we assume a total cover of 30 percent cover, the calculated curve number is

CN = 72.

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WATER RESOURCES BULLETIN
VOL. 22, NO. 1 AMERICAN WATER RESOURCES ASSOCIATION FEBRUARY 1986

APPLICABILITY OF THE GREEN AND AMPT INFILTRATION EQUATION TO RANGELANDS[1]

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ABSTRACT: The objective of this study was to investigate the use of Green and Ampt infiltration equation parameters (determined by least squares fitting of field infiltration data or predicted from soil texture properties) to characterize infiltration on spatially varying rangeland sites. It was found that a least squares regression approach reduces the physically based parameters in the Green and Ampt to empirical coefficients since negative coefficients are obtained, particularly on plots with low infiltration rates. Green and Ampt parameters predicted from soil texture data describe infiltration rates less than 3 cm/hr. The applicability of these Green and Ampt parameters appears limited to sites with lower infiltration rates. Results indicate that soil texture predictive triangles, developed to describe infiltration on agricultural soils, need revision to adequately describe infiltration patterns on rangelands.
(KEY TERMS: infiltration; Green and Ampt; soil texture; rainfall simulation.)

INTRODUCTION

Characterization of infiltration on rangeland sites is receiving increased attention as hydrologists must predict watershed responses to rainfall events. It would be advantageous to use model parameters to index infiltration characteristics on rangelands. Attempts have been made to fit the Horton, Kostiakov and Philip's infiltration equations (Gifford, 1976; Jaynes and Gifford, 1981) to rangeland infiltrometer data. However, with the exception of Philip's equation, these models do not have physically based parameters. If a model such as the Green and Ampt (1911) infiltration equation (widely used for modeling infiltration on agricultural lands), with physically based parameters, could accurately fit rangeland infiltrometer data, model parameters could serve as physically interpretable indexes of infiltration.

A number of recent studies have illustrated great spatial variation in hydrologic properties within short distances on semi-arid rangeland sites (Achouri, 1982; Merzougui, 1982; Springer and Gifford, 1982). Whether an infiltration equation such as the Green and Ampt can characterize a potentially variable hydrologic site is not known. Other studies (McCuen, *et al.*, 1981) have suggested that soil texture data can be used to predict Green and Ampt infiltration equation parameters on agricultural lands. If applicable to rangelands, such a predictive model would reduce collection of field infiltrometer data. However, it is not known whether predictive models are useful when variability of hydrologic response is considered.

The Green and Ampt Infiltration Equation

The Green and Ampt (1911) infiltration equation has been used widely for modeling infiltration on agricultural lands. The rate form of the model is:

$$f = K(1+nS/F)$$

where f = infiltration rate (cm/hr), k = hydraulic conductivity in the wetted zone (cm/hr), n = available porosity, S = suction parameter (cm), and F = cumulative infiltration (cm).

The equation can be fitted to infiltrometer data by determining parameter values. However, direct measurement of physical parameters such as capillary pressure head, available porosity and hydraulic conductivity is difficult: relationships among these parameters and more easily measured soil properties would be useful. It has been shown by McCuen, *et al.* (1981), that, for agricultural soils, soil texture is a major discriminator of Green and Ampt infiltration parameters.

The Green and Ampt infiltration equation assumes a homogeneous soil with uniform moisture content; a negligible depth of water ponded on the surface throughout the calculation; that each small plot acts as a point; and that the entire plot is contributing when runoff begins. Mein and Larson (1973) adapted the Green and Ampt model to the steady rainfall case, which allows for intermediate ponding time during rainfall. The model's assumptions are not met in most infiltrometer studies, and may limit the usefulness of the

[1]Paper No. 84069 of the *Water Resources Bulletin*. Discussions are open until October 1, 1986.
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Green and Ampt in fitting field infiltrometer data. The Green and Ampt also does not explicitly consider vegetation, land condition or spatial variability.

The objectives of this study were: (1) to examine the ability of the Green and Ampt infiltration equation to represent spatially varying infiltration measures using a least squares fit to measured field data, and (2) to examine the use of measured rangeland soil properties for predicting parameters in the Green and Ampt infiltration equation.

SITE DESCRIPTION

The infiltrometer data were collected on rangeland sites located on the Reynolds Creek Experimental Watershed near Boise, Idaho. The watershed soils, geology, vegetation and land use represent plateau and foothill grazing areas of the Northwest (Stephenson, 1977). Elevations range from about 1097 m to 2225 m. The climate of the watershed ranges from arid to temperate, with annual precipitation varying from 250 mm at the lower elevations to 1270 mm at the higher elevations. Nearly 75 percent of the annual runoff is from snowmelt; however, runoff from smaller areas can occur following intensive summer rain storms.

Three sites on the Reynolds Creek Experimental Watershed (referred to as Flats, Nancy and Lower Sheep) were selected for this study. A description of these sites is given in Table 1. Additional detail concerning these sites is given in U.S. Department of Agriculture (1976).

Rainfall simulator plots were located on the three sites in grazed, ungrazed, and tilled conditions. Average plot slopes were 3, 6, and 9 percent on the Flats, Nancy, and Lower Sheep sites, respectively. Tilled plots were tilled up- and down-slope to approach a fallow condition approximately one week prior to rainfall simulation and restored to the original (measured by soil cores taken randomly within and adjacent to plots bulk density (1.1-1.4 g/cm^3) by natural settling and human trampling before simulator runs. Fenced sites have been protected from grazing by domestic livestock since 1971. Unfenced sites are grazed both by domestic livestock and wildlife, but exact stocking rates, season of use and duration of use data are not available. Generalized grazing allotment data are available from local Bureau of Land Management offices, but the applicability of these data to specific locations on the watershed is questionable.

METHODS

Infiltrometer Methodology

All infiltrometer data were collected using a modular drop-forming device (Malekuti and Gifford, 1978). Small plots (0.37 m^2) were run with soils at field capacity to start (pre-wet and allowed to drain) or under very wet conditions (half-an-hour after the infiltrometer run ended, stimulated rainfall was again applied for one-half-hour). Antecedent soil moisture was determined for each small plot prior to the infiltrometer run. Runoff was measured at select time intervals during each 30-minute infiltrometer run and infiltration was assumed to be the difference between rainfall applied and runoff. Rainfall application rates were either 6.35 cm/hr or 12.7 cm/hr.

Small plots were located within large (3.05 m X 10.67 m, or 32.5 m^2) rainfall simulator plots, which were part of a concurrent Agricultural Research Service study. On plots in either an unfenced or fenced condition, 20 small plots were sampled within each large plot, ten each on two randomly located belt transects within each large plot. On plots in a rototilled condition, ten small plots, randomly located within the large plot, were sampled.

After obtaining runoff data from a small plot, surface soil characteristics were sampled. Two samples of surface material (with a core diameter of 5.4 cm and core depths of 2.54 cm and 7.62 cm) were taken for determination of bulk density (g/cm^3), particle size distribution (hydrometer method, Bouyoucos, 1962), and soil organic matter (colorimetric analysis; Sims and Haby, 1971).

TABLE 1. Site Characteristics on the Reynolds Creek Experimental Watershed.

Site	Average Elevation (meters)	Average Annual Precipitation (mm)	Soil Description	Dominant Vegetation
Flats	1219	250	Fine, loamy, mixed mesic Typic Haplargids	Shadscale (*Atriplex confertifolia*) Cheatgrass (*Bromus tectorum*) Bottlebrush squirreltail (*Sitanion hystrix*)
Nancy	1402	330	Fine, montmorillonitic, Mesic Xerollic Durargid	Big sagebrush (*Artemisia tridentata* subsp. *wyomingensis*) Sandberg Bluegrass (*Poa sandbergii*) Bottlebrush squirreltail (*Sitanion hystrix*)
Lower Sheep	1646	380	Fine, montmorillonitic, Frigid Pachic Argixeroll	Low sagebrush (*Artemisia arbuscula*) Sandberg bluegrass (*Poa sandbergii*) Bottlebrush squirreltail (*Sitanion hystrix*)

Calculation Methodology

The runoff data for each plot were integrated numerically to determine the cumulative infiltration (F), and the infiltration rate (f), at any time (t). For each site all small plot infiltration curves were used to investigate site variability.

The rate form of the Green and Ampt infiltration equation is $f = K(1+nS/F)$ where the factors are as defined above. Cumulative infiltration is determined from the time simulated rainfall begins. Using the standard equation of a line $Y = mX+b$, where m is the slope and b is the intercept, if $Y=f$ and $X=1/F$, the slope is KnS and the intercept is K. Note that separate values for n and S cannot be obtained. The Green and Ampt infiltration equation was fitted to the f versus 1/F pairs for each infiltration run by least squares linear regression. The time to ponding (tp) was determined using the Mein and Larson equation (1973), which states that $tp = ns \div [i/K\ (i-K)]$ where i = rainfall intensity and the other terms are as defined above.

The field-obtained soil texture, bulk density (7.62 cm depth) and antecedent moisture data were used to predict Green and Ampt equation parameters using procedures detailed in Brakensiek, *et al.* (1982). These soil texture triangles were developed for agricultural soils data. Soil texture triangles for (a) 1.5 percent organic matter and (b) 3 percent organic matter were used to obtain the Green and Ampt suction parameter, S, and the saturated hydraulic conductivity, Ks. It was assumed that no porosity changes occurred during each small plot run (referred to as zero percent porosity change). The available porosity, n was calculated as the effective porosity, θ_e, (total porosity (ϕ) minus residual soil water (θ_r)), minus the antecedent soil moisture. The antecedent soil moisture was obtained from field data as discussed above. The total porosity was determined from field-obtained bulk density data, assuming a soil particle density of 2.65 g/cc. The residual soil water was obtained from an unpublished table (Brakensiek, personal communication). Using the K and nS obtained, the integrated form of the Green and Ampt infiltration equation $[F-nS(\ln(1+F/nS))=Kt]$ was interactively solved for F using Newton's method.

Infiltration rates and the time to ponding predicted from the soil texture determined Green and Ampt infiltration equation were statistically compared to the values of infiltration rates and time to ponding from (1) field data (field-observed time to ponding was defined as the time when measurable runoff, i.e., 10-15 ml runoff in 15 seconds, occurred from the small plot), and (2) least squares fit of field data to the Green and Ampt infiltration equation.

For both the soil texture predicted and least squares fit determined curves of infiltration versus time, the time scale must be adjusted for the preponding time period so that it is initialized at the start of rainfall. TC, the time correction, is equal to TP, the time to ponding, minus TE, the equivalent time for the preponding infiltration if it occurred with ponded conditions. Calculation of TE is facilitated by an approximation derived by Li, *et al.* (1976): $TE = (F1)^2/[K(2(nS)+F1)]$ where F1 is the infiltration amount at ponding exclusive of surface interception (cm), K is the hydraulic conductivity (cm/hr), n is the available porosity, and S is the suction parameter (cm).

RESULTS AND DISCUSSION

Least Squares Fitting of Field Data

Least squares estimation of Green and Ampt infiltration equation parameters K and nS resulted in negative parameters that were not physically interpretable. Table 2 shows that negative parameters occurred with the greatest frequency on those sites with the lowest final 30-minute infiltration rates (particularly rototilled plots). Previous studies using least squares estimation of infiltration model coefficients have also found negative parameters (Gifford, 1982; Grah, 1983; Jaynes and Gifford, 1981).

Infiltration Parameters from Soil Texture Data

Green and Ampt parameters predicted from soils data (McCuen, *et al.*, 1981) were compared with Green Ampt parameters predicted from least squares fitting of field infiltration data. The results obtained using soil texture predictive triangles for S and Ks for soil with 1.5 percent organic matter and 0 percent porosity change (Brakensiek, personal communication) are discussed first.

On the rototilled plot (Figure 1), the soil texture predicted Green and Ampt parameters resulted in an infiltration curve that approximates the field data fairly well. (Rototilled plots probably approach an agricultural situation similar to that for which the predictive soil texture triangles were developed.) Figure 2 shows the results of regressing observed field data (infiltration rate) against (1) least squares fit of field data, and (2) data predicted from soil texture. Note that the regression equation for the least squares data is not significantly different from a 1:1 relationship. However, in the case of the infiltration curve predicted from soil texture data, both the slope and the intercept differ significantly from those predicted from a 1:1 relationship. Recalling that least squares estimation of Green and Ampt parameters sometimes resulted in negative values, this result was not surprising.

On unfenced and fenced plots (see Figure 3) the soil texture predicted Green and Ampt parameters best mimicked field observed infiltration rates when the infiltration rate was low (less than 3 cm/hr) and there was sufficient drawdown. The results of regressing the observed field data against (a) least squares fit of the field data, and (b) data predicted from soil texture are given in Figure 4. As on the rototilled plot, although results from the observed field data and those predicted from soil texture data could be correlated, the result was significantly different from a one-to-one relationship.

On unfenced and fenced plots with a higher infiltration rate (Figure 5), from 12 to 30 minutes (0.20-0.50 hr), there

TABLE 2. Mean Final Infiltration Rate and Least Squares Predicted Green and Ampt Parameters for Each Large Plot.*

Site	Condition	Slope (percent)	Rain (cm/hr)	N	Final 30 Min. Inf. Rate (cm/hr)	K (cm/hr)	nS (cm)	n
				WET RUNS				
Flats	Unfenced	3	6.35	19	2.53 ± 1.05	0.48 ± 2.24	1.89 ± 6.94	4
Flats	Fenced	3	6.35	15	4.01 ± 1.05	−0.16 ± 3.38	−14.8 ± 25.9	9
Flats	Tilled	9	6.35	10	1.69 ± 0.22	−0.30 ± 1.26	0.91 ± 4.31	5
Flats	Tilled	3	6.35	10	1.27 ± 0.29	−2.96 ± 2.12	−0.45 ± 2.49	9
Flats	Tilled	3	12.7	10	1.34 ± 0.65	−5.97 ± 2.29	−0.45 ± 2.49	10
Nancy	Unfenced	6	12.7	19	5.40 ± 2.31	1.62 ± 4.47	−14.8 ± 65.6	7
Nancy	Fenced	6	12.7	19	7.17 ± 2.96	4.69 ± 4.47	0.44 ± 8.77	4
Nancy	Tilled	6	12.7	10	2.31 ± 0.72	−2.97 ± 2.64	−1.26 ± 1.49	8**
Lower Sheep	Unfenced	9	12.7	19	7.65 ± 2.30	5.66 ± 2.82	2.98 ± 3.39	0
Lower Sheep	Fenced	9	12.7	15	9.55 ± 1.23	7.53 ± 2.48	2.83 ± 5.68	0
Lower Sheep	Tilled	9	12.7	10	2.29 ± 0.48	−1.30 ± 1.42	−7.91 ± 12.6	9
				VERY WET RUNS				
Flats	Unfenced	3	6.35	15	2.97 ± 0.67	0.47 ± 1.11	0.44 ± 6.20	9
Flats	Fenced	3	6.35	20	2.06 ± 0.93	0.20 ± 1.33	−1.05 ± 5.62	7
Flats	Tilled	9	6.35	9	1.45 ± 0.39	−0.14 ± 0.68	0.94 ± 3.92	5

*Values in this table are reported as mean ± standard deviation where N=number of small plots where runoff occurred and n=number of negative K and nS values obtained by least squares fitting.

**Number of negative K's on this plot is 9, number of negative nS's is 8.

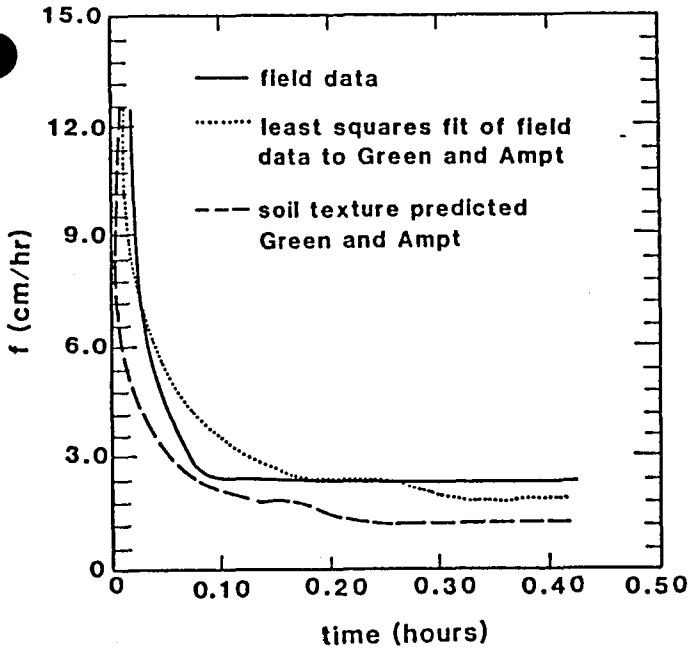

Figure 1. Comparisons of (1) Observed Field Data, (2) Least Squares Fit of Field Data to the Green and Ampt, and (3) Soil Texture Predicted Green and Ampt Infiltration Rate on a Lower Sheep Tilled, 9 Percent Slope, Small Plot at the Rainfall Intensity of 12.7 cm/hr.

was an approximately 5 cm/hr gap between the field infiltration rate and soil texture predicted infiltration rate. Note also that only the least squares fit of field data and not data predicted from soil texture, when regressed against the observed field data, fit a 1:1 relationship (Figure 6).

The results obtained using soil texture predictive triangles for nS and K for soil with 3 percent organic matter (Brakensiek, personal communication) were not significantly different from those obtained using values predicted for 1.5 percent organic matter. For example, on the Lower Sheep "grazed" site, with an average field-determined organic matter content of 4.7 percent, there was no consistent pattern with respect to whether the 1.5 percent or 3 percent organic matter soil texture triangles fit the data better (Table 3). Generally, when the 3 percent organic matter soil texture triangle is used, K is smaller and nS is larger than the parameter values obtained using the 1.5 percent organic matter soil texture triangle. Only insignificant increases or decreases in the slope, intercept and R^2 resulted when the field data (as infiltration rate) was regressed against the soil texture predicted Green and Ampt infiltration rate using soil texture predictive triangles for 1.5 percent or 3 percent organic matter.

These soil texture predictive triangles, developed for agricultural soils, need revision for use on rangelands. First, rangeland sites often have an organic matter content greater than 3 percent; predic tive triangles for such conditions are

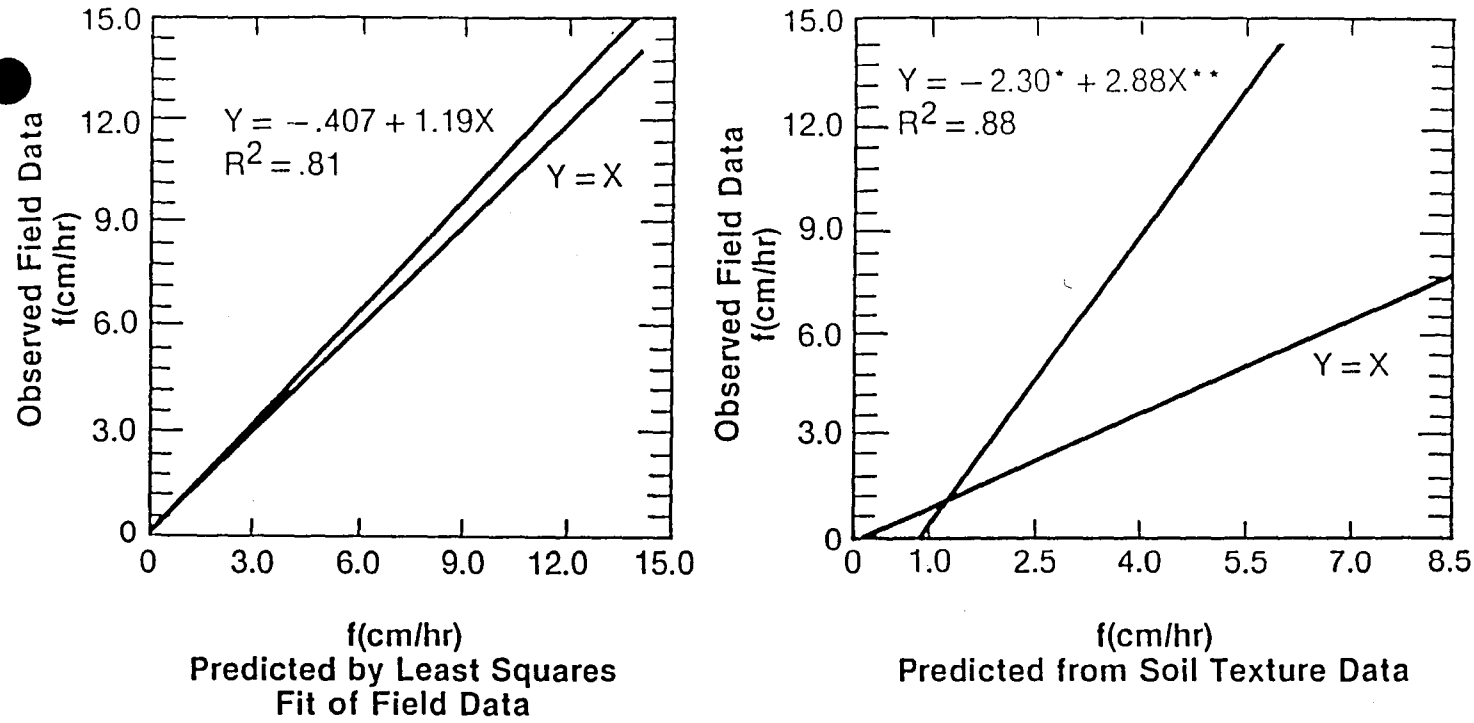

Figure 2. Regressions of Observed Field Data Against (1) Least Squares Fit of Field Data and (2) Data Predicted from Soil Texture for Data Given in Figure 1. A star (*) indicates the intercept is significantly different from zero at 0.05 level. Two stars (**) indicate the slope is significantly different from one at 0.05 level.

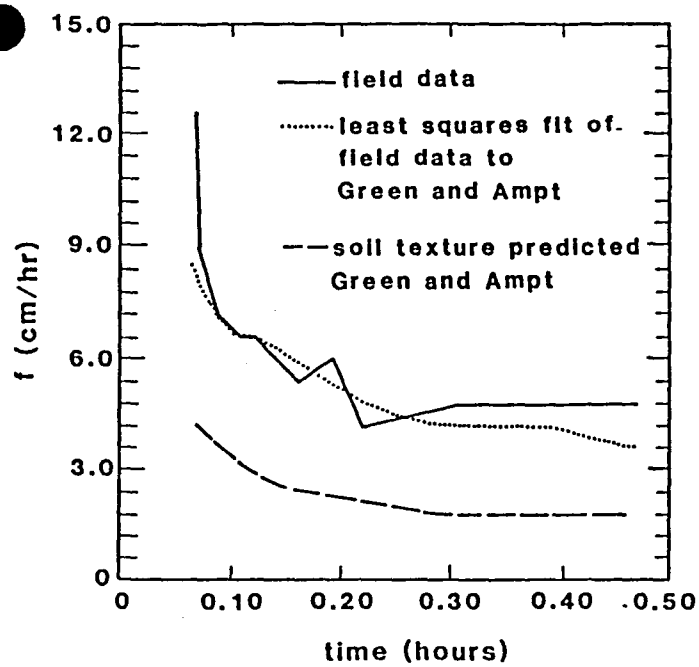

Figure 3. Comparisons of: (1) Observed Field Data, (2) Least Squares Fit of Field Data to the Green and Ampt, and (3) Soil Texture Predicted Green and Ampt Infiltration Rate on a Lower Sheep Unfenced, 9 Percent Slope, Small Plot at the Rainfall Intensity of 12.7 cm/hr.

not available. Secondly, rangeland soils often have a significant fraction of coarse fragments (greater than 2 mm), whereas agricultural soils generally have few coarse fragments. Thirdly, it may be that soil porosities are higher on vegetated rangeland sites than on rototilled or agricultural sites.

Time to Ponding Predictions

Table 4 shows that least squares fitting of field data to the Green and Ampt infiltration equation gave time to ponding values that were significantly different from field-observed values on certain rototilled plots. Soil texture predicted time to ponding estimated field-observed values best on the tilled plots when the drawdown in infiltration was rapid. Significant differences in soil texture predicted time to ponding and both (a) field observed tp and (b) least squares fit of field data predicted tp, occurred only on selected unfenced and fenced sites, and not on rototilled plots. Large differences in texture on the Flats fenced plot resulted in large standard deviations for the soil texture predicted time to ponding.

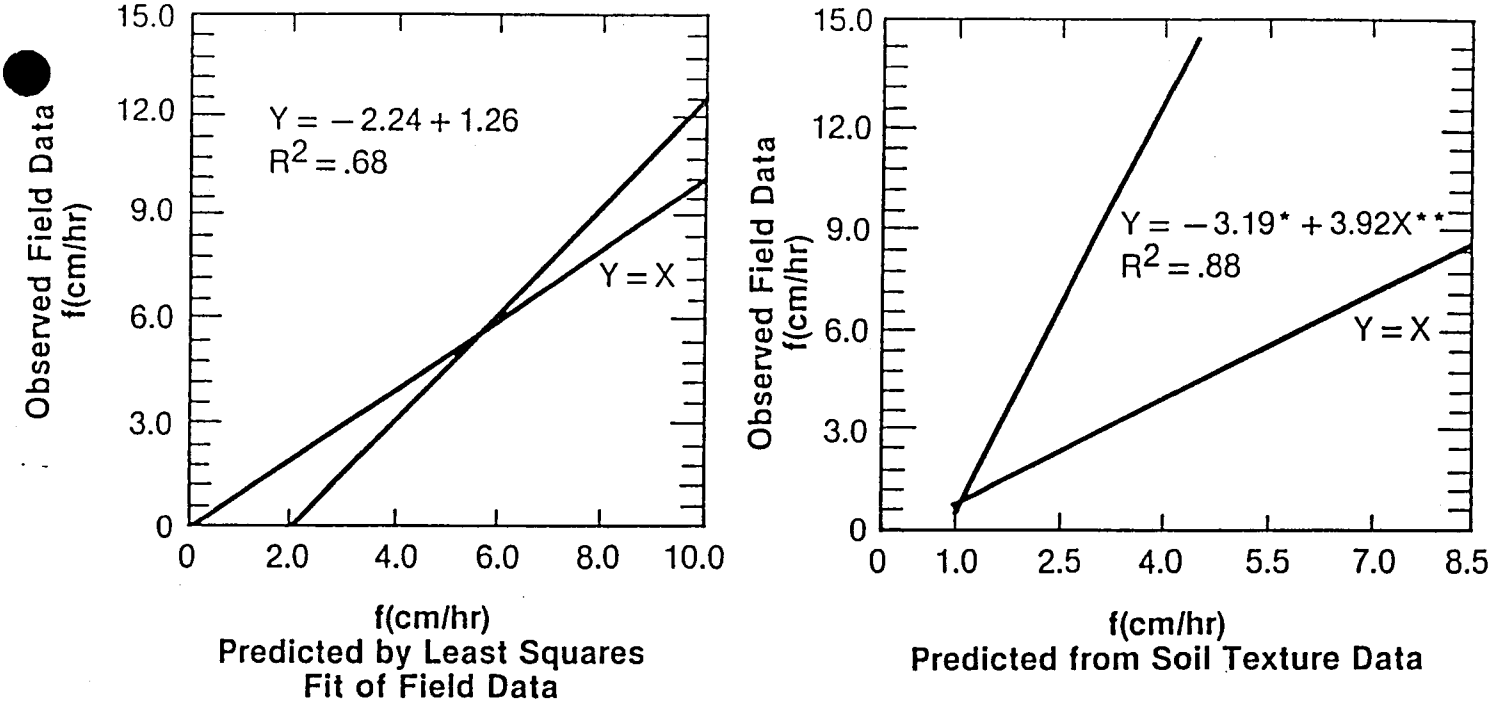

Figure 4. Regressions of Observed Field Data Against (1) Least Squares Fit of Field Data and (2) Data Predicted from Soil Texture for Data Given in Figure 3. A star (*) indicates the intercept is significantly different from zero at 0.05 level. Two stars (**) indicate the slope is significantly different from one at 0.05 level.

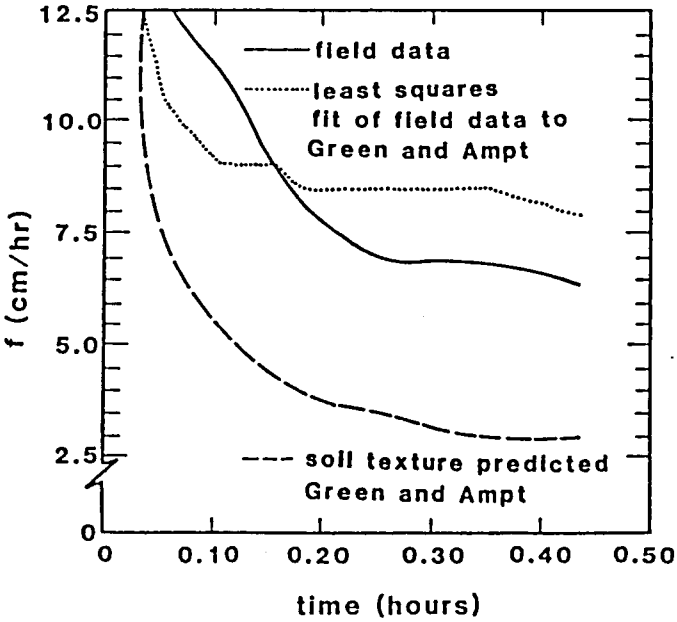

Figure 5. Comparisons of: (1) Observed Field Data, (2) Least Squares Fit of Field Data to the Green and Ampt, and (3) Soil Texture Predicted Green and Ampt Infiltration Rate on a Lower Sheep Unfenced, 9 Percent Slope, Small Plot at the Rainfall Intensity of 12.7 cm/hr.

CONCLUSIONS

Least Squares Fitting of Field Data

There are limitations in the ability of the Green and Ampt infiltration equation, as applied in this study, to describe the observed variable infiltration patterns on rangelands. (It must also be remembered that the field conditions in this study differed from the assumptions used in deriving the Green and Ampt infiltration equation.) Least squares estimation of the model coefficients, K and nS, from infiltrometer data resulted in negative parameters which were not physically interpretable. The R^2 values indicated that, although there is no physical basis for the fitting of the model, the Green and Ampt infiltration equation can mimic field-obtained rangeland infiltration curves.

If least squares fitting of field infiltration data to the Green and Ampt infiltration equation continues to result in negative parameters (indicating an empirical rather than physical basis) on diverse sites, it may be useful to either: (1) index the negative parameters to either nonnegative Green and Ampt parameters (perhaps those predicted from soil texture data) or other factors such as the final 30-minute infiltration rate; (2) alter the model so the resulting parameters have physical meaning; or (3) find another model that more accurately describes the data (the Philipp's and Horton equations are feasible models for estimating infiltration on rangelands (Gifford, 1976; Jaynes and Gifford, 1981)).

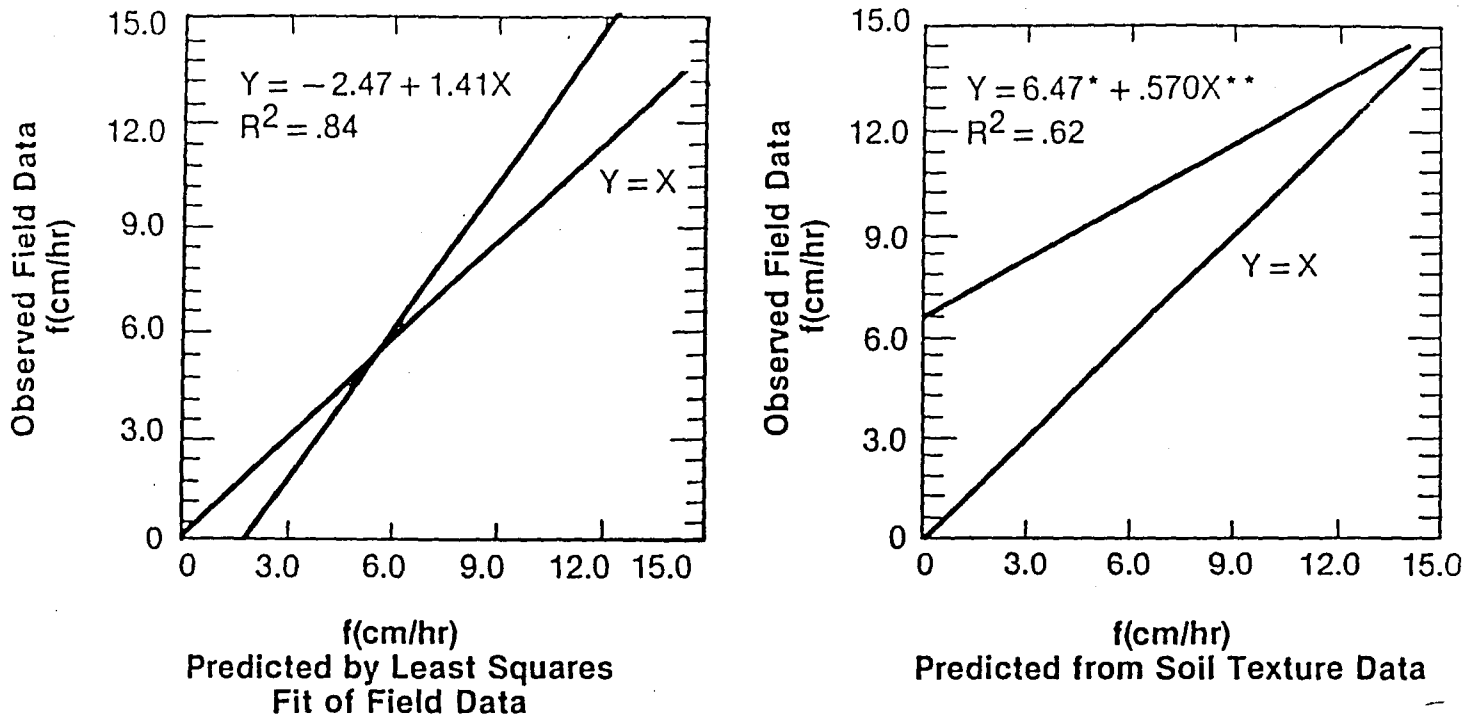

Figure 6. Regressions of Observed Field Data Against (1) Least Squares Fit of Field Data and (2) Data Predicted from Soil Texture for Data Given in Figure 5. A star (*) indicates the intercept is significantly different from zero at 0.05 level. Two stars (**) indicate the slope is significantly different from one at 0.05 level.

TABLE 3. Differences in Soil Texture Predicted Green and Ampt Parameters Obtained Using Soil Texture Predictive Triangles for Different Organic Matter Contents on the Lower Sheep Unfenced Site.[1]

	Organic Matter Content for Soil Texture Predictive Triangles									
	1.5 Percent					3.0 Percent				
Plot	K (cm/hr)	nS (cm)	Slope	Intercept (cm/hr)	R^2 (percent)	K (cm/hr)	nS (cm)	Slope	Intercept (cm/hr)	R^2 (percent)
1	0.75	6.28	0.57	6.47**	62.5	0.60	6.55	1.01	4.86	81.0
2	0.15	8.36	3.06	3.05	32.6	0.13	9.35	3.04	3.35	28.5
3	0.48	9.13	0.78	8.04**	69.8	0.35	9.93	0.86	8.13**	64.9
4	0.33	8.90	3.43	1.92	47.7	0.25	9.79	3.30	3.04	35.2
5	0.33	7.73	2.03*	6.17**	77.1	0.25	8.50	2.23*	6.20**	75.9
6	1.63	4.10	3.87*	−5.67	68.3	1.25	4.48	3.88	−3.61	53.3
7	0.55	5.24	2.34*	2.11**	94.5	0.38	5.82	2.73*	2.23**	92.0
8	0.26	8.29	1.65	5.80**	65.0	0.23	8.93	1.71	5.85**	63.5
9	1.25	4.33	0.80	6.38**	82.4	0.88	4.69	0.92	6.53**	80.4
10	0.30	6.81	2.47	−0.29	54.4	0.25	7.40	2.57	−0.13	51.5
11	0.20	6.73	1.86*	5.47**	80.3	0.15	7.33	2.09*	5.47**	78.7
12	0.23	8.07	2.45*	−1.43	93.9	0.19	8.61	2.60*	−1.42	93.8
13	0.75	5.42	−1.76	16.5**	89.6	0.50	5.78	−1.49	15.1**	92.8
14	0.50	6.57	−0.20	11.9**	−16.5	0.38	7.61	−0.78	13.0**	−13.6
15	0.25	7.95	3.87*	0.0003	49.0	0.20	8.90	3.92	0.50	43.0
16	0.20	7.31	2.78*	−0.73	88.6	0.18	8.35	2.78*	−0.69	88.5
17	0.20	8.26	1.38	5.48**	79.3	0.18	9.44	1.38	5.50**	79.3
19	0.28	7.62	1.14	7.50**	24.0	0.20	8.50	1.14	7.84**	16.0
20	0.30	8.13	2.36*	3.26**	72.9	0.23	8.73	2.56*	3.56**	64.5

[1]These slope and intercept values are the result of regressing observed field infiltration rates against the soil texture predicted Green and Ampt infiltration rate, where * = slope significantly different from one at = 0.05, and ** = intercept significantly different from zero at $\alpha = 0.05$. R^2 values given are adjusted for degrees of freedom (Ryan, *et al.*, 1976).

TABLE 4. Mean Time to Ponding Values for Each Large Plot Obtained Using Three Methods.*

Site	Condition	Slope (percent)	Rain (cm/hr)	Field Observed Time to Ponding (min)	Least Squares Predicted Time to Ponding (min)	Soil Texture Predicted Time to Ponding (min)
				WET RUNS		
Flats	Unfenced	3	6.35	6.10 ± 4.40	6.05 ± 4.30	6.73 ± 3.43
Flats	Fenced	3	6.35	15.7 ± 6.27	14.6 ± 6.30	15.3 ± 23.4
Flats	Tilled	9	6.35	2.80 ± 0.62a	2.23 ± 0.50b	14.3**
Flats	Tilled	3	6.35	4.22 ± 0.33	3.43 ± 1.33	4.72**
Flats	Tilled	3	12.7	1.82 ± 0.67	1.55 ± 0.38	1.07**
Nancy	Unfenced	6	12.7	5.23 ± 3.42a	4.62 ± 3.17a	1.22 ± 0.47b
Nancy	Fenced	6	12.7	6.67 ± 4.00a	5.65 ± 3.05a	1.23 ± 0.62b
Nancy	Tilled	6	12.7	2.30 ± 0.53a	1.67 ± 0.75b	0.53 ± 0.0018
Lower Sheep	Unfenced	9	12.7	7.57 ± 6.78a	7.02 ± 6.42a	1.13 ± 0.65b
Lower Sheep	Fenced	9	12.7	10.08 ± 5.82a	9.20 ± 5.58a	1.47 ± 0.67b
Lower Sheep	Tilled	9	12.7	1.30 ± 0.33	1.32 ± 0.30	0.28**
Flats	Unfenced	3	6.35	2.67 ± 2.15	2.70 ± 2.15	6.90 ± 3.40
Flats	Fenced	3	6.35	7.72 ± 3.72	6.97 ± 3.27	15.3 ± 23.4
Flats	Tilled	3	6.35	1.15 ± 0.18	0.80 ± 0.18	14.3**

*Values are given as means ± standard deviation. Alphabetic letters following time to ponding values indicate significant differences within a given row at $\alpha = 0.05$.

**All soil samples had the same soil texture, hence only one time to ponding value was predicted.

Infiltration Parameters from Soil Texture Data

This study has shown that Green and Ampt parameters predicted from soil texture data describe infiltration rates best on rototilled sites with infiltration rates less than 3 cm/hr. However, the applicability of these Green and Ampt predicted parameters appears limited on sites with higher infiltration rates. Soil texture predicted time to ponding estimates were best on rototilling sites.

Given that soil texture predictive triangles to discriminate Green and Ampt parameters were developed to describe infiltration on agricultural soils, which correspond most closely to rototilled soils, it is not surprising that the equation works best on rototilled (previously rangeland) sites. This study identified limitations in using the soil texture predictive triangles developed for agricultural lands, when the goal is to adequately describe observed infiltration patterns on rangelands. These soil texture predictive triangles may need revision for use on rangelands; the soil coarse fraction, rangeland soil porosities and percent organic matter may need to be considered. The reliability of prediction parameters in the Green and Ampt infiltration equation in the context of spatial variability of field-measured soil physical properties also needs to be investigated further.

ACKNOWLEDGMENTS

This project was supported through the Northwest Watershed Research Center, U.S.D.A., A.R.S., Boise, Idaho, and the Utah Agricultural Experiment Station, Projects 749 and 771. Technical Paper 3379, Utah Agricultural Experiment Station, Logan, Utah 84322.

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DETERMINING THE SATURATED HYDRAULIC CONDUCTIVITY OF A SOIL CONTAINING ROCK FRAGMENTS[1]

D. L. BRAKENSIEK, W. J. RAWLS, AND G. R. STEPHENSON[2]

Abstract

Many rangeland soils contain various amounts of rock fragments (>2 mm and <75 mm), which influence soil hydraulic and water storage properties. Most published data on these properties are only for the fine earth fraction (<2 mm). Determining properties for soils containing rock fragments requires either in situ measurements or procedures that adjust fine earth fabric properties for the coarse fraction content. The hydraulic conductivity is a major determinant of the infiltration and water movement properties of soils. Additionally, the saturated conductivity is used as a scaling parameter in modeling partially saturated flow in porous media. In this Note, literature is reviewed on calculating the saturated hydraulic conductivity for soils containing rock fragments. The two most widely used methodologies are based on knowing either the volume fraction of the rock fragments or the void ratio of the field soil and the fine earth fabric. Both of these soil properties require somewhat laborious laboratory procedures. We show that a calculation of the saturated conductivity of the bulk soil can be accomplished by using only the rock fragment fraction on a weight basis. For many soils the rock fragment fraction on a weight basis is routinely determined and published. For example, the Soil Conservation Service pedon data files list the rock fraction on a weight basis. We test our calculation of the saturated hydraulic conductivity with published data on the saturated conductivity of a stony soil. We show that our simple formulation using the rock fraction on a weight basis duplicates the observed data. Furthermore, it is as accurate as the more complicated procedure requiring void ratio information.

Additional Index Words: stony soils, fine earth, soil coarse fraction.

Brakensiek, D.L., W.J. Rawls, and G.R. Stephenson. 1986. Determining the saturated conductivity of a soil containing rock fragments. Soil Sci. Soc. Am. J. 50:834–835.

IN AN UNPUBLISHED PAPER, Peck and Watson[3] (see Fig. 1), utilizing a heat flow analogy for a medium with noninteracting spherical inclusions, derived the following equation for the ratio of the field soil saturated hydraulic conductivity, K_b, to the fine-earth fraction saturated conductivity, K_s, as

$$K_b/K_s = 2(1 - R_v)/(2 + R_v) \qquad [1]$$

where R_v is the volume fraction of rock fragments. Equation [1] assumes zero conductivity for the inclusions.

Bouwer and Rice (1984) intuitively derived a prediction equation for the ratio as

$$K_b/K_s = e_b/e_s \qquad [2]$$

where e_b is the void ratio of the field soil; and e_s is the void ratio of the fine-earth fraction. Calculation of the void ratio requires the porosity of both the field soil and the fine earth fraction. They presented experimental data for validating their prediction equation and compared it with Eq. [1].

We will use their data to compare a simpler equation for predicting the field saturated hydraulic ratio.

Table 1. An error analysis for Eq. [4] and [6].

α	R_w	K_b/K_s Eq. [4]	K_b/K_s Eq. [6]
0.4	0.2	0.87	0.80
0.5	0.2	0.84	0.80
0.6	0.2	0.82	0.80
0.4	0.3	0.80	0.70
0.5	0.3	0.76	0.70
0.6	0.3	0.72	0.70
0.4	0.4	0.71	0.60
0.5	0.4	0.67	0.60
0.6	0.4	0.63	0.60

Equation Development

Equation [1] requires the volumetric rock fragment content for the particular soil. Rock fragment content on a volume basis is generally not as available as that on a weight basis. Referring to Flint and Childs (1984), the volume of rock fragments, R_v (decimal form), can be expressed as

$$R_v = \alpha(R_w)/[1 - R_w(1 - \alpha)] \qquad [3]$$

where R_w is the rock fragment content by weight (decimal); and α is the ratio of the bulk density of the fine-earth fabric divided by the bulk density of rock fragments.

Substituting [3] into [1] gives

$$K_b/K_s = (1 - R_w)/[1 - R_w(1 - 3\alpha/2)]. \qquad [4]$$

From Table 1 in Flint and Childs (1984), α was calculated by the authors from 40 sets of bulk densities representing soil parent materials in southwest Oregon. The mean $\alpha \pm$ 1 standard deviation was

$$\alpha = 0.49 \pm 0.11.$$

Using an average α of 0.5, Eq. [4] becomes

$$K_b/K_s = (1 - R_w)/(1 - R_w/4). \qquad [5]$$

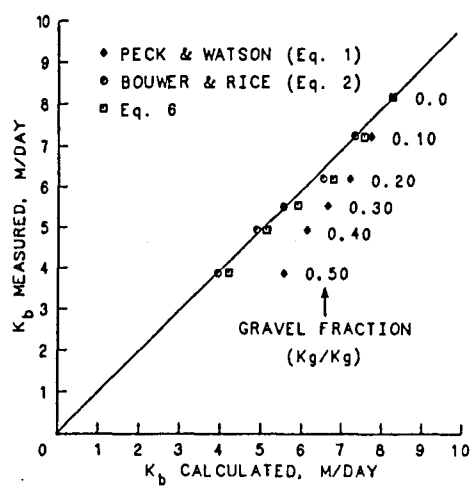

Fig. 1. Relationship between measured K_b and calculated K_b for sand-gravel mixtures.

[1] Contribution from the USDA, Agricultural Research Service; Northwest Watershed Research Center, 270 South Orchard, Boise, ID 83705 and the Hydrology Laboratory, BARC-West, Beltsville, MD 20705. Received 3 Sep. 1985.

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Equation [5] requires only the rock fragment on a weight basis. By assuming that the denominator is close to 1, the ratio K_b/K_s can be approximated by

$$K_b/K_s = (1 - R_w). \qquad [6]$$

The utility of Eq. [5] and [6] is that the rock fragment on a weight basis is much easier to obtain, usually available in most soil descriptions. The value of R_w is expressed as a decimal.

Results

Using the Bouwer and Rice (1984) data, Eq. [6] is compared with Eq. [1] and [2]. Figure 1 shows the comparison. Equation [6] provides estimates very close to Eq. [2] and also to the measured values for the sand-gravel mixtures.

In Table 1 we have compared Eq. [4] and [6] for a range of values for α and R_w. We see that the difference in (K_b/K_s) between Eq. [6] and [4] is probably not important for practical application.

To calculate K_b requires an independent estimate of K_s. We recommend a measured value or estimating K_s by the procedure of Rawls and Brakensiek (1985; Table 1).

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INFILTRATION DEVELOPMENT AND APPLICATION

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WRRC

INFILTRATION DEVELOPMENT AND APPLICATION

Proceedings of the
International Conference on
Infiltration Development
and Application

6-9 January 1987
Jefferson Hall
The East-West Center
Honolulu, Hawaii

Edited by Yu-Si Fok
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LARGE-PLOT INFILTRATION STUDIES IN DESERT AND SEMIARID RANGELAND AREAS OF THE SOUTHWESTERN U.S.A.

Leonard J. Lane, J. Roger Simanton, Thomas E. Hakonson and Evan M. Romney

ABSTRACT

Thirty-six large (3.05 by 10.7 m) experimental plots were established in semiarid rangeland and desert areas in Arizona and Nevada. Rainfall simulator data from these plots are used to investigate the influence of soil characteristics, vegetative cover, and surface rock and gravel cover (desert or erosion pavement) upon runoff and infiltration rates and amounts. The experimental design incorporated the influence of these factors using replicated plots and simulated rainfall during the spring and fall for four years in Arizona and two years in Nevada. Relationships between the mean final infiltration rate (a statistic representing the saturated hydraulic conductivity) and the three treatments (natural, vegetation removed, and bare soil) are established for the five sites/soils. Vegetative canopy cover and surface rock and gravel exhibited comparable, and statistically significant, influences on final infiltration rates. Final infiltration rates decreased as vegetative canopy cover and rock and gravel cover decreased. These findings have important implications for evaluation of land uses and management practices which reduce the vegetative canopy cover and/or disturb the rock and gravel cover in areas such as studied in this experiment. Such uses and practices are expected to reduce infiltration, and thus increase surface runoff which, in turn, would lead to increased erosion rates.

INTRODUCTION

Arid zones and semiarid rangelands cover extensive areas of the world (e.g., Branson et al. 1981), and form an important land resource of the United States, especially in the Southwest. Precipitation in these regions is generally less than potential evapotranspiration, so water availability is the most important environmental factor controlling survival and growth of desert and range plants (Brown 1977). Water balance calculations are necessary in soil-water-plant relationship studies, and infiltration calculations are necessary to partition precipitation into runoff and soil water recharge.

As is often the case in hydrology and agricultural science, more attention and resources have been devoted to infiltration research in humid areas subject to cultivated agriculture than to rangelands and desert areas. If we are to make better use of limited water resources in arid and semiarid areas, additional experimental data and research efforts are needed to understand and predict water infiltration on rangelands. Of the many factors controlling infiltration on rangelands, the role of desert and range vegetation and the

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role of desert or erosion pavement are not very well understood or quantified. Additional research is needed to quantify their role in determining components of the water balance, including the infiltration process. Recent advances in hydrologic modeling (e.g., Knisel 1980; Haan, Johnson, and Brakensiek 1982; and others), and extension of those models and concepts to semiarid and arid areas (e.g., Wight and Hanks 1981; Lane, Romney, and Hakonson 1984), have made hydrologic models more readily available for applications in the western United States.

The availability of these hydrologic models has important implications in current waste management studies (e.g., Hakonson et al. 1982). Recently developed rules and regulations require the ability to model hydrologic processes at shallow land burial facilities used to dispose of low-level radioactive wastes. Thus, it is important in these applications of hydrologic models to predict the amount and rates of infiltration, as they provide the source term for subsequent unsaturated flow and transport modeling. Because of the water problems associated with waste disposal, it is likely that arid and semiarid areas in the West and Southwest will receive increasing attention as possible sites for waste disposal facilities in the future. It is apparent there is a need for additional research and experimental data to quantify infiltration processes in arid and semiarid areas.

The purposes of this paper are to describe some recent rainfall simulator studies, particularly plot characteristics and summary infiltration data, in southeastern Arizona and southern Nevada, to relate this infiltration data to previously collected experimental data, and to discuss relationships among parameters expressing infiltration rates and experimental plot characteristics. Because of the large amount of data (several hundred rainfall simulator runs on several dozen plots), only summary analyses can be presented.

EXPERIMENTAL METHODS AND PROCEDURES

In the period 1981-1983, experimental plots were established in Arizona and Nevada to conduct rainfall simulator studies of erosion, runoff, and infiltration processes (Simanton and Renard 1982). These studies were conducted using a rotating boom rainfall simulator (see Swanson 1965 and Neff 1979 for details) on 3.05 by 10.7 m plots. The rainfall simulator is trailer mounted, with 10 booms 7.6 m in length supporting a total of 30 V-Jet 80100 nozzles. These nozzles apply simulated rainfall intensities of about 60 or 120 mm/hr, and produce drop-size distributions comparable with natural rainfall, but with about 80% of natural rainfall energy. The general procedure involved spring and fall rainfall applications on paired plots representing two soils in Nevada and three soils in Arizona. Location and climatic features of the plots are summarized in Table 1, and soils and vegetation are summarized in Table 2.

TABLE 1. SUMMARY OF CLIMATIC FEATURES AT STATIONS NEAR THE RAINFALL SIMULATOR PLOTS IN ARIZONA AND NEVADA

Station	Location Lat N	Location Long W	Elevation (m)	Mean Annual Temperature (C)	Mean Annual Precipitation (mm)	Period of Record (yr)
Tombstone, AZ	31°42'	110°03'	1405	17.6	324	1941-1970
Rock Valley, NV	36°40'	116°05'	1020	17.0	161	1968-1976

TABLE 2. SUMMARY OF SOIL AND VEGETATION CHARACTERISTICS FOR THE RAINFALL SIMULATOR PLOTS IN ARIZONA AND NEVADA

Site	Soil	Predominant Vegetation
Arizona Plots (Walnut Gulch)		
Bernardino	Thermic, Ustollic Haplargid	Blackgrama (Bouteloua eriopoda), sideoats grama (B. curtipendula), snakeweed (Gutierrezia sarothrae)
Cave	Thermic, shallow Typic Palerorthid	Creosote bush (Larrea tridentata), white-thorn (Acacia constricta)
Hathaway	Thermic, Aridic Calciustoll	False mesquite (Calliandra eriophylla), creosote bush, snakeweed, blue grama (B. gracilis), blackgrama
Nevada Plots (Nev. Test Site)		
Mercury	Shallow, mixed thermic, Typic Durorthid	Spiney menodora (Menodora spinescens), creosote bush, shadscale (Atriplex confertifolia)
Area 11	Shallow, mixed thermic, Typic Durorthid	Boxthorn (Lycium andersonii), Indian ricegrass Oryzopsis hymenoides), shadscale

An updated soil survey underway on Walnut Gulch is changing the names of some of the soils. Bernardino will probably be called Bernardo, Cave will be called Baseal, and Hathaway will probably be called a Tombstone soil.

The Bernardino series is a deep, well-drained, fine-textured soil formed in old calcareous alluvium. The soil can have up to 50%, by volume, gravel and cobbles in the surface 10 cm, and usually less than 35% gravel in the remaining profile. Percent sand, silt, clay, and organic matter in the surface 5 cm are 84, 10, 6, and 0.8, respectively. The Cave series is a shallow, well-drained, medium-textured soil with indurated lime hardpans that have developed at less than 45 cm in old gravelly and cobbly calcareous alluvium. This soil can have up to 60%, by volume, gravel and cobbles in the surface 10 cm, and usually less than 40% gravel in the remaining profile. Sand, silt, clay, and organic matter in the surface 5 cm are 66, 26, 8, and 1.8%, respectively. The Hathaway series is a deep, well-drained, gravelly medium and moderately coarse-textured soil over very gravelly, coarse-textured materials of moderate depths. This soil was formed from gravelly or very gravelly calcareous old alluvium, and can have up to 70%, by volume, gravel and occasional cobbles in the surface 10 cm, and usually less than 50% in the remainder of the profile. Percent sand, silt, clay, and organic matter in the surface 5 cm are 74, 17, 9, and 1.5, respectively. The Bernardino, Cave, and Hathaway soils are located on the Walnut Gulch Experimental Watershed near Tombstone, Arizona (see Renard 1970 for a detailed watershed description), in an area which represents highlands in a transition zone between the Chihuahuan and Sonoran Deserts.

The Mercury plots are located on the Nevada Test Site near Mercury, Nevada in the northern Mojave Desert, and the Area 11 plots are in a transition zone between the Mojave Desert and the Great Basin. The two sites are about 35 km apart on soils that have not been officially named, but are referred to hereafter as Mercury and Area 11. The Mercury soil is loamy, underlain by silica-lime hardpan, well drained, and formed in material weathered from limestone, quartz, and tuff. Percent coarse sand, fine sand, silt, and clay in the surface 5 cm are 20.4, 58.8, 14.8, and 6.0, respectively. The Area 11 soil is coarse-loamy, underlain by silica-lime hardpan, well drained, and formed in material weathered from tuff, basalt, and limestone. Percent coarse sand, fine sand, silt, and clay in the surface 5 cm are 15.2, 69.6, 14.5, and 0.7, respectively. Additional information on soils, vegetation, and climate is given by Romney et al. (1973).

Six plots were selected on each of the five soils to receive three treatments. Two of the six plots at each site were "control" plots, and were left in their natural cover condition. Two of the six plots at each site were "clipped" plots, where all vegetation was cut at the ground surface and removed with minimal soil surface disturbance. The remaining two plots at each site were "bare" plots, where vegetation was clipped and removed, and all nonembedded rock fragments greater than 5 mm were removed. These treatments were designed to determine the influence of vegetative cover and surface rock fragment (desert or erosion pavement) cover on runoff, erosion, and infiltration. A point-frame meter with pins spaced every 60 mm of its 3.05 m length was used to determine surface and canopy measurements at 490 points on the 3.05 by 10.7 m plots. The characteristics measured at each point were: bare soil (particles < 2 mm), gravel (particles 2 to 20 mm), rock (particles > 20 mm), litter, and vegetation basal and canopy cover. Average surface characteristics for the three treatments at the five sites are summarized in Table 3. The data in Table 3 (and subsequent tables) represent averages of two replications for each treatment, and thus do not represent plot to plot variations (see Simanton and Renard 1982 for additional information).

As expected, the climatic, soil, and plot characteristics were somewhat variable among the sites. At the Arizona sites, vegetative canopy cover varied from 35% (Cave site, Table 3) to 65% (Bernardino site, Table 3). Vegetative canopy cover was about one half to one third as dense (about 20%, Table 3) at the Nevada sites. The percent rock and gravel cover on the Arizona natural plots ranged from 45 to 51%, and 49 to 58% on the Arizona clipped plots (Table 3). Rock and gravel cover was somewhat higher on the Nevada plots, and ranged from 63 to 65% on the natural plots and 66 to 75% on the clipped plots. The bare plots (after treatment) at all sites had a rock and gravel cover that averaged about 16% (range of 13 to 19%, Table 3).

The same rainfall simulation sequence was applied at all sites. Rainfall was applied in the spring and fall at each site in the following sequence. A one-hour run (DRY) was made under initially dry soil conditions followed 24 h later by a 30 minute run (WET), which was followed 30 minutes later by another 30 minute run (VERY WET). Rainfall application rates were held as constant as possible during all experimental runs, and usually varied from 55 to 60 mm/h. This experimental design allowed for comparisons among sites and at sites for varying initial soil mositure. Because rainfall rates and durations were held constant, the experimental design does not allow analyses of the influence of rainfall amount, rates, or durations. Because of the large amount of data

generated by these experiments, the limited space here, and the focus of many investigations upon saturated hydraulic conductivity, subsequent discussions emphasize data from the very wet runs. In most cases, steady-state runoff rates were reached well before the very wet run ended at 30 minutes.

TABLE 3. SUMMARY OF PLOT SURFACE CHARACTERISTICS FOR THE THREE TREATMENTS AT THE FIVE SITES; DATA ARE AVERAGES OF TWO REPS, SPRING AND FALL DATA FOR 1981-1984 FOR THE ARIZONA PLOTS, AND 1983-1984 FOR THE NEVADA PLOTS

			Percent Cover							
			Surface				Canopy			
Site/plot	Trt.	Slope (%)	Rock	Gravel	Soil	Litter	Grass	Forb	Shrub	Total
Ariz. (WG)										
Bernardino										
pl 6 & 7	Nat	11.3	22.3	28.6	42.7	6.4	39.1	20.7	5.3	65.2
pl 5 & 9	Clip	10.6	22.6	35.3	37.6	4.6	-	-	-	-
pl 4 & 8	Bare	12.0	4.5	14.6	76.4	4.5	-	-	-	-
Cave										
pl 21 & 26	Nat	10.0	18.1	26.5	42.1	13.6	9.5	23.7	1.6	34.7
pl 19 & 25	Clip	10.3	16.7	32.2	40.6	10.5	-	-	-	-
pl 20 & 23	Bare	10.0	6.6	6.8	82.0	4.7	-	-	-	-
Hathaway										
pl 12 & 15	Nat	10.3	21.7	29.3	36.1	12.9	33.1	12.4	3.2	48.7
pl 14 & 17	Clip	10.6	25.1	32.3	35.0	7.6	-	-	-	-
pl 11 & 16	Bare	9.8	6.6	8.2	78.1	7.1	-	-	-	-
Nevada (NTS)										
Mercury										
pl 7 & 11	Nat	8.8	13.1	51.6	23.5	11.8	0.6	18.6	2.8	22.0
pl 8 & 10	Clip	8.6	17.5	58.2	21.9	2.4	-	-	-	-
pl 9 & 12	Bare	8.7	5.2	10.9	83.4	1.3	-	-	-	-
Area 11										
pl 1 & 4	Nat	7.2	14.0	48.8	21.6	15.7	3.9	14.4	2.9	21.2
pl 3 & 6	Clip	6.4	14.2	51.3	29.2	5.4	-	-	-	-
pl 2 & 5	Bare	7.8	3.0	12.4	83.2	1.5	-	-	-	-

RESULTS AND DATA

Selected data from the very wet runs at the five sites are summarized in Table 4. Again, notice that rainfall depth, P, and intensity, I, are nearly constant for the 8 experimental runs at the Arizona sites and the 4 experimental runs at the Nevada sites.

Because of water shortages, a few runs at the Nevada sites were for 25 minutes, rather than the full 30 minutes. In all cases, the runoff amount, Q,

TABLE 4. SUMMARY OF RAINFALL, RUNOFF, AND INFILTRATION DATA FOR THE VERY WET RUNS AT THE FIVE SITES; DATA ARE AVERAGES FOR THE TWO REPS, SPRING AND FALL DATA FOR 1981-1984 FOR THE ARIZONA PLOTS, AND 1983-1984 FOR THE NEVADA PLOTS.

		Simulated rainfall		Measured runoff		Infiltration		Time to runoff[2]
Site/plot	Trt.	Depth P (mm)	Intensity[1] I (mm/h)	Depth Q (mm)	Peak Q_p (mm/h)	Depth F (mm)	Final K_f (mm/h)	t_r (min)
Ariz.(WG)								
Bernardino								
pl 6 & 7	Nat	28.5	56.9	8.9	22.7	19.6	35.3	3.1
pl 5 & 9	Clip	27.6	55.2	15.1	35.1	12.4	21.0	2.2
pl 4 & 8	Bare	28.1	56.2	20.8	44.0	7.3	13.7	1.0
Cave								
pl 21 & 26	Nat	28.6	57.1	13.6	31.5	14.9	26.3	2.5
pl 19 & 25	Clip	27.4	54.8	18.7	40.8	8.8	15.0	1.9
pl 20 & 23	Bare	28.0	55.9	21.4	45.0	6.5	11.6	1.2
Hathaway								
pl 12 & 15	Nat	28.7	57.4	11.4	26.6	17.2	31.6	2.9
pl 14 & 17	Clip	28.7	57.6	18.3	40.2	10.4	19.3	1.6
pl 11 & 16	Bare	28.5	57.0	21.1	44.7	7.4	12.4	1.1
Nevada (NTS)								
Mercury								
pl 7 & 11	Nat	27.8	59.5	17.0	40.4	10.8	20.5	1.7
pl 8 & 10	Clip	25.9	54.0	20.9	47.0	5.0	7.3	1.3
pl 9 & 12	Bare	26.3	54.5	23.8	52.1	2.5	4.8	0.9
Area 11								
pl 1 & 4	Nat	26.1	54.7	7.6	21.0	18.5	33.7	4.1
pl 3 & 6	Clip	26.8	55.9	9.3	26.6	17.5	29.4	3.3
pl 2 & 5	Bare	26.5	55.4	16.7	39.0	9.8	16.3	1.2

[1]Rainfall duration is about 30 min for all very wet runs.
[2]Time from beginning of rainfall until runoff begins as measured in the flume at the lower end of the plot.

was lowest from the natural plots, intermediate from the clipped plots, and highest from the bare plots. The same (but opposite direction) relationships held for total infiltration, F, calculated as P-Q, and final infiltration rate K_f calculated as the difference between application and runoff rates at the end of a run. The time to runoff, t_r, is the time from the beginning of simulated rainfall until runoff is observed in the measuring flume at the lower end of the plot. The time to runoff, t_r, includes time delays due to interception, storage, and routing, and is thus always greater than the actual time to ponding. The differences between t_r and t_p are greatest on the natural plots and least on the bare plots. With these qualifications, time to ponding

was largest on the natural plots, intermediate on the clipped plots, and smallest on the bare plots.

A simple correlation matrix, for the data shown in Table 4 and for selected plot characteristics, is shown in Table 5.

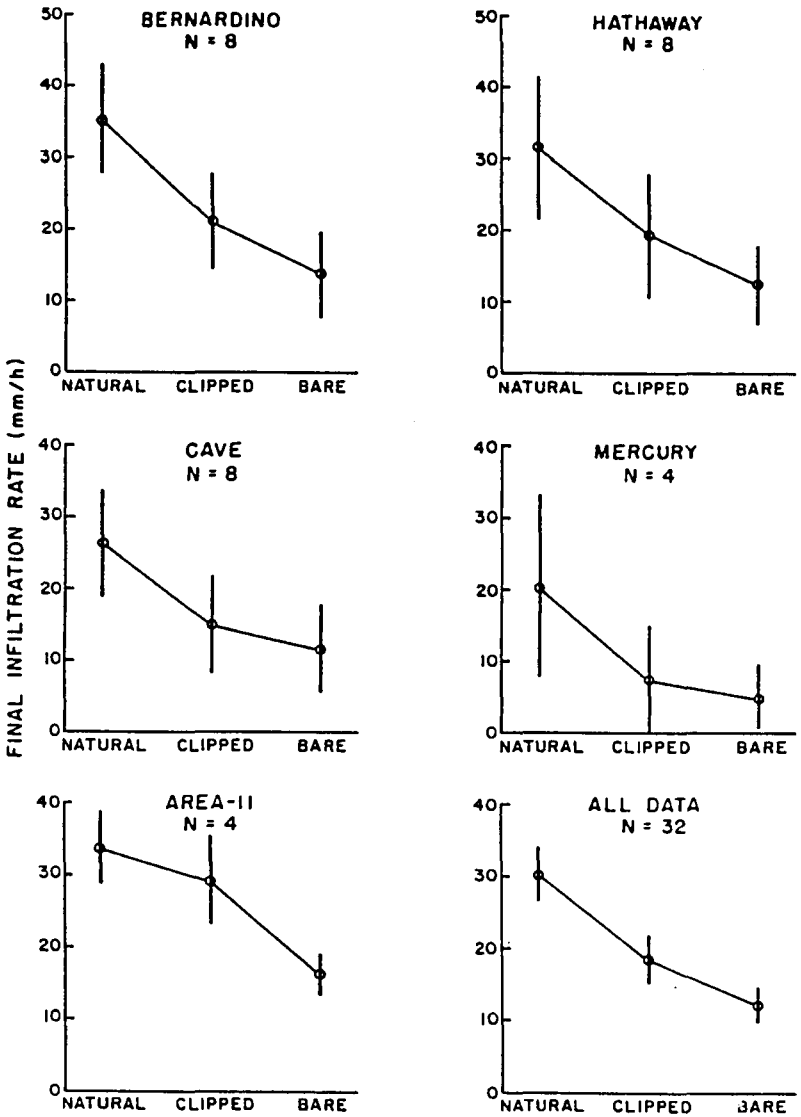
TABLE 5. CORRELATION MATRIX FOR PLOT CHARACTERISTICS, RUNOFF, AND INFILTRATION VARIABLES; DATA ARE AVERAGES OF TWO REPLICATIONS FOR VERY WET RUNS ON EXPERIMENTAL PLOTS IN ARIZONA (1981-1984) AND NEVADA (1983-1984)

	Q[1] (mm)	Q_p (mm/h)	t_r (min)	F (mm)	K_f (mm/h)	PC[2] (%)	PRG (%)	CC (%)
Q	1.00[3]	0.99*	-0.96*	-0.98*	-0.97*	0.45	-0.54*	-0.65*
Q_p		1.00	-0.95*	-0.99*	-0.98*	0.37	-0.48	-0.68*
t_r			1.00	0.93*	0.92*	-0.39	0.60*	0.59*
F				1.00	0.99*	-0.31	0.49	0.71*
K_f					1.00	-0.27	0.48	0.74*
PC						1.00	-0.15	0.13
PRG							1.00	0.26
CC								1.00

[1]See Table 4 for definition of variables.
[2]PC = % clay in soil 0-5 cm; PRG = % rock and gravel on plot surface, and CC = % canopy cover.
[3]Correlation coefficients for d.f. = N-2 = 13 are significant at the 5% level if r > = 0.514. Significant values are shown with *.

Notice that the runoff and infiltration variables are highly intercorrelated, as they should be when rainfall application rates and amounts are held nearly constant and uniform. This suggests that analyses with a single variable such as K_f would indicate the expected relationships and trends with the other intercorrelated variables. The data in Table 5 are suggested as qualitative measures of the influence of the treatments upon infiltration rates and amounts. For example, final infiltration rate, and thus saturated hydraulic conductivity, should decrease with increasing percent clay in the soil, and increase with rock and gravel cover (desert or erosion pavement) and vegetative canopy cover. The data shown in Tables 3, 4, and 5 suggest relationships among plot characteristics, treatments, soils/sites, and runoff and infiltration variables. Again, they do not suggest anything about variations in runoff and infiltration with precipitation amount or rate or antecedent moisture.

Means and 95% confidence limits on the mean final infiltration rates for the three treatments at each of the five sites, and for all sites together, are shown in Figure 1. This graph emphasizes the influence of treatments at each site. At the Bernardino site, there are significant differences between the natural and bare plots, with the clipped plots intermediate. However, there appear to be greater differences between the natural and clipped plots than between the clipped and bare plots. Similar relationships and patterns are evident for the Hathaway and Cave sites. At the three Arizona sites, there is a statistically significant difference between final infiltration



rates on the natural and bare plots. Bare soil plots always had significantly lower infiltration rates than the corresponding natural plots. While not statistically significant at the 95% level, the final infiltration rates were lower on the clipped plots than on the natural plots, and higher than on the bare plots. This same pattern was observed at all five sites, suggesting statistical significance at the 3% level, since this outcome would be expected only once in 32 times by chance. The results shown for the Mercury and Area 11 sites are based on only 4 observations, so they should be given qualitative interpretation only. However, the Nevada results shown in Figure 1 do seem to match the results observed at the Arizona sites. When all data are pooled (lower right hand corner of Figure 1), the results are significant at the 95% level. Final infiltration rates are lower on the clipped plots than on the natural plots, and lower on the bare plots than on the clipped. With respect to the pooled data, removing the vegetative canopy cover resulted in a 39% decrease in mean final infiltration rate, and also removing the rock and gravel cover resulted in an additional 34% decrease in final infiltration rate.

RELATION TO PREVIOUS STUDIES

Previous studies of infiltration on the Walnut Gulch Experimental Watershed in Arizona include early Type F infiltrometer studies on 1.8 by 3.7 m plots as reported by Kincaid, Gardner, and Schreiber (1964). These plots represented two soil types with predominately brush on one site and grass vegetative cover on the other. The soil characteristics and vegetation cover were similar, but not identical to, those used in the present study. Kincaid, Gardner, and Schreiber (1964) found that total infiltration amount increased with surface gravel cover, that shrub canopy cover together with surface cover of grass, litter, and gravel was most strongly related to infiltration amount, and that final infiltration rate increased as the crown spread of shrubs and half-shrubs increased.

Kincaid and Williams (1966) used similar 1.8 by 3.7 m plots to evaluate the influence of range improvement practices upon runoff (and thus infiltration) over a summer runoff season. Their most significant finding of interest here was that runoff volume showed a significant negative correlation with vegetation canopy cover. A subsequent study reported by Schreiber and Kincaid (1967) developed regression equations relating precipitation quanity, vegetation canopy cover, and antecedent soil moisture to runoff volume for 34 natural storms on 1.8 by 3.7 m plots. Their study indicated that total precipitation or rainfall intensity was most significant, that total runoff volume had a significant negative correlation with vegetation canopy cover, and that antecedent soil mositure was not significantly correlated with runoff volume. Smith and Chery (1973) reported on the results of application of a parametric infiltration model to a subset of data (events with a recorded hydrograph rather than just total runoff for the storms) from the 1.8 by 3.7 m plots. Their results reported potential advantages of their infiltration model over another empirical infiltration model. Smith and Chery (1973) concluded that instruments used to measure rainfall and runoff on the 1.8 by 3.7 m plots

Walnut Gulch Experimental Watershed. Their results were for 1 m square plots on Bernardino, Cave, and Hathaway soil with 3 replications at seven sites. The Bernardino soil was represented by 3 natural plots in grass cover. The Cave soil was represented by 3 natural brush plots, 3 natural grass plots, and 3 bare soil plots. The Hathaway soil was represented by 9 plots with 3 grazed grass plots, 3 ungrazed grass plots, and 3 natural brush plots. Their results showed higher infiltration on the brush plots than on ungrazed grass plots which had higher infiltration rates than the grazed grass plots. In agreement with the present study and the previously cited studies, Tromble, Renard, and Thatcher (1974) found significant increases in infiltration with increases in vegetative canopy cover and significant decrease in infiltration on bare soil plots.

Dixon, Simanton, and Lane (1978) evaluated several algebraic infiltration equations on a variety of data including some from the Santa Rita Experimental Range located approximately 80 km W,NW of the Walnut Gulch Experimental Watershed. Their most significant finding relative to the present study was a listing of the most important soil surface conditions affecting infiltration as microroughness, macroporosity, plant litter, and effective surface head. Lane et al. (1978) used similar infiltrometer data from the Santa Rita Experimental Range to evaluate the capillary and saturated hydraulic conductivity term in the Philip (1957) equation. They found (on 1 m square plots) that plots including a dense cover of grass plants had significantly higher final infiltration rates than adjacent bare soil plots.

Simanton and Renard (1982) developed the experimental design upon which the present study is based, and reported on the first full year of data (spring and fall, 1981) from Walnut Gulch. They found runoff, infiltration, and soil loss to vary with treatments (following the patterns described in the previous sections of this paper), and with season as well. The initial experimental design developed by Simanton and Renard (1982) was intended to develop Universal Soil Loss Equation (Wischmeier and Smith 1978) parameters for rangeland conditions. Since that time, however, the data have been utilized in infiltration and erosion modeling studies.

Previous studies of infiltration on the Walnut Gulch Experimental Watershed, and similar semiarid rangeland areas, have produced quantitative and qualitative relationships among vegetative canopy cover, rock and gravel surface cover, and infiltration rates and amounts. Data presented in Tables 1-5 and Figure 1 support the previous studies. The large-plot infiltration data reported herein for the Nevada sites in the Mojave desert appear to be unique in that no comparable results in Nevada were found in the literature surveyed.

SUMMARY AND DISCUSSION

Rainfall simulator data on 3.05 by 10.7 m plots, at three semiarid sites in Arizona and two arid sites in Nevada, were used to investigate the influence of soil surface characteristics and surface treatments (natural vegetation and rock and gravel cover, clipped or vegetation removed, and bare soil plots) upon runoff and infiltration rates and amounts. Site characteristics are summarized in Tables 1 and 2, plot surface characteristics are summarized in Table 3, rainfall, runoff, and infiltration data are summarized in Table 4, and Table 5 presents a correlation matrix for plots characteristics with runoff and infiltration variables. Because rainfall application rates were held constant and uniform (except for the dry runs as noted earlier), runoff and infiltration variables exhibited strong intercorrelation. Final infiltration rate at the end of the very wet runs was selected as the infiltration variable for further analyses and for investigation of the influence of the treatment upon infiltration.

Relationships between the mean final infiltration rates and treatments for the five sites/soils are summarized in Figure 1. Vegetative canopy cover and surface cover of rock and gravel exhibited comparable influences on final infiltration rates. Final infiltration rates decreased significantly as vegetative canopy cover and soil surface rock and gravel cover decreased. These findings are in agreement with previous studies at the same or similar locations.

These findings (particularly the relationships shown in Figure 1) have important implications for management of semiarid and arid rangelands. Land uses and management practices which reduce the vegetative canopy cover and/or disturb the rock and gravel (desert or erosion pavement) in areas such as studied in this experiment are expected to significantly decrease infiltration with resulting increases in runoff and erosion.

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

Factors influencing infiltrability of semiarid mountain slopes

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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).

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

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

(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.

Vegetation types labelled by dominant Species	Slope	Infiltrability (cm/hr) Year 1 Dry	Year 1 Wet	Year 2 Dry	Year 2 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

Both years of data indicate a strong relationship between infil-

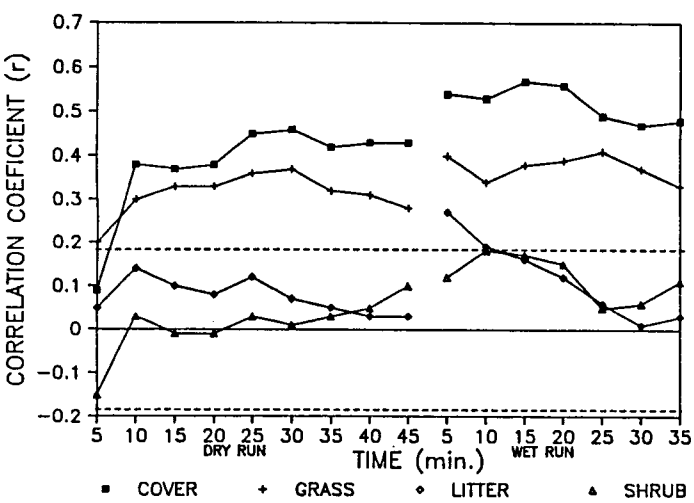

Fig. 1. *Year 1 correlations between vegetal cover and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

trability 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

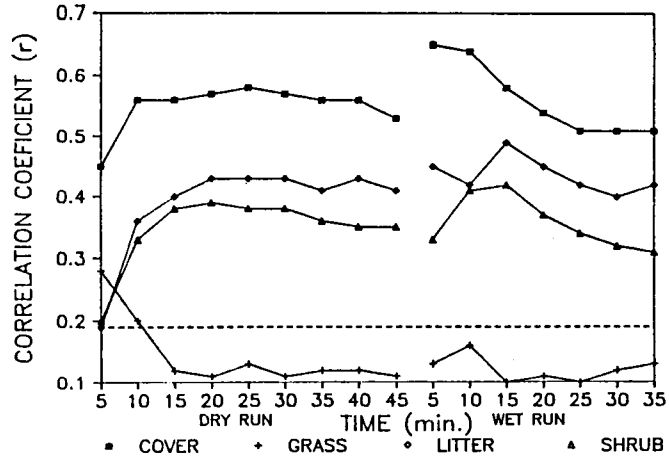

Fig. 2. *Year 2 correlations between vegetal cover and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value the which correlations are significant (p≤0.05).*

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.

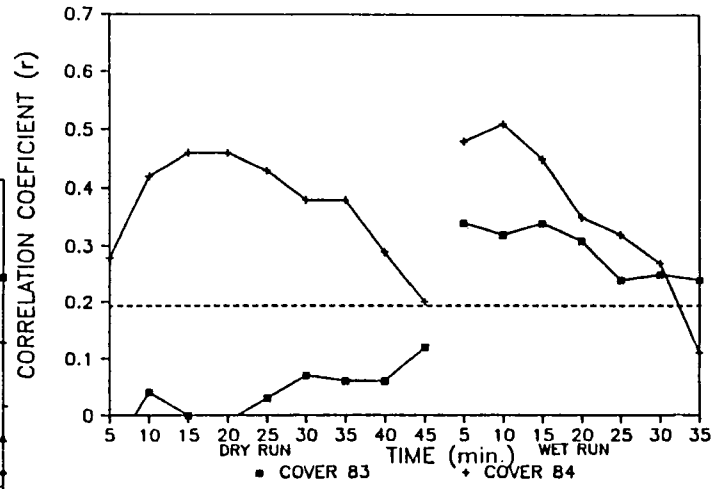

Fig. 3. *Partial correlations (effect of rock cover and slope gradient removed) between total vegetal cover and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

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

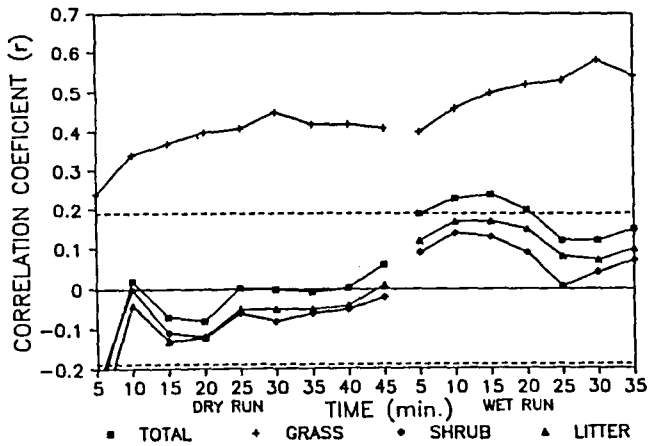

Fig. 4. *Year 1 correlation between vegetal biomass and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

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

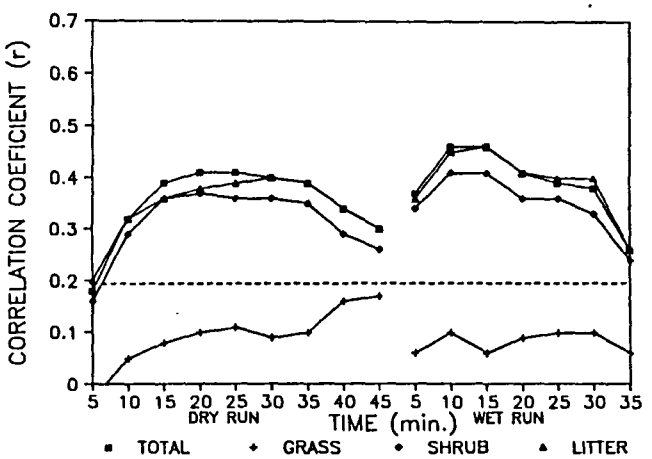

Fig. 5. *Year 2 correlations between vegetal biomass and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

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.

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

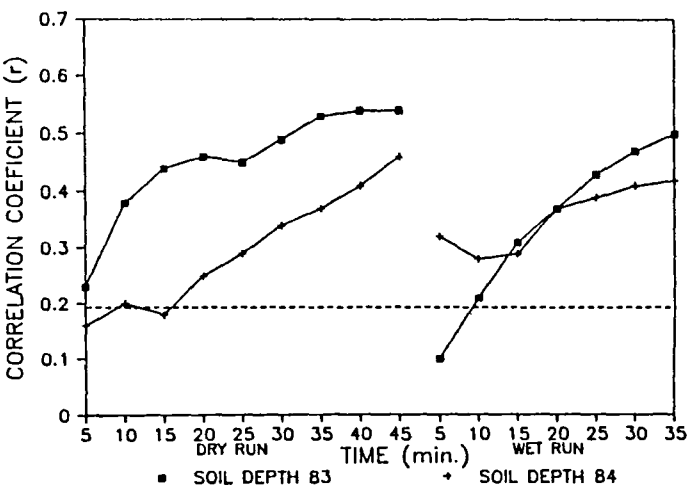

Fig. 6. *Correlations between soil depth and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

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).

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/cm³)			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

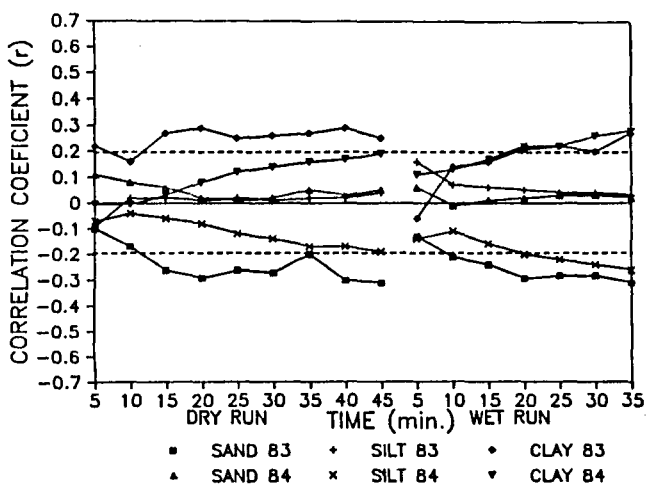

Fig. 7. *Correlations between soil texture and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

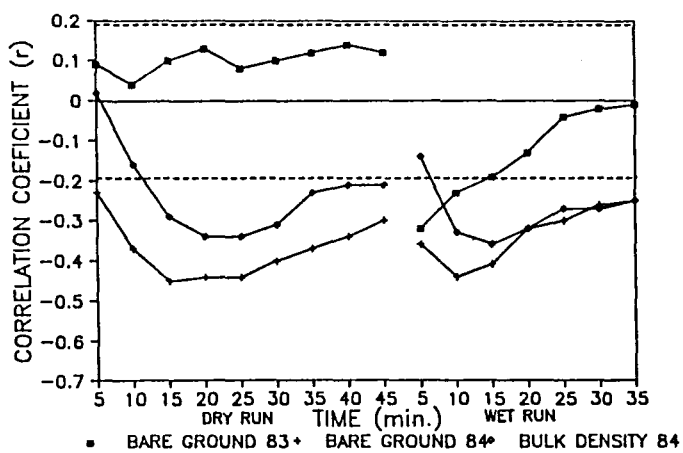

Fig. 8. *Correlations between bulk density and bare ground and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

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).

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

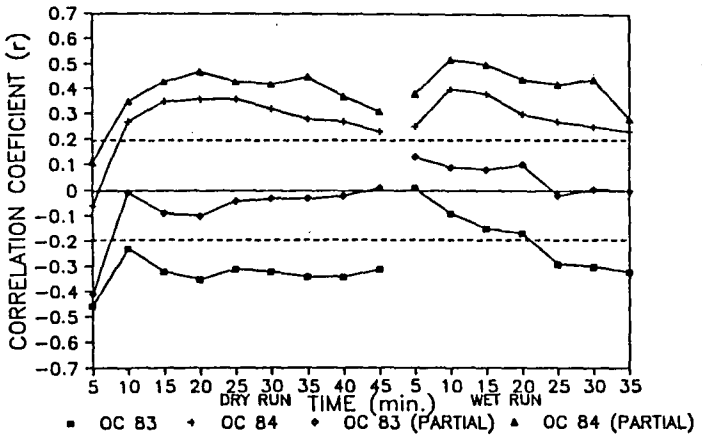

Fig. 9. *Correlations and partial correlations (effect of soil depth removed) between organic carbon and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

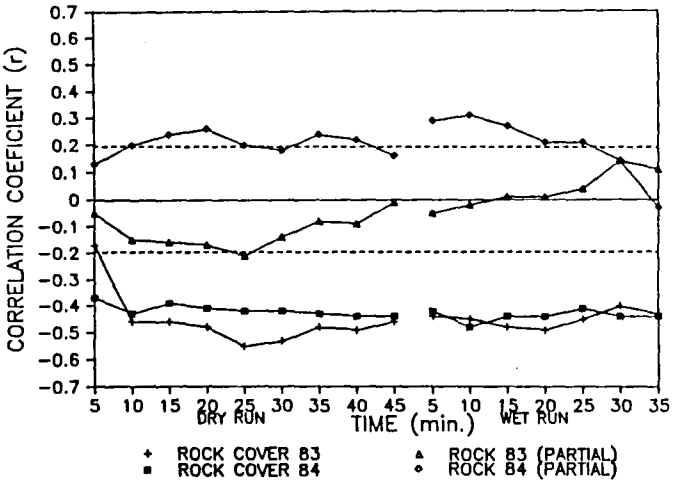

Fig. 10. *Correlations and partial correlations (effect of vegetation and slope removed) between rock cover and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

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	Commun-ality	Factor Loadings 1	2	3	4	5	6	7
	Shrub biomass	.85	.88	0	-.23	.16	-.03	-.03	.04
	Shrub cover	.89	.86	.03	-.32	.17	.04	-.07	.09
1	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
	Rock cover	.85	-.31	-.80	-.19	-.18	-.10	.15	.07
	Total cover	.89	.42	.78	.14	.15	-.11	.22	.07
2	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
	Total basal cover	.87	-.20	.41	.81	-.03	-.04	.06	-.04
3	Basal grass cover	.88	-.28	.43	.78	-.05	-.05	.03	-.03
	Slope gradient	.65	.16	.21	-.69	.07	.28	-.09	-.10
	Litter cover	.83	.15	.17	-.04	.85	.06	-.18	-.11
4	Bareground	.72	-.29	-.01	.08	-.69	.22	-.33	-.07
	Organic carbon (0-5 cm)	.78	.37	-.31	.01	.52	.06	.47	-.23
	Forb cover	.83	-.22	-.19	-.19	.02	.84	.04	.07
5	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
	Clay (0-5 cm)	.91	-.12	0	-.01	-.14	.13	-.43	.82
7	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

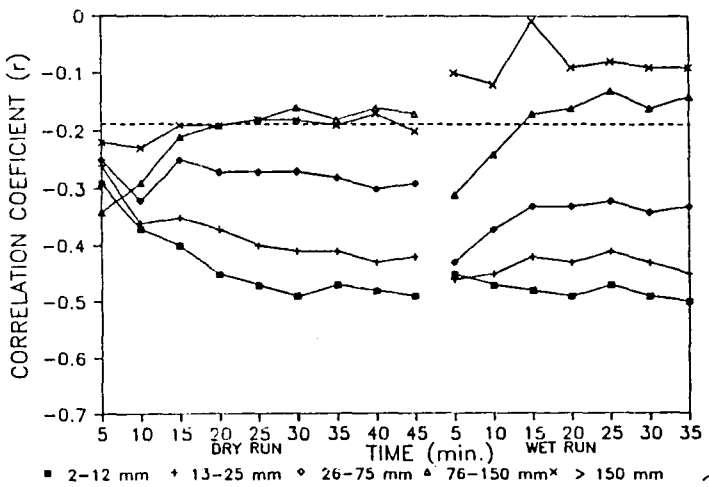

Fig. 11. *Year 2 correlations between rock cover by size class and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

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.

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

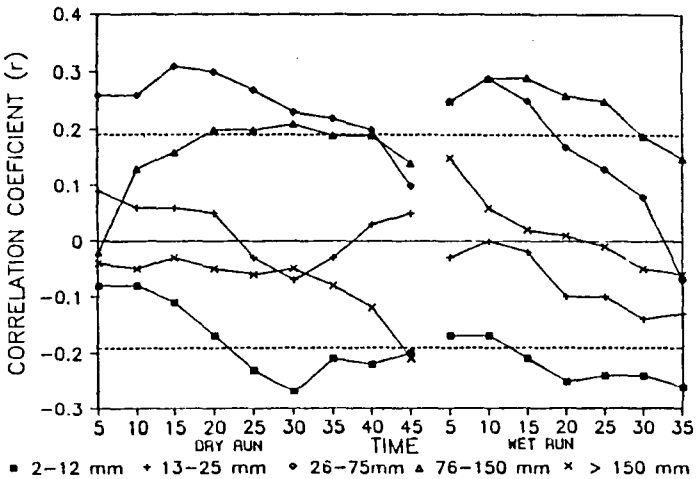

Fig. 12. *Year 2 partial correlations (effect of vegetal cover and slope removed) between rock cover by size class and infiltrability. Dashed lines represent the value at which correlations are significant. (p≤0.05).*

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.

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

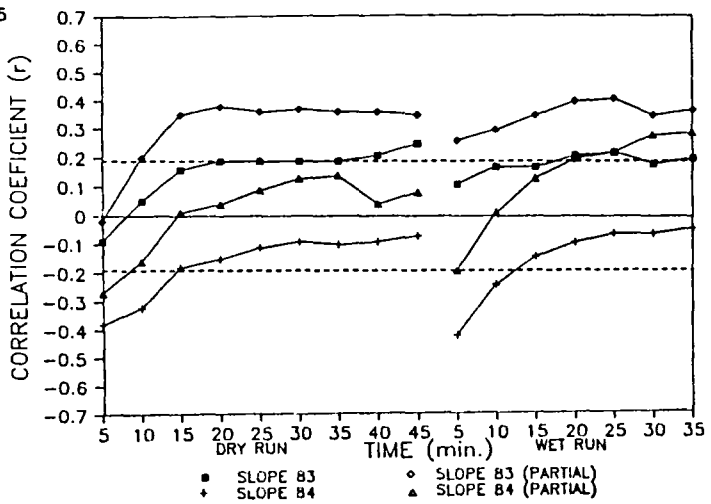

Fig. 13. *Correlations between slope and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

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 Loadings					
Factor	Variable	Communality	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

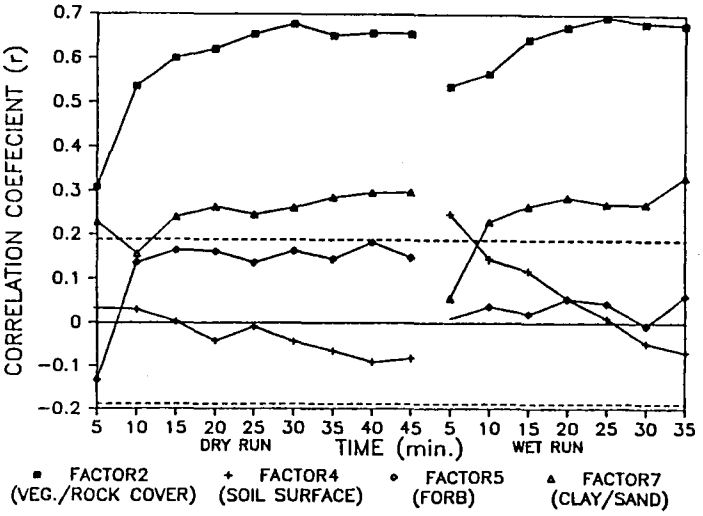

Fig. 14. *Positive correlations between the year 1 PCA factors and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

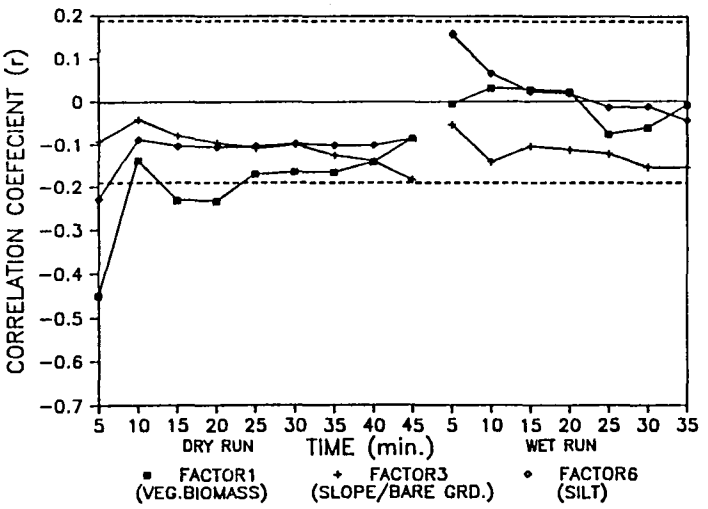

Fig. 15. *Negative correlations between the year 1 PCS factors and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

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.

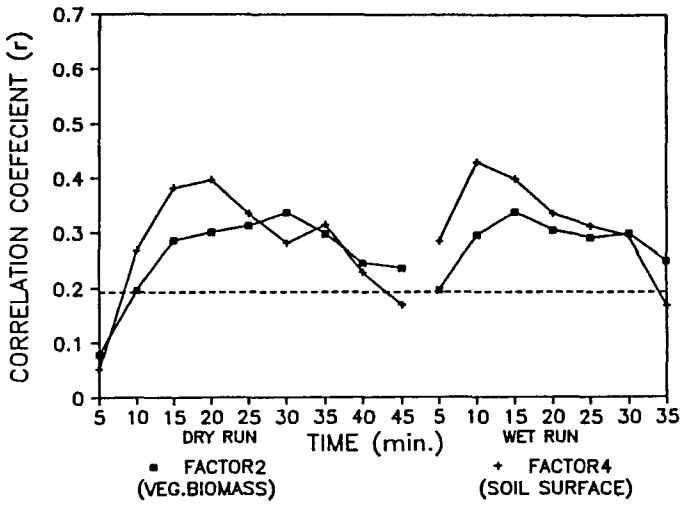

Fig. 16. *Positive correlations between the year 2 PCA factors and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

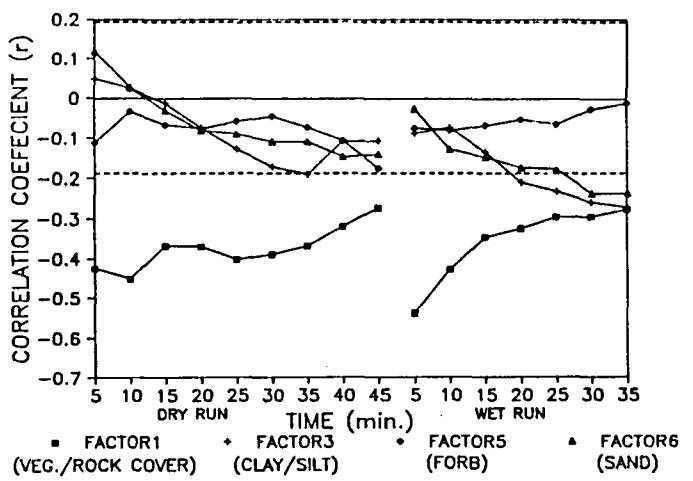

Fig. 17. *Negative correlations between the year 2 PCA factors and infiltrability at 5-minute intervals for the dry and wet runs. Dashed lines represent the value at which correlations are significant (p≤0.05).*

(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.

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Infiltration parameters for rangeland soils

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Abstract

Important to the management of rangelands is knowledge of the water intake properties of their soils and the effect of soil surface and canopy cover. Using a data base of rangeland infiltration runs covering a wide range of soil and cover conditions, a procedure incorporating the effects of soil properties, soil surface cover, and vegetative canopy on the Green-Ampt hydraulic conductivity parameter was developed. Test results indicate that the estimated Green-Ampt parameters provided good predictions of the mean final infiltration rates and volumes for a variety of soil-cover situations.

Key Words: Green-Ampt, infiltration rates, soil properties

The importance of ground and canopy cover on rangeland infiltration characteristics has long been recognized (Gifford 1984). Generally, it has been shown that as ground cover or canopy cover increase, infiltration amounts increase while increases in bare ground decreases infiltration amounts (Gifford 1984). Most recently Hutten and Gifford (1988) showed that Green-Ampt parameters estimated from soil texture data alone do not adequately model rangeland infiltration. Mehan (1986) showed that infiltration increases with increases in surface rock for a range of soil textures. Also, Lane et al. (1987) conducted infiltration studies on 5 soils in Arizona and Nevada where rainfall simulation experiments were run on plots with natural cover canopy removed and bare plots where the canopy and most of the surface rock and litter were removed. They found that infiltration was greatest for the natural condition, declining when canopy was removed and further declining when surface rock and litter were removed.

At present there are methods for predicting parameters for the Green-Ampt infiltration model based on soil properties (Rawls and Brakensiek, 1983, 1985); however, there is no method for incorporating the effects of rangeland ground cover and canopy cover on infiltration parameters. Therefore, it is the purpose of this paper to develop procedures for incorporating the effects of ground cover and canopy cover into the Green-Ampt infiltration parameters, which may alleviate some of the problems identified by Hutten and Gifford (1988).

The Green-Ampt infiltration rate equation is

$$f = K \left(1 + \frac{(\phi_c - ASW)\ \Psi_f}{F} \right) \qquad [1]$$

and its integrated form is

$$K(T) = F - (\phi_c - ASW)\ \Psi_f \ln \left(1 + \frac{F}{(\phi_c - ASW)\ \Psi_f} \right) \qquad [2]$$

where
- f = infiltration rate (cm/hr)
- F = infiltration amount (cm)
- T = time (hrs)
- K = hydraulic conductivity (cm/hr)
- Ψ = wetting front capillary potential (cm)
- ϕ_c = corrected porosity (total porosity corrected for rocks and air) (vol)
- ASW = antecedent soil water (vol)

In order to predict infiltration with equations [1] or [2], the antecedent soil water (ASW) needs to be inputted and hydraulic conductivity (K), wetting front capillary potential (Ψ_f) and the porosity corrected for rocks and entrapped air (ϕ_c) need to be estimated. The following are equations used for predicting the parameters based only on soil properties:

Effective Porosity (ϕ_c)

$$\phi_c = \phi = (CFC)\ (EAC) \qquad [3]$$

where
- ϕ = total porosity (vol) = (2.65) - BD)/2.65
- CFC = Correction for coarse fragments (Brakensiek et al. 1986) = ((100 - VCF)/100)
- EAC = correction for entrapped air (Rawls and Baumer 1989) = 1.0 - (3.8 + 0.00019 (CL^2) - 0.337 (SA) + 0.126 (CEC) (CL) + OM ($(SA/200)^2$))/100
- BD = 33 KPa bulk density of the fine earth soil (<2 mm) g/cm³
- OM = % organic matter
- CL = % clay
- SA = % sand
- CEC = cation exchange capacity/%clay (ranges 0-1)
- VCF = % volume coarse fragments (>2 mm) computed from Brakensiek et al. 1986
- VCF = ((WCF/2.65) * 100)/((100-WCF/BD + WCF/2.65))
- WCF = %weight of coarse fragements (>2 mm)

Wetting Front Capillary Potential (Ψ_f)

$$\Psi_f = e^x \qquad [4]$$

where x = 5.34 + 0.185 (CL^2) - 2.484 (ϕ) - 0.0021 (CL^2) - 0.0436 (SA) (ϕ) - 0.6175 (CL) (ϕ) + 0.00144 (SA^2) (ϕ^2) - 0.00855 (CL^2) (ϕ^2) - 0.000013 (CL) (SA^2) + 0.009 (ϕ) (CL^2) - 0.00073 (ϕ) (SA^2) + 0.000005 (SA) (CL^2) + 0.5003 (CL) (ϕ^2) (Rawls and Brakensiek, 1985)

Hydraulic Conductivity (K)

$$K = K_s\ (FGC)\ (CFC) \qquad [5]$$

where K_s = saturated hydraulic conductivity (Rawls and Baumer 1989)

$$= \left(\frac{(\phi_c - \Theta_r)^3}{(1 - \phi_c)^2} \right) \left(\frac{BD}{\Theta_r} \right)^2 \left(.0002\ (C^2) \right)$$

- FGC = frozen ground correction (Lee 1983) = 2 - .019 * PFC
- Θ_r = residual soil water (vol) (Rawls and Baumer 1989) = 0.2 + 0.1 (OM) + 0.25 (CL) ($CEC^{0.45}$) (BD/100) (BD/100) (EAC) (CFC)
- C = -0.17 + 0.181 (CL) - 0.00000069 (SA^2) (CL^2) - 0.00000041 (SA^2) (SI^2) + 0.000118 (SA^2) (BD^2) + 0.00069 (CL^2) (BD^2) + 0.000049 (SA^2) (CL) - 0.000085 (SI) (CL^2)
- SI = percent silt.
- PFC = soil water at freezing (% vol)/soil water held at 33 KPa (% vol). If PFC ≥ 1, then FGC = .1 (Lee 1983).

Brakensiek and Rawls (1983) developed a factor for reducing the saturated hydraulic conductivity for an established soil crust. The crust factor is

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Without the cooperation of those investigators who provided data given in Table 1, this study would not have been possible.

Manuscript accepted 8 August 1988.

$$CRC = \frac{L}{\frac{L-TC}{SC} + \frac{TC}{B}} \quad [6]$$

where CRC = soil crust correction (Brakensiek and Rawls, 1983)
L = wetting front depth (cm) (assume 6 cm)
TC = crust thickness (cm) (assume 0.5 cm)
B = $0.0099 + 0.0721\,(TC) + 0.0000068\,(SA^2) + 0.000021\,(SA^2)\,(TC) - 0.000315\,(SA)\,(TC^2)$
SC = correction factor for partial saturation of the subcrust soil (Brakensiek and Rawls 1983)

Management changes are reflected in the above parameters only by changes in the bulk density of the soil.

Methods

An extensive data search was performed to compile infiltration data sets which included detailed soils, ground cover, and canopy cover information. The physical characteristics of the data sets located are summarized in Table 1.

Table 1. Summary description of data sets.

Study reference	State	General description
Devaurs (1984)	ID	3 soil series, grazed and non-grazed sites and 2 soil water levels; 38–59% sand; 9–18% clay; bulk density 1.1–1.5 g/cm³; 30–52% canopy; and 7–32% bare ground.
Hutten (1984)	UT	5 soil sites with 2 management practices (plowed and unplowed); 25–68% sand; 15–33% clay; bulk density 0.9–1.3 g/cm³; 0.65% canopy; and 0–50% bare ground.
Lane et al. (1987)	AZ NV	Natural, clipped and bare range cover at 3 sites in AZ and 2 sites in NV; 66–84% sand; 1–9% clay; 0–75% canopy; and 0–41% bare ground.
Thurow (1985)	TX	27–88% sand; 7–42% clay; bulk density 0.85–0.95 g/cm³; 27–57% canopy; and 21–43% bare ground.
Ward and Wood (1982)	NM	Grazing levels, pinyon-juniper mgt, sagebrush mgt and others at 3 sites; 32–90% sand; 14–33% clay; 1–90% canopy; and 3–89% bare ground.
Williams (1969)	UT	4 chained pinyon-juniper sites; 16–65% sand, 16–33% clay; bulk density .9–1.6 g/cm³; 0.20% canopy; and 38–97% bare ground.
Wood[1]	NM	Dry and wet soil water levels on one range site; 29% sand; 44% clay; and 35% canopy.

[1]Personal communication

For each infiltration test we calculated the effective conductivity using an approximation to the Green-Ampt equation derived by Li et al. (1976),

$$KE = 2(FR) - (F/T) \quad [7]$$

where KE = effective conductivity (cm/hr)
FR = final infiltration rate (cm/hr)
F = total infiltration at the final infiltration rate (CM)
T = accumulated time corresponding to the final rate and infiltration amount (hr)

Since the studies contained various replications at each site, we used the mean site value for soil—ground cover, canopy cover, and the geometric mean effective conductivity which represents an area integrated value—for the analyses.

Parameter Development

Past research (Moore 1981) has shown that the wetting front capillary potential parameter is relatively insensitive in comparison with the hydraulic conductivity parameter. It was thus assumed that ground cover and canopy cover affect only the hydraulic conductivity parameters. Since rangeland conditions reflect long-term climate, cover, and land use patterns, we assumed that all bare soil is crusted and that the bare or covered soil under a canopy has a higher conductivity than the bare or covered soil in the interspace area. In addition, the covered soil has a higher effective conductivity than the uncovered soil surface whether under a canopy or in the interspace area. These assumptions reflect that canopy, ground cover, litter, or surface rocks reduce crust formation. Further, they enhance macroporosity caused by biotic activity and other processes especially in the soil under or around the litter rock soil interface.

We incorporated the canopy and ground cover effect into a simple weighting by the proportions of the unit area composed of canopy and open space and by the proportion of the canopy space and open space in which the soil surface was covered or bare. For the portion of unit area under canopy cover we estimate the effective conductivity parameter, $(KE)_c$, as

$$KE_c = (CF)\,[(BC/CAN)(CRC) + A(1-(BC/CAN))]\,(K) \quad [8]$$

and for the portion of the unit area outside of canopy cover we estimated the effective conductivity (KE_O) as

$$KE_O = [(BO/OP)(CRC)+A(1-(BO/OP))]\,(K) \quad [9]$$

where
KE_c = effective conductivity under canopy (cm/hr)
KE_O = effective conductivity outside of canopy (cm/hr)
CF = canopy factor
BC = bare area under canopy (%)
CAN = canopy area (%)
OP = open area outside canopy (%)
BO = bare area in open space (%)
CRC = crust factor (equation [6])
A = macro-porosity factor
K = hydraulic conductivity of soil (cm/hr) (equation [5])

Combining equations [8] and [9] for the total unit area consisting of canopy covered area (CAN) and open area (OP), we have

$$KE = (CAN)KE_c + (OP)KE_O \quad [10]$$

or

$$KE = (CF)\,[(A)(CAN-BC) + CRC(BC)](K) + [(A)(OP-BO) + CRC(BO)](K) \quad [11]$$

The canopy factor (CF) and macroporosity factor (A) are the only unknown parameters in equation [11]. In the following sections estimators for these parameters will be developed.

Canopy Factor

The canopy factor (CF) is defined as the ratio of effective conductivity under canopy (KE_c) to effective conductivity without canopy (KE_{nc}).

The Hutten (1984) data set was chosen to develop the canopy factor because it covered a wide range of soil texture, ground cover, and canopy cover conditions (Table 1) and included infiltration runs with and without canopy. A geometric mean KE without canopy was determined for the 4 soils and used to determine CF for each of the 12 treatments. Using the data the following equation was developed relating canopy to CF

$$CF = \frac{KE_c}{KE_{nc}} = \left(1 + 0.96\frac{CAN}{100}\right) \quad r^2 = 0.88 \quad n = 13; \qquad [12]$$

where CAN = canopy (%)

Macroporosity Factor

The macroporosity factor (A) in equation [11] is assumed to represent an enhancement of the infiltration potential of soil that is covered by rocks or litter (Mehan 1986). The Hutten (1984), Devaurs (1984) and Thurou (1985) data sets were chosen for evaluating the macroporosity factor because they covered a range of soil conditions including bulk density and ground cover conditions. Using the previously developed CF predictor equation [12] we solved equation [11] for a mean A for each treatment and then using regression techniques related to A to soil properties resulting in the following prediction equation:

$$A = e^{(2.82 - 0.099\,SA + 1.94\,BD)} \quad r^2 = .88 \quad n = 41 \qquad [13]$$

where

SA = % sand

BD = 33 KPa bulk density of fine earth soil (<2 mm) g/cm³

In fitting equation [13], A was constrained to be greater than one because macroporosity was assumed to only increase hydraulic conductivity. Also, since the data did not include soils with less than 20 % sand, and the form of equation [13] will produce extremely high A values for soils with less than 20% sand, we would limit the equation to a maximum A value of 18 which was the largest value in the data set.

Testing

We used the Lane et al. (1987), Ward and Wood (1982), Williams (1969) and Wood data sets (Table 1) to test equations [11, 12 and 13] because these data sets were not used in parameter development. Since each data set had different run durations, we predicted the final infiltration rate, total infiltration amount, and the average measured antecedent soil moisture using the Green-Ampt infiltration model equation [1] from equations [3,4,5,6,11,12, and 13]. The predicted infiltration values were compared with the mean and standard deviations of the observed values for each site. The results of the testing are summarized in Table 2.

Lane et al. (1987) reported infiltration results from studies on large rangeland plots in Arizona and Nevada under simulated rainfall. At each of the 5 sites they had 2 plots evaluated spring and fall for several consecutive years with the following designated treatments:

natural – natural site conditions

clipped – all vegetation cut and removed

bare – canopy and nonembedded (>5 mm) surface matrial removed

They reported mean final infiltration rates and amounts for the 30 minute very wet run at each site. As they did not measure bulk density it was calculated with the equation reported by Rawls (1983). Rock, litter, bare soil, under and outside canopy were measured for each AZ plot. The proportion of bare ground beneath the canopy and outside of the canopy was estimated for

Table 2. Summary of test results.

				Infiltration final rate and volume			
				Measured		Predicted	
Study reference	Site	Treatment	Sample size	Final rate* cm/hr	Volume* cm	Final rate cm/hr	Volume cm
Lane et al. (1987)	Bernardino	Natural	8	3.53 ± 0.77	1.96 ± 0.82	3.87	2.19
		Clipped	8	2.10 ± 0.75	1.24 ± 0.65	2.69	1.67
		Bare	8	1.37 ± 0.62	.73 ± 0.60	1.79	1.21
	Cave	Natural	8	2.63 ± 0.70	1.49 ± 0.77	1.96	1.32
		Clipped	8	1.50 ± 0.62	.88 ± 0.80	1.81	1.23
		Bare	8	1.16 ± 0.60	.65 ± 0.65	1.08	0.81
	Hathaway	Natural	8	3.16 ± 0.99	1.72 ± 0.85	2.65	1.62
		Clipped	8	1.93 ± 0.85	1.04 ± 0.80	2.16	1.38
		Bare	8	1.24 ± 0.52	.74 ± 0.58	1.32	0.92
	Mercury	Natural	4	2.05 ± 0.48	1.08 ± 0.98	1.97	1.32
		Clipped	4	.73 ± 0.55	.50 ± 0.70	1.93	1.29
		Bare	4	.48 ± 0.30	.25 ± 0.46	1.04	.77
	Area 11	Natural	4	3.37 ± 1.30	1.85 ± 0.75	2.55	1.60
		Clipped	4	2.94 ± 0.75	1.75 ± 1.00	2.18	1.42
		Bare	4	1.63 ± 0.48	.98 ± 0.48	1.31	0.94
Williams (1969)	Intermediate sandy soils (30–45%)		8	4.4 ± 0.98	1.88 ± 0.59	2.25	1.71
	High sand soils (50–65%)		8	4.98 ± 2.61	1.61 ± 0.82	5.32	3.19
Wood		Dry	24	6.94 ± 0.32	6.28 ± 0.12	7.08	6.21
		Wet	21	4.60 ± 0.45	5.34 ± 0.20	5.66	5.28
Ward and Wood (1982)	Grazing	Dry	6	8.56 ± 1.13	5.91 ± 0.73	7.62	5.90
		Wet		7.63 ± 1.85	4.25 ± 0.80	7.50	4.34
	Sagebrush	Dry	5	6.35 ± 2.21	4.15 ± 1.10	7.88	4.81
		Wet		5.81 ± 1.79	2.96 ± 0.73	4.83	2.79
	Pinyon/Juniper	Dry	5	7.50 ± 2.29	4.6 ± 1.53	11.3	6.20
		Wet		7.30 ± 1.65	3.86 ± 0.72	9.5	5.00

* ± value is the standard deviation for each measured mean.

the NV sites. Soil rock was estimated from their soil report.

Table 2 compares the predicted Green-Ampt final infiltration rates and total infiltration amount with the measured mean final infiltration rate and amount at each site and treatment. As shown in Table 2, predictions for all sites except Mercury bare and clipped were within ± 1 standard deviation of the measured mean. Since Lane's sites had very high sand (>65) the macroporosity factor derived from equation [11] becomes 1; thus this study gives an independent test of the crust and canopy factors in equation [11]. The natural plots test our procedures for predicting the canopy and crust factors. The clipped plots test our procedure for predicting surface cover factors, while the bare soil plots tested our procedures for predicting crusted soil hydraulic conductivity. The bare plots independently tested the crust factor since the soil surface was primarily bare.

Williams (1969) conducted a number of infiltration tests in Utah on pinyon juniper sites in 1967 and 1968. We stratified the Williams data into 2 groups, intermediate sand and high sand, and the results are shown in Table 2. The predicted rates and amounts are within the 95% confidence intervals; however, the confidence intervals are very wide and absolute error is up to 100% for the high sand total infiltration. The high sand tests the effect of the canopy and crust factors while the intermediate sand soils incorporates the crust, canopy and macroporosity factors.

Wood conducted infiltration tests on a clay loam soil in New Mexico. We ran predictions on the dry and wet treatments; all predictions except the dry final rate, which could be a result of antecedent soil water conditions, were within the 95% confidence intervals.

Ward and Wood (1982) conducted 4 replicate infiltration tests at 17 sites. We subdivided the sites according to cover (grazing sagebrush and pinyon juniper) and dry or wet treatments. The predicted final infiltration rates and amounts were within 95% confidence intervals; however, the standard deviation of the means are very large (Table 2). The numerical error in the pinyon/juniper estimates are 30–50% high.

Regression analysis was performed on the mean measured final infiltration rate versus the predicted final infiltration rate given in Table 2 and the mean measured total infiltration volume versus the predicted infiltration volume given in Table 2. This analysis indicated that the intercepts and slopes were not significantly different from 0 and 1, respectively, at the 0.05 significance level. This indicates that the model predicts accurate and unbiased estimates of the mean final infiltration rate and total infiltration volume.

Conclusion

A method was developed for incorporating readily available rangeland soil, surface cover, and canopy cover properties into the predictions of the Green-Ampt hydraulic conductivity parameter. The method was evaluated on ten diverse independent rangeland areas and generally predicted the mean final infiltration rate and amount within one standard deviation of the measured mean, indicating that our assumptions and parameter estimators are acceptable. Since the development and testing of data sets did not include high silt soils and grass-dominated vegetative cover, using the proposed procedure may yield questionable results. Also, the proposed procedure yields one of the first quantitative methods for evaluating the relative effects of rangeland treatments on infiltration.

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TECHNICAL MEMORANDUM

TO: Joe Rumann, FCDMC
FROM: G.V. Sabol
SUBJECT: Areal Averaging Green and Ampt Parameters
DATE: 29 April 1991

Presently, use of the Green and Ampt infiltration equation has included area weighted averaging of the individual parameter values (XKSAT, PSIF and DTHETA). At our recent review meetings (16-17 April), it was decided that we should determine the area weighted average of XKSAT and then determine the representative values of PSIF and DTHETA from graphs of XKSAT versus PSIF and DTHETA. Use of such graphs is to reduce the computation effort. I recently performed some computational comparisons that indicate that large error could be introduced by arithmetically averaging the XKSAT values. Much greater accuracy is achieved by using the area weighted average of the logarithms of the XKSAT values. Both methods used the same procedure to estimate PSIF and DTHETA from the calculated value of XKSAT. The procedure and results of my comparison is enclosed.

PROCEDURE

Four soil distributions (% of drainage area being comprised of various percentages of each soil texture) were created from three soil textures as shown below:

	% of Drainage Area			
	Soil Distribution			
Soil Texture	A	B	C	D
loamy sand	33 1/3	60	25	15
loam	33 1/3	25	60	25
clay	33 1/3	15	15	60

Two graphs were prepared of XKSAT versus PSIF and DTHETA (dry) from Table 4.2 (Figure 1). The area weighted values of XKSAT were calculated for these soil

distributions based on the arithmetic values of XKSAT and log XKSAT. Corresponding values of PSIF and DTHETA were taken from Figure 1 in both cases. The area weighted values of the Green and Ampt parameters are shown in Table 1.

The runoff volumes were calculated by three methods:

1. The "actual" runoff volume was estimated by calculating the rainfall excess for <u>each</u> portion of the total area that contains a single soil texture. The volume is the sum of the runoff volumes from each soil texture type. The depths of rainfall excess for four different drainage areas and the three soil textures are shown in Table 2. These rainfall excess depths were calculated with HEC-1.
2. The runoff volumes were then calculated by using the area weighted average arithmetic values of XKSAT and related PSIF and DTHETA (shown in Table 1). This is the procedure that is presently used.
3. The runoff volumes were then calculated by using the area weighted average log values of XKSAT and related PSIF and DTHETA (shown in Table 1).

RESULTS

The results are shown in Table 3 for four drainage areas. The drainage areas were selected such that they corresponded to Pattern Nos:

0.5 sq. mi. - Pattern No. 1
2.8 sq. mi. - Pattern No. 2
16 sq. mi. - Pattern No. 3
100 sq. mi. - Pattern No. 4.07 (area limit of procedure)

The results from Table 3 are shown in Figures 2 and 3. Notice that the presently used method <u>always</u> results in an underestimation of the runoff volume. The log method of averaging provides very close estimates of runoff volume to the actual volume.

The % error using each procedure is shown in Table 4. The method of arithmetic averaging becomes worse with increasing drainage area size. The log averaging method shows some small overestimation for small to medium sized areas, and underestimation for large areas.

CONCLUSIONS

1. Area weighting of arithmetic parameters will generally (maybe always) result in underestimation of runoff volumes. The error seems to grow increasingly worse as drainage area size increases.
2. This underestimation of rainfall excess also affects the calculation of T_c. This error is partially responsible for the problem in using the Clark unit hydrograph method wherein the duration of rainfall excess is often too short.
3. It appears that the area weighting of log XKSAT is a preferred method.
4. Area averaging of parameters should be avoided for large watersheds if there is a large range of XKSAT for the subareas. The limit for averaging of XKSAT (by any method) may be around 16 sq. mi.
5. We need to check the log averaging procedure for some real watersheds. I will check the procedure for the Agua Fria R. trib. and the Tucson Arroyo.
6. This appears to be a <u>critical</u> concern. We need to carefully review this and make more comparisons before making a decision.

TABLE 1 - Calculation of area weighted XKSAT and related PSIF & DTHETA.

	XKSAT in/hr	PSIF in	DTHETA	% Total Area Soil Distribution A	B	C	D
loamy sand	1.2	2.4	.35	33 1/3	60	25	15
loam	.25	3.5	.35	33 1/3	25	60	25
clay	.01	12.4	.15	33 1/3	15	15	60
	XKSAT - area wt'd. (arith.)			.49	.78	.45	.25
	PSIF *			3.7	3.1	3.9	5.0
	DTHETA *			.35	.35	.35	.35
	XKSAT - area wt'd (log)			.14	.40 **	.23	.046
	PSIF *			6.4	4.1	5.2	9.3
	DTHETA *			.40	.35	.35	.26

* PSIF & DTHETA from the attached graph of XKSAT vs PSIF & DTHETA

** Calculation of $\overline{XKSAT}$ = antilog (.60 log 1.2 + .25 log .25 + .15 log .01)

= antilog (.60 × .0792 + .25 × -.6021 + .15 × -2.0)

= antilog (-.4030) = .40

GEORGE V. SABOL CONSULTING ENGINEERS, INC.

CLIENT

PROJECT

SUBJECT

SHEET ____ OF ____

DATE 26 April 91

BY GVS

PROJECT NO. 5-5-F

GEORGE V. SABOL CONSULTING ENGINEERS, INC.

CLIENT

PROJECT

SUBJECT

SHEET ____ OF ____

DATE 27 April 91

BY GVS

PROJECT NO. 5-5-F

TABLE 2 - Depths of rainfall excess for each soil texture and each drainage area <u>without</u> area weighted averaging.

			Rainfall Excess, inches		
			Soil		
			loamy sand	loam	clay
		XKSAT	1.2	.25	.01
	Rainfall, inches	PSIF	2.4	3.5	12.4
Area sq. mi.	Point	Areal	DTHETA .35	.35	.16
.5	3.22	3.20	.99	1.82	2.73
2.8	3.22	3.14	.41	1.56	2.67
16	3.22	2.97	.14	1.23	2.48
100	3.22	2.58	0.0	.77	2.08

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PROJECT NO. 5-5-F

TABLE 3 – Results

Soil Distribution ①	Parameter Method ②	Runoff Volume, in ac-ft — Total Area, sq. mi. .5	2.8	16	100
A	I	49.2	231.0	1,095.1	5,066.7
A	II	37.6	153.8	614.4	1,653.3
A	III	49.3	243.4	1,117.9	4,533.3
B	I	38.9	154.8	651.5	2,690.7
B	II	31.7	113.5	358.4	320.0
B	III	40.3	173.2	708.3	2,133.3
C	I	46.6	214.9	977.1	4,128.0
C	II	38.7	164.3	648.5	1,813.3
C	III	45.9	218.0	964.3	3,573.3
D	I	59.8	306.7	1,550.1	7,682.7
D	II	45.3	212.1	930.1	3,360.0
D	III	59.5	316.6	1,587.2	7,573.3

① Soil Distribution:

A – 33⅓ %	loamy sand	33⅓ % loam	33⅓ % clay
B – 60 %		25 %	15 %
C – 25 %		60 %	15 %
D – 15 %		25 %	60 %

② Parameter Method:

I – soil specific parameters for <u>each</u> subbasin

II – XKSAT from area wt'd. arith. avg.

III – XKSAT from area wt'd. log. avg.

TABLE 4 - Error in runoff volumes by each method of averaging XKSAT.

Soil Distribution	% Error in Runoff Volume — Total Area, sq. mi. 0.5	2.8	16	100
	By Arith. Avg. of XKSAT			
A	-23.6	-33.4	-43.9	-67.4
B	-18.5	-26.7	-45.0	-88.1
C	-17.0	-23.5	-33.6	-56.1
D	-24.2	-30.8	-40.0	-56.3
avg.	-20.8	-28.6	-40.6	-67.0
	By Log. Avg. of XKSAT			
A	0.2	5.4	2.1	-10.5
B	3.6	11.9	8.7	-20.7
C	-1.5	1.4	-1.3	-13.4
D	-0.5	3.2	2.4	-1.4
avg.	0.5	5.5	3.0	-11.5

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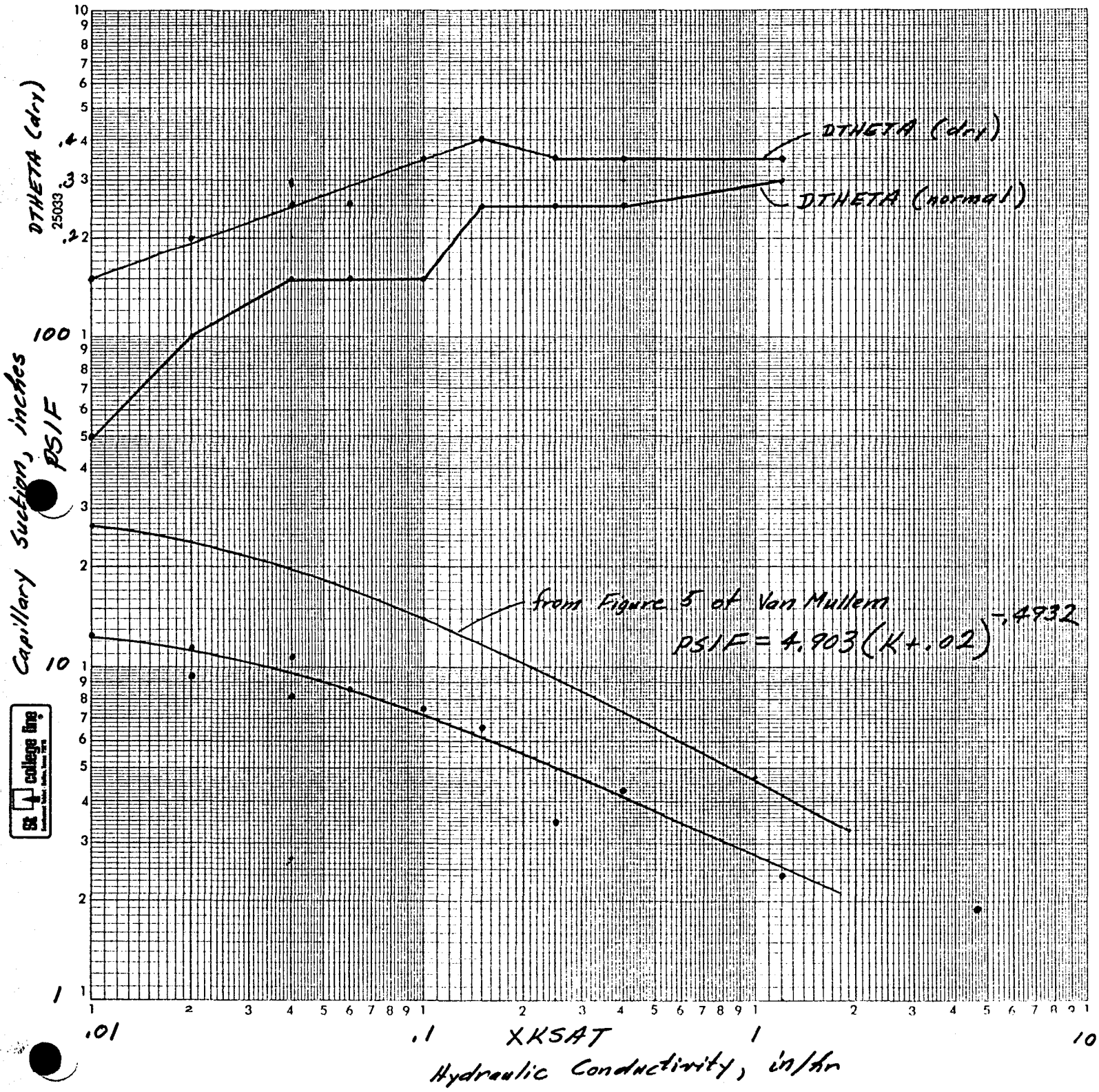
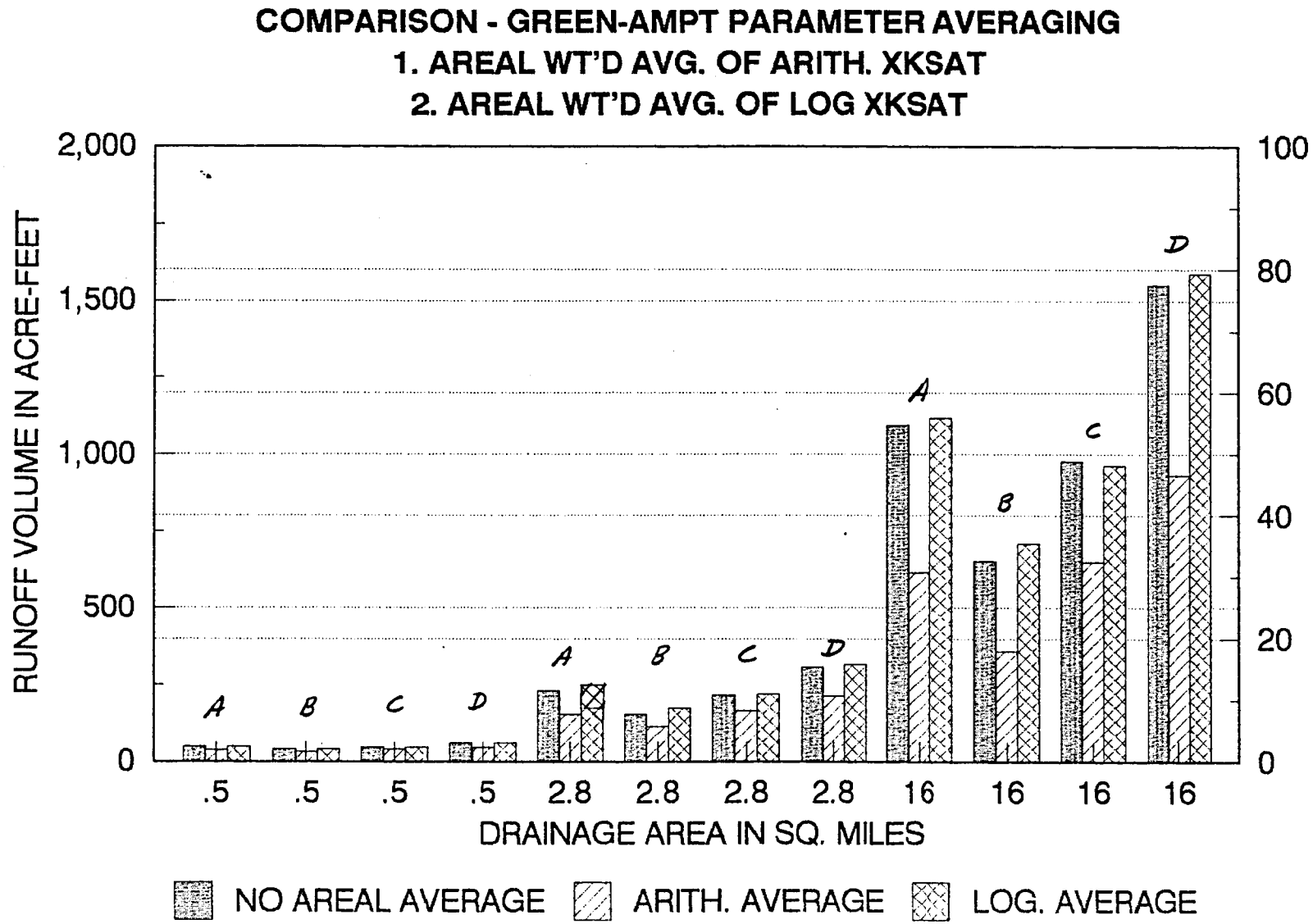
FIGURE 1

Comparison of XKSAT vs PSIF from Table 4.2 and the relation by Van Mullem (1989)



Logarithmic 3 X 3 Cycles

FIGURE 2

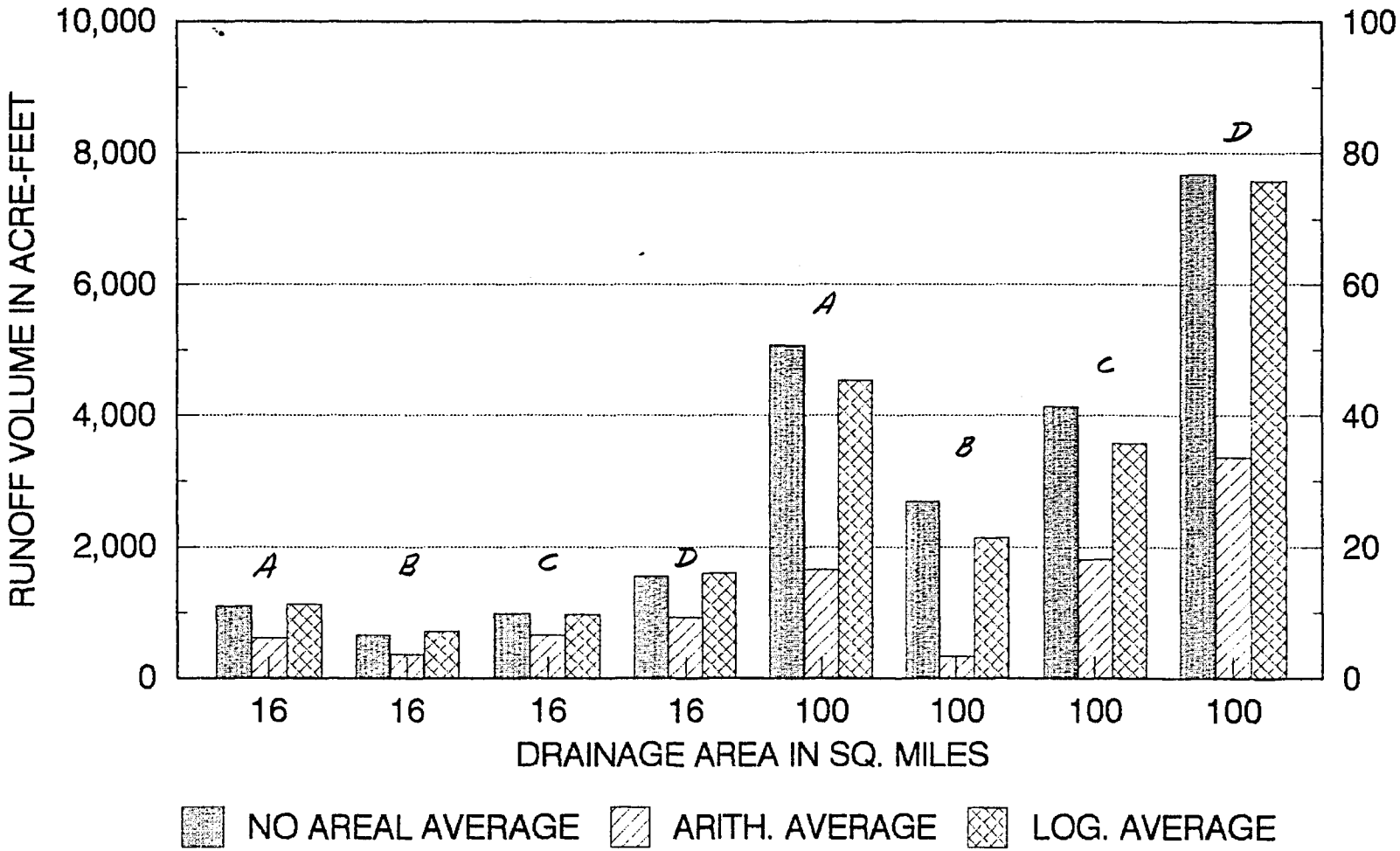


(4) SOIL DISTRIBUTIONS
(3) DRAINAGE AREAS

File: ARITH3

FIGURE 3

COMPARISON - GREEN-AMPT PARAMETER AVERAGING
1. AREAL WT'D AVG. OF ARITH. XKSAT
2. AREAL WT'D AVG. OF LOG XKSAT



(4) SOIL DISTRIBUTIONS
(2) DRAINAGE AREAS

File: ARITH2

LOST DOG WASH SUB 4

LINEAR (MAP UNIT) — LINEAR (AREAL AVERAGE)

#52 XKSAT = .66 (.06) + .34 (.40) = .18 IN/HR

#31 XKSAT = .85 (.40) + .15 (.06) = .35 IN/HR

#10 XKSAT = .40 (1.2) + .40 (1.2) + .15 (.4) + .05 (.25) = 1.03 IN/HR

#44 XKSAT = .85 (.06) + .06 (.4) + .06 (.25) + .03 (.04) = .09 IN/HR

⟹ XKSAT = .431 (.18) + .34 (.35) + .133 (1.03) + .096 (.09) = .52 IN/HR

XKSAT = .52 PSIF = 3.70 θ = .35 IA = .15

LINEAR (MAP UNIT) — LOG (AREAL AVERAGE)

XKSAT = ANTILOG [.431 (log .18) + .34 (log .35) + .133 (log 1.03) + .096 (log .09)] = .266 IN/HR

XKSAT = .266 PSIF = 4.9 θ = .35 IA = .15

LOG (MAP UNIT) — LINEAR (AREAL AVERAGE)

#10 ANTILOG [.40 (log 1.2) + .40 (log 1.2) + .15 (log .4) + .05 (log .25)] = .94

#31 ANTILOG [.85 (log .40) + .15 (log .06)] = .30

#52 ANTILOG [.66 (log .06) + .34 log (.40)] = .114

#44 ANTILOG [.85 (log (.06)) + .06 (log (.4)) + .06 (log (.25)) + .03 (log (.04))] = .072

XKSAT = .431 (.114) + .34 (.30) + .133 (.94) + .096 (.072) = .283

XKSAT = .283 PSIF = 4.75 θ = .35 IA = .15

LOG (MAP UNIT) — LOG (AREAL AVERAGE)

XKSAT = ANTILOG [.431 (log .114) + .34 (log .30) + .133 (log .94) + .096 (log .072)] = .2 IN/HR

XKSAT = .200 PSIF = 5.50 θ = .375 IA = .15

1. Tiger Wash Sub 8 A = 9.78 sq. mi.

			XKSAT
Map Units:	#19,20	38.6%	(.08)
	# 92	50.1%	(.59)
	# 100	11.3%	(.63)

2. Tiger Wash Sub 3 A = 18.76 mi^2

Map Units	#16,17	57.3%	(.08)
	# 65	42.7%	(.20)

3. Youngtown (GVS) A = .13 mi^2

Map Units	LcA	50%
	PcA	35%
	Vf	15%

4. Coot Dog Sub 4 A = .42 mi^2

# 52	43.1%
# 31	34%
# 10	13.3%
# 44	9.6%

5. Carefree Sub 5 (1989) A = ~~.66~~ 1.122 mi^2

# 41	3%
# 61	4%
# 63	21%
# 72	72%

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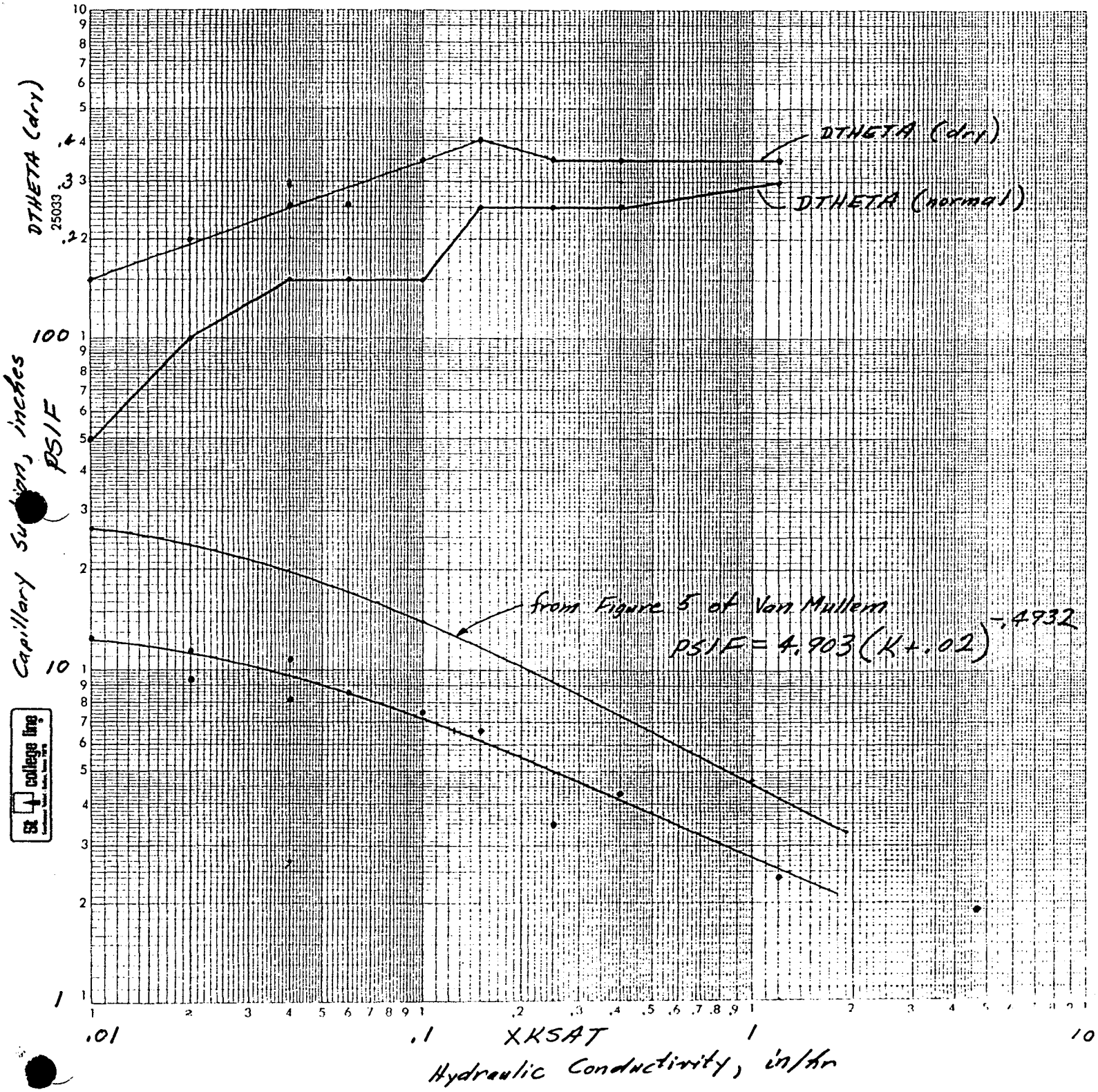
FIGURE 1

Comparison of XKSAT vs PSIF from Table 4.2 and the relation by Van Mullem (1989)



Logarithmic 3 X 3 Cycles

LOGARTHMIC AREAL AVERAGING OF THE GREEN & AMPT SATURATED HYDRAULIC CONDUCTIVITY PARAMETER (XKSAT) ON FOUR DESERT WATERSHEDS IN MARICOPA COUNTY, ARIZONA

Purpose

The Green & Ampt loss rate method is currently recommended for use in hydrologic analyses by the Hydrologic Design Manual for Maricopa County (manual). The established procedure for developing the average saturated hydraulic conductivity parameter (XKSAT) for a subbasin involves linear (arithmetic) averaging of first the conductivity for each soil texture within a soil map unit, then for the various map units within a subbasin. The Wetting Front Capillary Suction (PSIF) and Volumetric Soil Moisture Deficit (DTHETA) values for the subbasin are then chosen from a graph (Figure 1) based on the average XKSAT.

Users of the manual have expressed concern with the present method. Subbasin average parameters seem to be biased toward higher infiltration rates when soils of high conductivity (say a loamy sand, XKSAT = 1.20 in/hr) are averaged with soils of low conductivity (say a sandy clay loam, XKSAT = 0.06 in/hr). Since some research in this area has already been done (Sabol, 1991; Van Mullen, 1989) this paper will investigate the results of logarithmically averaging the XKSAT parameter, within both the map unit and the subbasin.

Procedure

Four subbasins, ranging in size from 0.42 to 9.78 square miles were chosen for this analysis, without regard to the types of soils they contained. The subbasins were part of previous hydrologic analyses by the Flood Control District and Burgess & Niple, with soil map unit percentages already delineated. All subbasins are located within the boundaries of the Soil

Survey of Aguila-Carefree Area, Parts of Maricopa and Pinal Counties, Arizona, because it contains the most detailed soil texture data of the three available soil surveys in Maricopa County.

Map units (designated by numbers) were described for each subbasin. XKSAT values for each major and minor soil were assigned from Appendix A in the manual. Each minor soil was given equal weight in the averaging process. Two average XKSAT values were calculated for each map unit, one using the arithmetic average of the individual XKSATs times the partial areas, and one using the log of the individual XKSATs times the partial areas, with the antilog taken at the end of the calculation. At this point, the average XKSAT value for the subbasin was calculated in four ways:

1. A/A - (Arithmetic/Arithmetic): The arithmetically averaged map unit XKSAT values are averaged arithmetically (this procedure is currently recommended by the manual).
2. A/L - (Arithmetic/Log): The logarithmically averaged map unit XKSAT values are averaged arithmetically.
3. L/A - (Log/Arithmetic): The arithmetically averaged map unit XKSAT values are averaged logarithmically.
4. L/L - (Log/Log): The logarithmically averaged map unit XKSAT values are averaged logarithmically.

Appendix 1 contains all of the calculations used in the averaging process.

To develop the Modeled Runoff quantities, values of PSIF and DTHETA (dry) were read from Figure 1 for each of the four XKSAT values, and the loss parameters became input to an HEC-1 model for each subbasin on the LG card. Table 2 lists the loss parameters for the different subbasins and methods of areal averaging. Also included in the HEC-1 input were the following constants:

1. 6-hour rainfall from the manual, pattern number and areal reduction are based on the area of each subbasin.

2. A rainfall depth of 3 inches (a typical 100-year, 6-hour design rainfall depth in Maricopa County).

3. A five-minute hydrograph timestep.

The model was run four times for each subbasin, and after each run the value of total excess rainfall was converted to a runoff volume in acre-feet. The Modeled Runoff values are listed in Table 1.

As a comparison to the Modeled Runoff values, an attempt was made to quantify the Expected Runoff volume for each watershed by separating the soil textures, running an HEC-1 model for each using the same constant inputs, then summing the totals. A key assumption here is that all the individual soil textures contribute runoff to the outlet, i.e. runoff from an area of clay loam does not traverse an area of sandy loam and infiltrate en-route. This seems to be a reasonable assumption for low frequency design rainfall events because rainfall rates are generally greater than saturated conductivity rates and soils are nearly saturated at the point in the storm when large quantities of runoff begin. The Expected Runoff values are listed in Table 1.

Results

The results of the HEC-1 analyses are presented in Table 1.

Conclusions (from Table 1)

1. The present method of arithmetically averaging the XKSAT parameter (A/A) generally results in a large (12-31%) underestimation of the true runoff volume. Since rainfall excess is underestimated, the time of

concentration parameter in the Clark Unit Hydrograph method will be overestimated, resulting in underestimation of the peak discharge.

2. The Log/Log (L/L) method of averaging XKSAT seems to yield the best results when compared to the Expected Runoff, even for large basins and differing soil texture compositions.

Recommendations

If the Youngtown and Tucson Arroyo testing by GVS yields similar results, incorporate the Log/Log method of areal averaging the XKSAT parameter into the Hydrologic Design Manual. Include a detailed example of the procedure in the manual. Provide the weighted XKSAT values for each map unit in Appendicies similar to the current ones using the procedures developed herein. Provide guidance on developing an alternative map unit XKSAT for small drainage areas which might be dominated by one or more major or minor soils or a particular geomorphic regime.

TABLE 1

SUMMARY OF LOG AREAL AVERAGING TESTING RESULTS

SUBBASIN NUMBER	AREA (sq.mi)	DOMINANT SOIL TEXTURES (approx. percentage)	EXPECTED RUNOFF (ac-ft)	MODELED RUNOFF (% error) (ac-ft) A/A	A/L	L/A	L/L
LD4	0.42	Sandy Loam (45) Sandy Clay Loam (39) Loamy Sand (13)	32.1	28.2 (-12.1)	30.2 (-5.9)	30.5 (-5.0)	32.5 (+1.2)
CF5	1.12	Sandy Clay Loam (65) Sandy Loam (28)	91.4	77.2 (-15.5)	86.8 (-5.0)	77.2 (-15.5)	87.4 (-4.4)
JR6	6.74	Sandy Loam (70) Sandy Clay Loam (11) Loamy Sand (11)	296.	262. (-11.5)	291. (-1.7)	266. (-10.1)	306. (+3.4)
TW8	9.78	Sandy Clay Loam (37) Sandy Loam (34) Loamy Sand (26)	461.	318. (-31.0)	386. (-16.3)	412. (-10.6)	475. (+3.0)
		Average Error (absolute value) ---------->		17.5 %	7.2 %	10.3 %	3.0 %

TABLE 2

SUBBASIN LOSS PARAMETERS

Subbasin	Averaging Method (subbasin/map unit)	XKSAT (in/hr)	PSIF (in)	DTHETA (in)
LD4	A/A	.367	4.30	.350
	A/L	.301	4.65	.350
	L/A	.295	4.70	.350
	L/L	.217	5.35	.365
CF5	A/A	.234	5.20	.355
	A/L	.127	6.55	.380
	L/A	.232	5.20	.360
	L/L	.125	6.60	.375
JR6	A/A	.431	3.95	.350
	A/L	.362	4.30	.350
	L/A	.423	4.00	.350
	L/L	.344	4.30	.350
TW8	A/A	.476	3.85	.350
	A/L	.370	4.25	.350
	L/A	.337	4.40	.350
	L/L	.260	4.95	.350

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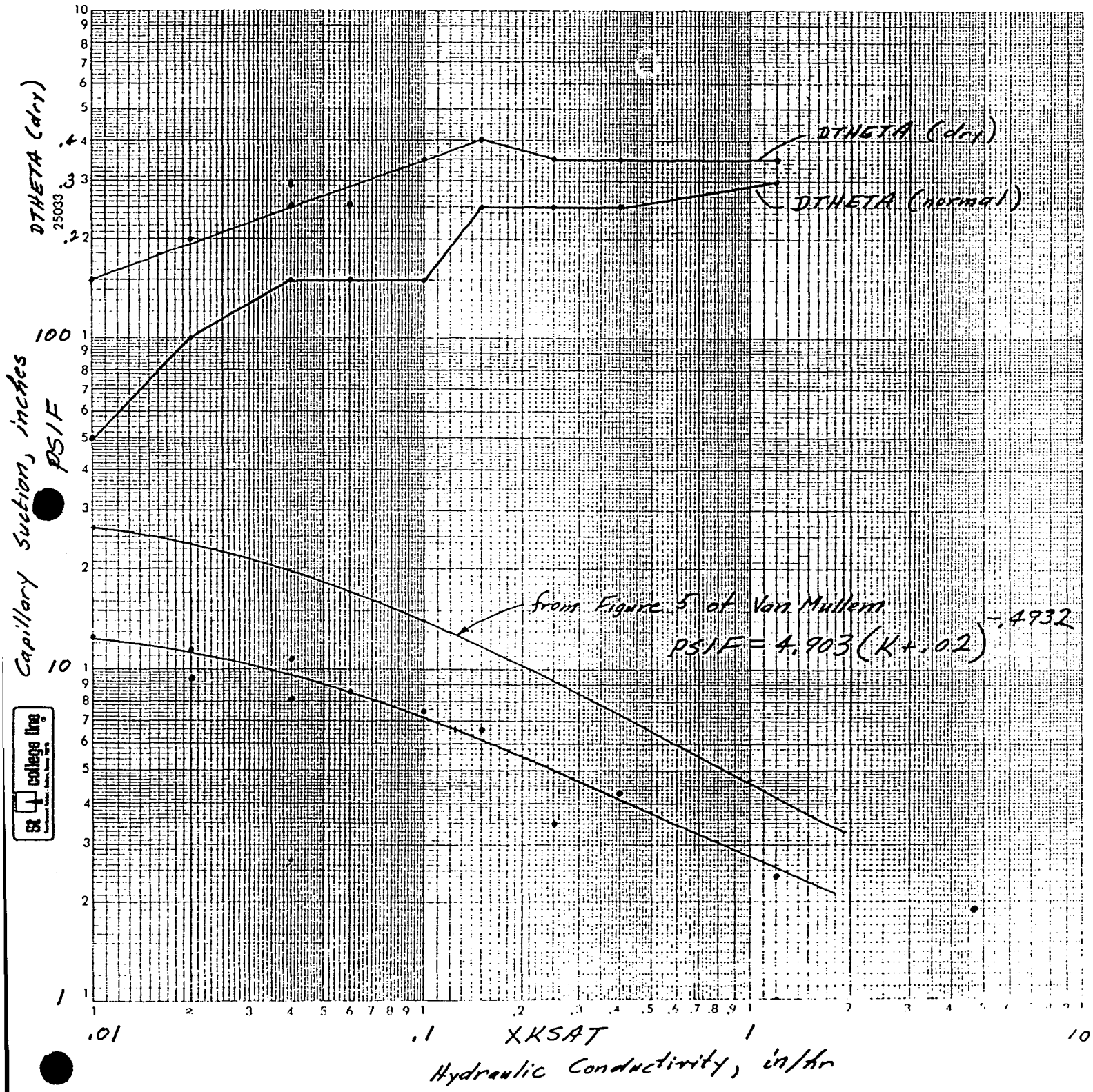
25 April 91

FIGURE 1

Comparison of XKSAT vs PSIF from Table 4.2 and the relation by Van Mullem (1989)



Logarithmic 3 X 3 Cycles

APPENDIX 1

LOST DOG #4

AREA = 0.42 mi^2

MAP UNITS:				
	#10	13.3%	=	.056 mi^2
	#31	34.0%	=	.143 mi^2
	#44	9.6%	=	.040 mi^2
	#52	43.1%	=	.181 mi^2

SOIL DESCRIPTIONS:

#10 Brios - Carrizo Complex			XKSAT
40%	Brios Loamy Sand		1.20
40%	Carrizo Sand		1.20
20%	Antho (5%)	Benches	.40
	Gilman (5%)	Benches	.25
	Maripo (5%)	Benches	.40
	Vint (5%)	Benches	.40

XKSAT (ARITH) = .80(1.2) + .15(.40) + .05(.25) = 1.033 in/hr

XKSAT (Log) = [.8(log 1.2) + .15(log .40) + .05(log .25)] ALOG = 0.941 in/hr

#31 DIXALETA COMPLEX			XKSAT
84.6%	Dixaleta Extremely Channery Sandy Loam		.40
15.4%	Ohaco (2.567% ea.)	FAN Terraces	.06
	Nickel (2.567% ea.)	FAN Terraces	.40
	Caue (2.567% ea.)	FAN Terraces	.25
	Eba (2.567% ea.)	FAN Terraces	.40
	Gran (2.567% ea.)	Mtn. Slopes	.06
	Lehmans (2.567% ea.)	Mtn. Slopes	.06

XKSAT (ARITH) = .89734 (.40) + .02567(.25) + .07701(.06) = .370 in/hr

XKSAT (Log) = Alog [.89734(log .40) + .02567(log .25) + .07701(log .06)] = .341 in/hr

#44 EBON VERY GRAVELLY LOAM

			XKSAT
80%	Ebon Sandy Clay Loam		.06
20%	Cipriano	(2.857% ea.) FAN TERRACES	.06
	Contine		.04
	Beardsley		.25
	Luke		.06
	Gunsight		.40
	MOHALL		.25
	Pinamt		.06

XKSAT (ARITH) = .02857(.40) + .05714 (.25) + .88571 (.06) + .02857 (.04) = .080 in/hr

XKSAT (Log) = ALOG [.02857 (log .40) + .05714 (log .25) + .88571 (log .06) + .02857 (log .04)] = .068 in/hr

#52 Gachado - Lomitas Complex

			XKSAT
56.3%	Gachado Very Gravelly Sandy Clay Loam		.06
25%	Lomitas Gravelly Sandy Loam		.40
18.7%	Carrizo	(2.671% ea.) Fan Terraces	1.20
	Cherioni		1.20
	Ebon		.06
	Gunsight		.40
	Pinamt		.06
	Shenco	Hillslopes	.06
	Vaiva		.40

XKSAT = .05343(1.20) + .30342(.40) + .64313 (.06) = .224 in/hr

XKSAT (Log) = ALOG[.05343(log 1.20) + .30342(log .40) + .64313(log .06)] = .125 in/hr

SUBBASIN RUNOFF FROM INDIVIDUAL SOIL TEXTURES

#10 → 13.3% OF Subbasin

Loamy Sand → 80% (13.3) = 10.64% OF Subbasin
Sandy Loam → 15% (13.3) = 1.995%
Loam → 5% (13.3) = 0.665%

#31 → 34.0% OF Subbasin

Sandy Loam → 89.734% (34) = 30.510% OF Subbasin
Loam → 2.567% (34) = 0.873%
Sandy Clay Loam → 7.701% (34) = 2.618%

#44 → 9.6% OF SUBBASIN

Sandy Loam → 2.857% (9.6) = .274% OF Subbasin
Loam → 5.714% (9.6) = .549%
Sandy Clay Loam → 88.571% (9.6) = 8.503%
Clay Loam → 2.857% (9.6) = .274%

#52 → 43.1% OF Subbasin

Loamy Sand → 5.343 (43.1) = 2.303% OF Subbasin
Sandy Loam → 30.342 (43.1) = 13.077%
Sandy Clay Loam → 64.313 (43.1) = 27.719%

TOTALS FOR THE SUBBASIN

Loamy Sand →	12.943%	=	.054 mi^2
Sandy Loam →	45.856%	=	.193 mi^2
Loam →	2.087%	=	.009 mi^2
Sandy Clay Loam →	38.840%	=	.163 mi^2
Clay Loam →	.274%	=	.001 mi^2
	100.000%		.420 mi^2

RUNOFF BY SOIL TEXTURE

LOAMY SAND (LD4LS.DAT)	P_e = .84 in	V = 2.419 ac-ft
Sandy Loam (LD4SL.DAT)	P_e = 1.21 in	V = 12.455 ac-ft
Loam (LD4L.DAT)	P_e = 1.53 in	V = .734 ac-ft
Sandy Clay Loam (LD4SCL.DAT)	P_e = 1.89 in	V = 16.430 ac-ft
Clay Loam (LD4CL.DAT)	P_e = 2.02 in	V = .108 ac-ft
	TOTAL RUNOFF =	32.146 ac-ft

MODELED SUBBASIN RUNOFF

AVERAGED LOSSES: (XKSAT)

ARITH/ARITH : .133 (1.033) + .340(.370) + .096(.08) + .431 (.224) = .367 in/hr

ARITH/LOG : .133 (.941) + .340 (.341) + .096 (.068) + .431 (.125) = .301 in/hr

LOG/ARITH : [.133 (log 1.033) + .340 (log .370) + .096 (log .08) + .431 (log .224)] ALOG = .295 in/hr

LOG/LOG : [.133 (log .941) + .340 (log .341) + .096 (log .068) + .431 (log .125)] ALOG = .217 in/hr

RUNS (Subbasin, Map Unit)

1.	LD4AA.DAT	XKSAT = .367 in/hr,	PSIF = 4.3 in,	dθ = .35 in
2.	LD4AL.DAT	XKSAT = .301 in/hr,	PSIF = 4.65 in,	dθ = .35 in
3.	LD4LA.DAT	XKSAT = .295 in/hr,	PSIF = 4.7 in,	dθ = .35 in
4.	LD4LL.DAT	XKSAT = .217 in/hr,	PSIF = 5.35 in	dθ = .365 in

RUN RESULTS

1.	LD4AA.DAT	P_e = 1.26 in	V = 28.224 ac-ft
2.	LD4AL.DAT	P_e = 1.35 in	V = 30.240 ac-ft
3.	LD4LA.DAT	P_e = 1.36 in	V = 30.464 ac-ft
4.	LD4LL.DAT	P_e = 1.45 in	V = 32.480 ac-ft

JACKRABBIT WASH #6D

AREA = 6.74 mi^2

MAP UNIT	% AREA		mi^2
#3	0.742	4.896	.05
#4	4.154		.28
#30	62.315		4.20
#56	4.599		.31
#91	2.671		.18
#99	2.671		.18
#108	0.593		.04
#117	22.255		1.50

SOIL DESCRIPTIONS

#s 3 & 4:	ANTHO - Carrizo - Maripo Complex		XKSAT
35%	ANTHO Sandy Loam		.40
30%	Carrizo Very Gravelly Sand		1.20
20%	Maripo Sandy Loam		.40
15%	Brios	Drainageways	1.20
	Gilman	Floodplains	.25
	Vint	Floodplains	.40
	Denure (2.5% ea.)	Stream Terraces	.40
	Momoli (2.5% ea.)	Stream Terraces	.40
	Carrizo (2.5% ea.)	Stream Terraces	.40

XKSAT (ARITH) = .325(1.20) + .65(.40) + .025(.25) = 0.656 in/hr

XKSAT (Log) = ALOG[.325(log 1.20) + .65(log .40) + .025(log .25) = .565 in/hr

#30	DENURE - MOMOLI - Carrizo Complex			XKSAT
40%	DENURE Gravelly Sandy Loam			.40
30%	MOMOLI Gravelly Sandy Loam			.40
20%	Carrizo Gravelly Sandy Loam			.40
10%	GILMAN	(3.33% ea.)	FLOODPLAINS	.25
	Maripo			.40
	Carrizo			1.20

XKSAT (ARITH) = .9333 (.40) + .0333 (.25) + .0333 (1.20) = .422 in/hr

XKSAT (Log) = [.9333 (log .40) + .0333 (log .25) + .0333 (log 1.20)] Alog = .408 in/hr

#56	GILMAN LOAMS			XKSAT
80%	GILMAN Loam			.25
20%	ANTHO		Drainageways	.40
	Carrizo			1.20
	ESTRELLA		Throughout	.25
	Glenbar	(2.5% ea.)		.15
	Vint			.40
	Denure		Fan Terraces	.40
	Momoli			.40
	Carrizo			.40

XKSAT (ARITH) = .825(.25) + .125 (.40) + .025 (1.20) + .025 (.15) = .290 in/hr

XKSAT (Log) = Alog [.825 (log .25) + .125 (log .40) + .025 (log 1.20) + .025 (log .15)] = .272 in/hr

#91	Momoli - Carrizo Complex			XKSAT
45%	Momoli Very Gravelly Loam			.40
35%	Carrizo Very Gravelly Sandy Loam			1.20
20%	Mohall	(2.5% ea.)	High Terraces	.25
	Tremant			.40
	Gunsight			.06
	Chuckawalla			.06
	Denure		Throughout	.40
	GILMAN		Drainageways	.25
	Maripo			.40
	Carrizo			1.20

XKSAT (ARITH) = .375(1.20) + .525(.40) + .05(.25) + .05(.06) = .676 in/hr

XKSAT (Log) = ALOG[(.375(log 1.20) + .525(log .40) + .05(log .25) + .05(log .06)] = .537 in/hr

#99	Pinamt - Tremant Complex			XKSAT
45%	Pinamt Very Gravelly Sandy Clay Loam			.06
35%	Tremant Gravelly Loam			.40
20%	Carrizo		Drainageways	1.20
	Chuckawalla	(4% ea.)	FAN Terraces	.06
	Ebon			.06
	Gunsight			.40
	Rillito			.40

XKSAT (ARITH) = .04(1.2) + .43(.40) + .53(.06) = .252 in/hr

XKSAT (Log) = [.04 (log 1.2) + .43 (log .40) + .53 (log .06)] ALOG = .153 in/hr

#108	SHENCO COMPLEX			XKSAT
71.4 %	SHENCO			.06
28.6%	Antho		Drainageways	.40
	Beardsley	(2.86 % ea.)	Fan Terraces	.25
	Cherioni			.40
	Cipriano			.06
	Ebon			.06
	Gunsight			.40
	Sun City			.06
	Gachado		Hillslopes	.06
	Quilotosa		Throughout	1.20
	Vaiva			.40

XKSAT (ARITH) = .0286 (1.20) + .1144 (.40) + .0286 (.25) + .8284 (.06) = .137 in/hr

XKSAT (Log) = ALOG[.0286 (log 1.2) + .0858 (log .40) + .0286 (log .25) + .8284 (log .06)]
= .087 in/hr

# 117	TREMANT - GUNSIGHT - RILLITO COMPLEX			XKSAT
30%	Tremant			.06
20%	Gunsight			1.20
20%	RILLITO			.40
30%	Cipriano	(4.286 % ea.)	Terraces	.06
	Pinamt			.06
	Mohall			.25
	Contine			.04
	Antho		Alluvial Fans Drainageways	.40
	Carrizo			1.20
	GILMAN			.25

XKSAT (ARITH) = .24286 (1.2) + .24286 (.40) + .08572 (.25) + .38572 (.06) + .04286 (.04) = .435 in/hr

XKSAT (LOG) = ALOG[.24286 (log 1.2) + .24286 (log .40) + .08572 (log .25) + .38572 (log .06) + .04286 (log .04)] = .219 in/hr

SUBBASIN RUNOFF FROM INDIVIDUAL SOIL TEXTURES
JR6D

#3 & 4 → 4.9% of Subbasin

Loamy Sand → 32.5% (4.9) = 1.59% of Subbasin
Sandy Loam → 65% (4.9) = 3.19%
Loam → 2.5% (4.9) = 0.12%

#30 → 62.3% of SUBBASIN

Loamy Sand → 3.33% (62.3) = 2.07% of Subbasin
Sandy Loam → 93.33% (62.3) = 58.14%
Loam → 3.33% (62.3) = 2.07%

#56 4.6% of SUBBASIN

Loamy Sand → 2.5% (4.6) = 0.12% of Subbasin
Sandy Loam → 12.5% (4.6) = 0.58%
Loam → 82.5% (4.6) = 3.80%
Silty Loam → 2.5% (4.6) = 0.12%

#91 2.7% of SUBBASIN

Loamy Sand → 37.5% (2.7) = 1.01% of Subbasin
Sandy Loam → 52.5% (2.7) = 1.42%
Loam → 5% (2.7) = .14%
Sandy Clay Loam → 5% (2.7) = .14%

#99 2.7% of SUBBASIN

Loamy Sand → 4% (2.7) = .11% of Subbasin
Sandy Loam → 43% (2.7) = 1.16%
Sandy Clay Loam → 53% (2.7) = 1.43%

#108 0.6 % of Subbasin

Loamy Sand → 2.86 % (.6) = .02 % of Subbasin
Sandy Loam → 11.44 % (.6) = .07 %
Loam → 2.86 % (.6) = .02 %
Sandy Clay Loam → 82.84% (.6) = .50 %

#117 22.3 % of Subbasin

Loamy Sand → 24.286%(22.3) = 5.42 % of Subbasin
Sandy Loam → 24.286%(22.3) = 5.42 %
Loam → 8.572%(22.3) = 1.91 %
Sandy Clay Loam → 38.572%(22.3) = 8.60 %
Clay Loam → 4.286% (22.3) = 0.96 %

TOTALS FOR THE SUBBASIN (A = 6.74 mi^2)

LOAMY SAND →	10.34 %	=	.697 mi^2
Sandy Loam →	69.98 %	=	4.717 mi^2
Loam →	8.06 %	=	.543 mi^2
SILTY Loam →	.12 %	=	.008 mi^2
Sandy Clay Loam →	10.67%	=	.719 mi^2
Clay Loam →	.96%	=	.065 mi^2
	100.13%		6.749 mi^2

RUNOFF BY SOIL TEXTURE

LOAMY SAND	(JRLS.DAT)	P_e = .14 in,	V = 5.20 ac-ft
SANDY LOAM	(JRSL.DAT)	P_e = .75	V = 188.68
LOAM	(JRL.DAT)	P_e = 1.12	V = 32.44
SILTY LOAM	(JRSLL.DAT)	P_e = 1.12	V = 0.48
SANDY Clay Loam	(JRSCL.DAT)	P_e = 1.64	V = 62.89
Clay Loams	(JRCL.DAT)	P_e = 1.81	V = 6.28

TOTAL RUNOFF = 295.97 ac-ft

MODELED SUBBASIN RUNOFF

AVERAGED LOSSES (XKSAT)

Subbasin / Map Unit

ARITH / ARITH : .04896(.656) + .62315(.422) + .04599(.290) + .02671(.676) + .02671(.252) + .00593(.137) + .22255(.435) = .431 in/hr

PSIF = 3.95 in $d\theta$ = .35 in

ARITH / LOG : .04896(.565) + .62315(.408) + .04599(.272) + .02671(.537) + .02671(.153) + .00593(.087) + .22255(.219) = .362 in/hr

PSIF = 4.3 in $d\theta$ = .35 in

LOG / ARITH = ALOG[.04896(log .656) + .62315(log .422) + .04599(log .290) + .02671(log .676) + .02671(log .252) + .00593(log .137) + .22255(log .435)]

= .423 in/hr PSIF = 4.0 $d\theta$ = .35 in

LOG / LOG = ALOG[.04896(log .565) + .62315(log .408) + .04599(log .272) + .02671(log .537) + .02671(log .153) + .00593(log .087) + .22255(log .219)]

= .344 in/hr PSIF = 4.3 in $d\theta$ = .35 in

RUN RESULTS

	P_e (in)	V (ac-ft)
1. JRAA.DAT	.73	262.4
2. JRAL.DAT	.81	291.2
3. JRLA.DAT	.74	266.0
4. JRLL.DAT	.85	305.5

Carefree Subbasin #5

AGUILA - CAREFREE SOIL SURVEY

DRAINAGE AREA: 1.122 mi^2

MAP UNITS:

#41	3%	=	.034 mi^2
#61	4%	=	.045 mi^2
#63	21%	=	.236 mi^2
#72	72%	=	.808 mi^2

SOIL DESCRIPTIONS (MAP UNIT LOSSES)

#41 Eba - Pinaleno Complex

		XKSAT
45%	Eba very gravelly loam	.40
35%	Pinaleno very gravelly clay loam	.06
20%	Ohaco (5%) } THROUGHOUT	.04
	Tres Hermanos (5%)	.06
	ANTHONY (5%) } DRAINAGEWAYS	1.20
	ARIZO (5%)	1.20

XKSAT (ARITH) = .45(.40) + .40(.06) + .05(.04) + .10(1.20) = .326 in/hr

XKSAT (Log) = [.45(log .40) + .40(log .06) + .05(log .04) + .10(log 1.20)] ALOG = .186 in/hr

#61

Gran - Wickenburg Complex, 1 - 10% SLOPES

40%	Gran very gravelly sandy clay loam	(.06)
35%	Wickenburg gravelly sandy loam	(.40)
25%	Eba (8⅓%) } Toe Slopes	(.40)
	Pinaleno (8⅓%)	(.06)
	Arizo (8⅓%) } Drainageways	(1.20)

XKSAT (Arith) = .483(.06) + .433(.40) + .083(1.20) = .302 in/hr

XKSAT (Log) = ALOG [.483(log .06) + .433(log .40) + .083(log 1.20)] = .175 in/hr

#63

Gran - Wickenburg Complex, 10-65% Slopes

40%	Gran very gravelly sandy clay loam			(.06)
33%	Wickenburg gravelly sandy loam			(.40)
27%	Dixaleta		Mtn Slopes	(.40)
	Lehmans			(.06)
	Eba	5.4% ea	Toe Slopes	(.40)
	Pinaleno			(.06)
	Arizo		Drainageways	(1.20)

XKSAT (ARITH) .438(.40) + .508 (.06) + .054 (1.20) = .270 in/hr

XKSAT (Log) ALOG [.438(log .40) + .508(log .06) + .054(log 1.20)] = .162 in/hr

#72 LEHMANS Complex

64%	Lehmans very gravelly clay loam			(.06)
36%	ARIZO		Drainageways	(1.20)
	Eba		foot slopes	(.40)
	Pinaleno	7.2% ea.		(.06)
	Greycagle		Gentle Slopes	(.40)
	Nickel			(.40)

XKSAT (ARITH) = .712(.06) + .072(1.20) + .216(.40) = .216 in/hr

XKSAT (Log) = ALOG [.712(log .06) + .072(log 1.2) + .216(log .40)] = .112 in/hr

CAREFREE #5 SUBBASIN LOSSES

1. ARITH / ARITH

XKSAT = .03 (.326) + .04(.302) + .21(.270) + .72(.216) = .234 in/hr

2. ARITH / Log

XKSAT = .03 (.186) + .04 (.175) + .21 (.162) + .72 (.112) = .127 in/hr

3. Log / ARITH

XKSAT = ALOG [.03 (log .326) + .04 (log .302) + .21 (log .270) + .72 (log .216)]
= .232 in/hr

4. Log / Log

XKSAT = ALOG [.03 (log .186) + .04 (log .175) + .21 (log .162) + .72 (log .112)]
= .125 in/hr

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1. CF5AA.DAT → XKSAT = .234 in/hr PSIF = 5.2 in dθ = .355 in
2. CF5AL.DAT → XKSAT = .127 in/hr PSIF = 6.55 in dθ = .38 in
3. CF5LA.DAT → XKSAT = .232 in/hr PSIF = 5.2 in dθ = .36 in
4. CF5LL.DAT → XKSAT = .125 in/hr PSIF = 6.6 in dθ = .375 in

TIGER WASH SUB 8

DRAINAGE AREA : 9.78 mi^2

SOIL SURVEY : Aguila - Carefree

MAP UNITS :	#19, 20	38.6 %	=	3.775 mi^2
	# 92	50.1 %	=	4.900 mi^2
	# 100	11.3 %	=	1.105 mi^2

SOIL DESCRIPTIONS (MAP UNIT LOSSES)

#19,20

CHUCKAWALLA - GUNSIGHT COMPLEX				XKSAT
45%	CHUCKAWALLA Very Gravelly Sandy Clay Loam			.06
35%	GUNSIGHT Very Gravelly Loam			.06
20%	Sal	(2.857 % ea.)	FAN TERRACES	.06
	Pinamt			.06
	Tremant			.40
	RILLITO		Side Slopes	.40
	ANTHO		FLOODPLAINS	.40
	Gilman			.25
	Maripo			.40

XKSAT (ARITH) = .85714 (.06) + .114 (.40) + .02857 (.25) = .104 in/hr

XKSAT (Log) = ALOG[.85714 (log .06) + .114 (log .40) + .02857 (log .25)] = .078 in/hr

92

MOMOLI - CARRIZO COMPLEX			XKSAT
45%	MOMOLI Very Gravelly Loam		.40
35%	CARRIZO Very Gravelly Sandy Loam		1.20
20%	MOHALL	High Terraces	.25
	Tremant		.40
	Gunsight		.06
	Chuckawalla		.06
	DENURE (2.5% each)	Throughout	.40
	GILMAN	Drainageways	.25
	Maripo		.40
	Carrizo		1.20

XKSAT (ARITH) = .375 (1.20) + .525 (.40) + .05 (.25) + .05 (.06) = .676 in/hr

XKSAT (Log) = ALOG[.375 (log 1.2) + .525 (log .40) + .05 (log .25) + .05 (log .06)] = .537 in/hr

100

QUILOTOSA - VAIVA COMPLEX			XKSAT
62.5%	Quilotosa Extremely Gravelly Loam		1.20
25%	Vaiva Very gravelly Loam		.40
12.5%	Schenco	Mtn. Slopes	.06

XKSAT (ARITH) = .625 (1.20) + .25 (.40) + .125 (.06) = .858 in/hr

XKSAT (Log) = ALOG[.625 (log 1.20) + .25 (log .40) + .125 (log .06)] = .627 in/hr

TIGER WASH #8

SUBBASIN LOSSES

Subbasin / MAP UNIT

ARITH / ARITH

XKSAT = .386(.104) + .501(.676) + .113(.858) = .476 in/hr

ARITH / LOG

XKSAT = .386(.078) + .501(.537) + .113(.627) = .370 in/hr

LOG / ARITH

XKSAT = ALOG[.386(log .104) + .501(log .676) + .113(log .858)] = .337 in/hr

LOG / LOG

XKSAT = ALOG[.386(log .078) + .501(log .537) + .113(log .627)] = .260 in/hr

1. TWAA.DAT → XKSAT = .476 in/hr PSIF = 3.85 in dθ = .35 in
2. TWAL.DAT → XKSAT = .370 in/hr PSIF = 4.25 in dθ = .35 in
3. TWLA.DAT → XKSAT = .337 in/hr PSIF = 4.4 in dθ = .35 in
4. TWLL.DAT → XKSAT = .260 in/hr PSIF = 4.95 in dθ = .35 in

VOLUME RUNS

CAREFREE #5

HEC-1 MODEL :

RAINFALL → DEPTH = 3.0 in , IA = .25 in

DISTR. → 6-hour, Pattern based on 1.122 mi^2

RUNOFF FROM MAP UNITS

ARITH LOSSES

#41 →	(CF541A.DAT)	P_e = 1.17 in ,	V = 2.122 ac-ft
#61 →	(CF561A.DAT)	P_e = 1.20 in ,	V = 2.880 ac-ft
#63 →	(CF563A.DAT)	P_e = 1.24 in ,	V = 15.607 ac-ft
#72 →	(CF572A.DAT)	P_e = 1.30 in ,	V = 56.021 ac-ft

TOTAL RUNOFF = 76.630 ac-ft

LOG LOSSES

#41 →	(CF541L.DAT)	P_e = 1.34 in,	V = 2.430 ac-ft
#61 →	(CF561L.DAT)	P_e = 1.35 in,	V = 3.240 ac-ft
#63 →	(CF563L.DAT)	P_e = 1.37 in,	V = 17.240 ac-ft
#72 →	(CF572L.DAT)	P_e = 1.52 in,	V = 65.502 ac-ft

TOTAL RUNOFF = 88.412 ac-ft

SUBBASIN RUNOFF

(CF5AA.DAT)	P_e = 1.29 in ,	V = 77.194 ac-ft
(CF5AL.DAT)	P_e = 1.45 in ,	V = 86.768 ac-ft
(CF5LA.DAT)	P_e = 1.29 in ,	V = 77.194 ac-ft
(CF5LL.DAT)	P_e = 1.46 in ,	V = 87.366 ac-ft

MAP UNIT AVE.

Subbasin AVE.

SUBBASIN RUNOFF FROM INDIVIDUAL SOIL TEXTURES

#41 → 3% OF SUBBASIN

45%	Sandy Loam
40%	Sandy Clay Loam
10%	Loamy Sand
5%	Sandy Clay

% of Subbasin:

Loamy Sand → .10(3) = .3%
Sandy Loam → .45(3) = 1.35%
Sandy Clay Loam → .40(3) = 1.2%
Clay Loam → .05(3) = .15%

#61 → 4% OF SUBBASIN

8.33%	Loamy Sand
43.33%	Sandy Loam
48.33%	Sandy Clay Loam

% OF Subbasin:

Loamy Sand → .0833(4) = .333%
Sandy Loam → .4333(4) = 1.733%
Sandy Clay Loam → .4833(4) = 1.933%

#63 → 21% OF Subbasin

5.4%	Loamy Sand
43.8%	Sandy Loam
50.8%	Sandy Clay Loam

% OF SUBBASIN:

Loamy Sand → .054(21) = 1.134%
Sandy Loam → .438(21) = 9.198%
Sandy Clay Loam → .508(21) = 10.668%

#72 → 72% OF SUBBASIN

7.2%	Loamy Sand
21.6%	Sandy Loam
71.2%	Sandy Clay Loam

% OF SUBBASIN:

Loamy Sand → .072 (72) = 5.184%

Sandy Loam → .216 (72) = 15.552%

Sandy Clay Loam → .712 (72) = 51.264%

TOTALS FOR THE SUBBASIN

Loamy Sand →	6.951%	=	.078 mi^2
Sandy Loam →	27.833%	=	.312 mi^2
Sandy Clay Loam →	65.065%	=	.730 mi^2
Sandy Clay →	.150%	=	.002 mi^2
	99.999%		1.122 mi^2

RUNOFF BY SOIL TEXTURE:

Loamy Sand →	(CF5LS.DAT)	P_e = .55 in	V = 2.288 ac-ft
Sandy Loam →	(CF5SL.DAT)	P_e = 1.06 in	V = 17.638 ac-ft
Sandy Clay Loam →	(CF5SCL.DAT)	P_e = 1.83 in	V = 71.248 ac-ft
Clay Loam →	(CF5CL.DAT)	P_e = 1.97 in	V = 0.210 ac-ft

TOTAL RUNOFF = 91.384 ac-ft

TIGER WASH SUB 8

SUBBASIN RUNOFF FROM INDIVIDUAL SOIL TEXTURES

#19,20 → 38.6 % OF Subbasin

11.43 % Sandy Loam
2.86 % Loam
85.71 % Sandy Clay Loam

% OF Subbasin

SANDY Loam → .1143 (38.6) = 4.412 %
Loam → .0286 (38.6) = 1.104 %
Sandy Clay Loam → .8571 (38.6) = 33.084 %

#92 → 50.1 % OF SUBBASIN

Loamy Sand → 37.5 % (50.1) = 18.788 % of Subbasin
Sandy Loam → 52.5 % (50.1) = 26.303 %
Loam → 5 % (50.1) = 2.505 %
Sandy Clay Loam → 5 % (50.1) = 2.505 %

#100 → 11.3 % OF Subbasin

Loamy Sand → 62.5 % (11.3) = 7.063 % OF Subbasin
Sandy Loam → 25 % (11.3) = 2.825 %
Sandy Clay Loam → 12.5 % (11.3) = 1.413 %

TOTALS FOR THE SUBBASIN

Loamy Sand	→	25.851 %	=	2.528 mi^2
Sandy Loam	→	33.540 %	=	3.280 mi^2
Loam	→	3.609 %	=	.353 mi^2
Sandy Clay Loam	→	37.002 %	=	3.619 mi^2
		100.002 %		9.780 mi^2

RUNOFF BY SOIL TEXTURE

Loamy Sand →	(TW8LS.DAT)	P_e = .10 in	V = 13.483 ac-ft
Sandy Loam →	(TW8SL.DAT)	P_e = .68 in	V = 118.955 ac-ft
Loam →	(TW8L.DAT)	P_e = 1.06 in	V = 19.956 ac-ft
Sandy Clay Loam →	(TW8SCL.DAT)	P_e = 1.60 in	V = 308.821 ac-ft

TOTAL RUNOFF = 461.215 ac-ft

MODELED SUBBASIN RUNOFF

(TW8AA.DAT)	P_e = .61 in	V = 318.2 ac-ft
(TW8AL.DAT)	P_e = .74 in	V = 386.0 ac-ft
(TW8LA.DAT)	P_e = .79 in	V = 412.1 ac-ft
(TW8LL.DAT)	P_e = .91 in	V = 474.7 ac-ft

Subbasin MAP UNIT

FLOOD CONTROL DISTRICT OF MARICOPA COUNTY

PROJECT Averaging Comparisons PAGE ___ OF ___
DETAIL for Green & Ampt Losses COMPUTED TWL DATE 8/20
CHECKED BY ___ DATE ___

Steve-

I attached a few language / wording type comments to the text. Other comments I have include:

i) any idea why volumes are generally <u>under</u> predicted?

ii) another reference to the meaning of A/A, A/L, L/A, & L/L on the page with the actual Table would be helpful. {even as simple as in Table 2: i.e. (subbasin / map unit)

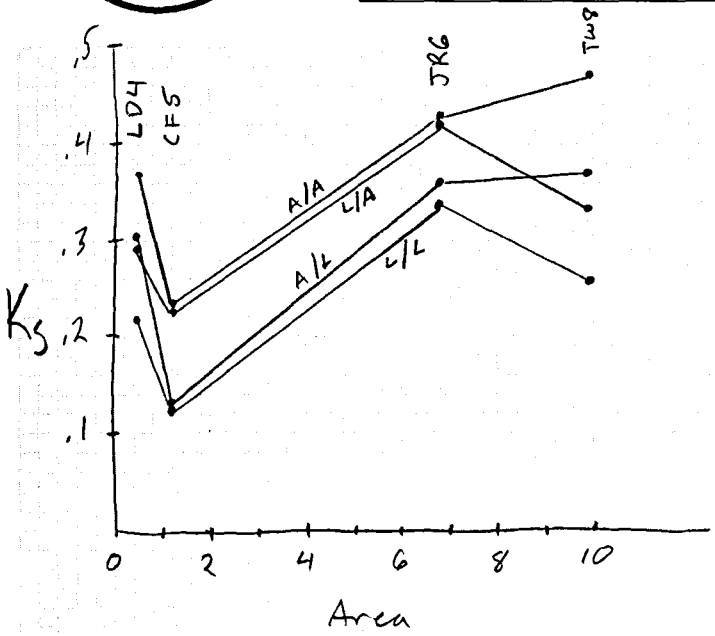
iii) do you feel a discussion of the reasons why the differences found are there? and why they are or are not expected?

FLOOD CONTROL DISTRICT OF MARICOPA COUNTY

PROJECT _____ PAGE ____ OF ____

DETAIL _____ COMPUTED _____ DATE ____

_____ CHECKED BY _____ DATE ____



(subbasin / map unit)

Notice that the subbasin averaging method "seems" to drive the change in XKSAT.

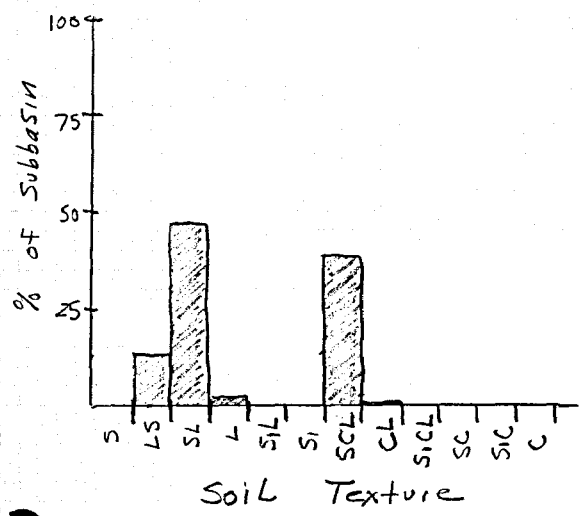
FLOOD CONTROL DISTRICT OF MARICOPA COUNTY

PROJECT _____ PAGE ____ OF ____

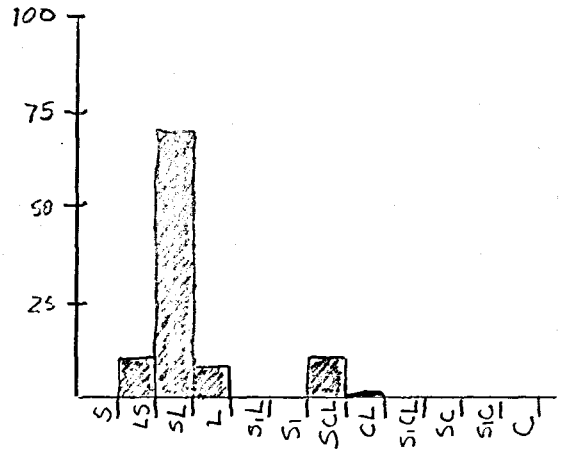
DETAIL _____ COMPUTED _____ DATE ____

_____ CHECKED BY _____ DATE ____

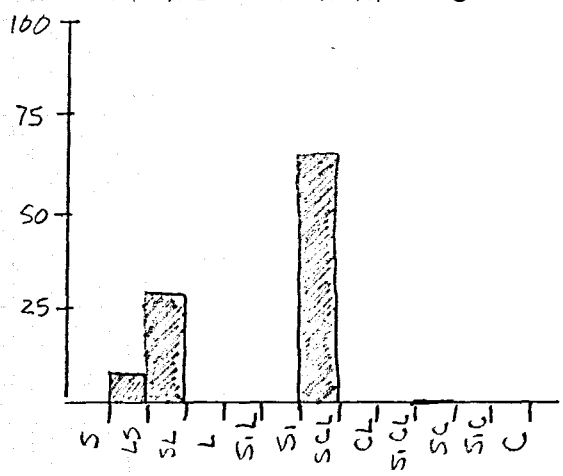
Lost Dog # 4



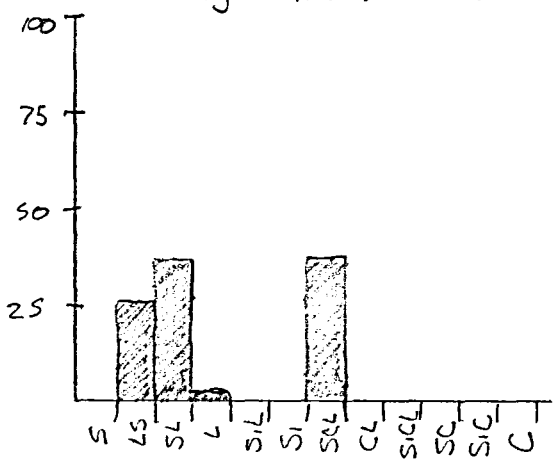
Jackrabbit Wash #6D



CareFree Subbasin #5



Tiger Wash Sub 8



LOGARTHMIC AREAL AVERAGING OF THE GREEN & AMPT SATURATED HYDRAULIC CONDUCTIVITY PARAMETER (XKSAT) ON FOUR DESERT WATERSHEDS IN MARICOPA COUNTY, ARIZONA

Purpose

The Green & Ampt loss rate method is currently recommended for use in hydrologic analyses by the Hydrologic Design Manual for Maricopa County (manual). The established procedure for developing the average saturated hydraulic conductivity parameter (XKSAT) for a subbasin involves linear (arithmetic) averaging of first the conductivity for each soil texture within a soil map unit, then for the various map units within a subbasin. The Wetting Front Capillary Suction (PSIF) and Volumetric Soil Moisture Deficit (DTHETA) values for the subbasin are then chosen from a graph (Figure 1) based on the average XKSAT.

Users of the manual have expressed concern with the present method. Subbasin average parameters seem to be biased toward higher infiltration rates when soils of high conductivity (say a loamy sand, XKSAT = 1.20 in/hr) are averaged with soils of low conductivity (say a sandy clay loam, XKSAT = 0.06 in/hr). Since some research in this area has already been done (Sabol, 1991; Van Mullen, 1989) this paper will investigate the results of logarithmically averaging the XKSAT parameter, within both the map unit and the subbasin.

Procedure

Four subbasins, ranging in size from 0.42 to 9.78 square miles were chosen for this analysis, without regard to the types of soils they contained. The subbasins were part of previous hydrologic analyses by the Flood Control District and Burgess & Niple, with soil map unit percentages already delineated. All subbasins are located within the boundaries of the Soil

Survey of Aguila-Carefree Area, Parts of Maricopa and Pinal Counties, Arizona, because it contains the most detailed soil texture data of the three available soil surveys in Maricopa County.

Map units (designated by numbers) were described for each subbasin. XKSAT values for each major and minor soil were assigned from Appendix A in the manual. Each minor soil was given equal weight in the averaging process. Two average XKSAT values were calculated for each map unit, one using the arithmetic average of the individual XKSATs times the partial areas, and one using the log of the individual XKSATs times the partial areas, with the antilog taken at the end of the calculation. At this point, the average XKSAT value for the subbasin was calculated in four ways:

1. A/A - (Arithmetic/Arithmetic): The arithmetically averaged map unit XKSAT values are averaged arithmetically (this procedure is currently recommended by the manual).
2. A/L - (Arithmetic/Log): The logarithmically averaged map unit XKSAT values are averaged arithmetically.
3. L/A - (Log/Arithmetic): The arithmetically averaged map unit XKSAT values are averaged logarithmically.
4. L/L - (Log/Log): The logarithmically averaged map unit XKSAT values are averaged logarithmically.

Appendix 1 contains all of the calculations used in the averaging process.

To develop the Modeled Runoff quantities, values of PSIF and DTHETA (dry) were read from Figure 1 for each of the four XKSAT values, and the loss parameters became input to an HEC-1 model for each subbasin on the LG card. Table 2 lists the loss parameters for the different subbasins and methods of areal averaging. Also included in the HEC-1 input were the following constants:

1. 6-hour rainfall from the manual, pattern number and areal reduction are based on the area of each subbasin.

2. A rainfall depth of 3 inches (a typical 100-year, 6-hour design rainfall depth in Maricopa County).

3. A five-minute hydrograph timestep.

The model was run four times for each subbasin, and after each run the value of total excess rainfall was converted to a runoff volume in acre-feet. The Modeled Runoff values are listed in Table 1.

As a comparison to the Modeled Runoff values, an attempt was made to quantify the Expected Runoff volume for each watershed by separating the soil textures, running an HEC-1 model for each using the same constant inputs, then summing the totals. A key assumption here is that all the individual soil textures contribute runoff to the outlet, i.e. runoff from an area of clay loam does not traverse an area of sandy loam and infiltrate en-route. This seems to be a reasonable assumption for low frequency design rainfall events because rainfall rates are generally greater than saturated conductivity rates and soils are nearly saturated at the point in the storm when large quantities of runoff begin. The Expected Runoff values are listed in Table 1.

Results

The results of the HEC-1 analyses are presented in Table 1.

Conclusions (from Table 1)

1. The present method of arithmetically averaging the XKSAT parameter (A/A) generally results in a large (12-31%) underestimation of the true runoff volume. Since rainfall excess is underestimated, the time of

concentration parameter in the Clark Unit Hydrograph method will be overestimated, resulting in underestimation of the peak discharge.

2. The Log/Log (L/L) method of averaging XKSAT seems to yield the best results when compared to the Expected Runoff, even for large basins and differing soil texture compositions.

Recommendations

If the Youngtown and Tucson Arroyo testing by GVS yields similar results, incorporate the Log/Log method of areal averaging the XKSAT parameter into the Hydrologic Design Manual. Include a detailed example of the procedure in the manual. Provide the weighted XKSAT values for each map unit in Appendicies similar to the current ones using the procedures developed herein. Provide guidance on developing an alternative map unit XKSAT for small drainage areas which might be dominated by one or more major or minor soils or a particular geomorphic regime.

TABLE 1

SUMMARY OF LOG AREAL AVERAGING TESTING RESULTS

SUBBASIN NUMBER	AREA (sq.mi)	DOMINANT SOIL TEXTURES (approx. percentage)	EXPECTED RUNOFF (ac-ft)	MODELED RUNOFF (% error) (ac-ft)			
				A/A	A/L	L/A	L/L
LD4	0.42	Sandy Loam (45) Sandy Clay Loam (39) Loamy Sand (13)	32.1	28.2 (-12.1)	30.2 (-5.9)	30.5 (-5.0)	32.5 (+1.2)
CF5	1.12	Sandy Clay Loam (65) Sandy Loam (28)	91.4	77.2 (-15.5)	86.8 (-5.0)	77.2 (-15.5)	87.4 (-4.4)
JR6	6.74	Sandy Loam (70) Sandy Clay Loam (11) Loamy Sand (11)	296.	262. (-11.5)	291. (-1.7)	266. (-10.1)	306. (+3.4)
TW8	9.78	Sandy Clay Loam (37) Sandy Loam (34) Loamy Sand (26)	461.	318. (-31.0)	386. (-16.3)	412. (-10.6)	475. (+3.0)
		Average Error (absolute value) ---------->		17.5 %	7.2 %	10.3 %	3.0 %

TABLE 2

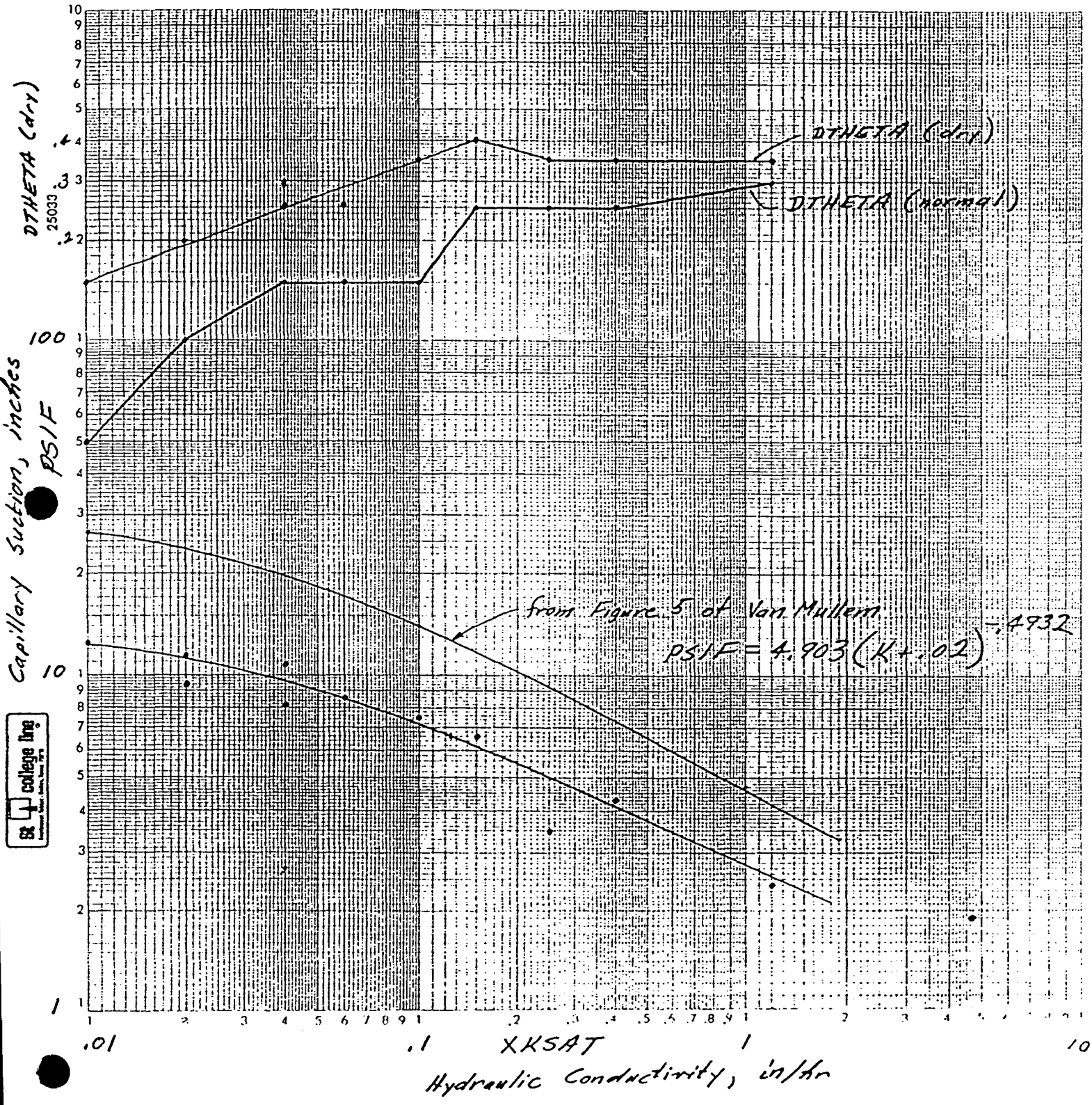
SUBBASIN LOSS PARAMETERS

Subbasin	Averaging Method (subbasin/map unit)	XKSAT (in/hr)	PSIF (in)	DTHETA (in)
LD4	A/A	.367	4.30	.350
	A/L	.301	4.65	.350
	L/A	.295	4.70	.350
	L/L	.217	5.35	.365
CF5	A/A	.234	5.20	.355
	A/L	.127	6.55	.380
	L/A	.232	5.20	.360
	L/L	.125	6.60	.375
JR6	A/A	.431	3.95	.350
	A/L	.362	4.30	.350
	L/A	.423	4.00	.350
	L/L	.344	4.30	.350
TW8	A/A	.476	3.85	.350
	A/L	.370	4.25	.350
	L/A	.337	4.40	.350
	L/L	.260	4.95	.350

amVg
25 April 91

FIGURE 1

Comparison of XKSAT vs PSIF from Table 4.2 and the relation by Van Mullem (1989)



Logarithmic 3 X 3 Cycles

APPENDIX 1

LOST DOG #4

AREA = 0.42 mi^2

MAP UNITS:				
	#10	13.3%	=	.056 mi^2
	#31	34.0%	=	.143 mi^2
	#44	9.6%	=	.040 mi^2
	#52	43.1%	=	.181 mi^2

SOIL DESCRIPTIONS:

#10 Brios - Carrizo Complex			XKSAT
40%	Brios Loamy Sand		1.20
40%	Carrizo Sand		1.20
20%	Antho (5%)	Benches	.40
	Gilman (5%)	Benches	.25
	Maripo (5%)	Benches	.40
	Vint (5%)	Benches	.40

XKSAT (ARITH) = .80(1.2) + .15(.40) + .05(.25) = 1.033 in/hr

XKSAT (Log) = [.8(log 1.2) + .15(log .40) + .05(log .25)] ALOG = 0.941 in/hr

#31 DIXALETA COMPLEX			XKSAT
84.6%	Dixaleta Extremely Channery Sandy Loam		.40
15.4%	Ohaco	FAN Terraces	.06
	Nickel (2.567% ea.)	FAN Terraces	.40
	Cave (2.567% ea.)	FAN Terraces	.25
	Eba (2.567% ea.)	FAN Terraces	.40
	Gran (2.567% ea.)	Mtn. Slopes	.06
	Lehmans (2.567% ea.)	Mtn. Slopes	.06

XKSAT (ARITH) = .89734 (.40) + .02567(.25) + .07701(.06) = .370 in/hr

XKSAT (Log) = Alog [.89734(log .40) + .02567(log .25) + .07701(log .06)] = .341 in/hr

#44 EBON VERY GRAVELLY LOAM

			XKSAT
80%	Ebon Sandy Clay Loam		.06
20%	Cipriano	FAN TERRACES	.06
	Contine		.04
	Beardsley		.25
	Luke		.06
	Gunsight		.40
	Mohall		.25
	Pinamt		.06

(2.857% ca.)

XKSAT (ARITH) = .02857(.40) + .05714 (.25) + .88571 (.06) + .02857 (.04) = .080 in/hr

XKSAT (Log) = ALOG [.02857 (log .40) + .05714 (log .25) + .88571 (log .06) + .02857 (log .04)] = .068 in/hr

#52 Gachado - Lomitas Complex

			XKSAT
56.3%	Gachado Very Gravelly Sandy Clay Loam		.06
25%	Lomitas Gravelly Sandy Loam		.40
18.7%	Carrizo	Fan Terraces	1.20
	Cherioni		1.20
	Ebon		.06
	Gunsight		.40
	Pinamt		.06
	Shenco	Hillslopes	.06
	Vaiva		.40

(2.67% ca.)

XKSAT = .05343 (1.20) + .30342 (.40) + .64313 (.06) = .224 in/hr

XKSAT (Log) = ALOG [.05343 (log 1.20) + .30342 (log .40) + .64313 (log .06)] = .125 in/hr

SUBBASIN RUNOFF FROM INDIVIDUAL SOIL TEXTURES

#10 → 13.3% of Subbasin

Loamy Sand → 80% (13.3) = 10.64% of Subbasin
Sandy Loam → 15% (13.3) = 1.995%
Loam → 5% (13.3) = 0.665%

#31 → 34.0% of Subbasin

Sandy Loam → 89.734% (34) = 30.510% of Subbasin
Loam → 2.567% (34) = 0.873%
Sandy Clay Loam → 7.701% (34) = 2.618%

#44 → 9.6% of Subbasin

Sandy Loam → 2.857% (9.6) = .274% of Subbasin
Loam → 5.714% (9.6) = .549%
Sandy Clay Loam → 88.571% (9.6) = 8.503%
Clay Loam → 2.857% (9.6) = .274%

#52 → 43.1% of Subbasin

Loamy Sand → 5.343 (43.1) = 2.303% of Subbasin
Sandy Loam → 30.342 (43.1) = 13.077%
Sandy Clay Loam → 64.313 (43.1) = 27.719%

TOTALS FOR THE SUBBASIN

Loamy Sand →	12.943%	=	.054 mi^2
Sandy Loam →	45.856%	=	.193 mi^2
Loam →	2.087%	=	.009 mi^2
Sandy Clay Loam →	38.840%	=	.163 mi^2
Clay Loam →	.274%	=	.001 mi^2
	100.000%		.420 mi^2

RUNOFF BY SOIL TEXTURE

LOAMY SAND (LD4LS.DAT)	P_e = .84 in	V = 2.419 ac-ft
Sandy Loam (LD4SL.DAT)	P_e = 1.21 in	V = 12.455 ac-ft
Loam (LD4L.DAT)	P_e = 1.53 in	V = .734 ac-ft
Sandy Clay Loam (LD4SCL.DAT)	P_e = 1.89 in	V = 16.430 ac-ft
Clay Loam (LD4CL.DAT)	P_e = 2.02 in	V = .108 ac-ft

TOTAL RUNOFF = 32.146 ac-ft

MODELED SUBBASIN RUNOFF

AVERAGED LOSSES: (XKSAT)

ARITH/ARITH : .133 (1.033) + .340(.370) + .096(.08) + .431(.224) = .367 in/hr

ARITH/Log : .133 (.941) + .340 (.341) + .096 (.068) + .431 (.125) = .301 in/hr

Log/ARITH : [.133 (log 1.033) + .340 (log .370) + .096 (log .08) + .431 (log .224)] ALOG = .295 in/hr

Log/Log : [.133 (log .941) + .340 (log .341) + .096 (log .068) + .431 (log .125)] ALOG = .217 in/hr

RUNS (Subbasin, Map Unit)

1.	LD4AA.DAT	XKSAT = .367 in/hr,	PSIF = 4.3 in,	dθ = .35 in
2.	LD4AL.DAT	XKSAT = .301 in/hr,	PSIF = 4.65 in,	dθ = .35 in
3.	LD4LA.DAT	XKSAT = .295 in/hr,	PSIF = 4.7 in,	dθ = .35 in
4.	LD4LL.DAT	XKSAT = .217 in/hr,	PSIF = 5.35 in	dθ = .365 in

RUN RESULTS

1.	LD4AA.DAT	P_e = 1.26 in	V = 28.224 ac-ft
2.	LD4AL.DAT	P_e = 1.35 in	V = 30.240 ac-ft
3.	LD4LA.DAT	P_e = 1.36 in	V = 30.464 ac-ft
4.	LD4LL.DAT	P_e = 1.45 in	V = 32.480 ac-ft

JACKRABBIT WASH #6D

AREA = 6.74 mi^2

MAP UNIT	% AREA		mi^2
#3	0.742	4.896	.05
#4	4.154		.28
#30	62.315		4.20
#56	4.599		.31
#91	2.671		.18
#99	2.671		.18
#108	0.593		.04
#117	22.255		1.50

SOIL DESCRIPTIONS

#s 3 & 4:	ANTHO - Carrizo - Maripo Complex		XKSAT
35%	ANTHO Sandy Loam		.40
30%	Carrizo Very Gravelly Sand		1.20
20%	Maripo Sandy Loam		.40
15%	Brios	Drainageways	1.20
	Gilman	Floodplains	.25
	Vint	Floodplains	.40
	Denure (2.5% ea.)	Stream Terraces	.40
	Momoli (2.5% ea.)	Stream Terraces	.40
	Carrizo (2.5% ea.)	Stream Terraces	.40

XKSAT (ARITH) = .325(1.20) + .65(.40) + .025(.25) = 0.656 in/hr

XKSAT (Log) = ALOG[.325(log 1.20) + .65(log .40) + .025(log .25) = .565 in/hr

#30	DENURE - MOMOLI - Carrizo Complex			XKSAT
40%	DENURE Gravelly Sandy Loam			.40
30%	MOMOLI Gravelly Sandy Loam			.40
20%	Carrizo Gravelly Sandy Loam			.40
10%	GILMAN	(3.33% ea.)	FLOODPLAINS	.25
	Maripo			.40
	Carrizo			1.20

XKSAT (ARITH) = .9333 (.40) + .0333 (.25) + .0333 (1.20) = .422 in/hr

XKSAT (Log) = [.9333 (log .40) + .0333 (log .25) + .0333 (log 1.20)] ALog = .408 in/hr

#56	GILMAN LOAMS			XKSAT
80%	GILMAN Loam			.25
20%	ANTHO		Drainageways	.40
	Carrizo			1.20
	ESTRELLA		Throughout	.25
	Glenbar	(2.5% ea.)		.15
	Vint			.40
	Denure		Fan Terraces	.40
	Momoli			.40
	Carrizo			.40

XKSAT (ARITH) = .825(.25) + .125 (.40) + .025 (1.20) + .025 (.15) = .290 in/hr

XKSAT (Log) = Alog [.825 (log .25) + .125 (log .40) + .025 (log 1.20) + .025 (log .15)] = .272 in/hr

#91	Momoli - Carrizo Complex			XKSAT
45%	Momoli Very Gravelly Loam			.40
35%	Carrizo Very Gravelly Sandy Loam			1.20
20%	Mohall	(2.5% ea.)	High Terraces	.25
	Tremant			.40
	Gunsight			.06
	Chuckawalla			.06
	Denure		Throughout	.40
	GILMAN		Drainageways	.25
	Maripo			.40
	Carrizo			1.20

XKSAT (ARITH) = .375(1.20) + .525(.40) + .05(.25) + .05(.06) = .676 in/hr

XKSAT (Log) = ALOG[(.375(log 1.20) + .525(log .40) + .05(log .25) + .05(log .06)] = .537 in/hr

#99	Pinamt - Tremant Complex			XKSAT
45%	Pinamt Very Gravelly Sandy Clay Loam			.06
35%	Tremant Gravelly Loam			.40
20%	Carrizo		Drainageways	1.20
	Chuckawalla	(4% ea.)	FAN Terraces	.06
	Ebon			.06
	Gunsight			.40
	Rillito			.40

XKSAT (ARITH) = .04(1.2) + .43(.40) + .53(.06) = .252 in/hr

XKSAT (Log) = [.04 (log 1.2) + .43 (log .40) + .53 (log .06)] ALOG = .153 in/hr

#108	SHENCO COMPLEX		XKSAT
71.4 %	SHENCO		.06
28.6%	Antho	Drainageways	.40
	Beardsley	Fan Terraces	.25
	Cherioni		.40
	Cipriano		.06
	Ebon		.06
	Gunsight		.40
	Sun City		.06
	Gachado	Hillslopes	.06
	Quilotosa	Throughout	1.20
	Vaiva		.40

(2.86 % ea.)

XKSAT (ARITH) = .0286 (1.20) + .1144(.40) + .0286 (.25) + .8284 (.06) = .137 in/hr

XKSAT (Log) = ALOG[.0286(log 1.2) + .0858 (log .40) + .0286 (log .25) + .8284(log .06)]
= .087 in/hr

# 117	TREMANT - GUNSIGHT - RILLITO COMPLEX		XKSAT
30%	Tremant		.06
20%	Gunsight		1.20
20%	RILLITO		.40
30%	Cipriano	Terraces	.06
	Pinamt		.06
	Mohall		.25
	Contine		.04
	Antho	Alluvial Fans Drainageways	.40
	Carrizo		1.20
	GILMAN		.25

(4.286 % ea.)

XKSAT (ARITH) = .24286 (1.2) + .24286 (.40) + .08572 (.25) + .38572 (.06) + .04286 (.04) = .435 in/hr

XKSAT (LOG) = ALOG[.24286 (log 1.2) + .24286 (log .40) + .08572 (log .25) + .38572 (log .06) + .04286 (log .04)] = .219 in/hr

SUBBASIN RUNOFF FROM INDIVIDUAL SOIL TEXTURES

JRGD

#3 & 4 → 4.9% of Subbasin

Loamy Sand → 32.5% (4.9) = 1.59% of Subbasin
Sandy Loam → 65% (4.9) = 3.19%
Loam → 2.5% (4.9) = 0.12%

#30 → 62.3% of SUBBASIN

Loamy Sand → 3.33% (62.3) = 2.07% of Subbasin
Sandy Loam → 93.33% (62.3) = 58.14%
Loam → 3.33% (62.3) = 2.07%

#56 4.6% of SUBBASIN

Loamy Sand → 2.5% (4.6) = 0.12% of Subbasin
Sandy Loam → 12.5% (4.6) = 0.58%
Loam → 82.5% (4.6) = 3.80%
SILTY Loam → 2.5% (4.6) = 0.12%

#91 2.7% of SUBBASIN

Loamy Sand → 37.5% (2.7) = 1.01% of Subbasin
Sandy Loam → 52.5% (2.7) = 1.42%
Loam → 5% (2.7) = .14%
Sandy Clay Loam → 5% (2.7) = .14%

#99 2.7% of SUBBASIN

Loamy Sand → 4% (2.7) = .11% of Subbasin
Sandy Loam → 43% (2.7) = 1.16%
Sandy Clay Loam → 53% (2.7) = 1.43%

#108 0.6 % of Subbasin

Loamy Sand → 2.86 % (.6) = .02 % of Subbasin
Sandy Loam → 11.44 % (.6) = .07 %
Loam → 2.86 % (.6) = .02 %
Sandy Clay Loam → 82.84% (.6) = .50 %

#117 22.3 % of Subbasin

Loamy Sand → 24.286%(22.3) = 5.42 % of Subbasin
Sandy Loam → 24.286%(22.3) = 5.42 %
Loam → 8.572%(22.3) = 1.91 %
Sandy Clay Loam → 38.572%(22.3) = 8.60 %
Clay Loam → 4.286% (22.3) = 0.96 %

TOTALS FOR THE SUBBASIN (A = 6.74 mi^2)

LOAMY SAND →	10.34 %	=	.697 mi^2
Sandy Loam →	69.98 %	=	4.717 mi^2
Loam →	8.06 %	=	.543 mi^2
SILTY Loam →	.12 %	=	.008 mi^2
Sandy Clay Loam →	10.67%	=	.719 mi^2
Clay Loam →	.96%	=	.065 mi^2
	100.13%		6.749 mi^2

RUNOFF BY SOIL TEXTURE

LOAMY SAND	(JRLS.DAT)	P_e = .14 in,	V = 5.20 ac-ft
SANDY LOAM	(JRSL.DAT)	P_e = .75	V = 188.68
LOAM	(JRL.DAT)	P_e = 1.12	V = 32.44
SILTY LOAM	(JRSLL.DAT)	P_e = 1.12	V = 0.48
SANDY Clay Loam	(JRSCL.DAT)	P_e = 1.64	V = 62.89
Clay Loams	(JRCL.DAT)	P_e = 1.81	V = 6.28

TOTAL RUNOFF = 295.97 ac-ft

MODELED SUBBASIN RUNOFF

AVERAGED LOSSES (XKSAT)

Subbasin / Map Unit

ARITH / ARITH : .04896(.656) + .62315(.422) + .04599(.290) + .02671(.676) + .02671(.252) + .00593(.137) + .22255(.435) = .431 in/hr

PSIF = 3.95 in $d\theta$ = .35 in

ARITH / LOG : .04896(.565) + .62315(.408) + .04599(.272) + .02671(.537) + .02671(.153) + .00593(.087) + .22255(.219) = .362 in/hr

PSIF = 4.3 in $d\theta$ = .35 in

LOG / ARITH = ALOG[.04896(log .656) + .62315(log .422) + .04599(log .290) + .02671(log .676) + .02671(log .252) + .00593(log .137) + .22255(log .435)]

= .423 in/hr PSIF = 4.0 $d\theta$ = .35 in

LOG / LOG = ALOG[.04896(log .565) + .62315(log .408) + .04599(log .272) + .02671(log .537) + .02671(log .153) + .00593(log .087) + .22255(log .219)]

= .344 in/hr PSIF = 4.3 in $d\theta$ = .35 in

RUN RESULTS

	P_e (in)	V (ac-ft)
1. JRAA.DAT	.73	262.4
2. JRAL.DAT	.81	291.2
3. JRLA.DAT	.74	266.0
4. JRLL.DAT	.85	305.5

Carefree Subbasin #5

AGUILA - CAREFREE SOIL SURVEY

DRAINAGE AREA: 1.122 mi^2

MAP UNITS:			
#41	3%	=	.034 mi^2
#61	4%	=	.045 mi^2
#63	21%	=	.236 mi^2
#72	72%	=	.808 mi^2

SOIL DESCRIPTIONS (MAP UNIT LOSSES)

#41 Eba - Pinaleno Complex

		XKSAT
45%	Eba very gravelly loam	.40
35%	Pinaleno very gravelly clay loam	.06
20%	Ohaco (5%) } THROUGHOUT	.04
	Tres Hermanos (5%)	.06
	ANTHONY (5%) } DRAINAGEWAYS	1.20
	ARIZO (5%)	1.20

XKSAT (ARITH) = .45(.40) + .40(.06) + .05(.04) + .10(1.20) = .326 in/hr

XKSAT (Log) = [.45(log .40) + .40(log .06) + .05(log .04) + .10(log 1.20)] ALOG = .186 in/hr

#61

Gran - Wickenburg Complex, 1-10% SLOPES

40%	Gran very gravelly sandy clay loam		(.06)
35%	Wickenburg gravelly sandy loam		(.40)
25%	Eba (8⅓%) } Toe Slopes		(.40)
	Pinaleno (8⅓%)		(.06)
	Arizo (8⅓%) } Drainageways		(1.20)

XKSAT (Arith) = .483(.06) + .433(.40) + .083(1.20) = .302 in/hr

XKSAT (Log) = ALOG [.483(log .06) + .433(log .40) + .083(log 1.20)] = .175 in/hr

#63

Gran - Wickenburg Complex, 10-65% Slopes

40%	Gran very gravelly sandy clay loam			(.06)
33%	Wickenburg gravelly sandy loam			(.40)
27%	Dixaleta		Mtn Slopes	(.40)
	Lehmans			(.06)
	Eba	5.4% ea	Toe Slopes	(.40)
	Pinaleno			(.06)
	Arizo		Drainageways	(1.20)

XKSAT (ARITH) .438(.40) + .508 (.06) + .054 (1.20) = .270 in/hr

XKSAT (Log) ALOG [.438(log .40) + .508(log .06) + .054(log 1.20)] = .162 in/hr

#72 LEHMANS Complex

64%	Lehmans very gravelly clay loam			(.06)
36%	ARIZO		Drainageways	(1.20)
	Eba		foot slopes	(.40)
	Pinaleno	7.2% ea.		(.06)
	Greyeagle		Gentle Slopes	(.40)
	Nickel			(.40)

XKSAT (ARITH) = .712(.06) + .072(1.20) + .216(.40) = .216 in/hr

XKSAT (Log) = ALOG [.712(log .06) + .072(log 1.2) + .216(log .40)] = .112 in/hr

CAREFREE #5 SUBBASIN LOSSES

1. ARITH / ARITH

XKSAT = .03 (.326) + .04(.302) + .21(.270) + .72(.216) = .234 in/hr

2. ARITH / Log

XKSAT = .03 (.186) + .04 (.175) + .21 (.162) + .72 (.112) = .127 in/hr

3. Log / ARITH

XKSAT = ALOG [.03 (log .326) + .04 (log .302) + .21 (log .270) + .72 (log .216)]
= .232 in/hr

4. Log / Log

XKSAT = ALOG [.03 (log .186) + .04 (log .175) + .21 (log .162) + .72 (log .112)]
= .125 in/hr

1. CF5AA.DAT → XKSAT = .234 in/hr PSIF = 5.2 in dθ = .355 in
2. CF5AL.DAT → XKSAT = .127 in/hr PSIF = 6.55 in dθ = .38 in
3. CF5LA.DAT → XKSAT = .232 in/hr PSIF = 5.2 in dθ = .36 in
4. CF5LL.DAT → XKSAT = .125 in/hr PSIF = 6.6 in dθ = .375 in

TIGER WASH SUB 8

DRAINAGE AREA : 9.78 mi^2

SOIL SURVEY : Aguila - Carefree

MAP UNITS :	#19, 20	38.6 %	=	3.775 mi^2
	# 92	50.1 %	=	4.900 mi^2
	# 100	11.3 %	=	1.105 mi^2

SOIL DESCRIPTIONS (MAP UNIT LOSSES)

#19,20

CHUCKAWALLA - GUNSIGHT COMPLEX

				XKSAT
45%	CHUCKAWALLA Very Gravelly Sandy Clay Loam			.06
35%	GUNSIGHT Very Gravelly Loam			.06
20%	Sal	(2.857 % ea.)	FAN TERRACES	.06
	Pinamt			.06
	Tremant			.40
	RILLITO		Side Slopes	.40
	ANTHO		FLOODPLAINS	.40
	Gilman			.25
	Maripo			.40

XKSAT (ARITH) = .85714 (.06) + .114 (.40) + .02857 (.25) = .104 in/hr

XKSAT (Log) = ALOG[.85714 (log .06) + .114 (log .40) + .02857 (log .25)] = .078 in/hr

92

MOMOLI - CARRIZO COMPLEX			XKSAT
45%	MOMOLI Very Gravelly Loam		.40
35%	CARRIZO Very Gravelly Sandy Loam		1.20
20%	MOHALL	High Terraces	.25
	Tremant	High Terraces	.40
	Gunsight	High Terraces	.06
	Chuckawalla	High Terraces	.06
	DENURE (2.5% each)	Throughout	.40
	GILMAN (2.5% each)	Drainageways	.25
	Maripo (2.5% each)	Drainageways	.40
	Carrizo (2.5% each)	Drainageways	1.20

XKSAT (ARITH) = .375 (1.20) + .525 (.40) + .05 (.25) + .05 (.06) = .676 in/hr

XKSAT (Log) = ALOG[.375 (log 1.2) + .525 (log .40) + .05 (log .25) + .05 (log .06)] = .537 in/hr

# 100	QUILOTOSA - VAIVA COMPLEX		XKSAT
62.5%	Quilotosa Extremely Gravelly Loam		1.20
25%	VAIVA Very gravelly Loam		.40
12.5%	Schenco	Mtn. Slopes	.06

XKSAT (ARITH) = .625 (1.20) + .25 (.40) + .125 (.06) = .858 in/hr

XKSAT (Log) = ALOG[.625 (log 1.20) + .25 (log .40) + .125 (log .06)] = .627 in/hr

TIGER WASH #8

SUBBASIN LOSSES

Subbasin / MAP UNIT

ARITH / ARITH

XKSAT = .386(.104) + .501(.676) + .113(.858) = .476 in/hr

ARITH / LOG

XKSAT = .386(.078) + .501(.537) + .113(.627) = .370 in/hr

LOG / ARITH

XKSAT = ALOG[.386(log .104) + .501(log .676) + .113(log .858)] = .337 in/hr

LOG / LOG

XKSAT = ALOG[.386(log .078) + .501(log .537) + .113(log .627)] = .260 in/hr

1. TWAA.DAT → XKSAT = .476 in/hr PSIF = 3.85 in dθ = .35 in
2. TWAL.DAT → XKSAT = .370 in/hr PSIF = 4.25 in dθ = .35 in
3. TWLA.DAT → XKSAT = .337 in/hr PSIF = 4.4 in dθ = .35 in
4. TWLL.DAT → XKSAT = .260 in/hr PSIF = 4.95 in dθ = .35 in

VOLUME RUNS

CAREFREE #5

HEC-1 MODEL :

RAINFALL → DEPTH = 3.0 in , IA = .25 in

DISTR. → 6-hour, Pattern based on 1.122 mi^2

RUNOFF FROM MAP UNITS

ARITH LOSSES

#41 →	(CF541A.DAT)	P_e = 1.17 in ,	V = 2.122 ac-ft
#61 →	(CF561A.DAT)	P_e = 1.20 in ,	V = 2.880 ac-ft
#63 →	(CF563A.DAT)	P_e = 1.24 in ,	V = 15.607 ac-ft
#72 →	(CF572A.DAT)	P_e = 1.30 in ,	V = 56.021 ac-ft

TOTAL RUNOFF = 76.630 ac-ft

LOG LOSSES

#41 →	(CF541L.DAT)	P_e = 1.34 in,	V = 2.430 ac-ft
#61 →	(CF561L.DAT)	P_e = 1.35 in,	V = 3.240 ac-ft
#63 →	(CF563L.DAT)	P_e = 1.37 in,	V = 17.240 ac-ft
#72 →	(CF572L.DAT)	P_e = 1.52 in,	V = 65.502 ac-ft

TOTAL RUNOFF = 88.412 ac-ft

SUBBASIN RUNOFF

(CF5AA.DAT)	P_e = 1.29 in ,	V = 77.194 ac-ft
(CF5AL.DAT)	P_e = 1.45 in ,	V = 86.768 ac-ft
(CF5LA.DAT)	P_e = 1.29 in ,	V = 77.194 ac-ft
(CF5LL.DAT)	P_e = 1.46 in ,	V = 87.366 ac-ft

MAP UNIT AVE.

Subbasin AVE.

SUBBASIN RUNOFF FROM INDIVIDUAL SOIL TEXTURES

#41 → 3% OF SUBBASIN

45%	Sandy Loam
40%	Sandy Clay Loam
10%	Loamy Sand
5%	Sandy Clay

% of Subbasin:

Loamy Sand → .10(3) = .3%

Sandy Loam → .45(3) = 1.35%

Sandy Clay Loam → .40(3) = 1.2%

Clay Loam → .05(3) = .15%

#61 → 4% OF SUBBASIN

8.33%	Loamy Sand
43.33%	Sandy Loam
48.33%	Sandy Clay Loam

% OF Subbasin:

Loamy Sand → .0833(4) = .333%

Sandy Loam → .4333(4) = 1.733%

Sandy Clay Loam → .4833(4) = 1.933%

#63 → 21% OF Subbasin

5.4%	Loamy Sand
43.8%	Sandy Loam
50.8%	Sandy Clay Loam

% OF SUBBASIN:

Loamy Sand → .054(21) = 1.134%

Sandy Loam → .438(21) = 9.198%

Sandy Clay Loam → .508(21) = 10.668%

#72 → 72% of Subbasin

7.2% Loamy Sand
21.6% Sandy Loam
71.2% Sandy Clay Loam

% of Subbasin:

Loamy Sand → .072 (72) = 5.184%
Sandy Loam → .216 (72) = 15.552%
Sandy Clay Loam → .712 (72) = 51.264%

Totals For The Subbasin

Loamy Sand →	6.951%	=	.078 mi^2
Sandy Loam →	27.833%	=	.312 mi^2
Sandy Clay Loam →	65.065%	=	.730 mi^2
Sandy Clay →	.150%	=	.002 mi^2
	99.999%		1.122 mi^2

Runoff By Soil Texture:

Loamy Sand →	(CF5LS.DAT)	P_e = .55 in	V = 2.288 ac-ft
Sandy Loam →	(CF5SL.DAT)	P_e = 1.06 in	V = 17.638 ac-ft
Sandy Clay Loam →	(CF5SCL.DAT)	P_e = 1.83 in	V = 71.248 ac-ft
Clay Loam →	(CF5CL.DAT)	P_e = 1.97 in	V = 0.210 ac-ft

Total Runoff = 91.384 ac-ft

TIGER WASH SUB 8

SUBBASIN RUNOFF FROM INDIVIDUAL SOIL TEXTURES

#19,20 → 38.6 % OF Subbasin

11.43 % Sandy Loam
2.86 % Loam
85.71 % Sandy Clay Loam

% OF Subbasin

SANDY Loam → .1143 (38.6) = 4.412 %
Loam → .0286 (38.6) = 1.104 %
Sandy Clay Loam → .8571 (38.6) = 33.084 %

#92 → 50.1% OF SUBBASIN

Loamy Sand → 37.5 % (50.1) = 18.788 % of Subbasin
Sandy Loam → 52.5% (50.1) = 26.303 %
Loam → 5% (50.1) = 2.505 %
Sandy Clay Loam → 5% (50.1) = 2.505 %

#100 → 11.3 % OF Subbasin

Loamy Sand → 62.5 % (11.3) = 7.063 % OF Subbasin
Sandy Loam → 25 % (11.3) = 2.825 %
Sandy Clay Loam → 12.5% (11.3) = 1.413 %

TOTALS FOR THE SUBBASIN

Loamy Sand	→	25.851 %	=	2.528 mi^2
Sandy Loam	→	33.540 %	=	3.280 mi^2
Loam	→	3.609 %	=	.353 mi^2
Sandy Clay Loam	→	37.002 %	=	3.619 mi^2
		100.002 %		9.780 mi^2

RUNOFF BY SOIL TEXTURE

Loamy Sand →	(TW8LS.DAT)	P_e = .10 in	V = 13.483 ac-ft
Sandy Loam →	(TW8SL.DAT)	P_e = .68 in	V = 118.955 ac-ft
Loam →	(TW8L.DAT)	P_e = 1.06 in	V = 19.956 ac-ft
Sandy Clay Loam →	(TW8SCL.DAT)	P_e = 1.60 in	V = 308.821 ac-ft

TOTAL RUNOFF = 461.215 ac-ft

MODELED SUBBASIN RUNOFF

(TW8AA.DAT)	P_e = .61 in	V = 318.2 ac-ft
(TW8AL.DAT)	P_e = .74 in	V = 386.0 ac-ft
(TW8LA.DAT)	P_e = .79 in	V = 412.1 ac-ft
(TW8LL.DAT)	P_e = .91 in	V = 474.7 ac-ft

Subbasin MAP UNIT

GVS

LOGARTHMIC AREAL AVERAGING OF THE GREEN & AMPT SATURATED HYDRAULIC CONDUCTIVITY PARAMETER (XKSAT) ON FOUR DESERT WATERSHEDS IN MARICOPA COUNTY, ARIZONA

Purpose

The Green & Ampt loss rate method is currently recommended for use in hydrologic analyses by the Hydrologic Design Manual for Maricopa County (manual). The established procedure for developing the average saturated hydraulic conductivity parameter (XKSAT) for a subbasin involves linear (arithmetic) averaging of first the conductivity for each soil texture within a soil map unit, then for the various map units within a subbasin. The Wetting Front Capillary Suction (PSIF) and Volumetric Soil Moisture Deficit (DTHETA) values for the subbasin are then chosen from a graph (Figure 1) based on the average XKSAT.

Users of the manual have expressed concern with the present method. Subbasin average parameters seem to be biased toward higher infiltration rates when soils of high conductivity (say a loamy sand, XKSAT = 1.20 in/hr) are averaged with soils of low conductivity (say a sandy clay loam, XKSAT = 0.06 in/hr). Since some research in this area has already been done (Sabol, 1991; Van Mullen, 1989) this paper will investigate the results of logarithmically averaging the XKSAT parameter, within both the map unit and the subbasin.

Procedure

Four subbasins, ranging in size from 0.42 to 9.78 square miles were chosen for this analysis, without regard to the types of soils they contained. The subbasins were part of previous hydrologic analyses by the Flood Control District and Burgess & Niple, with soil map unit percentages already delineated. All subbasins are located within the boundaries of the Soil

Survey of Aguila-Carefree Area, Parts of Maricopa and Pinal Counties, Arizona, because it contains the most detailed soil texture data of the three available soil surveys in Maricopa County.

Map units (designated by numbers) were described for each subbasin. XKSAT values for each major and minor soil were assigned from Appendix A in the manual. Each minor soil was given equal weight in the averaging process. Two average XKSAT values were calculated for each map unit, one using the arithmetic average of the individual XKSATs times the partial areas, and one using the log of the individual XKSATs times the partial areas, with the antilog taken at the end of the calculation. At this point, the average XKSAT value for the subbasin was calculated in four ways:

1. A/A - (Arithmetic/Arithmetic): The arithmetically averaged map unit XKSAT values are averaged arithmetically (this procedure is currently recommended by the manual).
2. A/L - (Arithmetic/Log): The logarithmically averaged map unit XKSAT values are averaged arithmetically.
3. L/A - (Log/Arithmetic): The arithmetically averaged map unit XKSAT values are averaged logarithmically.
4. L/L - (Log/Log): The logarithmically averaged map unit XKSAT values are averaged logarithmically.

Appendix 1 contains all of the calculations used in the averaging process.

To develop the Modeled Runoff quantities, values of PSIF and DTHETA (dry) were read from Figure 1 for each of the four XKSAT values, and the loss parameters became input to an HEC-1 model for each subbasin on the LG card. Table 2 lists the loss parameters for the different subbasins and methods of areal averaging. Also included in the HEC-1 input were the following constants:

1. 6-hour rainfall from the manual, pattern number and areal reduction are based on the area of each subbasin.

2. A rainfall depth of 3 inches (a typical 100-year, 6-hour design rainfall depth in Maricopa County).

3. A five-minute hydrograph timestep.

The model was run four times for each subbasin, and after each run the value of total excess rainfall was converted to a runoff volume in acre-feet. The Modeled Runoff values are listed in Table 1.

As a comparison to the Modeled Runoff values, an attempt was made to quantify the Expected Runoff volume for each watershed by separating the soil textures, running an HEC-1 model for each using the same constant inputs, then summing the totals. A key assumption here is that all the individual soil textures contribute runoff to the outlet, i.e. runoff from an area of clay loam does not traverse an area of sandy loam and infiltrate en-route. This seems to be a reasonable assumption for low frequency design rainfall events because rainfall rates are generally greater than saturated conductivity rates and soils are nearly saturated at the point in the storm when large quantities of runoff begin. The Expected Runoff values are listed in Table 1.

Results

The results of the HEC-1 analyses are presented in Table 1.

Conclusions (from Table 1)

1. The present method of arithmetically averaging the XKSAT parameter (A/A) generally results in a large (12-31%) underestimation of the true runoff volume. Since rainfall excess is underestimated, the time of

concentration parameter in the Clark Unit Hydrograph method will be overestimated, resulting in underestimation of the peak discharge.

2. The Log/Log (L/L) method of averaging XKSAT seems to yield the best results when compared to the Expected Runoff, even for large basins and differing soil texture compositions.

Recommendations

If the Youngtown and Tucson Arroyo testing by GVS yields similar results, incorporate the Log/Log method of areal averaging the XKSAT parameter into the Hydrologic Design Manual. Include a detailed example of the procedure in the manual. Provide the weighted XKSAT values for each map unit in Appendicies similar to the current ones using the procedures developed herein. Provide guidance on developing an alternative map unit XKSAT for small drainage areas which might be dominated by one or more major or minor soils or a particular geomorphic regime.

TABLE 1

SUMMARY OF LOG AREAL AVERAGING TESTING RESULTS

SUBBASIN NUMBER	AREA (sq.mi)	DOMINANT SOIL TEXTURES (approx. percentage)	EXPECTED RUNOFF (ac-ft)	MODELED RUNOFF (% error) (ac-ft) A/A	A/L	L/A	L/L
LD4	0.42	Sandy Loam (45) Sandy Clay Loam (39) Loamy Sand (13)	32.1	28.2 (-12.1)	30.2 (-5.9)	30.5 (-5.0)	32.5 (+1.2)
CF5	1.12	Sandy Clay Loam (65) Sandy Loam (28)	91.4	77.2 (-15.5)	86.8 (-5.0)	77.2 (-15.5)	87.4 (-4.4)
JR6	6.74	Sandy Loam (70) Sandy Clay Loam (11) Loamy Sand (11)	296.	262. (-11.5)	291. (-1.7)	266. (-10.1)	306. (+3.4)
TW8	9.78	Sandy Clay Loam (37) Sandy Loam (34) Loamy Sand (26)	461.	318. (-31.0)	386. (-16.3)	412. (-10.6)	475. (+3.0)
		Average Error (absolute value) ---------->		17.5 %	7.2 %	10.3 %	3.0 %

TABLE 2

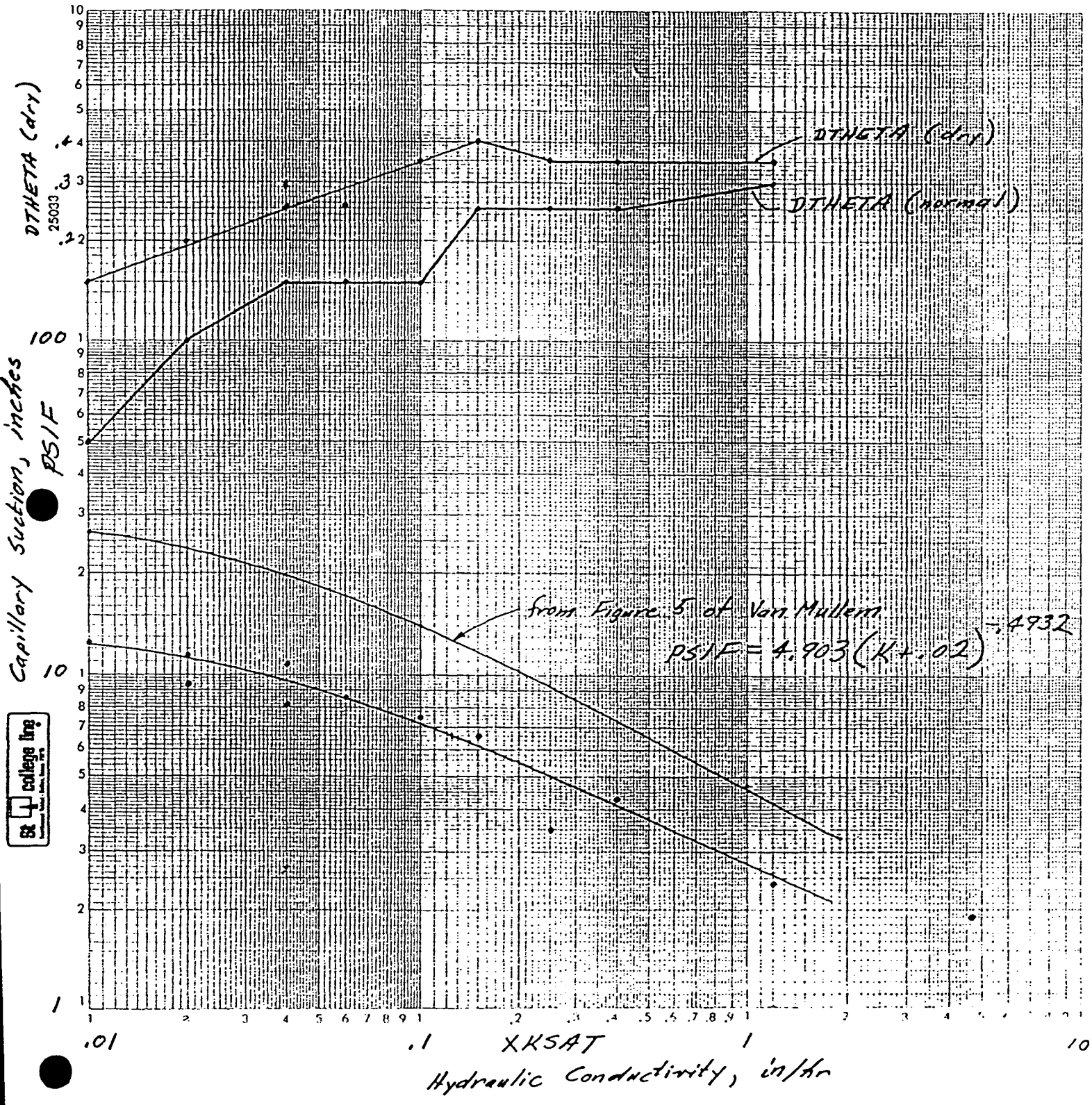
SUBBASIN LOSS PARAMETERS

Subbasin	Averaging Method (subbasin/map unit)	XKSAT (in/hr)	PSIF (in)	DTHETA (in)
LD4	A/A	.367	4.30	.350
	A/L	.301	4.65	.350
	L/A	.295	4.70	.350
	L/L	.217	5.35	.365
CF5	A/A	.234	5.20	.355
	A/L	.127	6.55	.380
	L/A	.232	5.20	.360
	L/L	.125	6.60	.375
JR6	A/A	.431	3.95	.350
	A/L	.362	4.30	.350
	L/A	.423	4.00	.350
	L/L	.344	4.30	.350
TW8	A/A	.476	3.85	.350
	A/L	.370	4.25	.350
	L/A	.337	4.40	.350
	L/L	.260	4.95	.350

am Vg
25 April 91

FIGURE 1

Comparison of XKSAT vs PSIF from Table 4.2 and the relation by Van Mullem (1989)



Logarithmic 3 X 3 Cycles

APPENDIX 1

LOST DOG #4

AREA = 0.42 mi^2

MAP UNITS:				
	#10	13.3%	=	.056 mi^2
	#31	34.0%	=	.143 mi^2
	#44	9.6%	=	.040 mi^2
	#52	43.1%	=	.181 mi^2

SOIL DESCRIPTIONS:

#10 Brios - Carrizo Complex			XKSAT
40%	Brios Loamy Sand		1.20
40%	Carrizo Sand		1.20
20%	Antho (5%)	Benches	.40
	Gilman (5%)	Benches	.25
	Maripo (5%)	Benches	.40
	Vint (5%)	Benches	.40

XKSAT (ARITH) = .80(1.2) + .15(.40) + .05(.25) = 1.033 in/hr

XKSAT (Log) = [.8(log 1.2) + .15(log .40) + .05(log .25)] ALOG = 0.941 in/hr

#31 DIXALETA COMPLEX			XKSAT
84.6%	Dixaleta Extremely Channery Sandy Loam		.40
15.4%	Ohaco (2.567% ea.)	FAN Terraces	.06
	Nickel (2.567% ea.)	FAN Terraces	.40
	Cave (2.567% ea.)	FAN Terraces	.25
	Eba (2.567% ea.)	FAN Terraces	.40
	Gran (2.567% ea.)	Mtn. Slopes	.06
	Lehmans (2.567% ea.)	Mtn. Slopes	.06

XKSAT (ARITH) = .89734 (.40) + .02567 (.25) + .07701 (.06) = .370 in/hr

XKSAT (Log) = Alog [.89734 (log .40) + .02567 (log .25) + .07701 (log .06)] = .341 in/hr

#44 EBON VERY GRAVELLY LOAM			XKSAT
80%	Ebon Sandy Clay Loam		.06
20%	Cipriano	(2.857% ca.) FAN TERRACES	.06
	Contine		.04
	Beardsley		.25
	Luke		.06
	Gunsight		.40
	MOHALL		.25
	Pinamt		.06

XKSAT (ARITH) = .02857(.40) + .05714 (.25) + .88571 (.06) + .02857 (.04) = .080 in/hr

XKSAT (Log) = ALOG [.02857 (log .40) + .05714 (log .25) + .88571 (log .06) + .02857 (log .04)] = .068 in/hr

#52 Gachado - Lomitas Complex			XKSAT
56.3%	Gachado Very Gravelly Sandy Clay Loam		.06
25%	Lomitas Gravelly Sandy Loam		.40
18.7%	Carrizo	(2.671% ca.) Fan Terraces	1.20
	Cherioni		1.20
	Ebon		.06
	Gunsight		.40
	Pinamt		.06
	Shenco	Hillslopes	.06
	Vaiva		.40

XKSAT = .05343(1.20) + .30342(.40) + .64313 (.06) = .224 in/hr

XKSAT (Log) = ALOG[.05343(log 1.20) + .30342(log .40) + .64313(log .06)] = .125 in/hr

SUBBASIN RUNOFF FROM INDIVIDUAL SOIL TEXTURES

#10 → 13.3% OF Subbasin

Loamy Sand → 80% (13.3) = 10.64% OF Subbasin
Sandy Loam → 15% (13.3) = 1.995%
Loam → 5% (13.3) = 0.665%

#31 → 34.0% OF Subbasin

Sandy Loam → 89.734% (34) = 30.510% OF Subbasin
Loam → 2.567% (34) = 0.873%
Sandy Clay Loam → 7.701% (34) = 2.618%

#44 → 9.6% OF SUBBASIN

Sandy Loam → 2.857% (9.6) = .274% OF Subbasin
Loam → 5.714% (9.6) = .549%
Sandy Clay Loam → 88.571% (9.6) = 8.503%
Clay Loam → 2.857% (9.6) = .274%

#52 → 43.1% OF Subbasin

Loamy Sand → 5.343 (43.1) = 2.303% OF Subbasin
Sandy Loam → 30.342 (43.1) = 13.077%
Sandy Clay Loam → 64.313 (43.1) = 27.719%

TOTALS FOR THE SUBBASIN

Loamy Sand →	12.943%	=	.054 mi^2
Sandy Loam →	45.856%	=	.193 mi^2
Loam →	2.087%	=	.009 mi^2
Sandy Clay Loam →	38.840%	=	.163 mi^2
Clay Loam →	.274%	=	.001 mi^2
	100.000%		.420 mi^2

RUNOFF BY SOIL TEXTURE

LOAMY SAND (LD4LS.DAT)	P_e = .84 in	V = 2.419 ac-ft
Sandy Loam (LD4SL.DAT)	P_e = 1.21 in	V = 12.455 ac-ft
Loam (LD4L.DAT)	P_e = 1.53 in	V = .734 ac-ft
Sandy Clay Loam (LD4SCL.DAT)	P_e = 1.89 in	V = 16.430 ac-ft
Clay Loam (LD4CL.DAT)	P_e = 2.02 in	V = .108 ac-ft

TOTAL RUNOFF = 32.146 ac-ft

MODELED SUBBASIN RUNOFF

AVERAGED LOSSES: (XKSAT)

ARITH/ARITH : .133 (1.033) + .340(.370) + .096(.08) + .431 (.224) = .367 in/hr

ARITH/Log : .133 (.941) + .340 (.341) + .096 (.068) + .431 (.125) = .301 in/hr

Log/ARITH : [.133 (log 1.033) + .340 (log .370) + .096 (log .08) + .431 (log .224)] ALOG = .295 in/hr

Log/Log : [.133 (log .941) + .340 (log .341) + .096 (log .068) + .431 (log .125)] ALOG = .217 in/hr

RUNS (Subbasin, Map Unit)

1. LD4AA.DAT XKSAT = .367 in/hr, PSIF = 4.3 in, dθ = .35 in
2. LD4AL.DAT XKSAT = .301 in/hr, PSIF = 4.65 in, dθ = .35 in
3. LD4LA.DAT XKSAT = .295 in/hr, PSIF = 4.7 in, dθ = .35 in
4. LD4LL.DAT XKSAT = .217 in/hr, PSIF = 5.35 in dθ = .365 in

RUN RESULTS

1. LD4AA.DAT	P_e = 1.26 in	V = 28.224 ac-ft
2. LD4AL.DAT	P_e = 1.35 in	V = 30.240 ac-ft
3. LD4LA.DAT	P_e = 1.36 in	V = 30.464 ac-ft
4. LD4LL.DAT	P_e = 1.45 in	V = 32.480 ac-ft

JACKRABBIT WASH #6D

AREA = 6.74 mi^2

MAP UNIT	% AREA		mi^2
#3	0.742	4.896	.05
#4	4.154		.28
#30	62.315		4.20
#56	4.599		.31
#91	2.671		.18
#99	2.671		.18
#108	0.593		.04
#117	22.255		1.50

SOIL DESCRIPTIONS

#s 3 & 4:	ANTHO - Carrizo - Maripo Complex		XKSAT
35%	ANTHO Sandy Loam		.40
30%	Carrizo Very Gravelly Sand		1.20
20%	Maripo Sandy Loam		.40
15%	Brios	Drainageways	1.20
	Gilman	Floodplains	.25
	Vint	Floodplains	.40
	Denure (2.5% ea.)	Stream Terraces	.40
	Momoli (2.5% ea.)	Stream Terraces	.40
	Carrizo (2.5% ea.)	Stream Terraces	.40

XKSAT (ARITH) = .325(1.20) + .65(.40) + .025(.25) = 0.656 in/hr

XKSAT (Log) = ALOG[.325(log 1.20) + .65(log .40) + .025(log .25) = .565 in/hr

#30	DENURE - MOMOLI - Carrizo Complex			XKSAT
40%	DENURE Gravelly Sandy Loam			.40
30%	MOMOLI Gravelly Sandy Loam			.40
20%	Carrizo Gravelly Sandy Loam			.40
10%	GILMAN	(3.33% ea.)	FLOODPLAINS	.25
	Moripo			.40
	Carrizo			1.20

XKSAT (ARITH) = .9333 (.40) + .0333 (.25) + .0333 (1.20) = .422 in/hr

XKSAT (Log) = [.9333 (log .40) + .0333 (log .25) + .0333 (log 1.20)] ALog = .408 in/hr

#56	GILMAN LOAMS			XKSAT
80%	GILMAN Loam			.25
20%	ANTHO		Drainageways	.40
	Carrizo			1.20
	ESTRELLA		Throughout	.25
	Glenbar	(2.5% ea.)		.15
	Vint			.40
	Denure		Fan Terraces	.40
	Momoli			.40
	Carrizo			.40

XKSAT (ARITH) = .825(.25) + .125 (.40) + .025 (1.20) + .025 (.15) = .290 in/hr

XKSAT (Log) = Alog [.825 (log .25) + .125 (log .40) + .025 (log 1.20) + .025 (log .15)] = .272 in/hr

#91	Momoli - Carrizo Complex			XKSAT
45%	Momoli Very Gravelly Loam			.40
35%	Carrizo Very Gravelly Sandy Loam			1.20
20%	Mohall	(2.5% ea.)	High Terraces	.25
	Tremant			.40
	Gunsight			.06
	Chuckawalla			.06
	Denure		Throughout	.40
	GILMAN		Drainageways	.25
	Maripo			.40
	Carrizo			1.20

XKSAT (ARITH) = .375(1.20) + .525(.40) + .05(.25) + .05(.06) = .676 in/hr

XKSAT (Log) = ALOG[(.375(log 1.20) + .525(log .40) + .05(log .25) + .05(log .06)] = .537 in/hr

#99	Pinamt - Tremant Complex			XKSAT
45%	Pinamt Very Gravelly Sandy Clay Loam			.06
35%	Tremant Gravelly Loam			.40
20%	Carrizo		Drainageways	1.20
	Chuckawalla	(4% ea.)	FAN Terraces	.06
	Ebon			.06
	Gunsight			.40
	Rillito			.40

XKSAT (ARITH) = .04(1.2) + .43(.40) + .53(.06) = .252 in/hr

XKSAT (Log) = [.04 (log 1.2) + .43 (log .40) + .53 (log .06)] ALOG = .153 in/hr

#108	SHENCO COMPLEX			XKSAT
71.4 %	SHENCO			.06
28.6%	Antho		Drainageways	.40
	Beardsley	(2.86 % ea.)	Fan Terraces	.25
	Cherioni			.40
	Cipriano			.06
	Ebon			.06
	Gunsight			.40
	Sun City			.06
	Gachado		Hillslopes	.06
	Quilotosa		Throughout	1.20
	Vaiva			.40

XKSAT (ARITH) = .0286 (1.20) + .1144 (.40) + .0286 (.25) + .8284 (.06) = .137 in/hr

XKSAT (Log) = ALOG[.0286 (log 1.2) + .0858 (log .40) + .0286 (log .25) + .8284 (log .06)]
= .087 in/hr

# 117	TREMANT - GUNSIGHT - RILLITO COMPLEX			XKSAT
30%	Tremant			.06
20%	Gunsight			1.20
20%	RILLITO			.40
30%	Cipriano	(4.286 % ea.)	Terraces	.06
	Pinamt			.06
	Mohall			.25
	Contine			.04
	Antho		Alluvial Fans Drainageways	.40
	Carrizo			1.20
	GILMAN			.25

XKSAT (ARITH) = .24286 (1.2) + .24286 (.40) + .08572 (.25) + .38572 (.06) + .04286 (.04) = .435 in/hr

XKSAT (LOG) = ALOG[.24286 (log 1.2) + .24286 (log .40) + .08572 (log .25) + .38572 (log .06) + .04286 (log .04)] = .219 in/hr

SUBBASIN RUNOFF FROM INDIVIDUAL SOIL TEXTURES

JRGD

#3 & 4 → 4.9% of Subbasin

Loamy Sand → 32.5% (4.9) = 1.59% of Subbasin
Sandy Loam → 65% (4.9) = 3.19%
Loam → 2.5% (4.9) = 0.12%

#30 → 62.3% of SUBBASIN

Loamy Sand → 3.33% (62.3) = 2.07% of Subbasin
Sandy Loam → 93.33% (62.3) = 58.14%
Loam → 3.33% (62.3) = 2.07%

#56 4.6% of SUBBASIN

Loamy Sand → 2.5% (4.6) = 0.12% of Subbasin
Sandy Loam → 12.5% (4.6) = 0.58%
Loam → 82.5% (4.6) = 3.80%
SILTY Loam → 2.5% (4.6) = 0.12%

#91 2.7% of SUBBASIN

Loamy Sand → 37.5% (2.7) = 1.01% of Subbasin
Sandy Loam → 52.5% (2.7) = 1.42%
Loam → 5% (2.7) = .14%
Sandy Clay Loam → 5% (2.7) = .14%

#99 2.7% of SUBBASIN

Loamy Sand → 4% (2.7) = .11% of Subbasin
Sandy Loam → 43% (2.7) = 1.16%
Sandy Clay Loam → 53% (2.7) = 1.43%

#108 0.6 % of Subbasin

Loamy Sand → 2.86 % (.6) = .02 % of Subbasin
Sandy Loam → 11.44 % (.6) = .07 %
Loam → 2.86 % (.6) = .02 %
Sandy Clay Loam → 82.84% (.6) = .50 %

#117 22.3 % of Subbasin

Loamy Sand → 24.286%(22.3) = 5.42 % of Subbasin
Sandy Loam → 24.286%(22.3) = 5.42 %
Loam → 8.572%(22.3) = 1.91 %
Sandy Clay Loam → 38.572%(22.3) = 8.60 %
Clay Loam → 4.286% (22.3) = 0.96 %

TOTALS FOR THE SUBBASIN (A = 6.74 mi^2)

LOAMY SAND →	10.34 %	=	.697 mi^2
Sandy Loam →	69.98 %	=	4.717 mi^2
Loam →	8.06 %	=	.543 mi^2
SILTY Loam →	.12 %	=	.008 mi^2
Sandy Clay Loam →	10.67%	=	.719 mi^2
Clay Loam →	.96%	=	.065 mi^2
	100.13%		6.749 mi^2

RUNOFF BY SOIL TEXTURE

LOAMY SAND	(JRLS.DAT)	P_e = .14 in,	V = 5.20 ac-ft
SANDY LOAM	(JRSL.DAT)	P_e = .75	V = 188.68
LOAM	(JRL.DAT)	P_e = 1.12	V = 32.44
SILTY LOAM	(JRSLL.DAT)	P_e = 1.12	V = 0.48
SANDY Clay Loam	(JRSCL.DAT)	P_e = 1.64	V = 62.89
Clay Loams	(JRCL.DAT)	P_e = 1.81	V = 6.28

TOTAL RUNOFF = 295.97 ac-ft

MODELED SUBBASIN RUNOFF

AVERAGED LOSSES (XKSAT)

Subbasin Map Unit

ARITH / ARITH : .04896(.656) + .62315(.422) + .04599 (.290) + .02671 (.676) + .02671 (.252) + .00593(.137) + .22255 (.435) = .431 in/hr

PSIF = 3.95 in $d\theta$ = .35 in

ARITH / LOG : .04896 (.565) + .62315 (.408) + .04599(.272) + .02671 (.537) + .02671 (.153) + .00593 (.087) + .22255(.219) = .362 in/hr

PSIF = 4.3 in $d\theta$ = .35 in

LOG / ARITH = ALOG[.04896 (log .656) + .62315 (log .422) + .04599 (log .290) + .02671 (log .676) + .02671 (log .252) + .00593 (log .137) + .22255 (log .435)]

= .423 in/hr PSIF = 4.0 $d\theta$ = .35 in

LOG / LOG = ALOG[.04896 (log .565) + .62315 (log .408) + .04599 (log .272) + .02671 (log .537) + .02671 (log .153) + .00593 (log .087) + .22255 (log .219)]

= .344 in/hr PSIF = 4.3 in $d\theta$ = .35 in

RUN RESULTS

	Pe (in)	V (ac-ft)
1. JRAA. DAT	.73	262.4
2. JRAL. DAT	.81	291.2
3. JRLA. DAT	.74	266.0
4. JRLL. DAT	.85	305.5

Carefree Subbasin #5

DRAINAGE AREA: 1.122 mi^2

AGUILA - CAREFREE SOIL SURVEY

MAP UNITS:

#41	3%	=	.034 mi^2
#61	4%	=	.045 mi^2
#63	21%	=	.236 mi^2
#72	72%	=	.808 mi^2

SOIL DESCRIPTIONS (MAP UNIT LOSSES)

#41 Eba - Pinaleno Complex

			XKSAT
45%	Eba very gravelly loam		.40
35%	Pinaleno very gravelly clay loam		.06
20%	Ohaco (5%)	THROUGHOUT	.04
	Tres Hermanos (5%)		.06
	ANTHONY (5%)	DRAINAGEWAYS	1.20
	ARIZO (5%)		1.20

XKSAT (ARITH) = .45(.40) + .40(.06) + .05(.04) + .10(1.20) = .326 in/hr

XKSAT (Log) = [.45(log .40) + .40(log .06) + .05(log .04) + .10(log 1.20)] ALOG

= .186 in/hr

#61

Gran - Wickenburg Complex, 1 - 10% SLOPES

40%	Gran very gravelly sandy clay loam		(.06)
35%	Wickenburg gravelly sandy loam		(.40)
25%	Eba (8⅓%)	Toe Slopes	(.40)
	Pinaleno (8⅓%)		(.06)
	Arizo (8⅓%)	Drainageways	(1.20)

XKSAT (Arith) = .483(.06) + .433(.40) + .083(1.20) = .302 in/hr

XKSAT (Log) = ALOG [.483(log .06) + .433(log .40) + .083(log 1.20)] = .175 in/hr

#63

Gron - Wickenburg Complex, 10-65% Slopes

40%	Gran very gravelly sandy clay loam			(.06)
33%	Wickenburg gravelly sandy loam			(.40)
27%	Dixaleta		Mtn Slopes	(.40)
	Lehmans			(.06)
	Eba	5.4% ea	Toe Slopes	(.40)
	Pinaleno			(.06)
	Arizo		Drainageways	(1.20)

XKSAT (ARITH) .438(.40) + .508 (.06) + .054 (1.20) = .270 in/hr

XKSAT (Log) ALOG [.438(log .40) + .508(log .06) + .054(log 1.20)] = .162 in/hr

#72 LEHMANS Complex

64%	Lehmans very gravelly clay loam			(.06)
36%	ARIZO		Drainageways	(1.20)
	Eba		foot slopes	(.40)
	Pinaleno	7.2% ea.		(.06)
	Greycagle		Gentle Slopes	(.40)
	Nickel			(.40)

XKSAT (ARITH) = .712(.06) + .072(1.20) + .216(.40) = .216 in/hr

XKSAT (Log) = ALOG [.712(log .06) + .072(log 1.2) + .216(log .40)] = .112 in/hr

CAREFREE #5 SUBBASIN LOSSES

1. ARITH / ARITH

XKSAT = .03 (.326) + .04(.302) + .21(.270) + .72(.216) = .234 in/hr

2. ARITH / Log

XKSAT = .03 (.186) + .04 (.175) + .21 (.162) + .72 (.112) = .127 in/hr

3. Log / ARITH

XKSAT = ALOG [.03 (log .326) + .04 (log .302) + .21 (log .270) + .72 (log .216)]
= .232 in/hr

4. Log / Log

XKSAT = ALOG [.03 (log .186) + .04 (log .175) + .21 (log .162) + .72 (log .112)]
= .125 in/hr

1. CF5AA.DAT → XKSAT = .234 in/hr PSIF = 5.2 in dθ = .355 in
2. CF5AL.DAT → XKSAT = .127 in/hr PSIF = 6.55 in dθ = .38 in
3. CF5LA.DAT → XKSAT = .232 in/hr PSIF = 5.2 in dθ = .36 in
4. CF5LL.DAT → XKSAT = .125 in/hr PSIF = 6.6 in dθ = .375 in

TIGER WASH SUB 8

DRAINAGE AREA : 9.78 mi^2

SOIL SURVEY : Aguila - Carefree

MAP UNITS :	#19, 20	38.6 %	=	3.775 mi^2
	# 92	50.1 %	=	4.900 mi^2
	# 100	11.3 %	=	1.105 mi^2

SOIL DESCRIPTIONS (MAP UNIT LOSSES)

#19,20

CHUCKAWALLA - GUNSIGHT COMPLEX

				XKSAT
45%	CHUCKAWALLA Very Gravelly Sandy Clay Loam			.06
35%	GUNSIGHT Very Gravelly Loam			.06
20%	Sal	(2.857 % ea.)	FAN TERRACES	.06
	Pinamt			.06
	Tremant			.40
	RILLITO		side Slopes	.40
	ANTHO		FLOODPLAINS	.40
	Gilman			.25
	Maripo			.40

XKSAT (ARITH) = .85714 (.06) + .114 (.40) + .02857 (.25) = .104 in/hr

XKSAT (Log) = ALOG[.85714 (log .06) + .114 (log .40) + .02857 (log .25)] = .078 in/hr

92

MOMOLI - CARRIZO COMPLEX			XKSAT
45%	MOMOLI Very Gravelly Loam		.40
35%	CARRIZO Very Gravelly Sandy Loam		1.20
20%	MOHALL	High Terraces	.25
	Tremant	High Terraces	.40
	Gunsight	High Terraces	.06
	Chuckawalla	High Terraces	.06
	DENURE (2.5% each)	Throughout	.40
	GILMAN (2.5% each)	Drainageways	.25
	Maripo (2.5% each)	Drainageways	.40
	Carrizo (2.5% each)	Drainageways	1.20

XKSAT (ARITH) = .375 (1.20) + .525 (.40) + .05 (.25) + .05 (.06) = .676 in/hr

XKSAT (Log) = ALOG[.375 (log 1.2) + .525 (log .40) + .05 (log .25) + .05 (log .06)] = .537 in/hr

# 100	QUILOTOSA - VAIVA COMPLEX		XKSAT
62.5%	Quilotosa Extremely Gravelly Loam		1.20
25%	VAIVA Very gravelly Loam		.40
12.5%	Schenco	Mtn. Slopes	.06

XKSAT (ARITH) = .625 (1.20) + .25 (.40) + .125 (.06) = .858 in/hr

XKSAT (Log) = ALOG[.625 (log 1.20) + .25 (log .40) + .125 (log .06)] = .627 in/hr

TIGER WASH #8

SUBBASIN LOSSES

Subbasin / MAP UNIT

ARITH / ARITH

XKSAT = .386(.104) + .501(.676) + .113(.858) = .476 in/hr

ARITH / LOG

XKSAT = .386(.078) + .501(.537) + .113(.627) = .370 in/hr

LOG / ARITH

XKSAT = ALOG[.386(log .104) + .501(log .676) + .113(log .858)] = .337 in/hr

LOG / LOG

XKSAT = ALOG[.386(log .078) + .501(log .537) + .113(log .627)] = .260 in/hr

1. TWAA.DAT → XKSAT = .476 in/hr PSIF = 3.85 in dθ = .35 in
2. TWAL.DAT → XKSAT = .370 in/hr PSIF = 4.25 in dθ = .35 in
3. TWLA.DAT → XKSAT = .337 in/hr PSIF = 4.4 in dθ = .35 in
4. TWLL.DAT → XKSAT = .260 in/hr PSIF = 4.95 in dθ = .35 in

VOLUME RUNS

CAREFREE #5

HEC-1 MODEL :

RAINFALL → DEPTH = 3.0 in , IA = .25 in

DISTR. → 6-hour, Pattern based on 1.122 mi^2

RUNOFF FROM MAP UNITS

ARITH LOSSES

#41 →	(CF541A.DAT)	P_e = 1.17 in ,	V = 2.122 ac-ft
#61 →	(CF561A.DAT)	P_e = 1.20 in ,	V = 2.880 ac-ft
#63 →	(CF563A.DAT)	P_e = 1.24 in ,	V = 15.607 ac-ft
#72 →	(CF572A.DAT)	P_e = 1.30 in ,	V = 56.021 ac-ft

TOTAL RUNOFF = 76.630 ac-ft

LOG LOSSES

#41 →	(CF541L.DAT)	P_e = 1.34 in,	V = 2.430 ac-ft
#61 →	(CF561L.DAT)	P_e = 1.35 in,	V = 3.240 ac-ft
#63 →	(CF563L.DAT)	P_e = 1.37 in,	V = 17.240 ac-ft
#72 →	(CF572L.DAT)	P_e = 1.52 in,	V = 65.502 ac-ft

TOTAL RUNOFF = 88.412 ac-ft

SUBBASIN RUNOFF

(CF5AA.DAT)	P_e = 1.29 in ,	V = 77.194 ac-ft
(CF5AL.DAT)	P_e = 1.45 in ,	V = 86.768 ac-ft
(CF5LA.DAT)	P_e = 1.29 in ,	V = 77.194 ac-ft
(CF5LL.DAT)	P_e = 1.46 in ,	V = 87.366 ac-ft

MAP UNIT AVE.

Subbasin AVE.

SUBBASIN RUNOFF FROM INDIVIDUAL SOIL TEXTURES

#41 → 3% OF SUBBASIN

45%	Sandy Loam
40%	Sandy Clay Loam
10%	Loamy Sand
5%	Sandy Clay

% of Subbasin:

Loamy Sand → .10(3) = .3%

Sandy Loam → .45(3) = 1.35%

Sandy Clay Loam → .40(3) = 1.2%

Clay Loam → .05(3) = .15%

#61 → 4% OF SUBBASIN

8.33%	Loamy Sand
43.33%	Sandy Loam
48.33%	Sandy Clay Loam

% OF Subbasin:

Loamy Sand → .0833(4) = .333%

Sandy Loam → .4333(4) = 1.733%

Sandy Clay Loam → .4833(4) = 1.933%

#63 → 21% OF Subbasin

5.4%	Loamy Sand
43.8%	Sandy Loam
50.8%	Sandy Clay Loam

% OF SUBBASIN:

Loamy Sand → .054(21) = 1.134%

Sandy Loam → .438(21) = 9.198%

Sandy Clay Loam → .508(21) = 10.668%

#72 → 72% OF SUBBASIN

7.2%	Loamy Sand
21.6%	Sandy Loam
71.2%	Sandy Clay Loam

% OF SUBBASIN:

Loamy Sand → .072 (72) = 5.184%

Sandy Loam → .216 (72) = 15.552%

Sandy Clay Loam → .712 (72) = 51.264%

TOTALS FOR THE SUBBASIN

Loamy Sand →	6.951%	=	.078 mi^2
Sandy Loam →	27.833%	=	.312 mi^2
Sandy Clay Loam →	65.065%	=	.730 mi^2
Sandy Clay →	.150%	=	.002 mi^2
	99.999%		1.122 mi^2

RUNOFF BY SOIL TEXTURE:

Loamy Sand →	(CF5LS.DAT)	P_e = .55 in	V = 2.288 ac-ft
Sandy Loam →	(CF5SL.DAT)	P_e = 1.06 in	V = 17.638 ac-ft
Sandy Clay Loam →	(CF5SCL.DAT)	P_e = 1.83 in	V = 71.248 ac-ft
Clay Loam →	(CF5CL.DAT)	P_e = 1.97 in	V = 0.210 ac-ft

TOTAL RUNOFF = 91.384 ac-ft

TIGER WASH SUB 8

SUBBASIN RUNOFF FROM INDIVIDUAL SOIL TEXTURES

#19,20 → 38.6 % OF Subbasin

11.43 % Sandy Loam
2.86 % Loam
85.71 % Sandy Clay Loam

% OF Subbasin

SANDY Loam → .1143 (38.6) = 4.412 %
Loam → .0286 (38.6) = 1.104 %
Sandy Clay Loam → .8571 (38.6) = 33.084 %

#92 → 50.1 % OF SUBBASIN

Loamy Sand → 37.5 % (50.1) = 18.788 % of Subbasin
Sandy Loam → 52.5 % (50.1) = 26.303 %
Loam → 5 % (50.1) = 2.505 %
Sandy Clay Loam → 5 % (50.1) = 2.505 %

#100 → 11.3 % OF Subbasin

Loamy Sand → 62.5 % (11.3) = 7.063 % OF Subbasin
Sandy Loam → 25 % (11.3) = 2.825 %
Sandy Clay Loam → 12.5 % (11.3) = 1.413 %

TOTALS FOR THE SUBBASIN

Loamy Sand	→	25.851 %	=	2.528 mi^2
Sandy Loam	→	33.540 %	=	3.280 mi^2
Loam	→	3.609 %	=	.353 mi^2
Sandy Clay Loam	→	37.002 %	=	3.619 mi^2
		100.002 %		9.780 mi^2

RUNOFF BY SOIL TEXTURE

Loamy Sand →	(TW8LS.DAT)	P_e = .10 in	V = 13.483 ac-ft
Sandy Loam →	(TW8SL.DAT)	P_e = .68 in	V = 118.955 ac-ft
Loam →	(TW8L.DAT)	P_e = 1.06 in	V = 19.956 ac-ft
Sandy Clay Loam →	(TW8SCL.DAT)	P_e = 1.60 in	V = 308.821 ac-ft

TOTAL RUNOFF = 461.215 ac-ft

MODELED SUBBASIN RUNOFF

(TW8AA.DAT)	P_e = .61 in	V = 318.2 ac-ft
(TW8AL.DAT)	P_e = .74 in	V = 386.0 ac-ft
(TW8LA.DAT)	P_e = .79 in	V = 412.1 ac-ft
(TW8LL.DAT)	P_e = .91 in	V = 474.7 ac-ft

Subbasin MAP UNIT