Variation within Texture Classes of Soil Water Parameters

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ABSTRACT

THE Brooks and Corey effective saturation-capillary pressure equation was fitted to 1,085 soil moisture characteristics for 10 soil texture classes ranging from sand to clay. The fitted parameters, λ-pore size index, ψ_b-bubbling pressure, and ϕ-total porosity, within each texture class were transformed to a normal distribution. The distribution statistics are presented.

Green and Ampt infiltration equation parameters, ψ_f-wetting front capillary head and K-conductivity, were estimated from the Brooks and Corey equation parameters and a transformation to a normal distribution was made. Statistics are presented for each soil texture.

INTRODUCTION

The Green and Ampt infiltration equation has been discussed by many investigators; for example, Mein and Larson (1973), and Smith and Parlange (1978). It appears to be a useful infiltration model. The Green and Ampt rate equation is written

$$f = K\left(1 + \frac{n\psi f}{F}\right) \quad \text{[1]}$$

and its integrated form is written

$$F - n\psi_f \ln\left(1 + \frac{F}{n\psi_f}\right) = Kt \quad \text{[2]}$$

The three parameters represent

K = Hydraulic conductivity, cm/h

ψ_f = Wetting front capillary pressure head, cm

and

n = Available porosity

Available porosity is calculated as total porosity, ϕ, minus antecedent soil moisture (ASM). Equation variables are f = infiltration rate, cm/h, F = infiltration amount, cm, and t = time, h.

Application of the equation first requires estimates of the parameters. Pioneering work on evaluating the parameters was first reported by Bouwer (1966). Additional work has been reported by Clapp and Hornberger (1978), Aggelides and Youngs (1978), and by Brakensiek (1977). As is well known, soil-water parameters exhibit extreme variability due to the inherent properties of soils and field and laboratory methodologies. Work on scaling the soil-water parameter varaibility has been published by Nielsen et al. (1973), and Warrick et al. (1977).

In this study, the Brooks and Corey equation was first fitted to available soil-water retention data from a number of soil textures. The Brooks and Corey equation (1964) is written as

$$S_e = (\psi_b/\psi)^\lambda \quad \text{[3]}$$

where

$$S_e \text{ (effective saturation)} = \frac{\Theta - \Theta_r}{\phi - \Theta_r}$$

and θ is soil water content, cm³/cm³; θ_r is residual soil water content, cm³/cm³; ϕ is total porosity, cm³/cm³; ψ_b is bubbling pressure, cm; ψ is capillary pressure, cm; and λ is the pore-size distribution index.

The Green and Ampt parameters were then estimated from the soil-water data and from the Brooks and Corey parameters. A discussion of equation [3] and its parameters can be found in Corey (1977).

PARAMETER ESTIMATION

Soil-water retention data for this study were taken from reports by Rawls et al. (1976), and Holton et al. (1968). Soil-water retentions (volume basis) were determined at five capillary pressures, i.e., 0.1, 0.3, 0.6, 3.0, and 15 bars. It was found from plotting the Holton data, that many of the determinations at 15 bars were not consistent with the other four values. However, this was not unexpected, as the introduction of the publication (ibid.) referred to problems at the 15-bar determination and stated that approximately 1000 samples were re-run. After deleting the inconsistent data sets and combining the remaining ones with the Rawls data, 1085 sets of data were analyzed. Ten soil textures were represented with this data.

Equation [3] was linearized by taking the logarithm of both sides. This gives an expression from which λ and ψ_b can be estimated by least squares if θ_r is known. First, the value of θ_r was varied until the "highest" correlation between in S_e and 1n ψ was obtained. Then the least squares estimate of λ and ψ_b was calculated for that value of θ_r. The method of determination for θ_r is similar in principle to that used by Mualem (1976).

Green and Ampt parameters were calculated from the estimated Brooks and Corey constants as follows:

The wetting front capillary pressure term, ψ_f, is calculated by equation [4] (Brakensiek, 1977).

$$\psi_f = \frac{\eta}{\eta - 1}\left(\frac{\psi_b}{2}\right) \quad \text{[4]}$$

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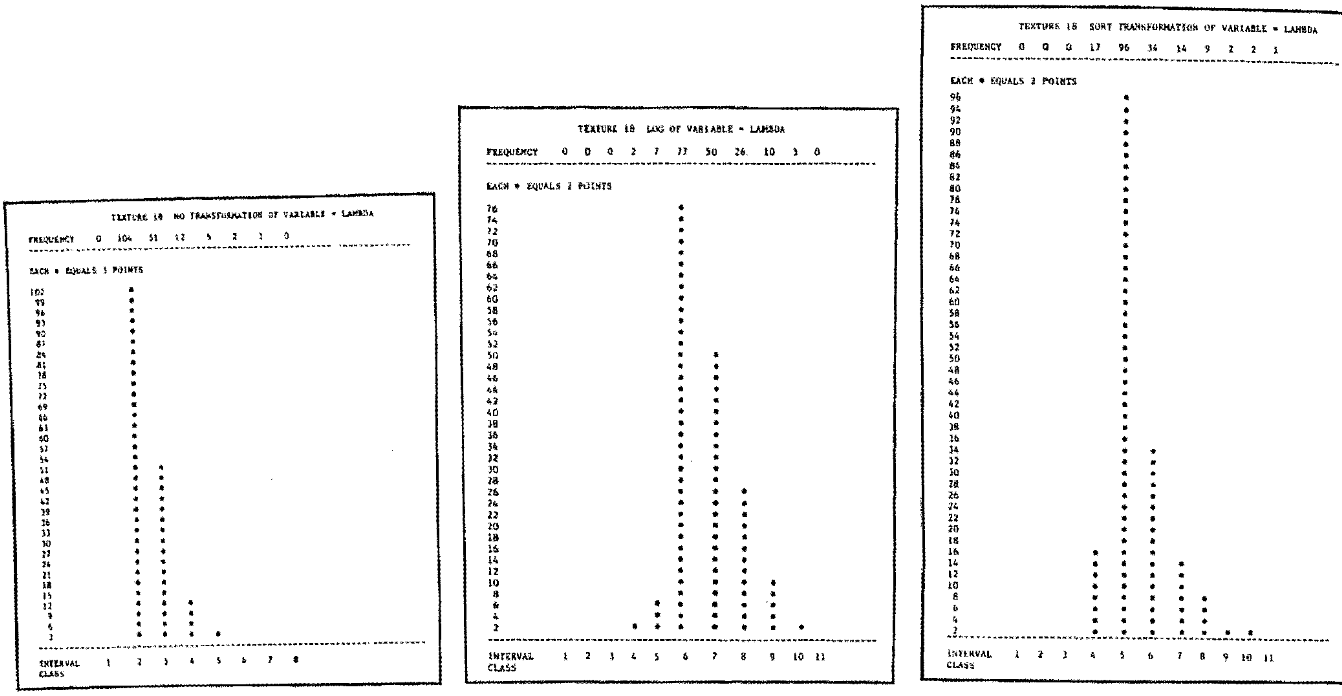


FIG. 1 Histograms for λ, Silty Clay Loam.

where $\eta = 2 + 3\lambda$
and ψ_b is the bubbling pressure. Following the suggestion of Bouwer (1966), ψ_b is divided by 2, since it is determined from desorption data. The work by Aggelides and Youngs (1979) indicates that a constant value for ψ_f for both drainage and wetting is quite accurate. Also, they showed that $\psi_b/2$ may be a good estimate of ψ_f. In Brakensiek (ibid.), a regression analysis of 5 texture classes ranging from sand to clay gave the relationship $\psi_f = 0.76\ \psi_b$. The results of this study gave an average λ over all textures of $\lambda = 1/3$. This results in an $\eta = 3$ and $\psi_f = 0.75\ \psi_b$.

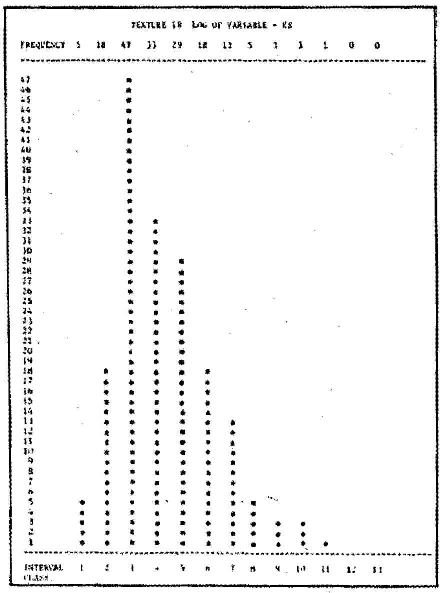
Calculation of the Green and Ampt hydraulic conductivity parameter, K, is based on Bouwer's (1966) suggestion that it is the re-wet conducticity or one-half of the saturated conductivity. The saturated conductivity was calculated by an equation (Brutsaert, 1967) derived by substituting the Brooks and Corey equation into the Childs, Collis-George permeability integral,

$$K_s = 270 \frac{\phi^2_e}{\psi_b^2} \frac{\lambda^2}{(\lambda+1)(\lambda+2)} \qquad [5]$$

where K_s is saturated hydraulic conductivity, cm/s; ϕ_e is effective porosity, cm³/cm³; ψ_b is bubbling pressure, cm; λ is the pore-size distribution index; and the factor 270 contains various fluid and gravity constants.
The effective porosity is calculated as $\phi_e = \phi - \theta_r$.

RESULTS

The Brooks and Corey and the Green and Ampt parameters for each soil texture were examined on an arithmetic, square root, and a logarithmic scale for normality. This would allow each parameter to be specified statistically by the mean and variance. In Figs. 1 and 2, the histograms for λ and K_s are respectively shown for a silty clay loam texture. In Table 1, the Kalmogorov-Smirnov statistics are shown for testing the goodness of fit to a normal distribution. A lack of fit is indicated by



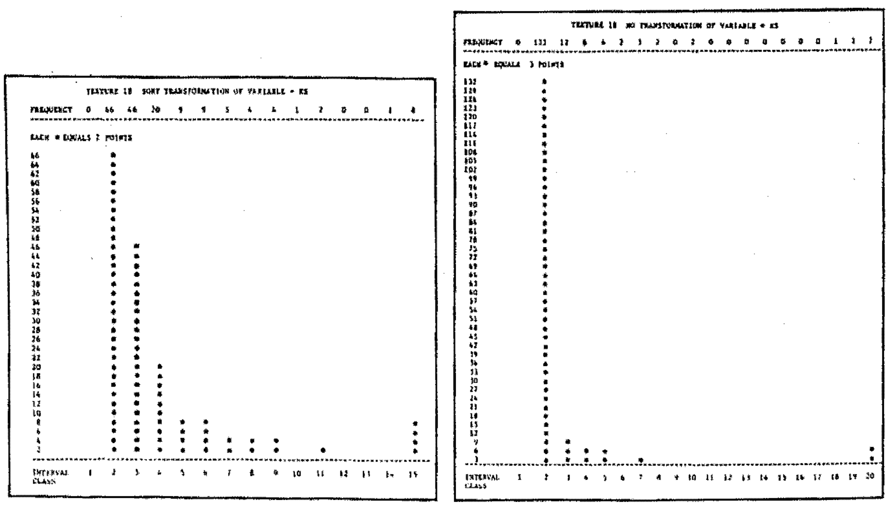


FIG. 2 Histograms for KS, Silty Clay Loam.

TABLE 1. D-VALUES IN THE KOLMOGOROV-SMIRNOV TEST FOR GOODNESS OF FIT TO A NORMAL DISTRIBUTION

Parameter and scale		Texture							
		Loamy sand	Sandy loam	Loam	Silt loam	Sandy clay loam	Clay loam	Silty clay loam	Clay
	D(1%):	0.198	0.159	0.179	0.116	0.140	0.154	0.123	0.156
λ		0.106	0.108	0.159	0.133	0.115	0.112	0.210	0.170
$\ln\lambda$		0.088	0.081	0.105	0.068	0.060	0.102	0.119	0.101
$\sqrt{\lambda}$		0.081	0.099	0.129	0.094	0.063	0.104	0.169	0.130
ψ_b		0.193	0.212	0.161	0.101	0.133	0.081	0.100	0.084
$\ln\psi_b$		0.086	0.065	0.090	0.160	0.141	0.171	0.110	0.138
$\sqrt{\psi_b}$		0.157	0.118	0.088	0.089	0.067	0.084	0.053	0.065
ϕ		0.092	0.071	0.066	0.093	0.081	0.045	0.112	0.086
$\ln\phi$		0.117	0.054	0.048	0.080	0.059	0.053	0.134	0.075
$\sqrt{\phi}$		0.101	0.063	0.051	0.086	0.069	0.045	0.123	0.080
θ_r		0.215	0.186	0.341	0.451	0.165	0.239	0.374	0.278
$\ln\theta_r$		0.892	0.153	0.879	0.898	0.142	0.121	0.154	0.226
$\sqrt{\theta_r}$		0.262	0.239	0.369	0.475	0.209	0.265	0.401	0.296
K_s		0.293	0.328	0.380	0.432	0.375	0.422	0.428	0.419
$\ln K_s$		0.114	0.049	0.068	0.114	0.129	0.142	0.094	0.140
$\sqrt{K_s}$		0.147	0.197	0.254	0.323	0.265	0.282	0.312	0.353
ψ_f		0.193	0.529	0.169	0.107	0.130	0.076	0.090	0.092
$\ln\psi_f$		0.102	0.177	0.092	0.156	0.138	0.142	0.099	0.151
$\sqrt{\psi_f}$		0.169	0.528	0.102	0.085	0.054	0.078	0.061	0.045
ϕ_e		0.123	0.120	0.066	0.076	0.083	0.084	0.152	0.141
$\ln\phi_e$		0.158	0.077	0.066	0.106	0.110	0.117	0.197	0.160
$\sqrt{\phi_e}$		0.141	0.098	0.065	0.087	0.097	0.101	0.175	0.153

the table value exceeding the D-value. It appears that a single transform can be selected for each parameter that gives normality. In Table 2 are shown correlations between the mean parameter value and its variance across all texture classes; in most cases, except ϕ, the variance is stabilized by the same transformation which achieves normality. Thus, a pooled value of variance can be estimated across the texture classes.

Mean values of each parameter for its particular transform scale, for each soil texture, are given in Tables 3 and 4. The estimated population standard deviation is given in parentheses. Note that mean values can be transformed to the arithmetic scale; however, the standard deviations cannot be transformed back. The value would be combined with the mean before the back transformation.

Tables 5 and 6 show the simple correlations calculated between the parameters within each texture class. In general, the Brooks and Corey parameters are weakly correlated with each other, except for θ_r and λ. The Green and Ampt parameters ln ψ_f and ln K_s are highly correlated. Except for these cases, the parameters are considered as independent.

TABLE 2. CORRELATION COEFFICIENT BETWEEN MEANS AND VARIANCES FOR ALL TEXTURES

Scale parameter	Arithmetic	Square root	Logarithm
λ	0.781	0.195	−0.591
ψ_b	0.880	0.704	−0.179
ϕ	−0.743	−0.836	−0.891
K_s	0.983	0.962	−0.232
ψ_f	0.894	0.721	−0.131
ϕ_e	−0.325	−0.481	−0.503

5%, 8d. f., r = 0.632
1%, 8d. f., r = 0.765

TABLE 3. BROOKS AND COREY PARAMETERS ESTIMATED FROM SOIL MOISTURE-CAPILLARY PRESSURE DATA (STANDARD DEVIATION IN PARENTHESIS)*

Texture	N sample size	$\sqrt{\lambda}$ (−)	ln ψ_b, cm	ϕ (−)	θ_r (−)
Sand	19	0.739 (0.170)	2.853 (1.174)	0.349 (0.107)	0.017
Loamy sand	69	0.670 (0.110)	2.273 (0.981)	0.410 (0.065)	0.024
Sandy loam	166	0.615 (0.143)	2.820 (1.042)	0.423 (0.076)	0.048
Loam	83	0.496 (0.109)	3.144 (1.233)	0.452 (0.069)	0.034
Silt loam	199	0.455 (0.094)	3.769 (0.966)	0.484 (0.057)	0.018
Sand clay loam	129	0.587 (0.155)	3.253 (1.064)	0.406 (0.049)	0.075
Clay loam	112	0.509 (0.164)	3.305 (0.924)	0.476 (0.054)	0.087
Silty clay loam	175	0.405 (0.118)	3.607 (0.939)	0.473 (0.046)	0.054
Silty loam	26	0.431 (0.162)	3.302 (0.919)	0.476 (0.064)	0.085
Clay	108	0.432 (0.166)	3.494 (1.136)	0.475 (0.048)	0.106

*Scale of variate selected to approximate normality and constancy of variance.

TABLE 4. GREEN AND AMPT PARAMETERS ESTIMATED FROM BROOKS AND COREY CONSTANTS (STANDARD DEVIATION IN PARENTHESES)*

Texture	N sample size	ln ψ_f, cm	ln K_s†, cm/s	ϕ_e (−)
Sand	19	2.307 (1.225)	−4.780 (2.458)	0.314 (0.132)
Loamy sand	68	1.939 (0.950)	−3.818 (1.793)	0.380 (0.086)
Sandy loam	166	2.493 (1.028)	−5.248 (2.025)	0.373 (0.089)
Loam	83	2.867 (1.270)	−6.314 (2.661)	0.412 (0.089)
Silt loam	199	3.551 (0.970)	−7.693 (1.993)	0.462 (0.075)
Sandy clay loam	129	2.949 (1.065)	−6.592 (2.151)	0.328 (0.093)
Clay loam	112	3.041 (0.950)	−6.844 (2.060)	0.384 (0.088)
Silty clay loam	175	3.406 (0.970)	−8.067 (2.069)	0.418 (0.096)
Silty clay	26	2.986 (1.100)	−7.331 (2.501)	0.381 (0.142)
Clay	108	3.259 (1.156)	−8.018 (2.474)	0.365 (0.132)

*Scale of variate selected to approximate normality and constancy of variance.
†Green-Ampt K = ½[EXP (ln K_s)], cm/s.

TABLE 5. SIGNIFICANT (5%) SIMPLE CORRELATIONS
Brooks and Corey Parameters
Correlation between:*

Texture	X_1, X_2	X_1, X_3	X_1, X_4	X_2, X_3	X_2, X_4	X_3, X_4
Sand	0.771	—	—	—	—	—
Loamy sand	0.594	0.545	—	—	—	—
Sandy loam	0.379	—	0.611	—	—	—
Loam	—	—	0.748	-0.220	—	—
Silt loam	0.276	—	0.622	-0.537	—	—
Sandy clay loam	0.391	—	0.668	-0.193	0.203	—
Clay loam	0.241	0.247	0.686	—	0.250	0.307
Silty clay loam	—	0.184	0.761	-0.394	—	0.268
Silty clay	—	—	0.891	—	—	—
Clay	0.240	—	0.843	-0.300	0.213	—

$^*X_1 = \sqrt{\lambda}$
$X_2 = \ln \psi_b$
$X_3 = \phi$
$X_4 = \theta_r$

TABLE 6. SIGNIFICANT (5%) SIMPLE CORRELATIONS
Green and Ampt Parameters
Correlation between:*

Texture	X_1, X_2	X_1, X_3	X_2, X_3
Sand	-0.939	—	—
Loamy sand	-0.966	0.299	—
Sandy loam	-0.958	0.227	—
Loam	-0.977	—	—
Silt loam	-0.950	0.331	-0.224
Clay loam	-0.931	0.253	-0.302
Silty clay loam	-0.953	—	—
Sandy clay loam	-0.950	0.331	-0.224
Silty clay	-0.943		
Clay	-0.961	—	-0.234

$^*X_1 = \ln K_s$
$X_2 = \ln \psi_f$
$X_3 = \phi_e$

APPLICATIONS

The Brooks and Corey parameters can be used for calculating water-holding capacities for particular soil textures. Rewriting equation [3] in terms of the volumetric water content gives

$$\Theta = \Theta_r + \frac{(\phi - \Theta_r)\psi_b^{\lambda}}{\psi^{\lambda}} \quad [6]$$

Thus, for a given value of capillary pressure, $\psi > \psi_b$, the corresponding volumetric water content can be calculated. For example, for a silt loam referring to Table 3, the so called "field capacity", i.e., θ at 1/3 bar (approximated 340 cm), is calculated as

$$FC = 0.018 + \frac{(0.484 - 0.018\ (43.32)^{0.21}}{(340)^{0.21}}$$

$$FC = 0.32\ \text{cm/cm}$$

Since a soil profile generally represents several textures, the volumetric water storage can be calculated by horizons and summed to represent any sequence of textures. Corey (1977) has a discussion of using equation [3] in evaluating specific yield. Considerable work has also been reported by Corey (ibid.) on using equation [3] or its parameters for the estimation of permeability.

Use of the Green and Ampt infiltration equation for computing surface runoff for a constant rainfall rate is fairly simple, once the parameters are known. First, the time of surface ponding, t_p, is computed as

$$t_p = F_p/I \quad [7]$$

where f = I (rainfall rate) and F_p is total infiltration at ponding and is calculated as

$$F_p = \frac{n\psi_f}{(I/K - 1)} \quad [8]$$

Equation [2] is a "ponded" equation, in that it assumes that the soil surface was ponded or saturated at time zero. Thus, to be applicable to the constant rainfall case, an "equivalent ponded" time scale must be used. As explained by Mein and Larson (1973), this is accomplished by applying a time correction to actual time. The time correction is

$$t_c = (t_p' - t_p) \quad [9]$$

where t_p' is the equivalent time calculated by equation [2] to infiltrate F_p. The corrected time, t^*, is then

$$t^* = t - t_c \quad [10]$$

where t is clock time. At any time during rainfall, the actual amount of infiltration can be computed from equation [2] by substituting t^* in place of t. Since equation [2] is implicit, its solution requires an iterative procedure. An approximation developed by Li et al. (1976) does, however, allow an explicit solution. The same basic procedures apply for the unsteady rainfall case; however, the application is more complex as computations consider each increment of the rainfall histogram.

The parameters of this study can also be used in an application of the Green and Ampt equation to nonuniform soils. For each soil texture change in the soil profile, a new set of parameters are specified. Utilizing procedures described by Bouwer (1969), an infiltration amount-time relationship can be developed for a profile with decreasing conductivities. The case for a profile with increasing conductivities has also been treated by Bouwer (1976).

The statistics in Tables 3 and 4, and the normality transformations, can be utilized as inputs to an analysis of the hydrologic effects of the spatial variability of infiltration and soil-water storage parameters. Following the approach taken by Smith and Hebbert (1979), the sensitivity of hydrologic processes such as infiltration, soil-water storage, and runoff to soil water properties can be determined.

CONCLUSIONS

If the Green and Ampt infiltration equation is to be useful in hydrologic computations, the equation parameters must be known. The results of this study provide values for these parameters. Increased attention is being given to the spatial variabilities of soil properties and their influence on watershed hydrologic outputs and/or inputs. The results of this study can provide inputs to such studies.

The Brooks and Corey equation fits the soil characteristics data very well for capillary pressure less than the bubbling pressure. For 10 soil texture classes, means and standard deviations were estimated for the equation parameters. A transformation for each parameter, which achieved normality and stabilized the variance, was determined. It would be assumed in field applications of these results, that within a field soil texture class, the parameter values are spatially independent, except for those parameters noted in Tables 5 and 6.

The Green and Ampt parameters were calculated from the Brooks and Corey equation parameters. Mean values and standard deviations were calculated for each soil texture class. A transformation for normality and variance stability was determined.

The parameter values developed in this study can be utilized for applying the Brooks and Corey equation and the Green and Ampt equation to sensitivity studies in testing soil-water process and runoff models.

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Drip Irrigation Network Design

(Continued from page 334)

system but is acceptable in a double-inlet or inflow-outflow system under even a very steep slope of ± 10 percent.

CONCLUSIONS AND DISCUSSION

1 The ideal pressure profile of a drip irrigation lateral is a curve showing equal pressures at both the upstream and downstream ends and a maximum pressure difference near the middle of the lateral.

2 The ideal pressure profile can be achieved by the double-inlet and inflow-outflow systems. Pressure profiles and the inlet discharges for both cases can be determined using the Poly-plot technique.

3 The maximum pressure difference for the double-inlet and inflow-outflow drip irrigation systems are usually smaller than for single inlet system.

4 The double-inlet and inflow-outflow systems can be used for both uniform and nonuniform slope situations, provided that each section length can be considered as being on a uniform slope between two inlets.

5 The concept of double-inlet and inflow-outflow systems can be expanded and applied to drip irrigation network design. A network of lateral lines can be designed for a wide range of uniform and nonuniform slope situations in the field. Further studies will be made to develöp design charts and computer programs to assist in network design.

6 The conventional single inlet drip irrigation systems limit length and location of laterals based upon topography and the hydraulics of laterals. The multiple inlet (outlet) systems permit design of laterals of any length in any terrain or location while maintaining any efficiency desired. This latter freature, desired efficiency, is particularly important for fertilizer and other chemical applications through the drip system.

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