DOCUMENTATION MANUAL

VOLUME 6

RAINFALL LOSSES

INTRODUCTION

Rainfall losses are, in the aggregate, the sum of all losses to applied rainfall that occur at or near the point of raindrop impact with the surface of the watershed. The difference between applied rainfall depth and runoff depth (rainfall excess) is rainfall loss. Other losses do occur in the rainfall-runoff process, specifically transmission losses during overland flow and in the conveyance channels, but these losses are not generally classified as rainfall losses, and these other losses are not included in the treatment of this section. For flood hydrology, it is not adequate to simply estimate the magnitude of rainfall losses; the time distribution of the losses must be estimated also.

Rainfall losses are generally composed of evaporation, interception, depression storage, and infiltration into the land surface. Factors that affect the magnitude (and the time distribution) of rainfall losses are; impervious land surfaces, soil type and texture, vegetation type and extent of surface cover, litter and other cover on the soil, surface roughness, surface temperature, ambient temperature, rainfall intensity in a very complex way, antecedent soil moisture, soil density, and numerous other factors. At this time, it has been possible to formulate theories to estimate the magnitude of rainfall excess for several of these rainfall loss mechanisms, however, no existing theory is adequate to completely describe the rainfall loss process. This situation is complicated by the fact that there is tremendous variability over both time and space in most of the factors controlling rainfall losses in watersheds. The best that can be expected is that general relations can be established to estimate rainfall losses with some degree of confidence that represent uniform, rather idealized conditions.

THEORY

Numerous theories have been formulated for the purpose of modeling the rainfall loss process. Some of the theories and models were developed to simulate the composite rainfall loss process that includes all sources of rainfall losses, and an example of such a model is the SCS CN method. Other theories were formulated for the purpose of modeling only the infiltration component of the rainfall loss process, and an example of such a model is the Green and Ampt infiltration equation. Use of an infiltration model requires a separate estimation of the rainfall losses that are due to factors other than infiltration.

It is not possible to provide a comprehensive discussion of all of the rainfall loss theories that have been developed. Text books, hydrology handbooks, and professional literature should be consulted for this purpose. A good overview of rainfall loss and infiltration theories and models will be presented in the new ASCE Handbook of Hydrology that will be published in about 1992/1993.

The Green and Ampt infiltration equation is the preferred method to be used to estimate rainfall losses due to infiltration for ADOT projects. A brief description of this equation and its computational procedure is contained in the Rainfall Losses section of the Drainage Design Manual for Maricopa County, Volume 1, Hydrology (Appendix 6-A). A good general discussion of the Green and Ampt equation is contained in Hydrology and Floodplain Analysis by P.B. Bedient and W.C. Huber, Addison-Wesley Publishing Company, 1988 (Appendix 6-B).

The Initial Loss plus Uniform Loss Rate (IL+ULR) method is also described in the Drainage Design Manual for Maricopa County, Volume 1, Hydrology. Two additional sources of information should be consulted when using that method for flood hydrology; the Flood Hydrology Manual by A.G. Cudworth, U.S. Bureau of Reclamation, 1989, and Design of Small Dams, Third Edition, U.S. Bureau of Reclamation, 1988. Although those references provide some good background information, they probably cannot be used to select uniform loss rates (CNSTL) for the IL+ULR method when that method is used for special cases in Arizona.

DEVELOPMENT OF ADOT RAINFALL LOSSES CRITERIA

The scope-of-work (March 1990) specifies that three rainfall loss methods will be considered, and that the recommended method(s) would be selected from those three. Those three methods are:

1. Green and Ampt infiltration equation plus a surface retention loss,
2. Initial Loss plus Uniform Loss Rate (IL+ULR) method, and

3. the SCS CN method.

At Meeting No. 1, it was decided that ADOT will provide examples of the various levels of information that are available for Arizona for use in estimating rainfall losses. In descending order, these were:

a. SCS soil surveys (usually by county),

b. ADOT county soils maps, and

c. ADOT map of Arizona indicating hydrologic soil group.

At Meeting No. 2, Mr. Robert Ward provided a map of Arizona indicating the availability and status of the detailed SCS soil surveys for Arizona. That map is shown in Appendix 6-C.

A Rainfall Losses Working Paper dated December 1989 (revised May 1990) was submitted prior to Meeting No. 2. That working paper recommended adoption of the Green and Ampt equation as the preferred method with the IL+ULR method as an alternative. At Meeting No. 2, Mr. George Lopez-Cepero suggested that the Green and Ampt equation be the recommended method and that suggestion was approved at the meeting. It was agreed that a preliminary draft of the Rainfall Losses Working Paper be submitted prior to Meeting No. 3 that would provide clear guidance on the selection of the Green and Ampt equation parameters from the best available information for Arizona.

The Preliminary Draft of Working Paper No. 3 (September 1990) was prepared and submitted. Procedures to estimate the Green and Ampt equation parameters were provided, and the IL+ULR method was recommended for special situations where rainfall infiltration losses would not be controlled by soil texture. Comments were received on the Preliminary Draft of Working Paper No. 3 at Meeting No. 3, and revised Working Paper No. 3 (October 1990) was submitted.

At Meeting No. 4, corrections were noted for the IL+ULR method and other editorial comments were received. A revision to Working Paper No. 3 (21 January 1991) was made.

At Meeting No. 5, Mr. Ray Jordan asked about determination of soil texture in Example No. 1. Subsequently, Mr. Robert Ward prepared a Technical Memorandum (Appendix 6-D). Dr. George Sabol responded to Mr. Ward's memorandum with Technical Memorandum No. 8 (Appendix 6-E). These were reviewed at Meeting No. 6 with the conclusion that the use of the "gravelly" modifier on soil texture will be treated as presented in the Working Paper.

Prior to Meeting No. 7, Mr. Ray Jordan distributed copies of miscellaneous infiltration articles to the Committee (Appendix 6-F). Dr. George Sabol summarized some data from one of those articles (also in Appendix 6-F), and it was concluded that the Green and Ampt parameters do not appear to be in doubt based on that data, and may be somewhat conservative.

Comments on Green and Ampt parameters were received from Mr. David Creighton of the Arizona Department of Water Resources (Appendix 6-G).

GREEN AND AMPT PARAMETERS

The procedure to estimate the Green and Ampt parameter values was determined by the consultant (GVSCE) while performing research and development for the Flood Control District of Maricopa County in producing the Drainage Design Manual for Maricopa County, Volume 1, Hydrology. The following describes the research and development for that manual that was subsequently adopted for the ADOT Manual.

The Green and Ampt equation as coded into HEC-1 requires three parameter values; hydraulic conductivity (XKSAT), capillary suction (PSIF), and soil moisture deficit (DTHETA). The primary reference for the green and Ampt equation parameters is the paper by Rawls and others (1983) (Appendix 6-H). Notice that there is an error in that reference and that the hydraulic conductivities for loam (.34 cm/hr, (.15 in/hr)) and silty loam (.65 cm/hr, (.25 in/hr)) are reversed. This error is corrected in the ADOT Manual. Green and Ampt equation parameters for silt are not contained in the above reference, and those soil texture parameter values were taken from a publication by Rawls and Brakensiek (1983) (Appendix 6-I).

Values of DTHETA as functions of Dry, Normal, or Saturated soil, as defined in the ADOT Manual, were developed from information presented by Rawls and Brakensiek (1983) (Appendix 6-I). The work sheets used to develop the DTHETA "Dry" and the DTHETA "Normal" values in the ADOT Manual are presented in Appendix 6-J.

VEGETATION COVER CORRECTION FACTOR

The effect of ground cover on infiltration rate was investigated. The equations presented by Rawls, Brakensiek and Savabi (1989) (Appendix 6-K) were investigated, and a discussion of results are shown in Appendix 6-L. Those equations were not accepted because they yielded inconsistent results across the range of soil textures. Attempts were made to develop a functional relation for hydraulic conductivity as a function of ground cover and canopy cover. Dr. Leonard Lane assisted with the analysis of data that has been published by various researchers. The results of Dr. Lane's work are contained in Appendix 6-M. No satisfactory results were obtained and the lack of an adequately developed and verified procedure for adjusting bare soil infiltration rates for the effects of ground cover and canopy cover remains a major deficiency.

Dr. Tim Ward assisted in providing infiltration data and reviewing work, and as an advisor. Recent research by Ward and others at New Mexico State University (Appendix 6-N) and elsewhere indicates that canopy cover can greatly increase the infiltration rate. As a result of those published research results and communication with Dr. Ward, a simplified relation was developed to adjust the bare ground hydraulic conductivity for vegetation cover.

AREA AVERAGING OF GREEN AND AMPT PARAMETERS

The procedure that was developed for the calculation of the area weighted Green and Ampt XKSAT value was adopted from work by Van Mullem (1991) (Appendix 6-O).

IMPERVIOUS AREA

Estimation of rainfall losses is highly sensitive to the percent impervious area in the watershed. Impervious area is often measured as total impervious area or as effective impervious area (that impervious area that is directly connected to the outlet of the watershed). Effective impervious area (RTIMP in HEC-1 notation) is the measure of impervious area that is to be used, and that is because runoff from the non-directly connected impervious area must flow onto impervious area where infiltration and other losses can occur. Two sources for estimating effective impervious area where used; TR-55 and a paper by Alley and Veenhuis (1983). Those references and a summary of estimates for RTIMP are provided in Appendix 6-P. Mr. Robert Ward provided information on impervious area from other studies in which he has been involved (Appendix 6-Q).

WORKING PAPER NO. 3

The final version of Working Paper No. 3 (16 April 1992) is shown in Appendix 6-R. That working paper was incorporated into the ADOT Manual.

BIBLIOGRAPHY

A bibliography on pertinent references to infiltration and rainfall losses is provided in Appendix 6-S. The bibliography is taken from the list of references to a draft of the ASCE Handbook of Hydrology that is in preparation.

Volume 6
Rainfall Losses

List of Appendices

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Book 1	
6-A	Rainfall Losses, from Drainage Design Manual for Maricopa County, June 1992.
6-B	Infiltration, from Hydrology and Floodplain Analysis, by Bedient and Huber, 1988.
6-C	Status of Soil Surveys Arizona, by Soil Conservation Service, June 1989.
6-D	Technical Mermorandum, Correlation Between SCS Soil Gradation Data & Soil Texture Descriptions, by Robert Ward, February 1991.
6-E	Technical Memorandum No. 8, Green and Ampt parameter values.
6-F	Miscellaneous infiltration articles sent by R. Jordan, 28 May 1991.
6-G	Information supplied by David Creighton (ADWR) on rainfall losses.
6-H	Green-Ampt Infiltration Parameters from Soils Data, by Rawls, Brakensiek, and Miller, 1983.
6-I	A Procedure to Predict Green and Ampt Infiltration Parameters, by Rawls and Brakensiek, 1983.
6-J	DTHETA worksheets.
6-K	Infiltration Parameters for Rangeland Soils, by Rawls, Brakensiek and Savabi, 1989.
6-L	Applicability of the hydraulic conductivity equation to incorporate canopy cover and ground cover effects, 28 April 1989.
6-M	Memo to G. Sabol from L. Lane on proposed Figure 7A as a method of adjusting values of bare soil hydraulic conductivity KsO to reflect canopy cover and ground cover.
6-N	Rainfall Infiltration and Loss on a Bajada in the Chihuahuan Desert, New Mexico, by Bolton, Ward and Witford.
6-O	Runoff and Peak Discharges Using Green-Ampt Infiltration Model, by Van Mullem, 1991.
6-P	Effective Impervious Area in Urban Runoff Modeling, by Alley and Veenhuis, 1983, and table from SCS TR-55.
6-Q	Development Design Guidelines for Environmentally Sensitive Lands, July 1989, City of Scottsdale.
6-R	Working Paper No. 3, Rainfall Losses, 20 April 1992.
6-S	Bibliography on rainfall losses.

APPENDIX 6-A

4

Rainfall Losses

4.1 General

Rainfall excess is that portion of the total rainfall depth that drains directly from the land surface by overland flow. By a mass balance, rainfall excess plus rainfall loss equals precipitation. When performing a flood analysis using a rainfall-runoff model, the determination of rainfall excess is of utmost importance. Rainfall excess integrated over the entire watershed results in runoff volume, and the temporal distribution of the rainfall excess will, along with the hydraulics of runoff, determine the peak discharge. Therefore, the estimation of the magnitude and time distribution of rainfall losses should be performed with the best practical technology, considering the objective of the analysis, economics of the project, and consequences of inaccurate estimates.

Rainfall losses are generally considered to be the result of evaporation of water from the land surface, interception of rainfall by vegetal cover, depression storage on the land surface (paved or unpaved), and infiltration of water into the soil matrix. A schematic representation of rainfall losses for a uniform intensity rainfall is shown in Figure 4.1. As shown in the figure, evaporation can start at an initially high rate depending on the land surface temperature, but the rate decreases very rapidly and would eventually reach a low, steady-state rate. From a practical standpoint, the magnitude of rainfall loss that can be realized from evaporation during a storm of sufficient magnitude to cause flood runoff is negligible.

Interception, also illustrated in Figure 4.1, varies depending upon the type of vegetation, maturity, and extent of canopy cover. Experimental data on interception have been collected by numerous investigators (Linsley and others, 1982), but little is known of the interception values for most hydrologic problems. Estimates of interception for various vegetation types (Linsley and others, 1982) are:

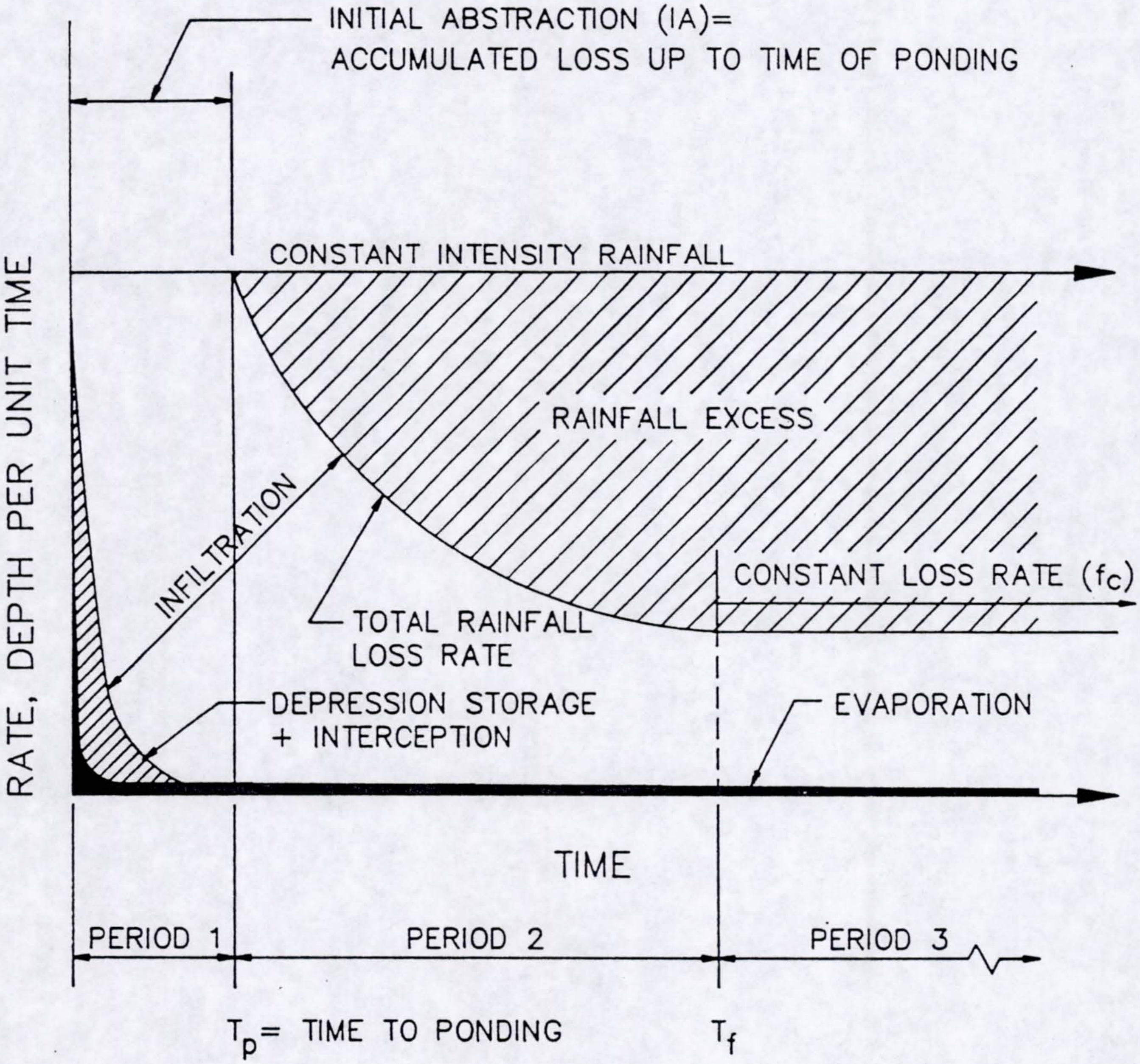

Figure 4.1
Schematic Representation of Rainfall Losses for a Uniform Intensity Rainfall

Vegetation Type	Interception, inches
hardwood tree	0.09
cotton	0.33
alfalfa	0.11
meadow grass	0.08

No interception estimates are known for natural vegetation that occurs in Maricopa County. For most applications in Maricopa County the magnitude of interception losses is essentially 0.0, and for practical purposes interception is not considered for flood hydrology in Maricopa County.

Depression storage and infiltration losses comprise the majority of the rainfall loss as illustrated in Figure 4.1. The estimates of these two losses will be discussed in more detail in later sections of this manual.

Three periods of rainfall losses are illustrated in Figure 4.1, and these must be understood and their implications appreciated before applying the procedures in this manual. First, there is a period of initial loss when no rainfall excess (runoff) is produced. During this initial period, the losses are a function of the depression storage, interception, and evaporation rates plus the initially high infiltration capacity of the soil. The accumulated rainfall loss during this period with no runoff is called the *initial abstraction.* The end of this initial period is noted by the onset of ponded water on the surface, and the time from start of rainfall to this time is the *time of ponding* (Tp). It is important to note that losses during this first period are a summation of losses due to all mechanisms including infiltration.

The second period is marked by a declining infiltration rate and generally very little losses due to other factors.

The third, and final, period occurs for rainfalls of sufficient duration for the infiltration rate to reach the *steady-state, equilibrium rate of the soil* (fc). The only appreciable loss during the final period is due to infiltration.

The actual loss process is quite complex and there is a good deal of interdependence of the loss mechanisms on each other and on the rainfall itself. Therefore, simplifying assumptions are usually made in the modeling of rainfall losses. Figure 4.2 represents a simplified set of assumptions that can be made. In Figure 4.2, it is assumed that surface retention loss is the summation of all losses other than those due to infiltration, and that this loss occurs from the start of rainfall and ends when the accumulated rainfall equals the magnitude of the capacity of the surface retention loss. It is assumed that infiltration does not occur during this time. After the surface retention is satisfied, infiltration begins. If the infiltration capacity exceeds the rainfall intensity, then no rainfall excess is produced. As the infiltration capacity decreases, it may eventually equal the rainfall intensity. This would occur at the time of ponding (Tp) which signals the beginning of surface runoff. As illustrated in both Figures 4.1 and 4.2, after the time of ponding the infiltration rate decreases exponentially and may reach a steady-state, equilibrium rate (fc). It is these simplified assumptions and processes, as illustrated in Figure 4.2, that are to be modeled by the procedures in this manual.

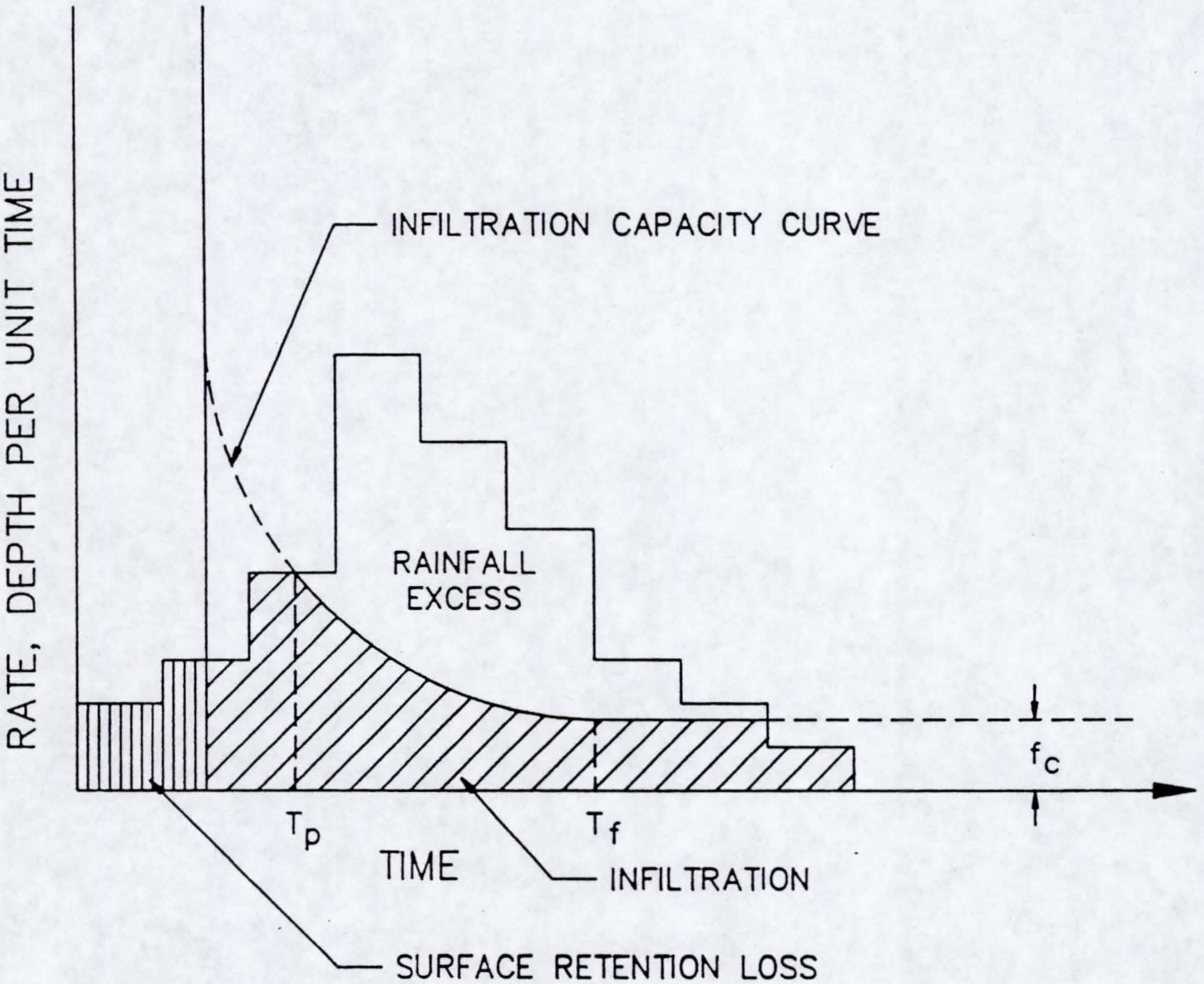

Figure 4.2
Simplified Representation of Rainfall Losses
A Function of Surface Retention Losses Plus Infiltration

4.2 Surface Retention Loss

Surface retention loss, as used herein, is the summation of all rainfall losses other than infiltration. The major component of surface retention loss is depression storage; relatively minor components of surface retention loss are due to interception and evaporation, as previously discussed. Depression storage is considered to occur in two forms. First, in-place depression storage occurs at, and in the near vicinity of, the raindrop impact. The mechanism for this depression storage is the microrelief of the soil and soil cover. The second form of depression storage is the retention of surface runoff that occurs away from the point of raindrop impact in surface depressions such as puddles, roadway gutters and swales, roofs, irrigation bordered fields and lawns, and so forth.

A relatively minor contribution by interception is also considered as a part of the total surface retention loss. Estimates of surface retention loss are difficult to obtain and are a function of the physiography and land-use of the area.

The surface retention loss on impervious surfaces has been estimated to be in the range 0.0625 inch to 0.125 inch by Tholin and Keefer (1960), 0.11 inch for 1 percent slope to 0.06 inch for 2.5 percent slopes by Viessman (1967), and 0.04 inch based on rainfall-runoff data for an urban watershed in Albuquerque by Sabol (1983). Hicks (1944) provides estimates of surface retention losses during intense storms as 0.20 inch for sand, 0.15 inch for loam, and 0.10 inch for clay. Tholin and Keefer (1960) estimated the surface retention loss for turf to be between 0.25 to 0.50 inch. Based on rainfall simulator studies on undeveloped alluvial plains in the Albuquerque area, the surface retention loss was estimated as 0.1 to 0.2 inch (Sabol and others, 1982a). Rainfall simulator studies in New Mexico result in estimates of 0.39 inch for eastern plains rangelands and 0.09 inch for pinon-juniper hillslopes (Sabol and others, 1982b). Surface retention losses for various land-uses and surface cover conditions in Maricopa County have been extrapolated from these reported estimates and these are shown in Table 4.1.

Table 4.1
Surface Retention Loss for Various Land Surfaces in Maricopa County

Land-use and/or Surface Cover (1)	Surface Retention Loss IA, inches (2)
Natural	
Desert and rangeland, flat slope	0.35
Hillslopes, Sonoran Desert	0.15
Mountain, with vegetated surface	0.25
Developed (Residential and Commercial)	
Lawn and turf	0.20
Desert landscape	0.10
Pavement	0.05
Agricultural	
Tilled fields and irrigated pasture	0.50

4.3 Infiltration

Infiltration is the movement of water from the land surface into the soil. Gravity and capillary forces drawing water into and through the pore spaces of the soil matrix are the two forces that drive infiltration. Infiltration is controlled by soil properties, by vegetation influences on the soil structure, by surface cover of rock and vegetation, and by tillage practices. The distinction between infiltration and percolation is that percolation is the movement of water through the soil *subsequent to* infiltration.

Infiltration can be controlled by percolation if the soil does not have a sustained drainage capacity to provide access for more infiltrated water. However, before percolation can be assumed to restrict infiltration for the design rainfalls being considered in Maricopa County, the extent by which percolation can restrict infiltration of rainfall should be carefully evaluated. SCS soil scientists have defined hydrologic soil group D as:

> "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."

This definition indicates that hydrologic soil groups A, B, or C could be classified as D if a near impervious strata of clay, caliche, or rock is beneath them. When these soils are considered in regard to long-duration rainfalls (the design events for many parts of the United States) this definition may be valid. However, when considered for short-duration and relatively small design rainfall depths in Maricopa County, this definition could result in underestimation of the rainfall losses. This is because even a relatively shallow horizon of soil overlaying an impervious layer still has the ability to store a significant amount of infiltrated rainfall.

For example, consider the situation where only 4 inches of soil covers an impervious layer. If the effective porosity is 0.30, then 1.2 inches (4 inches x 0.30) of water can be infiltrated and stored in the shallow soil horizon. For design rainfalls in Maricopa County, this represents a significant storage volume for infiltrated rainfall and so when developing loss rate parameters for areas of Maricopa County that contain significant areas classified as hydrologic soil group D, the reason for that classification should be determined.

Hydrologic soil group D should be retained only for:

» clay soils,

» soils with a permanent high water table, and

» rock outcrop.

Hydrologic soil group D should probably *not* be retained in all situations where the classification is based on shallow soils over nearly impervious layers; site specific studies and sensitivity analyses should be performed to estimate the loss rates to be used for such soils.

4.4 Recommended Methods for Estimating Rainfall Losses

Many methods have been developed for estimating rainfall losses; five are listed as options in the HEC-1 Flood Hydrology Package. They are:

1. Holtan Infiltration Equation

2. Exponential Loss Rate

3. SCS Curve Numbers (CN) Loss Rate

4. Green and Ampt Infiltration Equation

5. Initial Loss Plus Uniform Loss Rate (IL+ULR)

Of these five, however, only two—Green and Ampt and IL+ULR—are recommended for estimating rainfall losses in Maricopa County for the reasons discussed below.

The **Holtan Infiltration Equation** is an exponential decay type of equation for which the rainfall loss rate asymptotically diminishes to the minimum infiltration rate (fc). The Holtan equation is not extensively used and there is no known application of this method in Arizona. Data and procedures to estimate the parameters for use in Maricopa County are not available. Therefore, the Holtan equation is not recommended for general use in Maricopa County.

The **Exponential Loss Rate Method** is a four parameter method that is not extensively used, but it is a method preferred by of the U.S. Army Corps of Engineers. Data and procedures are not available to estimate the parameters for this method for all physiographic regions in Maricopa County, but Exponential loss rate parameters have been developed from the reconstitution of flood events for a flood hydrology study in a portion of Maricopa County (U.S. Army Corps of Engineers, 1982a). However, adequate data are not available to estimate the necessary parameters for all soil types and land uses in Maricopa County, and this method is not recommended for general use in Maricopa County.

The **SCS CN** method is the most extensively used rainfall loss rate method in Maricopa County and Arizona and it has wide acceptance among many agencies, consulting engineering firms, and individuals throughout the community. However, because of both theoretical concerns and practical limitations, the SCS CN method is not recommended for general use in Maricopa County.

As mentioned previously, the two recommended methods for estimating rainfall losses in Maricopa County are the Green and Ampt infiltration equation and the initial loss and uniform loss rate (IL+ULR) method. Both methods, as programmed into HEC-1, can be used to simulate the rainfall loss model as depicted in Figure 4.2. (For a full discussion of these methods, see Sections 4.4.1 and 4.4.2.) The IL+ULR is a simplified model that has been used extensively for flood hydrology and data often are available to estimate the two parameters for this method. The Green and Ampt infiltration equation is a physically based model that has been in existence since 1911, and has recently been incorporated as an option in HEC-1.

The preferred method, and the most theoretically accurate, is the Green and Ampt infiltration equation. This method should be used for most studies in Maricopa County where the land surface is soil, the infiltration of water is controlled by soil texture (see Appendix D), and the bulk density of the soil is affected by vegetation. Procedures were developed, and are presented, to estimate the three parameters of the Green and Ampt infiltration equation. The alternative method of IL+ULR can be used in situations where the Green and Ampt infiltration method is recommended, but its use in those situations is not encouraged, and, in general, should be avoided. Rather, the IL+ULR method should be used in situations where the Green and Ampt infiltration equation with parameters based on soil texture is not appropriate. Examples of situations where the IL+ULR method *is* recommended are: large areas of rock outcrop, talus slopes, forests underlain with a thick mantle of duff, land surfaces of volcanic cinder, and surfaces that are predominantly sand and gravel. Because of the diversity of conditions that could exist for which the IL+ULR method is to be used, it is not possible to provide extensive guidance for the selection of the two parameters of the IL+ULR method.

Other methods should be used only if there is technical justification for a variance from these recommendations and if adequate information is available to estimate the necessary parameters. Use of rainfall loss methods other than those recommended should not be undertaken unless previously approved by the Flood Control District and the local regulatory agency.

4.4.1 Green and Ampt Infiltration Equation

This model, first developed in 1911 by W.H. Green and G.A. Ampt, has since the early 1970s, received increased interest for estimating rainfall infiltration losses. The model has the form:

$$f = K_S \left(1 + \frac{\psi\theta}{F}\right) \qquad \text{for } f < i \qquad (4.1)$$

$$f = i \qquad \text{for } f \geq i$$

where

f	=	infiltration rate (L/T),
i	=	rainfall intensity (L/T),
K_S	=	hydraulic conductivity, wetted zone, steady-state rate (L/T)
Ψ	=	average capillary suction in the wetted zone (L),

θ = soil moisture deficit (dimensionless), equal to effective soil porosity times the difference in final and initial volumetric soil saturations, and

F = depth of rainfall that has infiltrated into the soil since the beginning of rainfall (L).

A sound and concise explanation of the Green and Ampt equation is provided by Bedient and Huber (1988).

It is important to note that as rain continues, F increases and f approaches K_S, and therefore, f is inversely related to time. Equation 4.1 is implicit with respect to f which causes computational difficulties. Eggert (1976) simplified Equation 4.1 by expanding the equation in a power series and truncating all but the first two terms of the expansion. The simplified solution (Li and others, 1976) is:

$$F = -0.5\,(2F - K_S\,\Delta t) + 0.5\,[(2F - K_S\,\Delta t)^2 + 8K_S\Delta t\,(\theta\psi + F)]^{1/2} \qquad (4.2)$$

where

Δt = the computation interval

F = accumulated depth of infiltration at the start of Δt.

The average infiltration rate is:

$$f = \frac{\Delta F}{\Delta t} \qquad (4.3)$$

Use of the Green and Ampt equation as coded in HEC-1 involves the simulation of rainfall loss as a two phase process, as illustrated in Figure 4.2. The first phase is the simulation of the surface retention loss as previously described; this loss is called the initial loss (IA) in HEC-1. During this first phase, all rainfall is lost (zero rainfall excess generated) during the period from the start of rainfall up to the time that the accumulated rainfall equals the value of IA. It is assumed, for modeling purposes, that no infiltration of rainfall occurs during this first phase. Initial loss (IA) is primarily a function of land-use and surface cover, and recommended values of IA for use with the Green and Ampt equation are presented in Table 4.1. For example, about 0.35 inches of rainfall will be lost to runoff due to surface retention for desert and rangelands on relatively flat slopes in Maricopa County.

The second phase of the rainfall loss process is the infiltration of rainfall into the soil matrix. For modeling purposes, the infiltration begins immediately after the surface retention loss (IA) is completely satisfied, as illustrated in Figure 4.2. The three Green and Ampt equation infiltration parameters as coded in HEC-1 are:

» hydraulic conductivity at natural saturation (XKSAT) equal to K_S in Equation 4.1;

» wetting front capillary suction (PSIF) equal to Ψ in Equation 4.1; and

» volumetric soil moisture deficit at the start of rainfall (DTHETA) equal to θ in Equation 4.1.

The three infiltration parameters are functions of soil characteristics, ground surface characteristics, and land management practices. The soil characteristics of interest are particle size distribution (soil texture), organic matter, and bulk density. The primary soil surface characteristics are vegetation canopy cover, ground cover, and soil crusting. The land management practices are identified as various tillages as they result in changes to soil porosity.

Values of Green and Ampt equation parameters as a function of soil characteristics alone (bare ground condition) have been obtained from published reports (Rawls and others, 1983; Rawls and Brakensiek, 1983), and average values of XKSAT and PSIF for each of the soil texture classes are shown in Columns (2) and (3) of Table 4.2. The values of XKSAT and PSIF from Table 4.2 or Figure 4.3 should be used if general soil texture classification of the drainage area is available. References used to create Table 4.2 can be found in the Documentation Manual.

In Table 4.2, loamy sand and sand are combined. The parameter values that are shown in the table are for loamy sand. The hydraulic conductivity (XKSAT) for sand is often used as 4.6 inches/hour, and the capillary suction (PSIF) is often used as 1.9 inches. Using those parameter values for drainage areas can result in the generation of no rainfall excess—which may or may not be correct. Incorrect results could cause serious consequences for flood control planning and design. Therefore, it is recommended that—for watersheds consisting of relatively small subareas of sand—the Green and Ampt parameter values for loamy sand be used for the sand portion of the watershed. If the area contains a large portion of sand, then either the Green and

Table 4.2
Green and Ampt Loss Rate Parameter Values for Bare Ground

Soil Texture Classification (1)	XKSAT Inches/hour (2)	PSIF Inches (3)	DTHETA[1]		
			Dry (4)	Normal (5)	Saturated (6)
loamy sand & sand	1.2	2.4	0.35	0.30	0
sandy loam	0.40	4.3	0.35	0.25	0
loam	0.25	3.5	0.35	0.25	0
silty loam	0.15	6.6	0.40	0.25	0
silt	0.10	7.5	0.35	0.15	0
sandy clay loam	0.06	8.6	0.25	0.15	0
clay loam	0.04	8.2	0.25	0.15	0
silty clay loam	0.04	10.8	0.30	0.15	0
sandy clay	0.02	9.4	0.20	0.10	0
silty clay	0.02	11.5	0.20	0.10	0
clay	0.01	12.4	0.15	0.05	0

[1] Selection of DTHETA:

Dry = Nonirrigated lands, such as desert and rangeland;
Normal = Irrigated lawn, turf, and permanent pasture;
Saturated = Irrigated agricultural land.

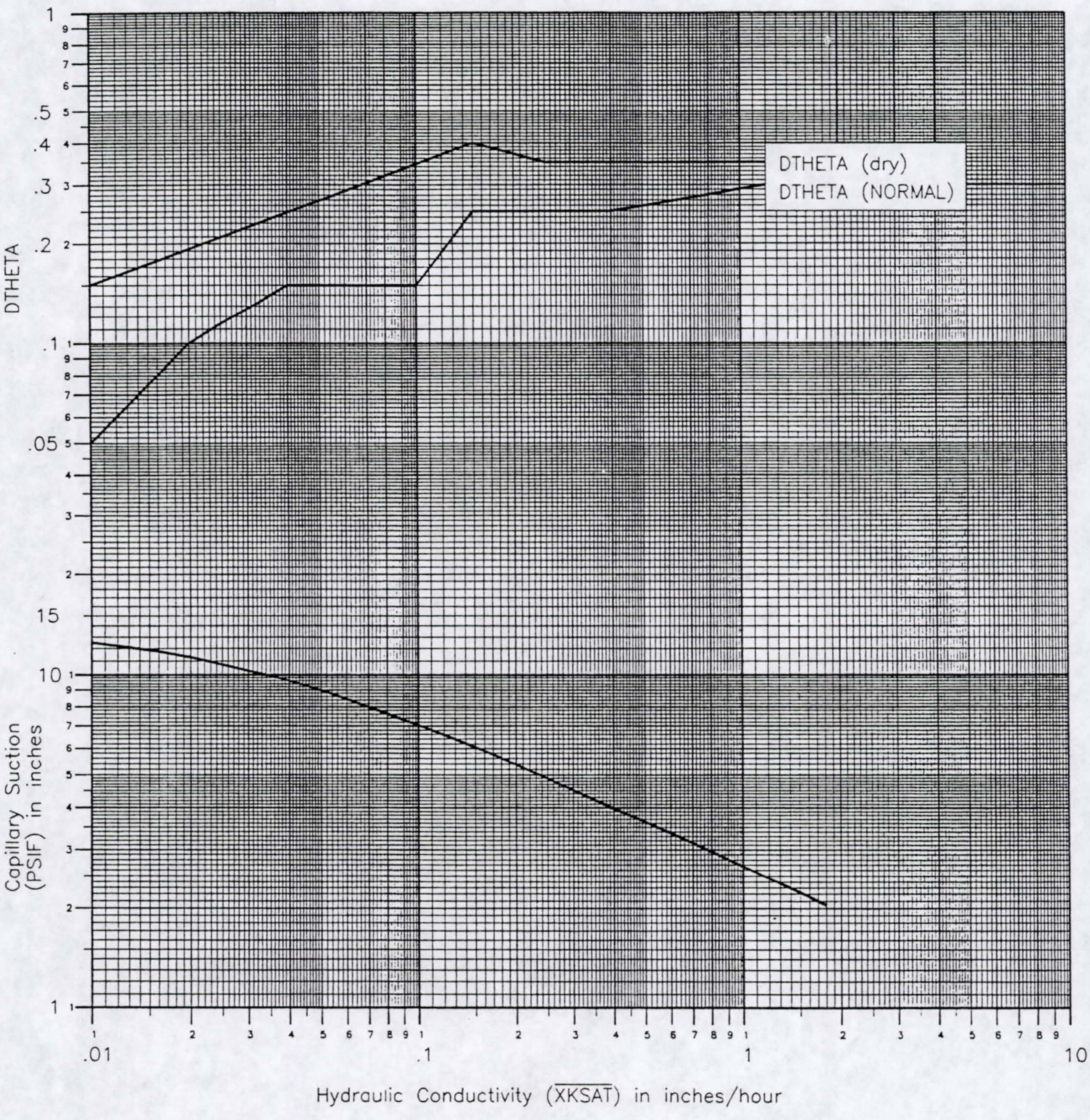

Figure 4.3
Composite Values of PSIF and DTHETA as a function of XKSAT
(To be used for area-weighted averaging of Green and Ampt parameters.)

Ampt method should be used with parameter values for loamy sand or the IL+ULR method should be used with appropriately determined values for the parameters.

The soil moisture deficit (DTHETA) is a volumetric measure of the soil moisture storage capacity that is available at the start of the rainfall. DTHETA is a function of the effective porosity of the soil. The range of DTHETA is 0.0 to the effective porosity. If the soil is effectively saturated at the start of rainfall then DTHETA equals 0.0; if the soil is devoid of moisture at the start of rainfall then DTHETA equals the effective porosity of the soil.

Under natural conditions, soil seldom reaches a state of soil moisture less than the wilting point of vegetation. Due to the rapid drainage capacity of most soils in Maricopa County, at the start of a design storm the soil would not be expected to be in a state of soil moisture greater than the field capacity.

However, Maricopa County also has a large segment of its land area under irrigated agriculture, and it is reasonable to assume that the design frequency storm could occur during or shortly after certain lands have been irrigated. Therefore, it would be reasonable to assume that soil moisture for irrigated lands could be at or near effective saturation during the start of the design rainfall.

Three conditions for DTHETA have been defined for use in Maricopa County based on the antecedent soil moisture condition that could be expected to exist at the start of the design rainfall. These three conditions are:

» "Dry" for antecedent soil moisture near the vegetation wilting point;

» "Normal" for antecedent soil moisture condition near field capacity due to previous rainfall or irrigation applications on nonagricultural lands; and

» "Saturated" for antecedent soil moisture near effective saturation due to recent irrigation of agricultural lands.

Values of DTHETA have been estimated by subtracting the initial volumetric soil moisture for each of the three conditions from the soil porosity.

The value of DTHETA "Saturated" is always equal to 0.0 because for this condition there is no available pore space in the soil matrix at the start of rainfall. Values of DTHETA for the three antecedent soil moisture conditions are shown in Table 4.2. DTHETA "Dry" should be used for soil that is usually in a state of low soil moisture such as would occur in the desert and rangelands of Maricopa County. DTHETA "Normal" should be used for soil that is usually in a state of moderate soil moisture such as would occur in irrigated lawns, golf courses, parks, and irrigated pastures. DTHETA "Saturated" should be used for soil that can be expected to be in a state of high soil moisture such as irrigated agricultural land.

4.4.1.1 Procedure for Aerially Averaging Green and Ampt Parameter Values: Most drainage areas or modeling subbasins will be composed of several subareas containing soils of different texutres. Therefore, a composite value for the Green and Ampt parameters that are to be applied to the drainage areas or modeling subbasins needs to be determined. The procedure for determining the composite value is to average the area-weighted logarithms of the XKSAT values and to select the PSIF and DTHETA values from a graph.

The composite XKSAT is calculated by Equation 4.4:

$$\overline{XKSAT} = ALOG\left(\frac{\Sigma\, A_i \log XKSAT_i}{A_T}\right) \tag{4.4}$$

where

$\overline{XKSAT}$ = composite subarea hydraulic conductivity, inches/hour

$XKSAT_i$ = hydraulic conductivity of a map unit, inches/hour (from Appendix A, B, or C)

A_i = size of subarea

A_T = size of the watershed or modeling subbasin

After $\overline{XKSAT}$ is calculated, the values of PSIF and DTHETA (normal or dry) are selected from Figure 4.3, at the corresponding value of $\overline{XKSAT}$.

4.4.1.2 Procedure for Adjusting XKSAT for Vegetation Cover: The hydraulic conductivity (XKSAT) can be affected by several factors besides soil texture. For example, hydraulic conductivity is reduced by soil crusting, increased by tillage, and increased by the influence of ground cover and canopy cover. The values of XKSAT that are presented for bare ground as a function of soil texture alone should be adjusted under certain soil cover conditions.

Ground cover, such as grass, litter, and gravel, will generally increase the infiltration rate over that of bare ground conditions. Similarly, canopy cover—such as from trees, brush, and tall grasses—can also increase the bare ground infiltration rate. The procedures and data that are presented are for estimating the Green and Ampt parameters based solely on soil texture and would be applicable for bare ground conditions. Past research has shown that the wetting front capillary suction parameter (PSIF) is relatively insensitive in comparison with the hydraulic conductivity parameter (XKSAT); therefore only the hydraulic conductivity parameter is adjusted for the influences of cover over bare ground.

Procedures have been developed (Rawls and others, 1989) for incorporating the effects of soil crusting, ground cover, and canopy cover into the estimation of hydraulic conductivity for the Green and Ampt equation; however, those procedures are not recommended for use in Maricopa County at this time. A simplified procedure to adjust the bare ground hydraulic conductivity for vegetation cover is shown in Figure 4.4. This figure is based on the documented increase in hydraulic conductivity due to various soil covers as reported by investigators using rainfall simulators on native western rangelands (Kincaid and others, 1964; Sabol and others, 1982a; Sabol and others, 1982b; Bach, 1984; Ward, 1986; Lane and others, 1987; Ward and Bolin, 1989). This correction factor can be used based on an estimate of vegetation cover as used by the Soil Conservation Service in soil surveys; that is, vegetation cover is evaluated on basal area for grasses and forbs, and is evaluated

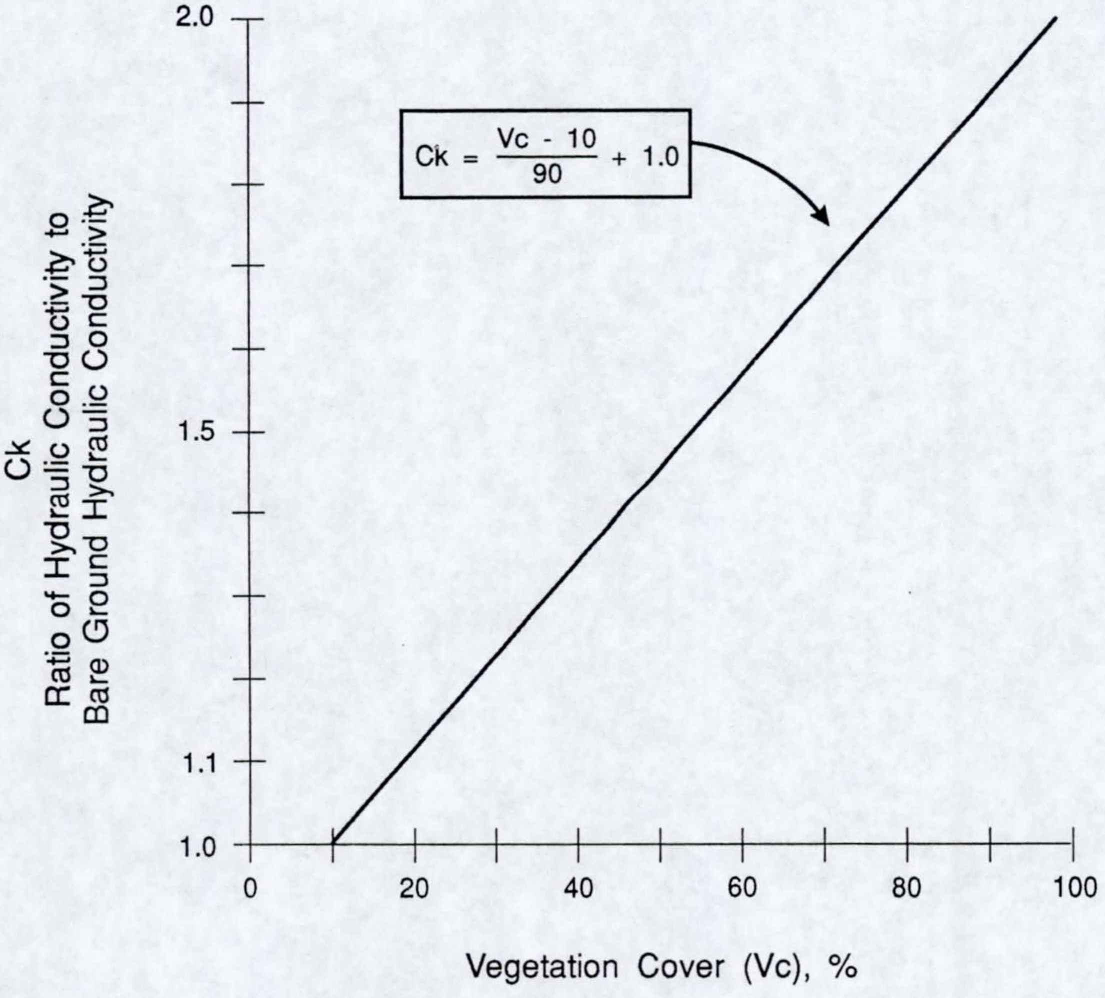

Figure 4.4
Effect of Vegetation Cover on Hydraulic Conductivity
For Hydraulic Soil Groups B, C, and D, and for all Soil Textures *other than* Sand and Loamy Sand

on canopy cover for trees and shrubs. Note that this correction can be applied only to soils other than sand and loamy sand.

The influence of tillage results in a change in total porosity and therefore a need to modify the three Green and Ampt equation infiltration parameters. The effect of tillage systems on soil porosity and the corresponding changes to hydraulic conductivity, wetting front capillary suction, and water retention is available (Rawls and Brakensiek, 1983). Although this information is available, it is not presented in this manual, nor is it recommended that these adjustments be made to the infiltration parameters for design purpose use in Maricopa County, because for most flood estimation purposes it cannot be assumed that the soil will be in any particular state of tillage at the time of storm occurrence and therefore the base condition infiltration parameters, as presented, should be used for flood estimation purposes. However, appropriate adjustments to the infiltration parameters can be made, as necessary, for special flood studies such as reconstitution of storm events.

4.4.2 Initial Loss Plus Uniform Loss Rate (IL+ULR)

This is a simplified rainfall loss method that is often used, and generally accepted, for flood hydrology. In using this simplified method it is assumed that the rainfall loss process can be simulated as a two-step procedure, as illustrated in Figure 4.5. First, all rainfall is lost to runoff until the accumulated rainfall is equal to the initial loss; and second, after the initial loss is satisfied, a portion of all future rainfall is lost at a uniform rate. All of the rainfall is lost if the rainfall intensity is less than the uniform loss rate.

According to HEC-1 nomenclature, two parameters are needed to use this method; the initial loss (STRTL) and the uniform loss rate (CNSTL).

Because this method is to be used for special cases where infiltration is not controlled by soil texture, or for drainage areas and subbasins that are predominantly sand, the estimation of the parameters will require model calibration, results of regional studies, or other valid techniques. It is not possible to provide complete guidance in the selection of these parameters; however, some general guidance is provided:

A. For the special cases of anticipated application, the uniform loss rate (CNSTL) will either be very low for nearly impervious surfaces, or possibly quite high for exceptionally fast-draining (highly pervious) land surfaces. For land surfaces with very low infiltration rates, the value of CNSTL will probably be 0.05 inches per hour or less. For sand, a CNSTL of 0.5 to 1.0 inch per hour or larger may be reasonable. Higher values of CNSTL for sand and other surfaces are possible, however, use of high values of CNSTL would require special studies to substantiate the use of such values.

B. Although the IL+ULR method is not recommended for watersheds where the soil textures can be defined and where the Green and Ampt method is encouraged, some general guidance in the selection of the uniform loss rate is shown in Tables 4.3 and 4.4. Table 4.4 was prepared based on the values in Table 4.3 and the hydraulic conductivities shown in Table 4.2. In Table 4.4, the initial infiltration (II) is an estimate of the infiltration loss that can be expected prior to the generation of surface runoff. The value of initial loss (STRTL) is the sum of initial infiltration (II) of Table 4.4 and surface retention loss (IA) of Table 4.1; STRTL = II + IA.

C. The estimation of initial loss (STRTL) can be made on the basis of calibration or special studies at the same time that CNSTL is estimated. Alternatively, since STRTL is equivalent to initial abstraction, STRTL can be estimated by use of the SCS CN equations for estimated initial abstraction, written as:

$$STRTL = \frac{200}{CN} - 2 \qquad (4.5)$$

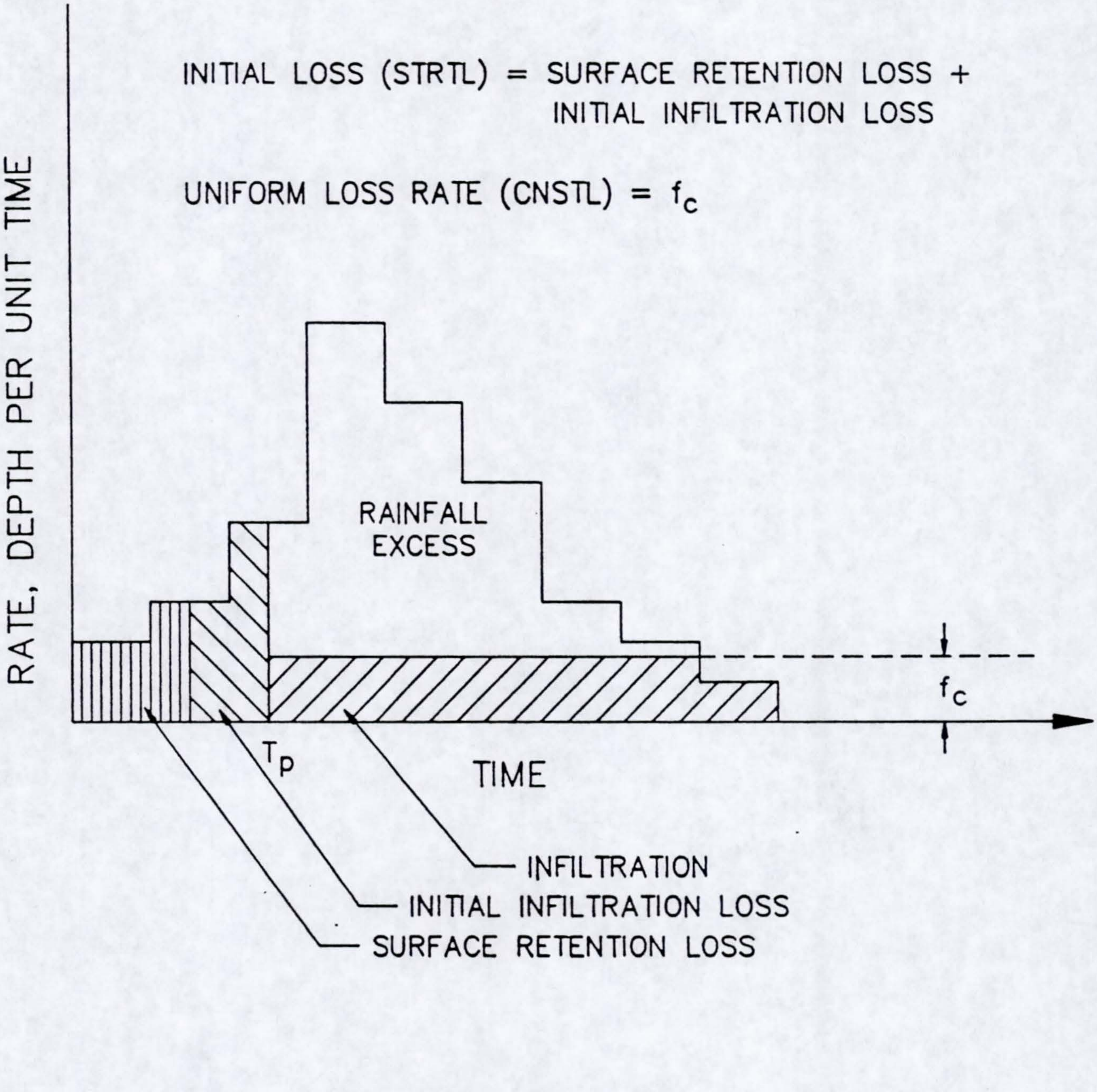

Figure 4.5
Representation of Rainfall Loss According to the Initial Loss Plus Uniform Loss Rate (IL+ULR)

Table 4.3
Published Values of Uniform Loss Rates

Hydrologic Soil Group (1)	Uniform Loss Rate, Inches/hour		
	Musgrave (1955) (2)	USBR (1975)[1] (3)	USBR (1987)[2] (4)
A	0.30 - 0.45	0.40	0.30 - 0.50
B	0.15 - 0.30	0.24	0.15 - 0.30
C	0.05 - 0.15	0.12	0.05 - 0.15
D	0 - 0.05	0.08	0 - 0.05

1 *Design of Small Dams*, Second Edition, 1975, Appendix A.
2 *Design of Small Dams*, Third Edition, 1987.

Table 4.4
Initial Loss Plus Uniform Loss Rate Parameter Values for Bare Ground according to Hydrologic Soil Group

Hydrologic Soil Group (1)	Uniform Loss Rate CNSTL (2)	Initial Infiltration, Inches II[1]		
		Dry (3)	Normal (4)	Saturated (5)
A	0.4	0.6	0.5	0
B	0.25	0.5	0.3	0
C	0.15	0.5	0.3	0
D	0.05	0.4	0.2	0

1 Selection of II:

Dry = Nonirrigated lands such as desert and rangeland;
Normal = Irrigated lawn, turf, and permanent pasture;
Saturated = Irrigated agricultural land.

Estimates of CN for the drainage area or subbasin should be made by referring to various publications of the SCS, particularly TR-55. Equation 4.5 should provide a fairly good estimate of STRTL in many cases, however, its use should be judiciously applied and carefully considered in all cases.

4.5 Procedure for Estimating Loss Rates

4.5.1 Green and Ampt Method

A. When soils data are available:

1. Prepare a base map of the drainage area delineating modeling subbasins, if used.

2. Delineate the subareas containing different soils (as determined from soil surveys, if available). Determine the soil texture for each soil type. Soils reports such as those of the Soil Conservation Service can be used, if available, or laboratory analysis of appropriate soil samples from the drainage area can be used if adequate documentation on the sampling and laboratory procedure is provided and approved. A soil texture classification triangle is provided in Appendix D.

3. If the watershed or subbasin contains soil of all one texture, then determine XKSAT, PSIF, and DTHETA from Table 4.2. Adjust XKSAT for vegetation cover using Figure 4.4, if appropriate.

4. If the watershed or subbasin is composed of soils of different textures, then area-weighted parameter values will be calculated:

   a. Determine the size (A_i) and the $XKSAT_i$ values for each soil subarea.

   b. Calculate the area-weighted value of $\overline{XKSAT}$ by using Equation 4.4.

   c. Select corresponding values of PSIF and DTHETA from Figure 4.3.

   d. Adjust the $\overline{XKSAT}$ value for vegetation cover using Figure 4.4, if appropriate. The adjustment factor may be area-weighted, if necessary.

5. Determine the land-use and/or soil cover for the drainage area and use Table 4.1 to estimate the surface retention loss (IA). Arithmetically area-weight average the values of IA if the drainage area or subbasin is composed of subareas of different IA.

6. Estimate the impervious area (RTIMP) for the drainage area or subbasin, and arithmetically area-weight average, if necessary.

7. Enter the area-weighted values of IA, DTHETA, PSIF, XKSAT, and RTIMP for the drainage area or each subbasin on the LG record of the HEC-1 input file.

B. Alternative methods:

As an alternative to the above procedures, Green and Ampt loss rate parameters can be estimated by reconstitution of recorded rainfall-runoff events on the drainage area or hydrologically similar watersheds, or parameters can be estimated by use of rainfall simulators in field experiments. Plans and procedures for estimating Green and Ampt loss rate parameters by either of these procedures should be approved by the Flood Control District and the local agency before initiating these procedures.

4.5.2 Initial Loss Plus Uniform Loss Rate Method

A. When soils data are available:

1. Prepare a base map of the drainage area delineating modeling subbasins, if used.

2. Delineate subareas of different infiltration rates (uniform loss rates) on the base map. Assign a land-use or surface cover to each subarea.

3. Determine the size of each subbasin and size of each subarea within each subbasin.

4. Estimate the impervious area (RTIMP) for the drainage area or each subarea.

5. Estimate the initial loss (STRTL) for the drainage area or each subarea by regional studies or calibration. Alternatively, Equation 4.5 or Tables 4.1 and 4.4 can be used to estimate or to check the value of STRTL.

6. Estimate the uniform loss rate (CNSTL) for the drainage area or each subarea by regional studies or calibration. Table 4.4 can be used, in certain situations, to estimate or to check the values of CNSTL.

7. Calculate the area-weighted values of RTIMP, STRTL, and CNSTL for the drainage area or each subbasin.

8. Enter the area-weighted values of RTIMP, STRTL, and CNSTL for the drainage area or each subbasin on the LU record of the HEC-1 input file.

APPENDIX 6-B

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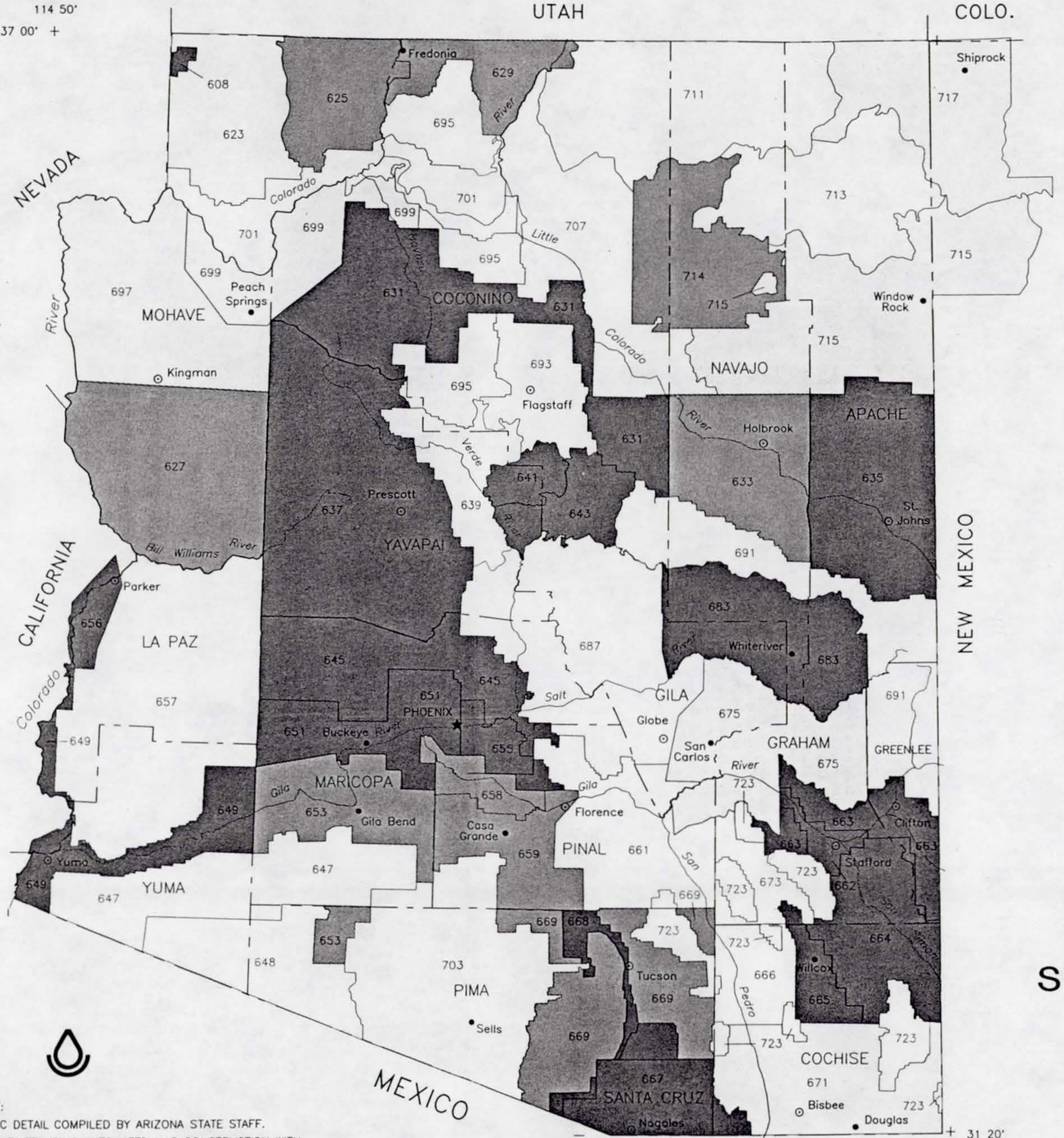
were not scanned

APPENDIX 6-C

U.S. DEPARTMENT OF AGRICULTURE

SOIL CONSERVATION SERVICE



LEGEND

⊙	COUNTY SEAT
———	SOIL SURVEY AREA BOUNDARY
624	SOIL SURVEY AREA NUMBER
(dark shading)	MODERN PUBLISHED SOIL SURVEY
(medium shading)	MODERN SURVEY, MAPPING COMPLETE
(light shading)	SURVEY IN PROGRESS, COMPLETION DATE SET
(no shading)	NO SIGNIFICANT OLD SURVEY, NO SURVEYS BEING CONDUCTED

STATUS OF SOIL SURVEYS
ARIZONA
JUNE 1989

0 25 50 75 100 MILES

SOURCE:
THEMATIC DETAIL COMPILED BY ARIZONA STATE STAFF.
MAP COMPILED USING AUTOMATED MAP CONSTRUCTION WITH THE *FOCAS* EQUIPMENT. NATIONAL CARTOGRAPHIC CENTER, FORT WORTH, TEXAS 1989.

REVISED MAY 1989 1000032

USDA SCS NATIONAL CARTOGRAPHIC CENTER, FT. WORTH, TX 1989

APPENDIX 6-D

TECHNICAL MEMORANDUM

To: Project Committee Members, ADOT Hydrology Manual

From: Robert L. Ward

Subject: Correlation Between SCS Soil Gradation Data & Soil Texture Descriptions

Date: February 19, 1991

During Work Group Meeting No. 5, Ray Jordan raised a question about the determination of the soil texture used in Example No. 1 to *Working Paper No. 3* (dated 21 January 1991). Specifically, the question focused on the correlation between the published SCS description of the Perryville soil series (PeA) as a "gravelly loam" and the soil texture that would be obtained by plotting the published gradation analysis of this soil on a USDA soil texture classification triangle. Concern was expressed that the gradation data listed in Example No. 1 might not support the published soil description of a "gravelly loam". I agreed to research this issue in order to identify and explain any potential conflicts. This memorandum summarizes my research.

During the course of this research, some secondary issues were also uncovered which should be addressed before the *ADOT Hydrology Manual* is published in final form. The first of these secondary issues is the fact that the Agua Fria River tributary at Youngtown is composed of three different soil series, rather than the single Perryville series that is referenced in Example No. 1. Based on my visual estimate from the SCS soil survey map, the watershed is composed of 50% Laveen loam, 12% Vecont clay, and 38% Perryville gravelly loam. The area-weighted Green-Ampt parameters for this 3-soil combination are computed on Attachment No. 1. The inclusion of the Vecont clay and Laveen loam changes the bare soil hydraulic conductivity (XKSAT) from the 0.40 in/hr. value, published in Example No. 1, to 0.278 in/hr. I noted in reviewing the September 1990 edition of the *MCFCD Hydrology Manual* that they also list all three of these soil series (in similar percentages to those on Attachment No. 1) when computing the Green-Ampt parameters for the Youngtown watershed. Accordingly, I would recommend that we revise Example No. 1 to reflect the published soil series that comprise this watershed. For consistency, we should probably use the same data that is published for the example in the MCFCD Manual. OK

Another secondary issue questions the source and shape of the soil texture diagram published in the *MCFCD Hydrology Manual*, and also used in *Working Paper No. 3.* I met with Bill Johnson, SCS Soil Scientist, Phoenix office, on February 13, 1991 to discuss SCS policies on soil classification. Bill stated that he had never seen a soil texture diagram shaped like the one in the MCFCD manual. He said SCS uses the equilateral triangle (see Attachment No. 6) as their official soil texture diagram. However, it should be noted that Brakensiek and Rawls (authors of A Procedure To Predict Green And Ampt Infiltration Parameters) are both USDA employees and utilize the texture diagram published in the *MCFCD Hydrology Manual.* I have discussed this issue with George Sabol and he has agreed to try and track down the source of this "hybrid" soil texture diagram. However, since the equilateral triangle shape (Attachment No. 6), with sand, silt, and clay axes, appears to be the standard for soil texture classifications, I would recommend that we stick with this standard shape so that this same question will not be raised by future users of the *ADOT Hydrology Manual.* oK

Finally, to the central issue of this memorandum. The gradation data published on pages 74 and 75 (Table 5) of the *Soil Survey Of Maricopa County, Arizona, Central Part*, September 1977, (this is the data that was used in Example No. 1 referenced at the beginning of this memorandum) is not sufficiently detailed to determine soil classification from a triangular soil texture diagram. This is not possible because the published gradation data does not separate the silt fraction from the clay fraction. At least two of the three soil textures (sand, silt, or clay) must be known to use the texture diagram. Also complicating this issue is the fact that the SCS texture diagram uses a No. 270 sieve (not a No. 200 sieve) to differentiate between silt and sand. The smallest sieve size published in the Soil Survey is a No. 200.

Further complications are created by the fact that Table 5 of the Soil Survey publishes the gradation data as percentage ranges for each sieve size, e.g., 55% to 75% passing a No. 10 sieve, etc. Depending upon which end of the range a specific soil sample might be associated with, a substantially different soil texture could be derived. For example, Attachments 2, 3, 4, and 5 show the four possible scenarios that exist for computing the percentage of sand in the Perryville gravelly loam. After correcting for the gravel fraction that is larger than a No. 10 sieve, the four scenarios illustrate how the sand component of the Perryville gravelly loam could range from a low value of 23% to a high value of 60%. Attachment No. 6 shows the soil texture envelope (red-shaded area) that would be defined by this range of sand percentages. Accordingly, depending upon the distribution of the silt/clay fraction, a Perryville gravelly loam could plot anywhere from a clay to a sandy loam, with associated hydraulic conductivities ranging from 0.01 to 0.40 in/hr!

Fortunately, our search for technical justification of the described soil texture does not end with the sieve data published in Table 5 of the Soil Survey report. Table 10 (pages 110-111) of the same report provides much more detailed data on the gradation of six benchmark soils that are included within the soil survey limits. Bill said that for those soils which are not tested to the level of detail published in Table 10 of the soil survey report, the soil scientist will usually field classify the soil by using simple tests, such as squeezing or rolling a ribbon of soil to estimate the clay content. He also indicated that field testing with hydrometers is sometimes used. When this type of testing is employed, there are no detailed sieve analyses performed that could be used to enter a soil texture diagram.

Table 10 provides a precise tabulation of the percents of sand, silt, and clay that comprise the Perryville gravelly loam. These percentages are:

1. Sand - 42.6%
2. Silt - 39.9%
3. Clay - 17.5%

   Total: 100%

Applying these percentages to the soil texture diagram on Attachment No. 6 indicates that a Perryville gravelly loam plots almost in the middle of the loam envelope. A small red "x" on Attachment No. 6 shows the precise plotting point (it lies in the middle of the "Loam" label). Accordingly, the basic soil texture of "loam" is confirmed by the gradation data.

However, another question now arises as to how we resolve the discrepancy between a texture plot indicating a "loam" soil and the narrative description in the report that defines this Perryville soil as a "gravelly loam". Additional discussions with Bill Johnson indicated that SCS policy for using "gravelly" modifiers is as follows:

1. *Gravelly* - 15% to 20% of the sample (by volume) has particle sizes bracketed by a No. 10 sieve and 3 inches.

2. *Very gravelly* - 35% to 60% of the sample is retained between a No. 10 sieve and 3 inches.

3. *Extremely gravelly* - more than 60% of the sample is retained between a No. 10 sieve and 3 inches. Note: A No. 10 sieve is the upper limit for the SCS sand size fraction.

I have enclosed Attachment No. 7 as the basis on which SCS applies "sand" modifiers to basic soil textures. Although I have no supporting test data, the above analysis suggests that we may be creating some inaccuracies in the selection of Green-Ampt parameters with our proposed treatment of "modifiers" to the basic soil textures, e.g., our assumption that a "gravelly loam" will have similar infiltration characteristics as a "sandy loam". In the case of the Perryville gravelly loam, the published SCS gradation data clearly indicates the soil is a "loam", not a "sandy loam". The associated hydraulic conductivities (XKSAT) of 0.25 (loam) and 0.40 (sandy loam) are substantially different. Perhaps we should revert back to our originally proposed treatment of modifiers (see *Working Paper No. 3* dated 7 January 1991) and simply drop the "gravelly" modifier from the soil texture when selecting Green-Ampt parameters. However, prior to doing this, I would recommend that we contact Brakensiek and Rawls (or any other Green-Ampt researchers) and ask if they have any test data on gravelly loams, etc., and also ask what their recommendations would be in assigning Green-Ampt parameters to soils with "gravelly" modifiers, or any other modifiers that might not fall into our current list of soils for which Green-Ampt parameters are published.

Conclusions

1. The "percentage ranges" of sieve analysis data published in Table 5 of the *Soil Survey of Maricopa County, Arizona, Central Part*, are not sufficient to use for the determination of soil texture. Unless detailed data, such as that presented in Table 10 of the same soil survey, is available, the engineer should use the soil texture defined in the text of the soil survey report. as described in W.P.

2. The treatment of "gravelly" modifiers to basic soil textures should be re-examined to determine their influence on the selection of Green-Ampt parameters.

3. The conventional "equilateral" triangle should be adopted as the soil texture diagram to be published in the *ADOT Hydrology Manual.*

Attachments: **No.1** - Soil composition & Green-Ampt parameters for Agua Fria River tributary at Youngtown

No.2, 3, 4, 5 - Plotting envelopes for USDA soil texture diagram, Perryville Gravelly Loam

No.6 - USDA soil texture diagram with plotting data for Perryville Gravelly Loam

No.7 - SCS criteria for using sand modifiers

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Youngtown Watershed - Agua Fria Tributary

Soil Composition

LcA	Vf	PeA
50 %	12 %	38 %

LcA - Laveen loam (HSG B)
95-100 % passing No. 4 sieve
85-100 % " No. 10 "
70 - 85 % " No. 40 "
50-70 % " No. 200 "

Vf - Vecont clay (HSG D)
100 % passing No. 4 sieve
95-100 % " No. 10 "
85-95 % " No. 40 "
75-90 % " No. 200 "

PeA - Perryville gravelly loam (HSG B)
80-90 % passing No. 4 sieve
55-75 % " No. 10 "
40-55 % " No. 40 "
30-40 % " No. 200 "

Green-Ampt Parameters Based On Area-Weighted Percentage of Soil Composition

XKSAT : (.50)(.25) + (.12)(.01) + (.38)(.40) = 0.278 in/hr.

PSIF : (.50)(3.5) + (.12)(12.4) + (.38)(4.3) = 4.872 in.

DTHETA (Dry) : (.50)(.35) + (.12)(.15) + (.38)(.35) = 0.326

DTHETA (Normal) : (.50)(.25) + (.12)(.05) + (.38)(.25) = 0.226

ATTACHMENT No. 1

ROBERT L. WARD, P.E. Consulting Engineer

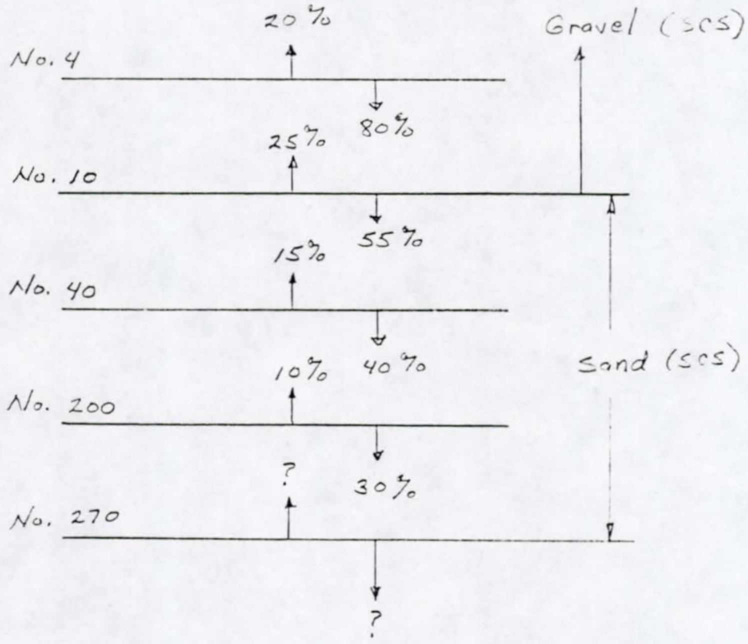
Client NBS/ADOT
Project No. NBS-01
Project Name ADOT Hydrology Manual
Page
Date 2/13/91
Computed By RLW

Perryville Gravelly Loam (PeA)

Plotting Envelope For USDA Soil Texture Diagram

Scenario No. 1

80 %	passing	No. 4	sieve
55 %	"	No. 10	"
40 %	"	No. 40	"
30 %	"	No. 200	"



15 % + 10 % + 30 % = 55 % of total sample size is composed of sand, silt, and clay.

Minimum sand percentage for plotting on soil texture diagram is:

$$\frac{15+10}{55} = 45\%$$

No data is available in the SCS soil survey for breakout between silt & clay.

ATTACHMENT No. 2

ROBERT L. WARD, P.E. — Consulting Engineer

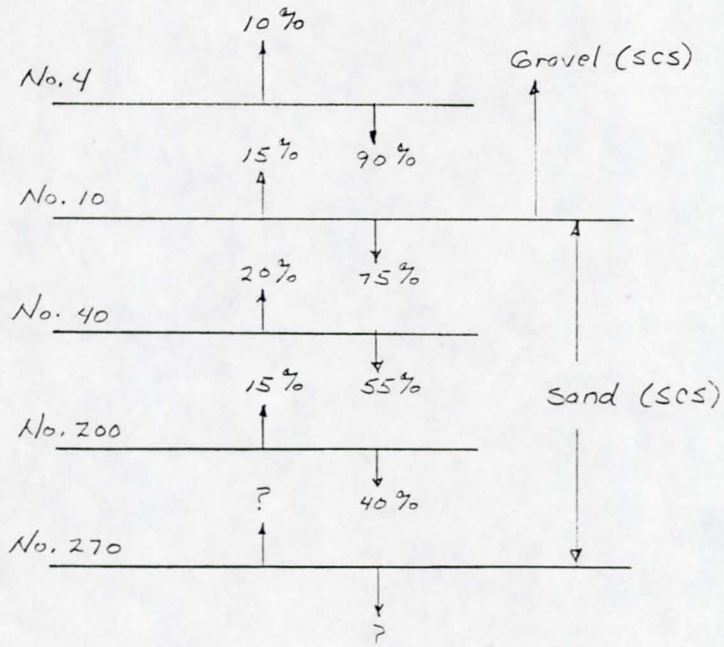
Client ______ Page ______

Project No. ______ Date 2/12/91

Project Name ______ Computed By RLW

Scenario No. 2

90% passing No. 4 sieve
75% " No. 10 "
55% " No. 40 "
40% " No. 200 "



20% + 15% + 40% = 75% of total sample size is composed of sand, silt, and clay.

Minimimum sand percentage for plotting on soil texture diagram is:

$$\frac{20+15}{75} = 47\%$$

No data is available in the SCS soil survey for breakout between silt & clay.

ATTACHMENT No. 3

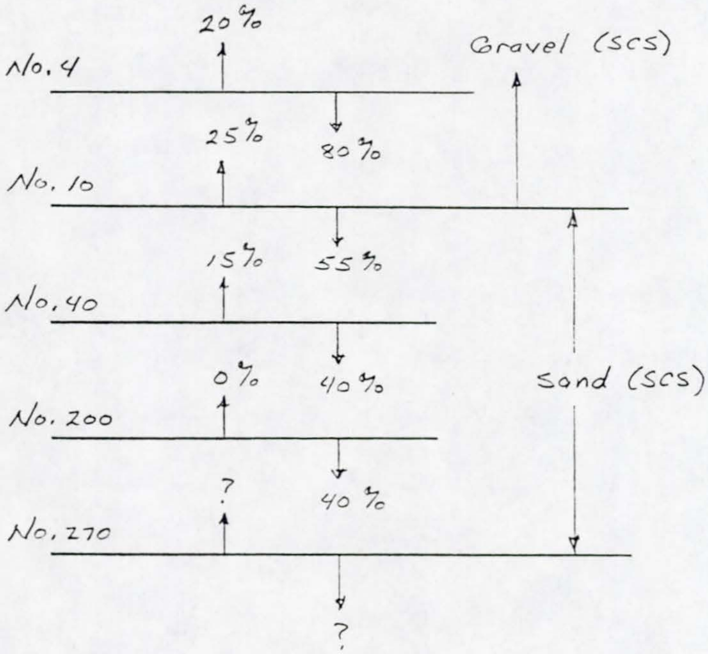
ROBERT L. WARD, P.E. — Consulting Engineer

Client ______
Project No. ______
Project Name ______

Page ______
Date 2/12/91
Computed By RLW

Scenario No. 3

80% passing No. 4 sieve
55% " No. 10 "
40% " No. 40 "
40% " No. 200 "



15% + 0% + 40% = 65% of total sample size is composed of sand, silt, and clay.

Minimum sand percentage for plotting on soil texture diagram is:

$$\frac{15}{65} = 23\%$$

No data is available in the SCS soil survey for breakout between silt & clay.

ATTACHMENT No. 4

ROBERT L. WARD, P.E. — Consulting Engineer

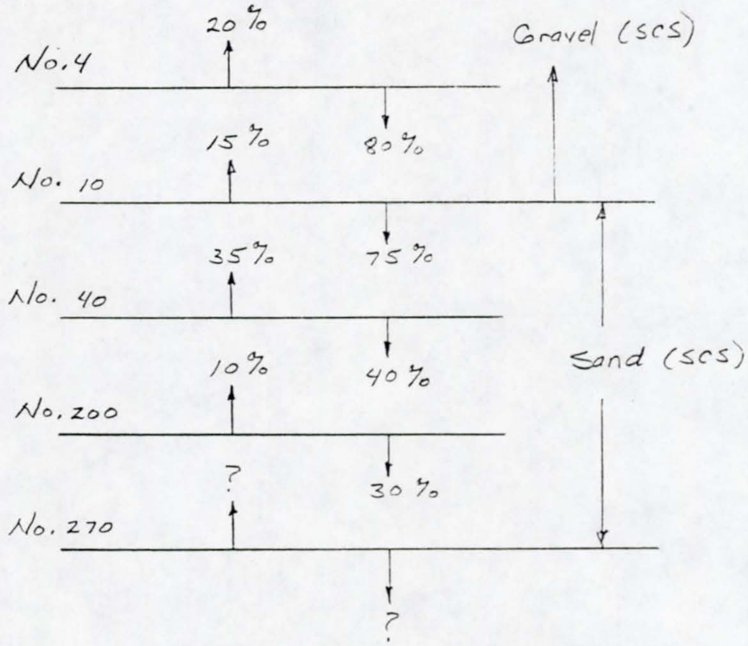
Client ____________ Page ____________

Project No. ____________ Date 2/12/91

Project Name ____________ Computed By RLW

Scenario No. 4

80% passing No. 4 sieve
75% " No. 10 "
40% " No. 40 "
30% " No. 200 "



35% + 10% + 30% = 75% of total sample size is composed of sand, silt, and clay.

Minimum sand percentage for plotting on soil texture diagram is:

$$\frac{35+10}{75} = 60\%$$

No data is available in the SCS soil survey for breakout between silt and clay.

ATTACHMENT No. 5

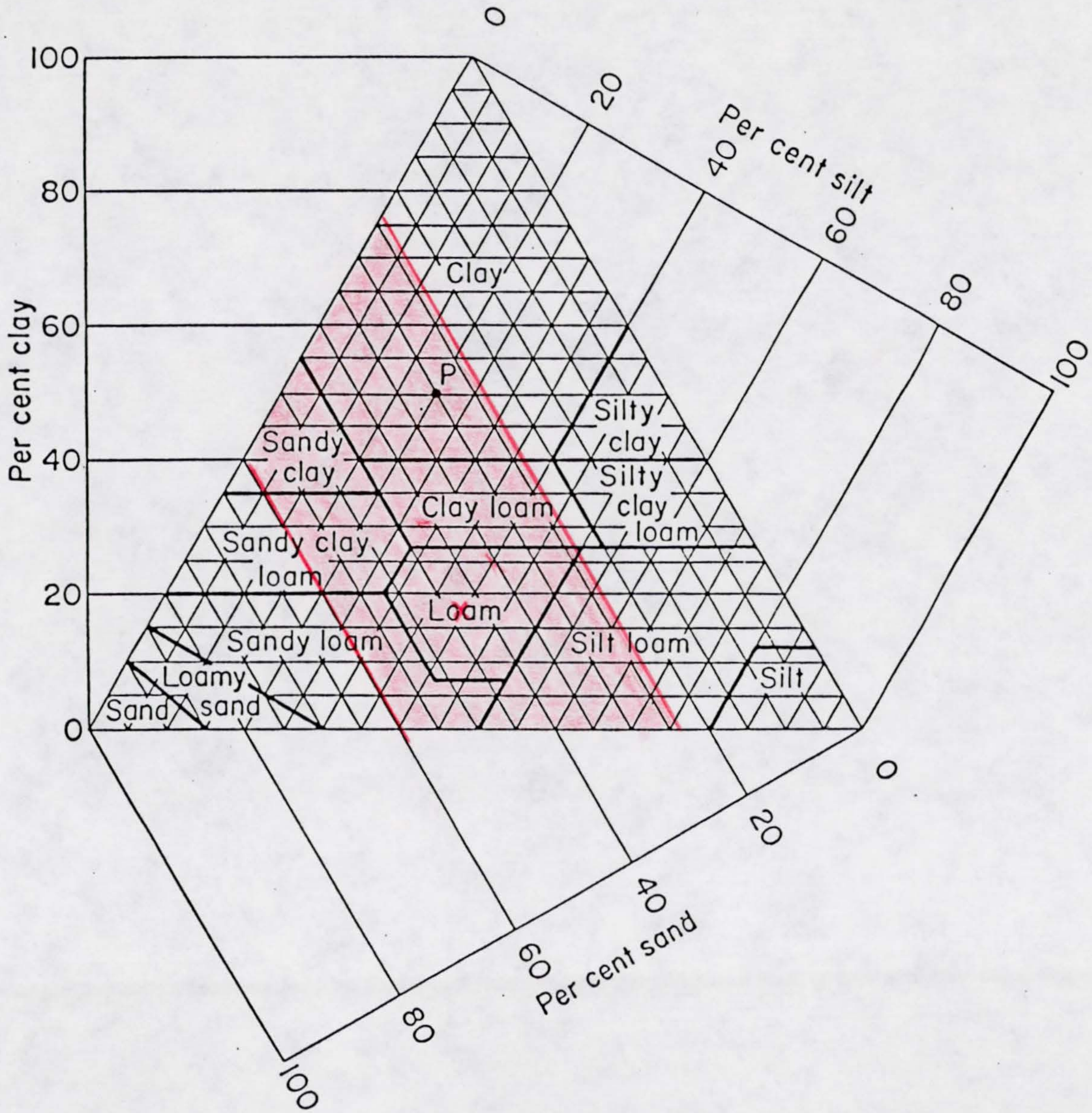


FIG. 5-1. U.S. Department of Agriculture textural classification triangle [3, p. 209] with axes added. The point P represents a clay (soil) containing 50 per cent clay, 20 per cent silt, and 30 per cent sand.

ATTACHMENT No. 6

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APPENDIX 6-E

TECHNICAL MEMORANDUM No. 8

TO: Project Committee Members
FROM: G.V. Sabol
DATE: 15 March 1991
SUBJECT: Green and Ampt parameter values

This technical memorandum is in response to Mr. Robert Ward's suggestion that the use of "gravelly" as a soil texture be re-examined (see Mr. Ward's Technical Memorandum of 19 February 1991).

I and others have spent considerable effort in trying to resolve the problem (and other similar problems) of relating Green and Ampt equation parameters to influences such as gravel content in the soil. It is my conclusion that we presently do not have the "full" answer to the selection of Green and Ampt parameters for soils existing in nature; i.e., parameter values incorporating the effects of coarse fragments in the soil, rock and litter cover of the soil, vegetation cover, impact of land-use, etc. However, it does appear from the literature that there is some confidence in selecting the parameters based on soil texture for <u>bare ground</u> conditions <u>without</u> the compounding effects as mentioned above. Answers to deviations from the simple bare ground condition will probably come with time as usage encourages additional research.

In again researching this topic in regard to the effect of coarse fragments (gravel) in the soil, I found three references that can be considered. Copies of these are attached, and they are:

(1) Determining the Saturated Hydraulic Conductivity of a Soil Containing Rock Fragments
Brakensiek, Rawls, and Stephenson (1986)
(2) Applicability of the Green and Ampt Infiltration Equation to Rangelands
Devaurs and Gifford (1986)
(3) Large-Plot Infiltration Studies in Desert and Semiarid Rangeland Areas of the Southwestern U.S.A.
Lane, Simanton, Hakonson, and Romney (1987)

I think that these will provide interesting reading and will lend some light on the topic - but will not provide a solution to the problem. First, there is no question that estimating the Green and Ampt parameters from bare ground, soil texture alone is inadequate for most natural watershed conditions. Devaurs and Gifford (1986, pg. 22) state, "These soil texture predictive triangles, developed for agricultural soils, need revision for use on rangelands." The problem of the soil coarse fraction is specificly mentioned as part of the problem for rangelands. No solution is offered in this relatively recent article.

Brakensiek and others (1986) have provided some evidence to indicate that the hydraulic conductivity of the fine earth fraction should be <u>reduced</u> as a function of the weight fraction of coarse material in the bulk soil. The reduction of hydraulic conductivity would be 30% for a bulk soil containing 30% gravel. That work would support Ward's suggestion that the parameters should be based on the fine earth fraction without regarding the soil texture modifier such as gravelly.

However, if the soil is gravelly then the land surface will have gravel and rock cover and there would be a surface soil effect that must be considered. Lane and others (1987) provides some valuable data on the effect of vegetation and ground cover on hydraulic conductivity (Table 4). The measured hydraulic conductivities from those experiments are reproduced below:

	Hydraulic Conductivity in mm/hr		
Site	Natural Ground Cover	Clipped Vegetation	Bare Ground
Bernardino	35.3	21.0	13.7
Cave	26.3	15.0	11.6
Hathaway	31.6	19.3	12.4
Mercury	20.5	7.3	4.8
Area 11	33.7	18.4	11.8
Average	29.5	18.4	11.8

Notice that the bare ground hydraulic conductivities compare quite nicely to the hydraulic conductivities that are provided for sandy loam, loam, and silty loam soils. Also notice the large increase in hydraulic conductivity for natural ground cover, an average of 250% increase.

My conclusions are the following:

1. It would not be reasonable to use the fine earth soil texture to classify the soil (disregard the coarse fraction), and maybe also reduce the hydraulic conductivity by up to 40% to account for the gravel content. This would be too conservative.
2. The presence of gravel in the soil probably has a much greater effect on the soil surface to increase the hydraulic conductivity.
3. The bare ground hydraulic conductivity is probably significantly lower than the natural condition hydraulic conductivity.
4. Retain the soil modifier "gravelly" as presently treated in Working Paper No. 3 when classifying soil. This may help to offset what are probably conservative hydraulic conductivities for natural conditions.

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APPENDIX 6-F

ARIZONA DEPARTMENT OF TRANSPORTATION

RESEARCH SECTION

075R

LETTER OF TRANSMITTAL

DATE 28 May 91

ATTENTION

RE: ADOT Hydrology Manual

CONTRACT NO.

PROJECT NO. HPR - PL - 1(3), Item 281

TO Dr. George V. Sabol
George V. Sabol Consulting Engineers, Inc.
1351 E. 141st Avenue
Brighton, Colo.
80601

WE ARE SENDING ☒ ATTACHED ☐ UNDER SEPARATE COVER VIA ____________:

☐ SAMPLES ☐ VIDEO TAPE ☐ CONTRACTS
☒ LITERATURE ☐ ENGINEERING DRAWINGS ☐ OTHER ____________
☐ PLANS ☐ CHANGE ORDERS
☐ PHOTOS ☐ LETTERS

COPIES	DATE	NO	DESCRIPTION
1 set	—	-	miscellaneous infiltration articles
			sent by Ray Jordan for
			distribution

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☒ FOR YOUR USE ☐ APPROVED AS SUBMITTED ☐ SUBMIT ______ COPIES FOR DISTRIBUTION
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NOTES

COPY TO R. Perry, B. Ward, file

SIGNATURE Joe Warren

TITLE T.E. I

DATE 28 May 91

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Comparison of data by Beutner, Gaebe & Horton to Green & Ampt Parameters

Site No.	Soil Type	Cover	f_c, in/hr dry	f_c, in/hr wet	Green & Ampt XKSAT	
5	gravelly sandy loam	none	.92	.42	.40	
6	"	"	1.42	.71	.40	
7	"	"	1.36	.65	.40	
10	sandy loam	"	.63	.44	.40	
11	"	sparse	.83	—	.40	
12	"	"	.75	—	.40	
13	silt-loam	some	.60	.34	.15	
14	sand	"	2.22	1.29	4.6	(1.2 for loamy sand) ← to be used
15	sandy clay loam	none	.28	.18	.06	
16	"	fair	1.78	1.05	.06	
18	"	sparse	.97	.69	.06	
19	stony loam	none	.87	.62	.40	(sandy loam)
20	"	sparse	1.52	1.08	.40	
21	sandy loam	"	1.15	.70	.40	

notice effect of cover (cover and wet f_c values for sites 15, 16 and 18 boxed)

GEORGE V. SABOL CONSULTING ENGINEERS, INC.

CLIENT

PROJECT

SUBJECT

SHEET ___ OF ___

DATE

BY 27 June 91

PROJECT NO. 5-15

APPENDIX 6-G

from D. Creighton
8/21/91

This set of sheets has been high lighted to flag differences in supposedly the same item values, or the same category identification

DTHETA
PSIF
XKSAT

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» hydraulic conductivity at natural saturation (XKSAT) equal to K_S in Equation 4.1;

» wetting front capillary suction (PSIF) equal to Ψ in Equation 4.1; and

» volumetric soil moisture deficit at the start of rainfall (DTHETA) equal to θ in Equation 4.1.

The three infiltration parameters are functions of soil characteristics, ground surface characteristics, and land management practices. The soil characteristics of interest are particle size distribution (soil texture), organic matter, and bulk density. The primary soil surface characteristics are vegetation canopy cover, ground cover, and soil crusting. The land management practices are identified as various tillages as they result in changes to soil porosity.

Values of Green and Ampt equation parameters as a function of soil characteristics alone (bare ground condition) have been obtained from published reports (Rawls and others, 1983; Rawls and Brakensiek, 1983), and average values of XKSAT and PSIF for each of the soil texture classes are shown in Columns (2) and (3) of Table 4.2. The values of XKSAT and PSIF from Table 4.2 should be used if general soil texture classification of the drainage area is available. References used to create Table 4.2 can be found in the Documentation Manual.

Table 4.2
Green and Ampt Loss Rate Parameter Values for Bare Ground

Soil Texture Classification (1)	XKSAT Inches/hour (2)	PSIF Inches (3)	DTHETA[1] Dry (4)	DTHETA[1] Normal (5)	DTHETA[1] Saturated (6)
sand	4.6	1.9	0.35	0.30	0
loamy sand	1.2	2.4	0.35	0.30	0
sandy loam	0.40	4.3	0.35	0.25	0
loam	0.25	3.5	0.35	0.25	0
silty loam	0.15	6.6	0.40	0.25	0
silt	0.10	7.5	0.35	0.15	0
sandy clay loam	0.06	8.6	0.25	0.15	0
clay loam	0.04	8.2	0.25	0.15	0
silty clay loam	0.04	10.8	0.30	0.15	0
sandy clay	0.02	9.4	0.20	0.10	0
silty clay	0.02	11.5	0.20	0.10	0
clay	0.01	12.4	0.15	0.05	0

1 Selection of DTHETA:

Dry = Nonirrigated lands, such as desert and rangeland;
Normal = Irrigated lawn, turf, and permanent pasture;
Saturated = Irrigated agricultural land.

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TABLE 5.17 Green-Ampt Infiltration Parameters for Various Soil Classes

Soil Class	Effective Porosity DTHETA	WEPP PSIF $c\lambda_1$	Wetting Front Suction PSIF (in)	WEPP PSIF $c\lambda_2$	WEPP	Hydraulic Conductivity XKSAT (in/hr) (Rawls Table 2)
Sand	0.417	4.07	1.95	4.17	4.13	4.64
Loamy Sand	0.401	5.36	2.41	5.57	1.20	1.18
Sandy Loam	0.412	8.10	4.33	8.73	0.51	0.43
Loam	0.434	11.05	3.50	12.40	0.26	0.13
Silt Loam	0.486	14.07	6.57	15.90	0.13	0.26
Sand Clay Loam	0.330	16.43	8.60	17.67	0.08	0.06
Clay Loam	? 0.390 0.309 ?	15.58	8.22 8.72	17.54	0.04	0.04
Silty Clay Loam	0.432	19.73	10.75	22.89	0.03	0.04
Sandy Clay	0.321	22.04	9.41	25.02	0.02	0.02
Silty Clay	0.423	21.62	11.50	25.46	0.02	0.02
Clay	0.385	24.98	12.45	32.02	0.01	0.01

Source: CHOW, MAIDMENT AND MAYS [1988]
: Conversions metric to English and
: Rawls, Brakensiek & Miller (1983) J. Hydr. Engr. Div. 109:1, 62-70, Table 2
: Rawls, Stone, & Brakensiek (1988) Chapt. 4 - Infiltration in WEPP model Documentation (Draft 1.0, July 1988) - Table 4.3 and conversions

Table 4.2
Green and Ampt Loss Rate Parameter Values for Bare Ground

Soil Texture Classification (1)	XKSAT Inches/hour (2)	PSIF Inches (3)	DTHETA[1] Dry (4)	DTHETA[1] Normal (5)	DTHETA[1] Saturated (6)
sand	4.6	1.9	0.35	0.30	0
loamy sand	1.2	2.4	0.35	0.30	0
sandy loam	0.40	4.3	0.35	0.25	0
loam	0.25	3.5	0.35	0.25	0
silty loam	0.15	6.6	0.40	0.25	0
silt	0.10	7.5	0.35	0.15	0
sandy clay loam	0.06	8.6	0.25	0.15	0
clay loam	0.04	8.2	0.25	0.15	0
silty clay loam	0.04	10.8	0.30	0.15	0
sandy clay	0.02	9.4	0.20	0.10	0
silty clay	0.02	11.5	0.20	0.10	0
clay	0.01	12.4	0.15	0.05	0

1 Selection of DTHETA:
- Dry = Nonirrigated lands, such as desert and rangeland;
- Normal = Irrigated lawn, turf, and permanent pasture;
- Saturated = Irrigated agricultural land.

TABLE 5.17 Green-Ampt Infiltration Parameters for Various Soil Classes

Soil Class	Effective Porosity DTHETA	Wetting Front Suction PSIF (in)	Hydraulic Conductivity XKSAT (in/hr)
Sand	0.417	1.95	4.64
Loamy Sand	0.401	2.41	1.18
Sandy Loam	0.412	4.33	0.43
Loam	0.434	3.50	0.13
Silt Loam	0.486	6.57	0.26
Sand Clay Loam	0.330	8.60	0.06
Clay Loam	0.309	8.72 8.22	0.04
Silty Clay Loam	0.432	10.75	0.04
Sandy Clay	0.321	9.41	0.02
Silty Clay	0.423	11.50	0.02
Clay	0.385	12.45	0.01

Source: CHOW, MAIDMENT AND MAYS [1988]

Table 4.2
Green and Ampt Loss Rate Parameter Values for Bare Ground

Soil Texture Classification (1)	XKSAT Inches/hour (2)	PSIF Inches (3)	DTHETA[1]		
			Dry (4)	Normal (5)	Saturated (6)
sand	4.6	1.9	0.35	0.30	0
loamy sand	1.2	2.4	0.35	0.30	0
sandy loam	0.40	4.3	0.35	0.25	0
loam	0.25	3.5	0.35	0.25	0
silty loam	0.15	6.6	0.40	0.25	0
silt	0.10	7.5	0.35	0.15	0
sandy clay loam	0.06	8.6	0.25	0.15	0
clay loam	0.04	8.2	0.25	0.15	0
silty clay loam	0.04	10.8	0.30	0.15	0
sandy clay	0.02	9.4	0.20	0.10	0
silty clay	0.02	11.5	0.20	0.10	0
clay	0.01	12.4	0.15	0.05	0

[1] Selection of DTHETA:

Dry = Nonirrigated lands, such as desert and rangeland;
Normal = Irrigated lawn, turf, and permanent pasture;
Saturated = Irrigated agricultural land.

from D. Creighton
8/21/91

The Green-Ampt procedure has been adopted by the Flood Control District of Maricopa County, Arizona in its adopted manual (Sept 1, 1990). With the growing popularity of the Green-Ampt procedure in the HEC-1 program modeling several sources and references have published conversions or abbreviated tabulations. In these secondary sources and the new WEPP model documentation differences in values for the parameters have crept into the public domain. With these differences, which have come to the authors attention, it is believed appropriate to initiate a review for the purpose of clarifying, correcting if necessary, and disseminating updated or revised parameter values.

References currently in hand are:

1. Hydrologic Design Manual for Maricopa County, Arizona

2. WEPP Profile Model Documentation, USDA.

3. Applied Hydrology, Chow, Maidment, & Mays - McGraw-Hill (1988)

4a Hands-On HEC-1, Dodson & Associates - 1990.
4b Hands On HEC-1 Pro HEC-1 Dodson. April 1991

WEPP Profile Model Documentation · USDA-SCS

Draft 1.0 July 1988, L.J. Lane & M.A. Nearing (Editors)

WEPP Prof. Mod. Version 7.3

WEPP — Water Erosion Prediction Project — USDA-SCS & FS, BLM (USDI)

Review for: Infiltration - Green & Ampt.

Pg 1.2 & 1.3.2 Infiltration - Rawls & Brakensiek (Chapt 4)

Chapter 4 - Infiltration: Rawls, Stone & Brakensiek.

References (A) Brakensiek & Rawls or (B) Rawls or Rawls & Brakensiek & others)

	JHYDENG 1-83		WEPP 7/88		MCFCD 9/90	
Number	A-2	B-2	A-4	B-7	A-0	B-3, S-3
Common Same Reference		1: S-2		2: S-1, S-2		2: S-1
Brooks & Corey	1 Same		1 - Same.		—	

PSIF ·

Eqn (4):

$$\psi_f = \left(\frac{2\lambda+3}{2\lambda+2}\right)\left(\frac{\psi_b}{2}\right)$$

@ $\lambda = 0.6$: $\left(\frac{(2\times0.6)+3}{(2\times0.6)+2}\right) = \frac{(1.2+3)}{(1.2+2)} = \frac{4.2}{3.2}$

$= 1.3125$

Eqn 4.4.1 R & B (1983)

$$Psif = \left(\frac{(2+3\times\lambda)}{(1+3\times\lambda)}\right) * \frac{Psib}{2}$$

$$\left(\frac{2+(3\times0.6)}{1+3\times0.6}\right) = \frac{2+1.8}{1+1.8} = \frac{3.8}{2.8} = 1.3571$$

1.034 = 103.4%

λ range - 0.694 to 0.150

Green-Ampt

$$f = K_s\left(1+\frac{\psi\theta}{F}\right)$$

K_s = XKSAT - hydraulic conductivity @ natural saturation

ψ = PSIF = wetting front capillary suction

θ = DTHETA = volumetric soil moisture deficit

F = Depth of Rainfall that has infiltrated since beginning of rain

Distribution for Reconciling Green-Ampt Parameters

Sources of Tables of Values.

1. Rawls Brakensiek, Miller 1983 JYHYDENG. Table 2. - Equation 4.
2. FCDMC Hydrologic Design Manual. - (Source 1 modified) Table 4.2
3. Applied Hydrology - Chow Maidment & Mays - Table 4.3.1 (Source 1) Metric
4. WEPP - Chapt 4. Rawls, Stone, Brakensiek (1988) Table 4.3
   & Equation 4.4.1 (Rawls & Brakensiek, 1983) (ASAE 102-112)
5. Dodson Hands-On HEC-1 Table 5.17
   English Conversion from Metric DTHETA PSIF XKSAT.

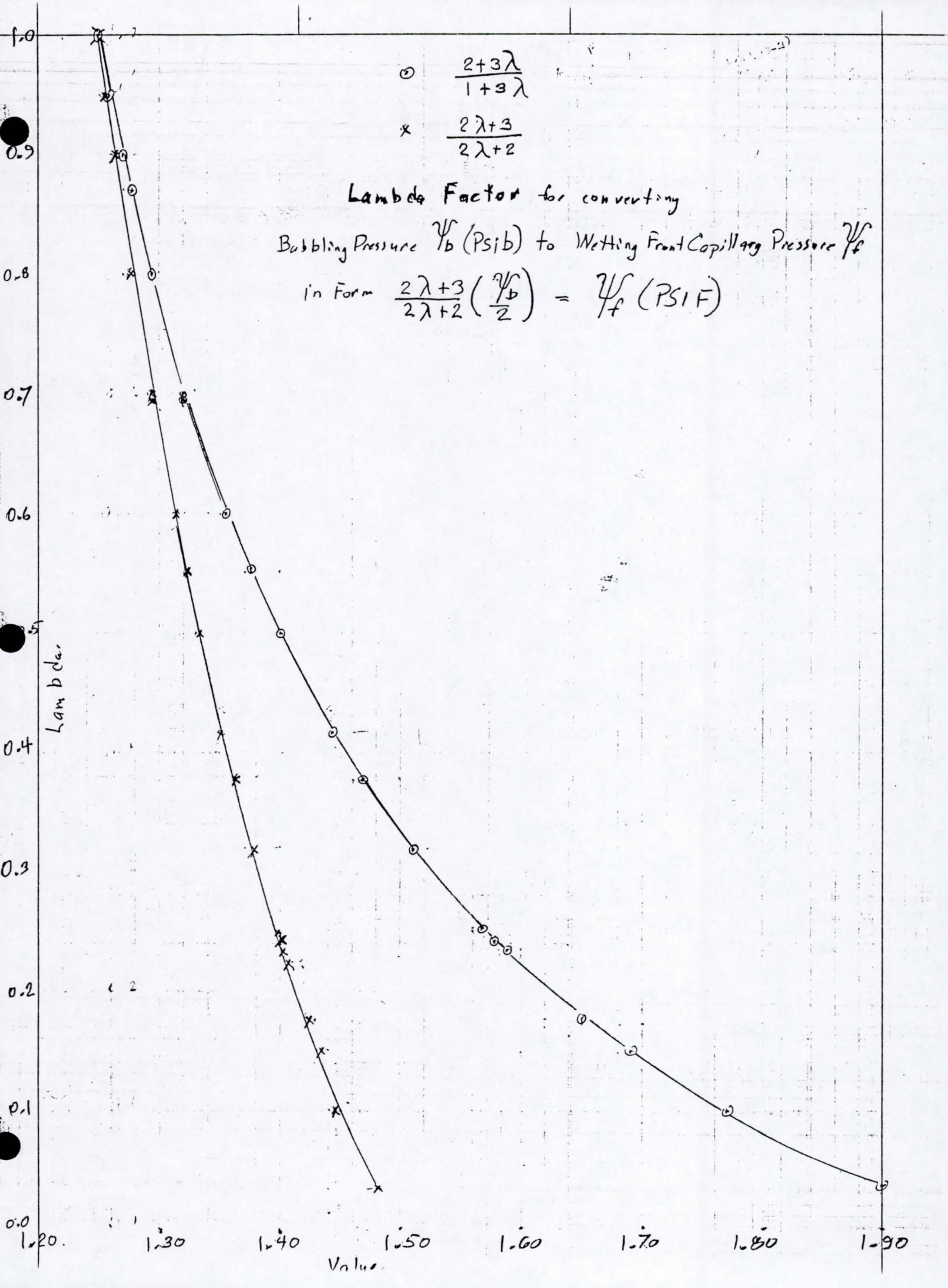
Contact/Copies to:

1. MCFCD - Stephen D. Waters.
2. George V. Sabol
3. Larry Mays.
4. Dodson.
5.a Rawls. ARS Beltsville, MD.
5.b Brakensiek ARS Boise, ID
5.c. ______ ARS - Tucson, AZ.

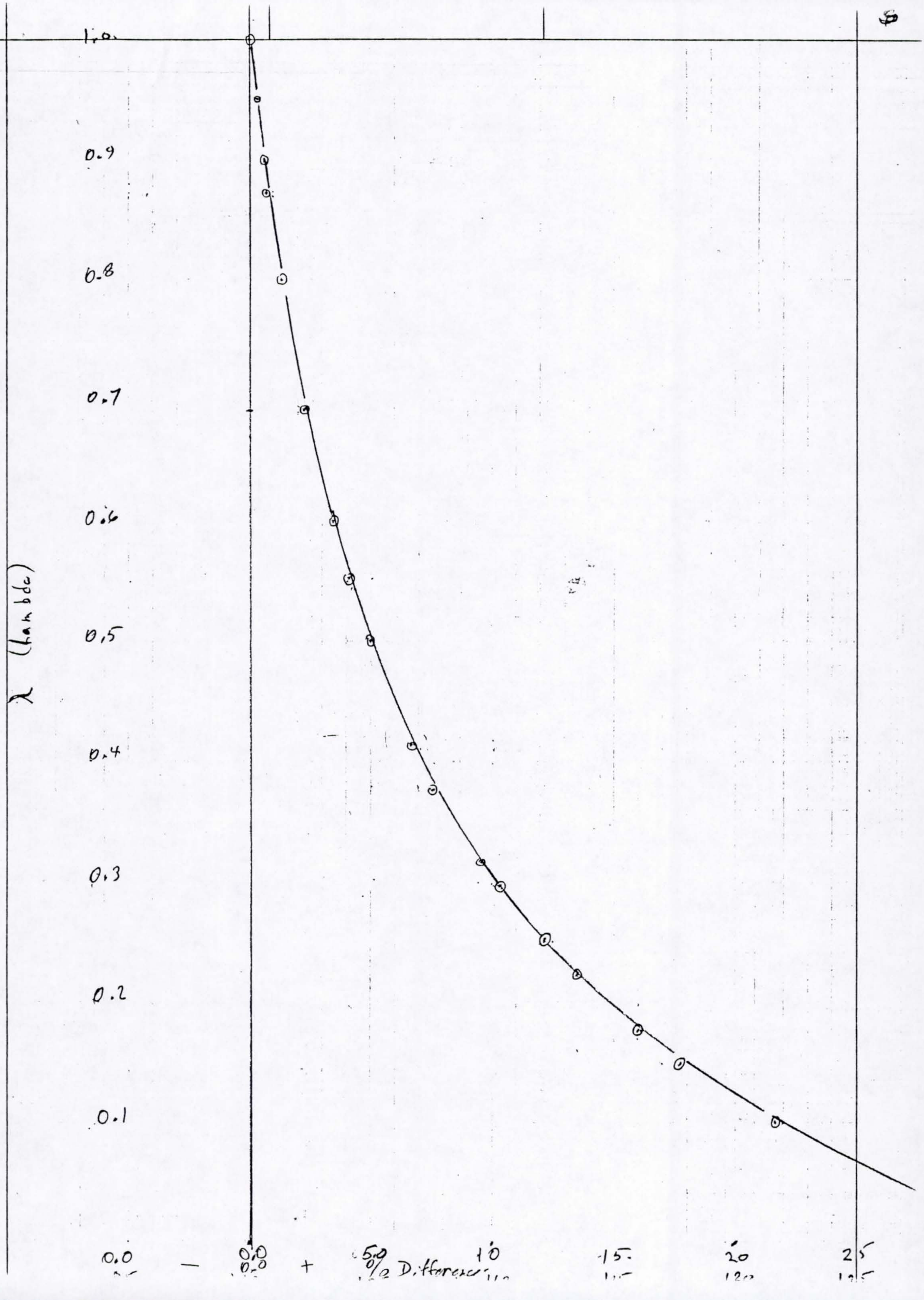
The role of pore size distribution (λ) in relation to bubbling pressure (Ψ_b) in the determination of the wetted front capillary pressure (Ψ_f) appears to have undergone some evolutionary change and modification. In Rawls, Brakensiek, and Miller (1983) in equation (4 the lambda (λ) factor was in the form $\frac{2\lambda+3}{2\lambda+2}$*. In the WEPP model, Chapter 4 (1988), Rawls, Stone and Brakensiek in equation [4.4.1] use the form $\frac{2+3\lambda}{1+3\lambda}$.

The impact of divergence of the lambda factor between λ values from 1.0 to 0.04 is graphically shown on Figure ___. The plotting shows the two lambda factors corresponding to the mean lambda value by texture class. The one standard deviation range is also shown.

* This is attributed to Brakensiek (1977)



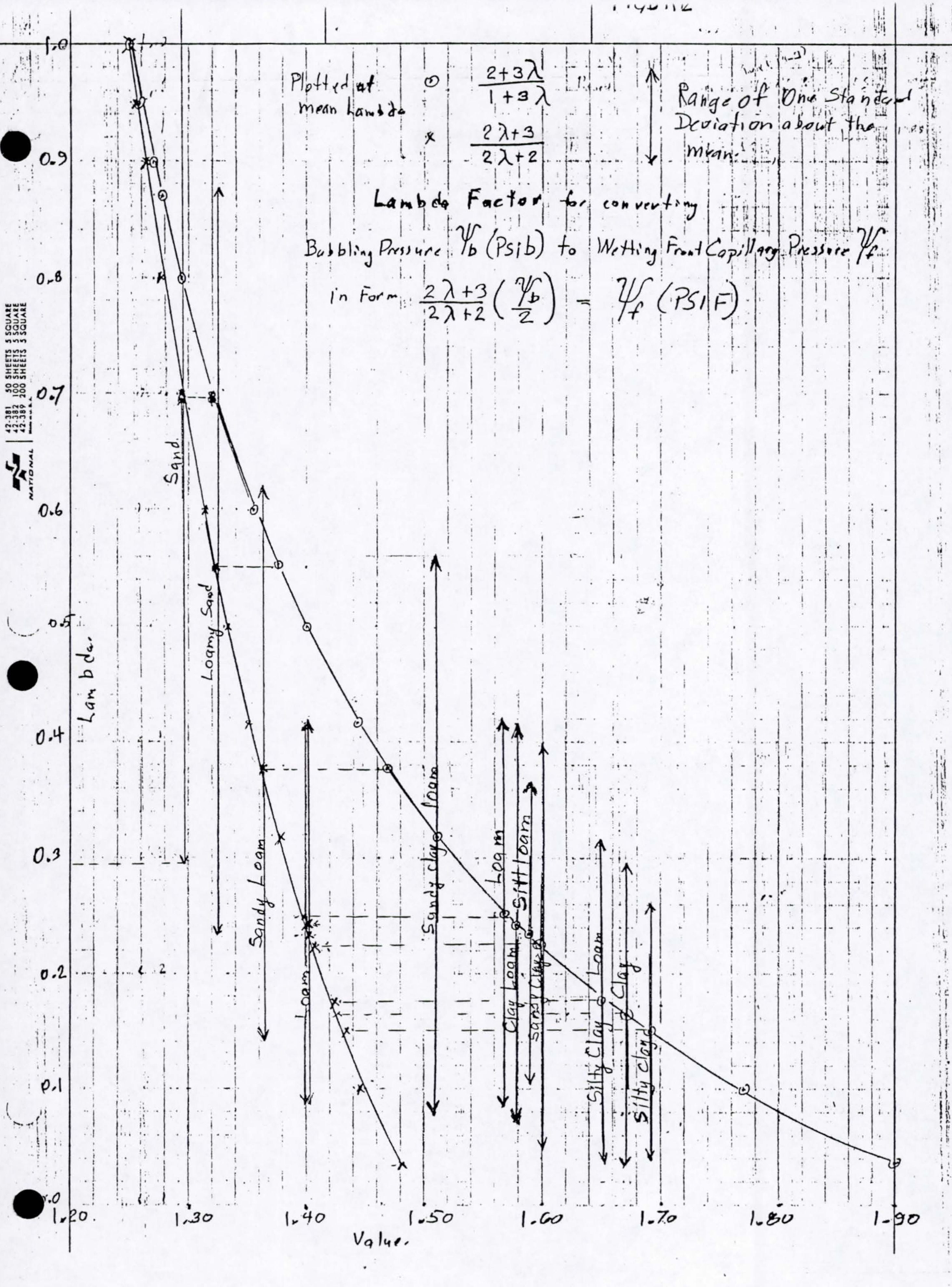
⊙ $\frac{2+3\lambda}{1+3\lambda}$
× $\frac{2\lambda+3}{2\lambda+2}$
Lambda Factor for converting
Bubbling Pressure ψ_b (PSib) to Wetting Front Capillary Pressure ψ_f
in Form $\frac{2\lambda+3}{2\lambda+2}\left(\frac{\psi_b}{2}\right) = \psi_f$ (PSIF)
Lambda
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1.20.
1.30
1.40
1.50
1.60
1.70
1.80
1.90
Value


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
λ (Lambda)
0.0
−
0.0
+
5.0
10
15
20
25
% Difference

Green-Ampt. | LAMBDA FACTOR. | PSIF

Ratio Difference in Lambda factor for converting Bubbling Pressure ψ_b to wetting front capillary pressure ψ_f PSIF (Arithmetic)

Lambda	Standard Deviation −	Standard Deviation +	Brakensiek (1977) $\psi_f = \frac{2\lambda+3}{2\lambda+2}\left(\frac{\psi_b}{2}\right)$ JHYDEND (4)		(1988) WEPP 4. PSIF (4.4.1) Rawls, Brakensiek (1983) $PSIF = \frac{2+3\lambda}{1+3\lambda}\left(\frac{PSIB}{2}\right)$		% Difference
Sand 0.694	.298	1.090	1.2952	1.2392✓ 1.3852	1.3295	1.2342 1.5280	0.995 −0.405 +2.26 +10.3
0.553	.234	.872	1.3220	1.2671✓	1.3761	1.2765	+0.75 ? +4.1
0.378	.140	.616	1.3628		1.4686		+7.76
0.252	.086	.418	1.3994	1.3526	1.5695	1.4437	+6.7 +12.2
0.234	.105	.363	1.4052		1.5875		+13.0
0.319	.079	.559	1.3791		1.5110		+9.6
0.242	.070	.414	1.4026		1.5794		+12.6
0.177	.039	.315	1.4248		1.6532		+16.0
0.223	.048	.398	1.4088		1.5992		+13.5
0.150	.040	.260	1.4248		1.6897		+17.8
Clay 0.165	.037	.293	1.4822		1.9000		+28.2
0.1			1.4545		1.7692		+21.6
0.5			1.3333		1.4000		+5.0
0.6			1.3125		1.3571		+3.4
0.7			1.2941		1.3226		+2.2
0.8			1.2778		1.2941		+1.3
0.9			1.2632		1.2703		+0.6
1.0			1.250		1.250		+0.0
0.95			1.2564		1.2597		0.27
0.44							


Plotted at mean Lambda
⊙ (2+3λ)/(1+3λ)
x (2λ+3)/(2λ+2)
Range of One Standard Deviation about the mean.
Lambda Factor for converting
Bubbling Pressure Ψb (Psib) to Wetting Front Capillary Pressure Ψf
in Form (2λ+3)/(2λ+2) (Ψb/2) = Ψf (PSIF)
Sand
Loamy Sand
Sandy Loam
Loam
Sandy clay Loam
Loam
Silt loam
Clay Loam
Sandy Clay
Silty Clay Loam
Clay
Silty clay
Lambda
Value.
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90

APPENDIX 6-H

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APPENDIX 6-I

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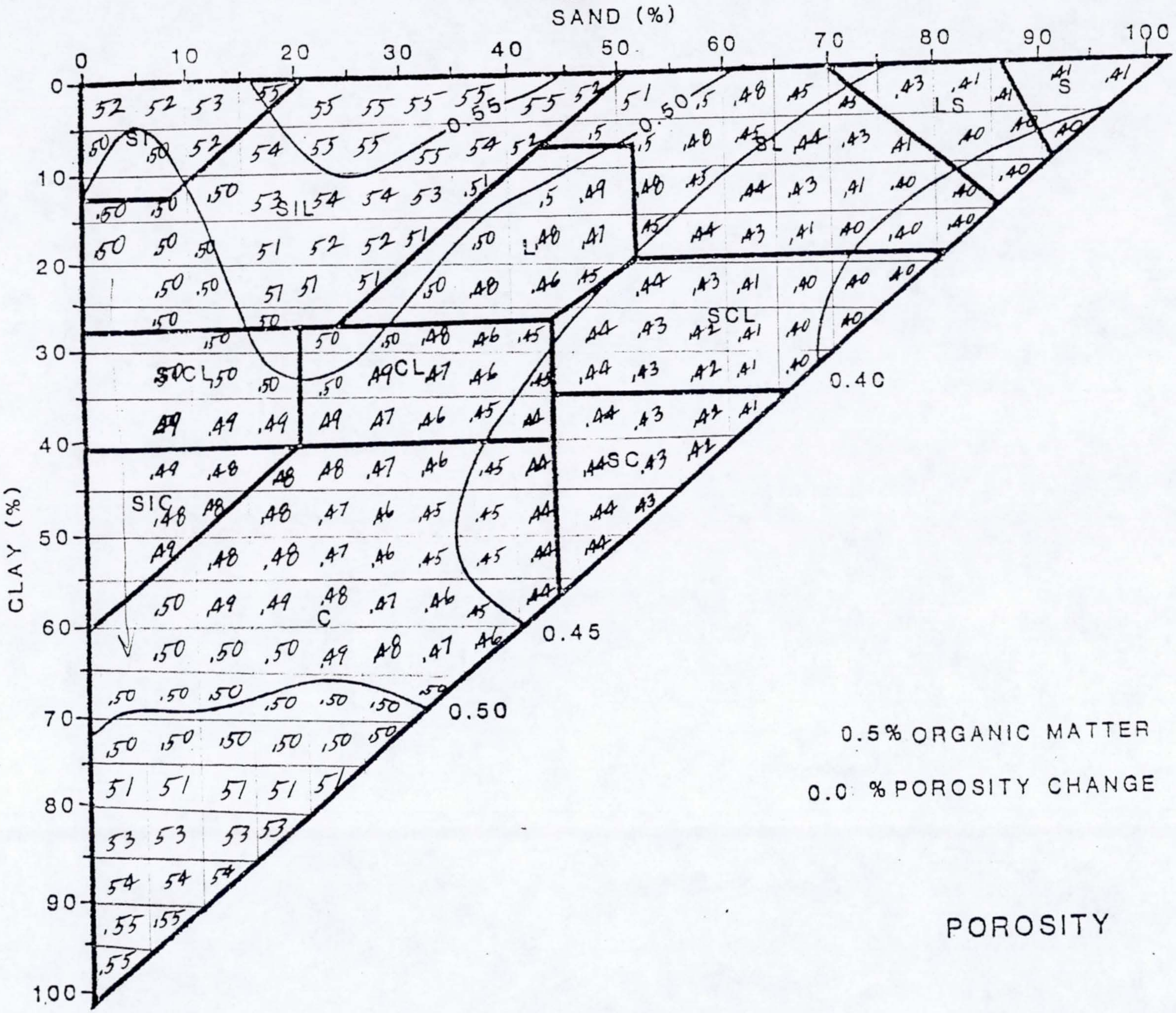
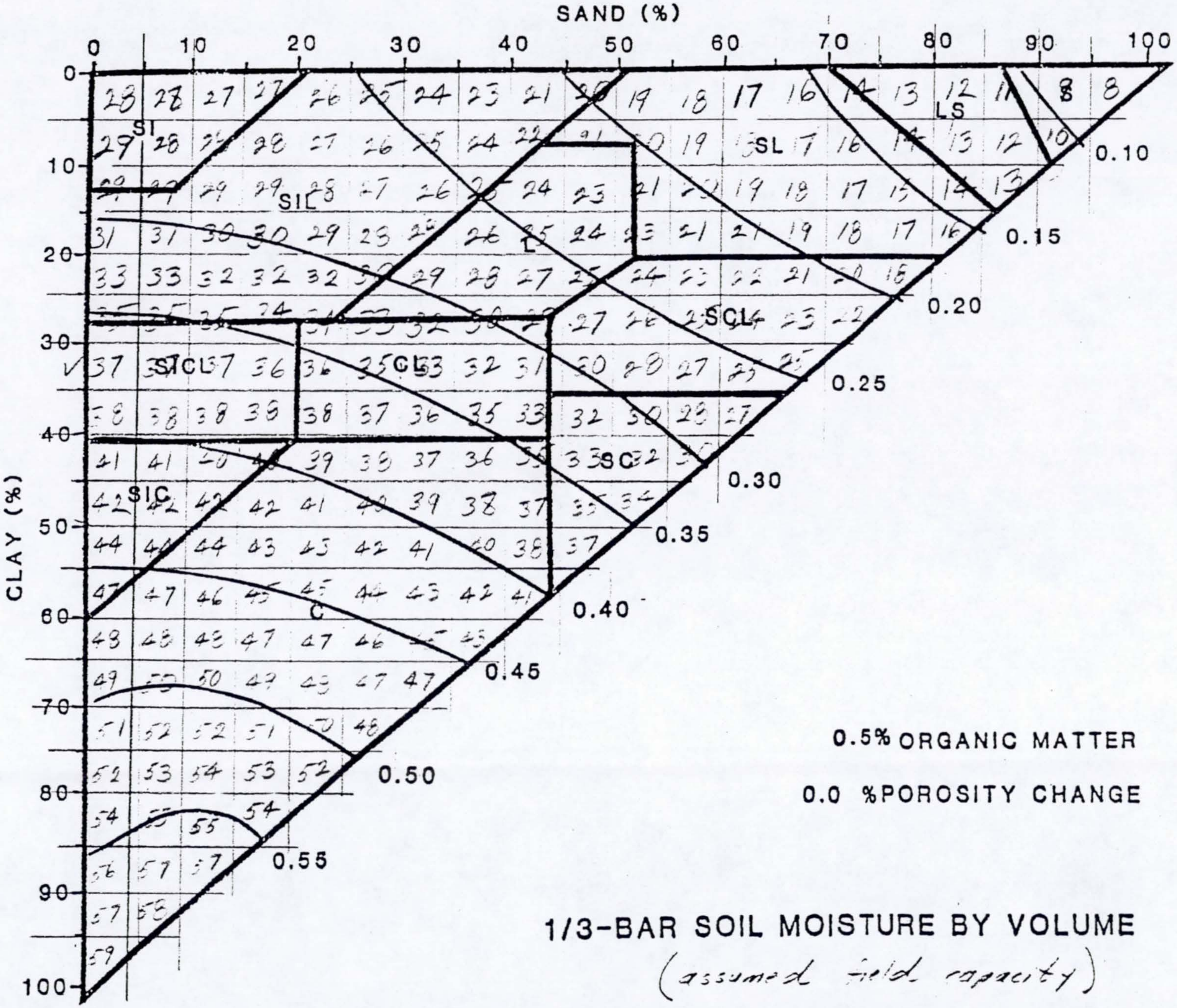
APPENDIX 6-J



0.5% ORGANIC MATTER

0.0 % POROSITY CHANGE

POROSITY

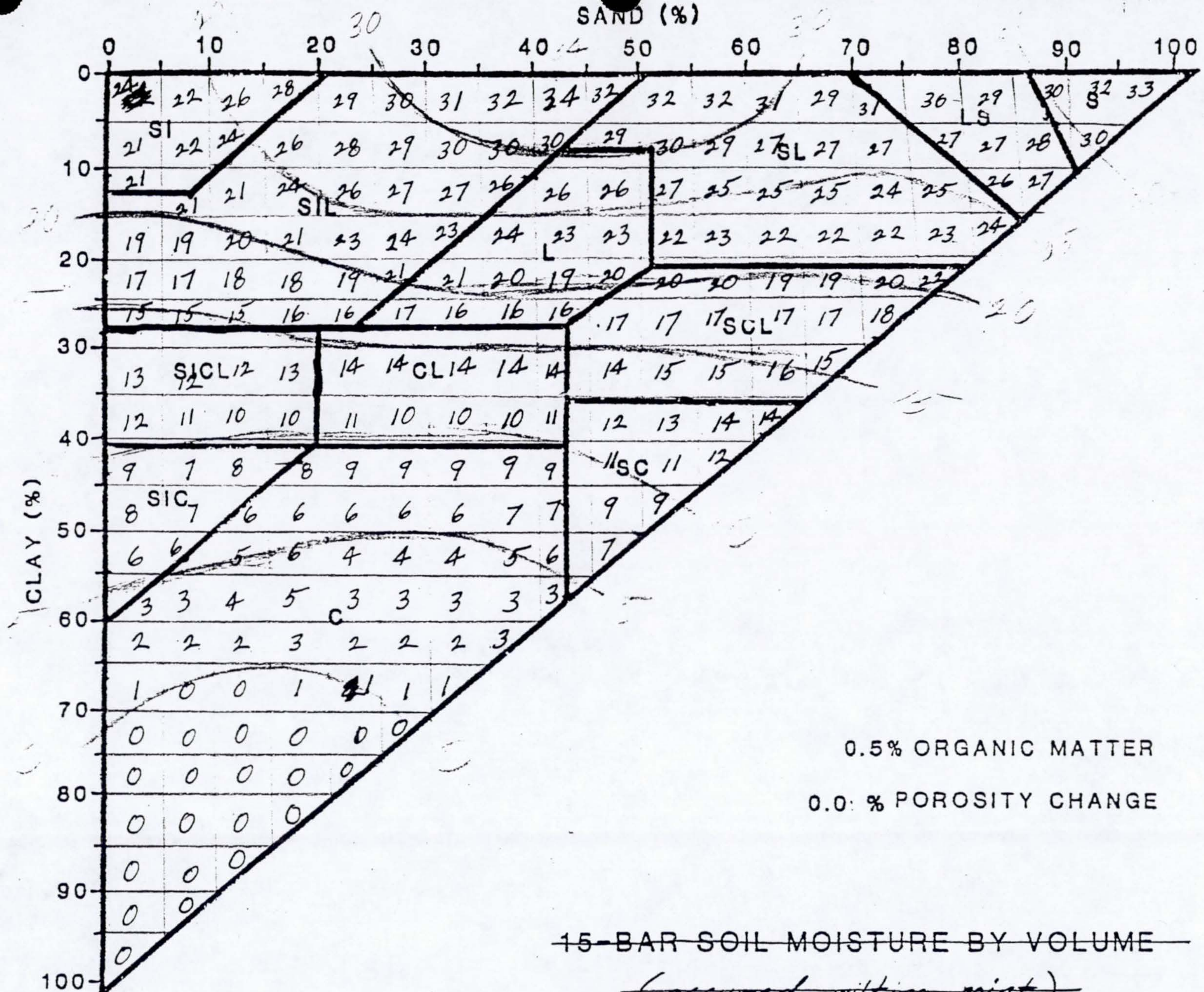


0.5% ORGANIC MATTER

0.0 %POROSITY CHANGE

1/3-BAR SOIL MOISTURE BY VOLUME

(assumed field capacity)



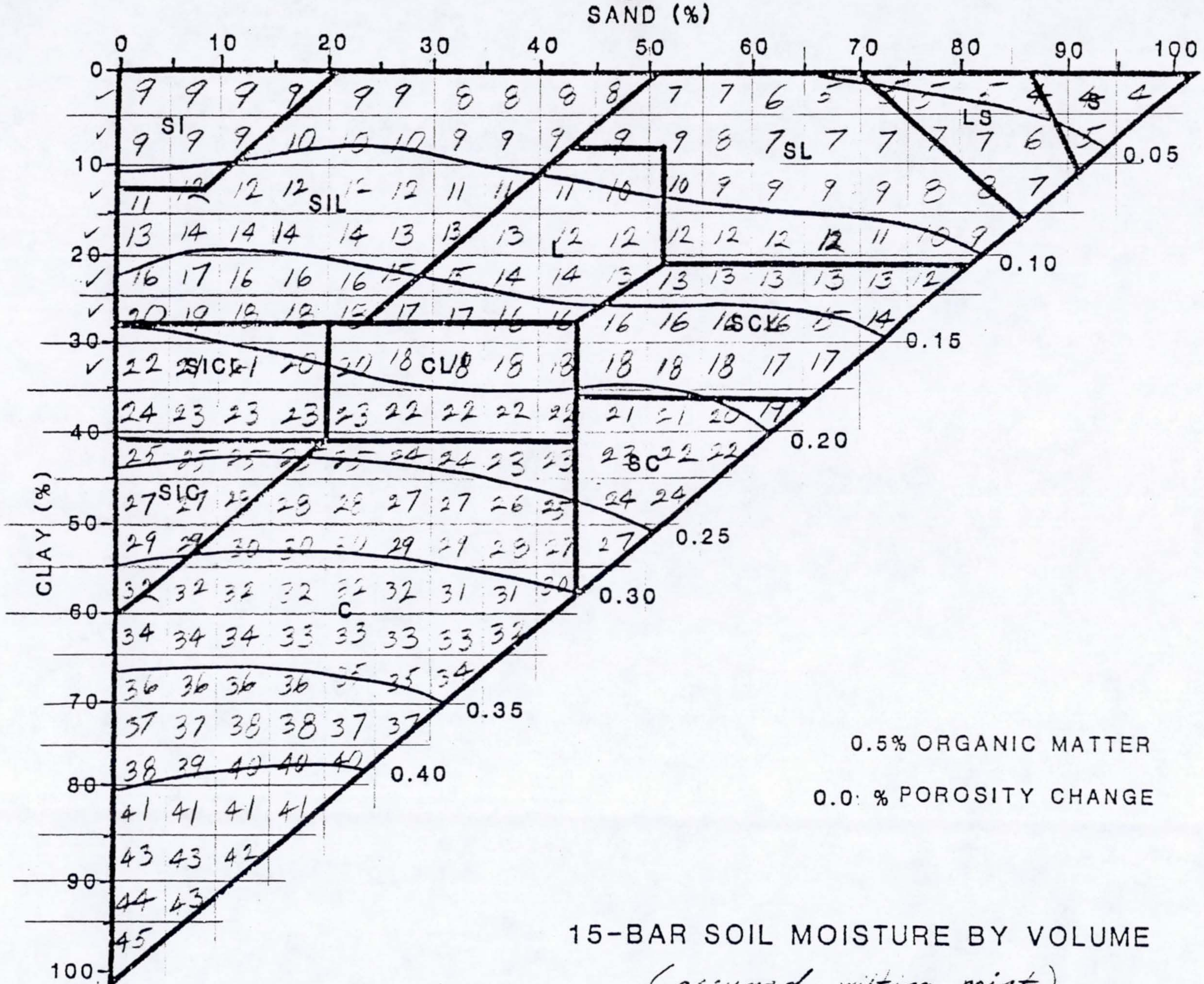
0.5% ORGANIC MATTER

0.0 % POROSITY CHANGE

~~15-BAR SOIL MOISTURE BY VOLUME~~

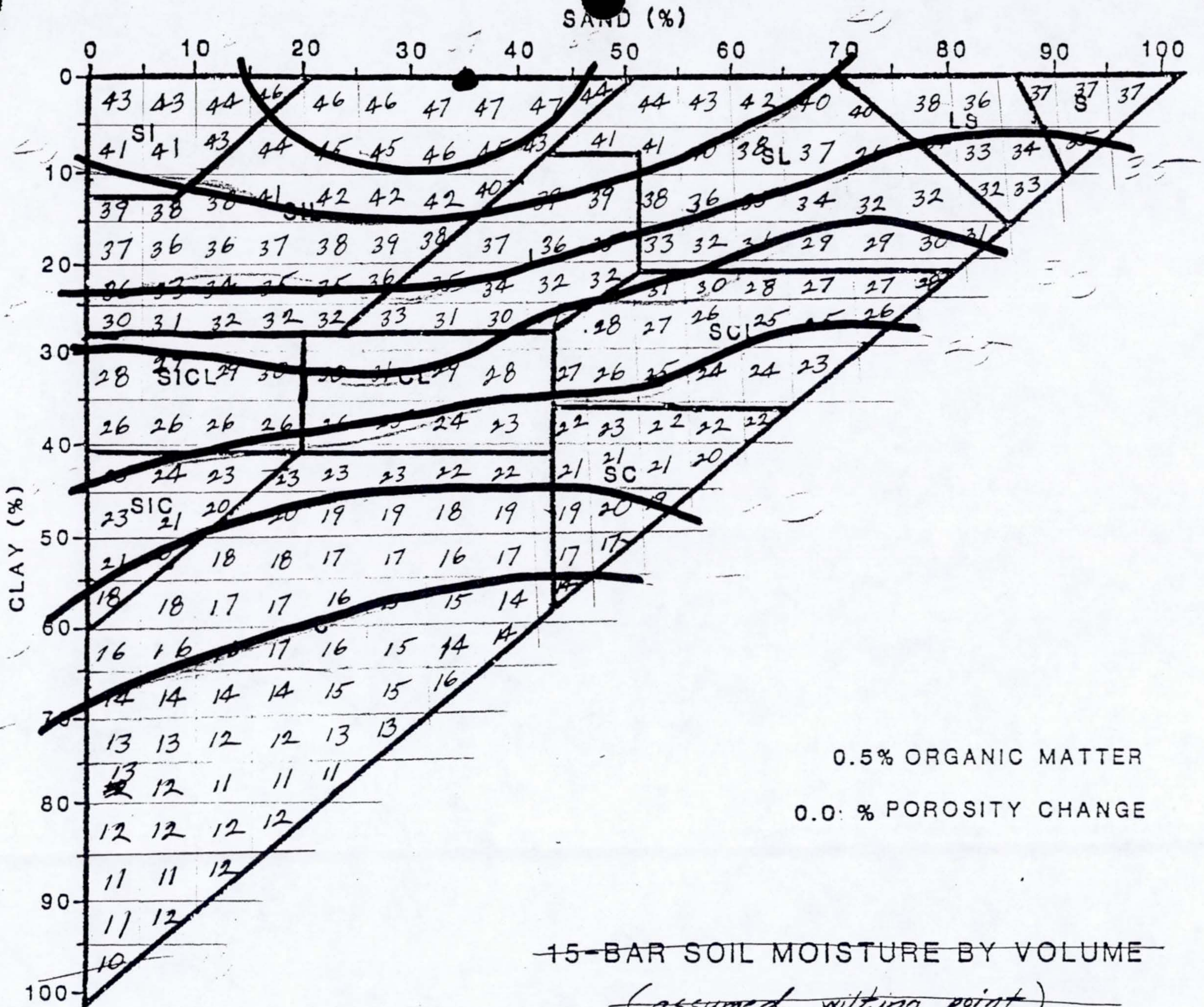
~~(assumed wilting point)~~

DTHETA for difference between porosity (saturation) and field capacity



15-BAR SOIL MOISTURE BY VOLUME

(assumed wilting point)



0.5% ORGANIC MATTER

0.0 % POROSITY CHANGE

~~15-BAR SOIL MOISTURE BY VOLUME~~

~~(assumed wilting point)~~

DTHETA for difference between Porosity (saturation) and wilting point

APPENDIX 6-K

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APPENDIX 6-L

28 April 89

Applicability of the hydraulic conductivity equation to incorporate canopy cover & ground cover effects

Reference - "Infiltration parameters for rangeland soils"
Rawls, Brakensiek, Savabi 1989
Journal of Range Management V. 42 No. 2 p. 139-142

Equations 8, 9, and 10 are very sensitive to the value of A.

$$A = \exp(2.82 - .099\,SA + 1.94\,BD) \qquad (Eq.\ 13)$$

SA = % sand
BD = bulk density, g/cm^3

And, therefore this is mainly a function of SA; BD being nearly constant for all soil types.

Eq'n. 13 was developed by regression of data for the following:

	SA, %	BD, g/cm^3	Canopy Cover, %	Ground Cover, %
Hutton (1984)	25-68	.9-1.3	0-65	50-100
Devaurs (1984)	38-59	1.1-1.5	30-52	69-93
Thurou (1985)	27-88	.85-.95	27-57	57-79

Rawls, Brakensiek and Savabi state beneath Eq. 13 that:

1. A was constrained to be > 1.0
2. Eq. 13 will produce extremely high A values for SA < 20%
3. limit the use of Eq. 13 to a maximum A of 18

Table 1A shows the assumed soil properties and values of A, B, and CRC. Notice that:

1. A < 1.0 for sand, loamy sand, and sandy loam
2. A > 18 for silt loam, silty clay loam, silty clay, and clay

A program was written (XKE.BAS) to perform the hyd. conductivity calculation. A copy of this program and results for sandy loam are enclosed. The results are reasonable for this soil, which is predominant in much of Maricopa County.

I wanted to compare the results that would be obtained for various soils. To do this I divided Eq. 10 by the bare soil hydraulic conductivity (XKSAT)

$$RKE = \frac{KE}{XKSAT} = \frac{CAN * KE_C + OP * KE_O}{XKSAT}$$

where RKE is the ratio of the hydraulic conductivity with canopy and ground cover influences to the bare ground hydraulic conductivity. A program was written (RKE.BAS) to perform the calculation. A copy of the program and results are enclosed. Some results are unbelievable (for soils with low SA).

I then plotted the results from RKE.BAS for several soils (enclosed). The results for ~~loam~~ sand and ~~sandy loam~~ loamy sand don't look reasonable; notice that $A < 1.0$ for these.

The results for sandy loam look reasonable, but $A = .811$
The results for sandy clay loam also look reasonable ($A = 1.61$).
The results for loam ($A = 3.94$) and sandy clay ($A = 2.65$) seem to over compensate for canopy and ground cover.

Finally, I modified the program to set $A = 1.0$ and the results are shown for sandy loam. Computer output are provided for sandy loam (XKSAT = .40 in/hr), loam (XKSAT = .25 in/hr), and sandy clay loam (XKSAT = .06 in/hr). As seen from the computer output, the graphs from these three soils would all look very much like Figure 7A.

Conclusions

Based on the results that are shown it appears that:

1. The procedure as provided by Rawls, Brakensiek, and Savabi should not be used for many of the soil texture classifications.

2. There is extremely high sensitivity to the value of A.

3. When A=1.0 is used, the ratio of hydraulic conductivities (RKE) converges to a single set of curves (Figure 7A) for sandy loam, loam, and sandy clay loam.

4. The soils for which it was shown that RKE converges have hydraulic conductivities from .06 to .40 in/hr. This is the range of hydraulic conductivities ~~that~~ is normally encountered.

5. Figure 7A demonstrates a range of RKE that compares with the results that Tim Ward is reporting for rainfall simulator studies.

6. Figure 7A is much easier to use than the equations in Rawls, Brakensiek, and Savabi.

7. It is possible that Figure 7A is applicable for most soils.

8. It is possible that A=1.0 for most soils and that A=1.0 should be used rather than Eq. 13.

Question

Can Figure 7A be used for most soils (exclusive of sand, silt, and clay texture classes - all of which are uncommon in nature, and for which there may not be a need to correct the bare soil hydraulic conductivity)?

TABLE 1A

Soil Texture	Bare Soil hyd. conductivity XKSAT in/hr	Sand Content SA %	Bulk Density BD gm/cm^3	Soil Crusting Factor SC	A[1]	B[2]	CRC[3]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
sand	4.6	90	1.55	.91	.046	.175	.674
loamy sand	1.2	80	1.55	.89	.123	.147	.626
sandy loam	.40	60	1.5	.86	.811	.102	.530
loam	.25	45	1.55	.82	3.94	.076	.452
silt loam	.15	20	1.25	.81	26.2 *	.051	.362
silt		5	1.40				
sandy clay loam	.06	55	1.60	.85	1.61	.092	.505
clay loam	.04	35	1.45	.82	8.74	.064	.412
silty clay loam	.04	10	1.4	.76	94.2 *	.047	.335
sandy clay	.02	50	1.6	.81	2.65	.084	.471
silty clay	.02	5	1.45	.73	170.4 *	.046	.326
clay	.02	20	1.4	.75	35.0 *	.051	.350

* A > 18 which exceeds the maximum value of A in the data set

1) $A = \exp\left[2.82 - .099(SA) + 1.94(BD)\right]$

2) $B = .0099 + .0721(TC) + .0000068(SA^2) + .00002(SA^2)(TC) - .000315(SA)(TC^2)$

3) $CRC = \dfrac{L}{\dfrac{L-TC}{SC} + \dfrac{TC}{B}}$

Note: $L = 6$ cm $TC = .5$ cm

Definition sketch of canopy cover and ground cover variables (Rawls, Brakensiek & Savabi, 1989)

canopy is crosshatch

ground cover* is solid

bare ground is unmar

*ground cover is : rock, litter, and vegetation basal area

Canopy cover – CAN as % of total area

Not under canopy – $OP = 100 - CAN$

Ground cover = GC is % of total area covered by ground cover

BC = % of bare soil under canopy to total area

$$BC = (100 - GC)(CAN/100)$$

BO = % of bare soil not under canopy to total area

$$BO = (100 - GC)(OP/100)$$

Example : canopy cover = 15 %
ground cover = 20 %

$CAN = 15\ \%$

$OP = 85\ \%$

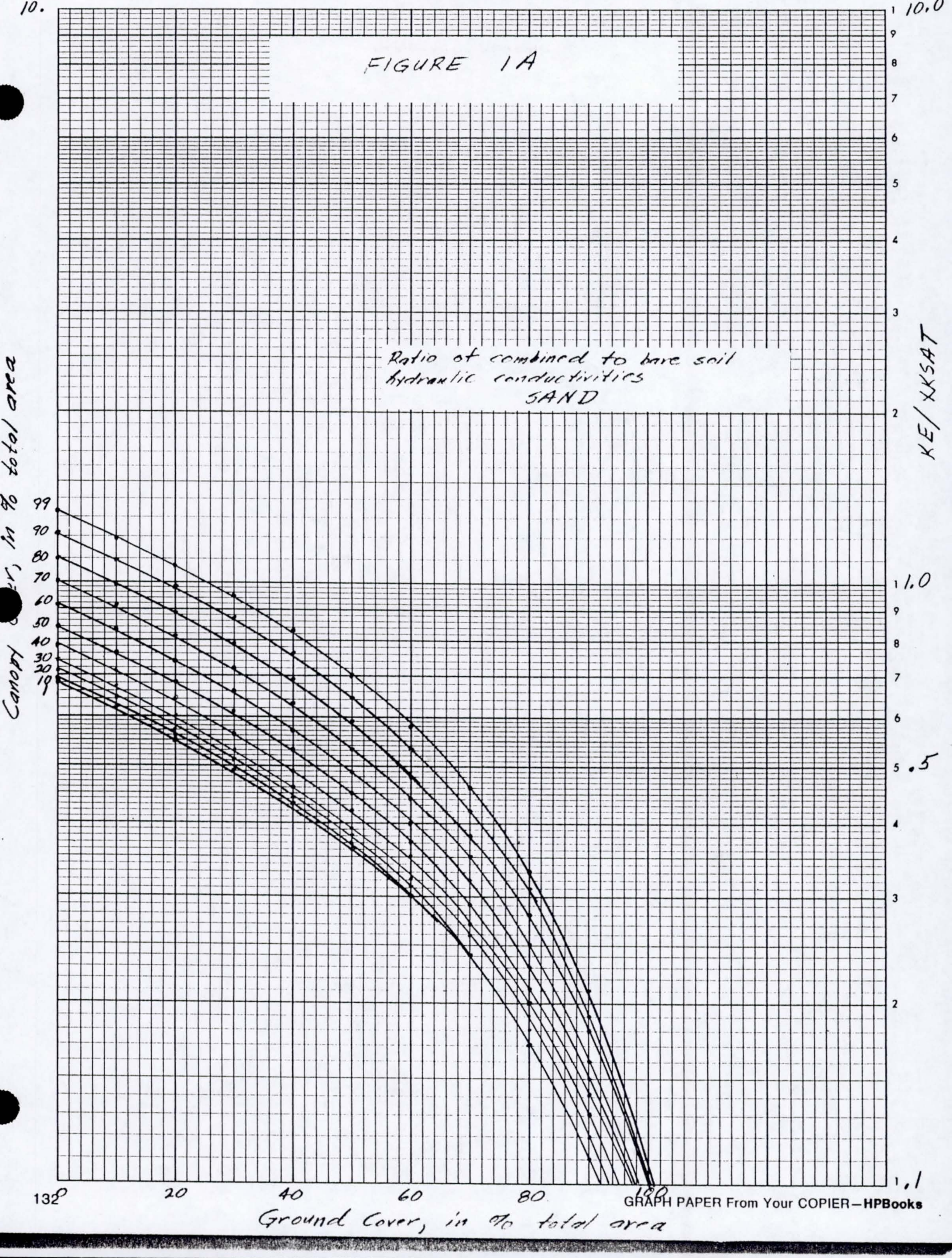
$BC = (100-20)(15/100) = 12\ \%$

$BO = (100-20)(85/100) = \underline{68\ \%}$

$80\ \%$

70 Divisions 5th, 10th Accent by 2 Cycle Semi-Log

27 April 89



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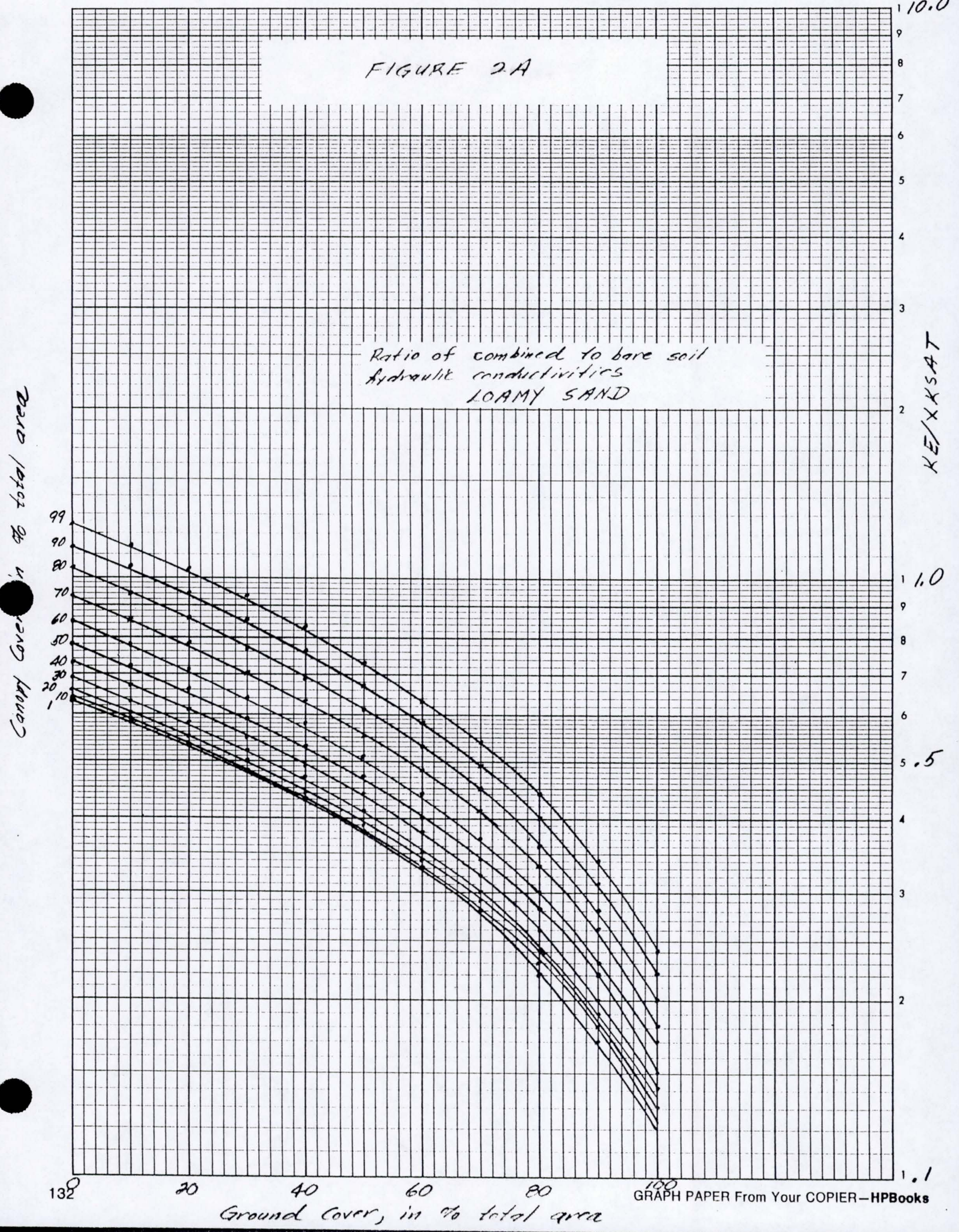
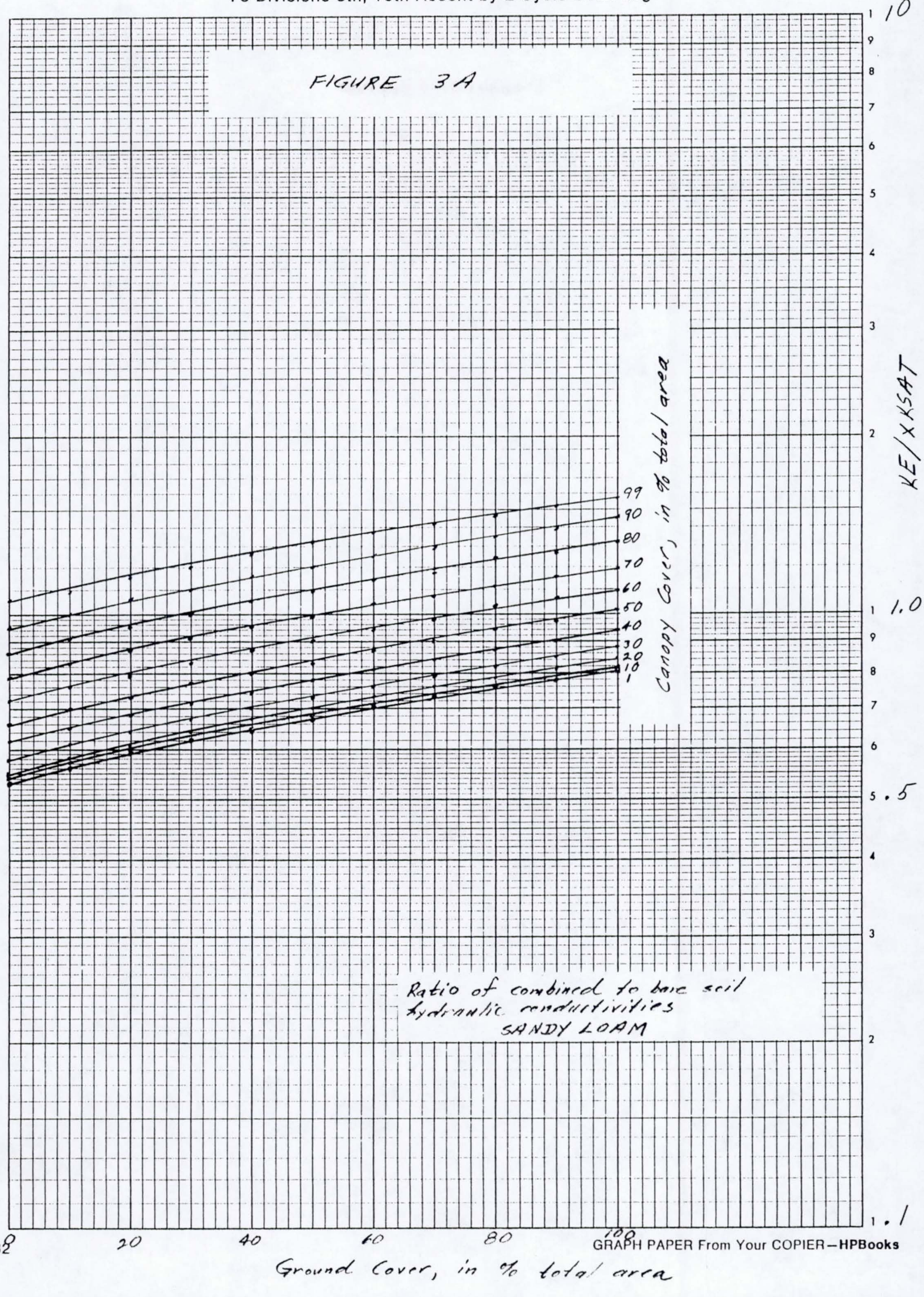
27 April 84

FIGURE 2A



70 Divisions 5th, 10th Accent by 2 Cycle Semi-Log



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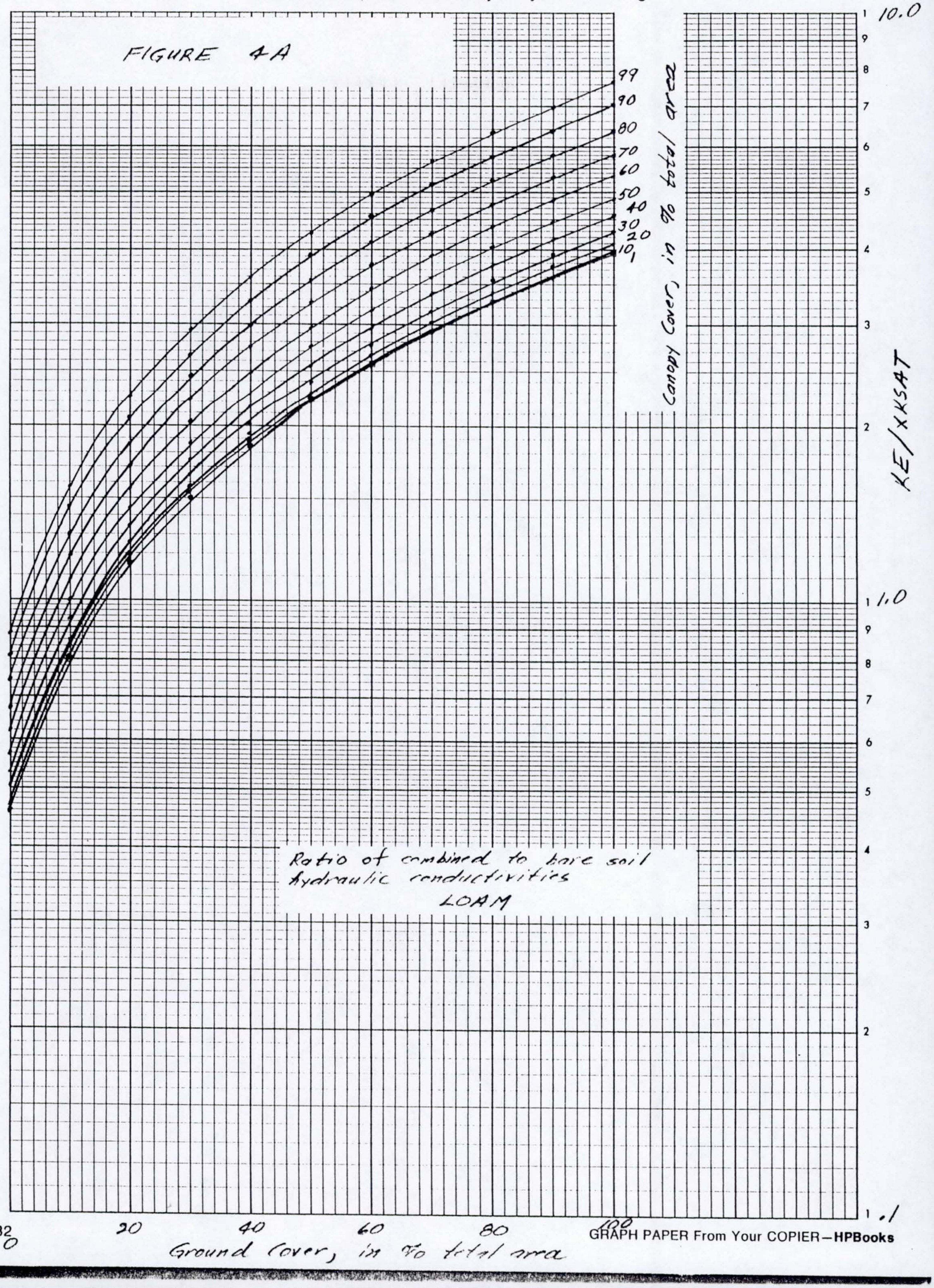


FIGURE 4A
99
90
80
70
60
50
40
30
20
10
1
Canopy Cover, in % total area
10.0
1.0
.1
KE/XKSAT
Ratio of combined to bare soil
hydraulic conductivities
LOAM
0
20
40
60
80
100
Ground Cover, in % total area

27 April 89

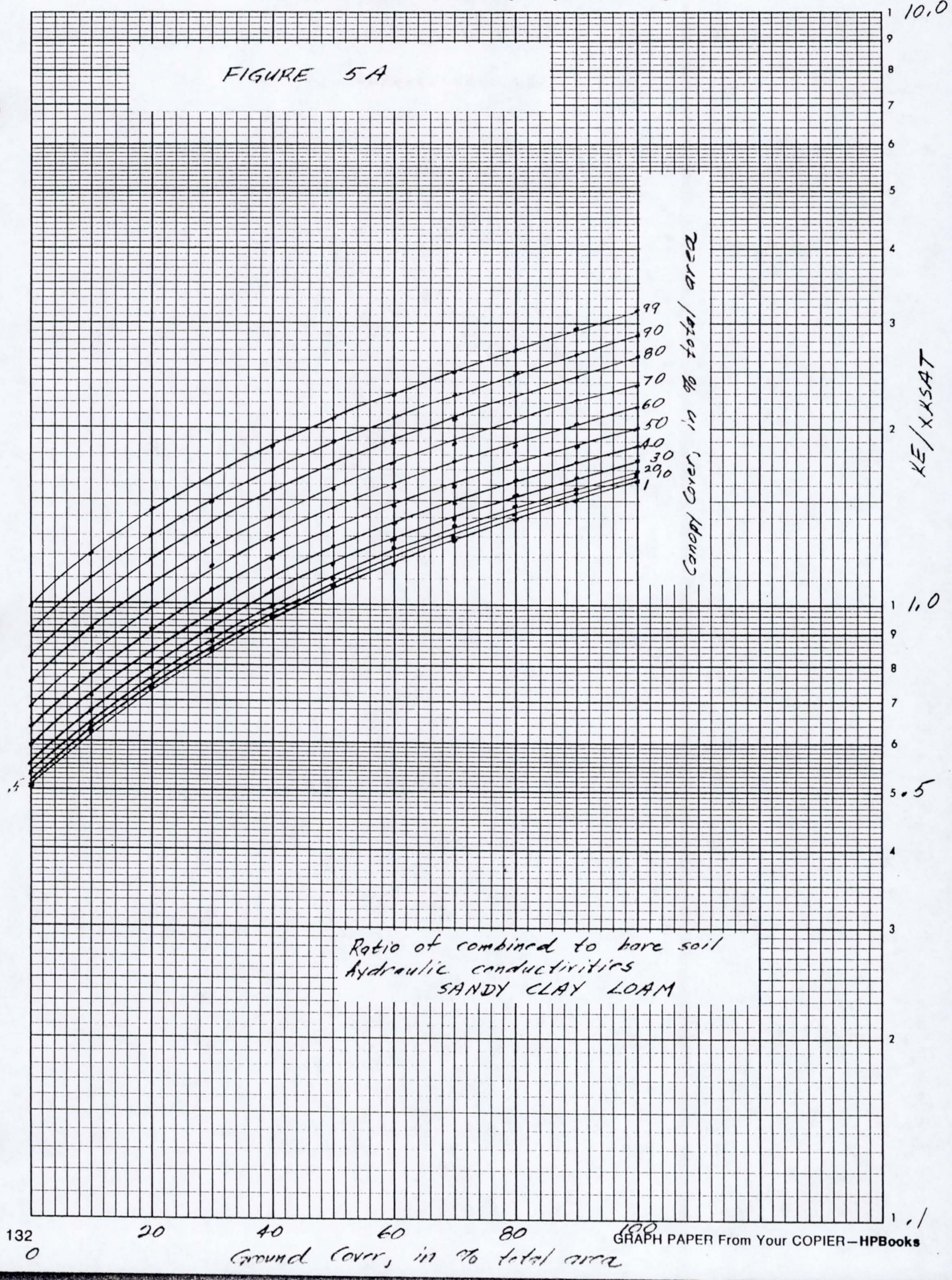
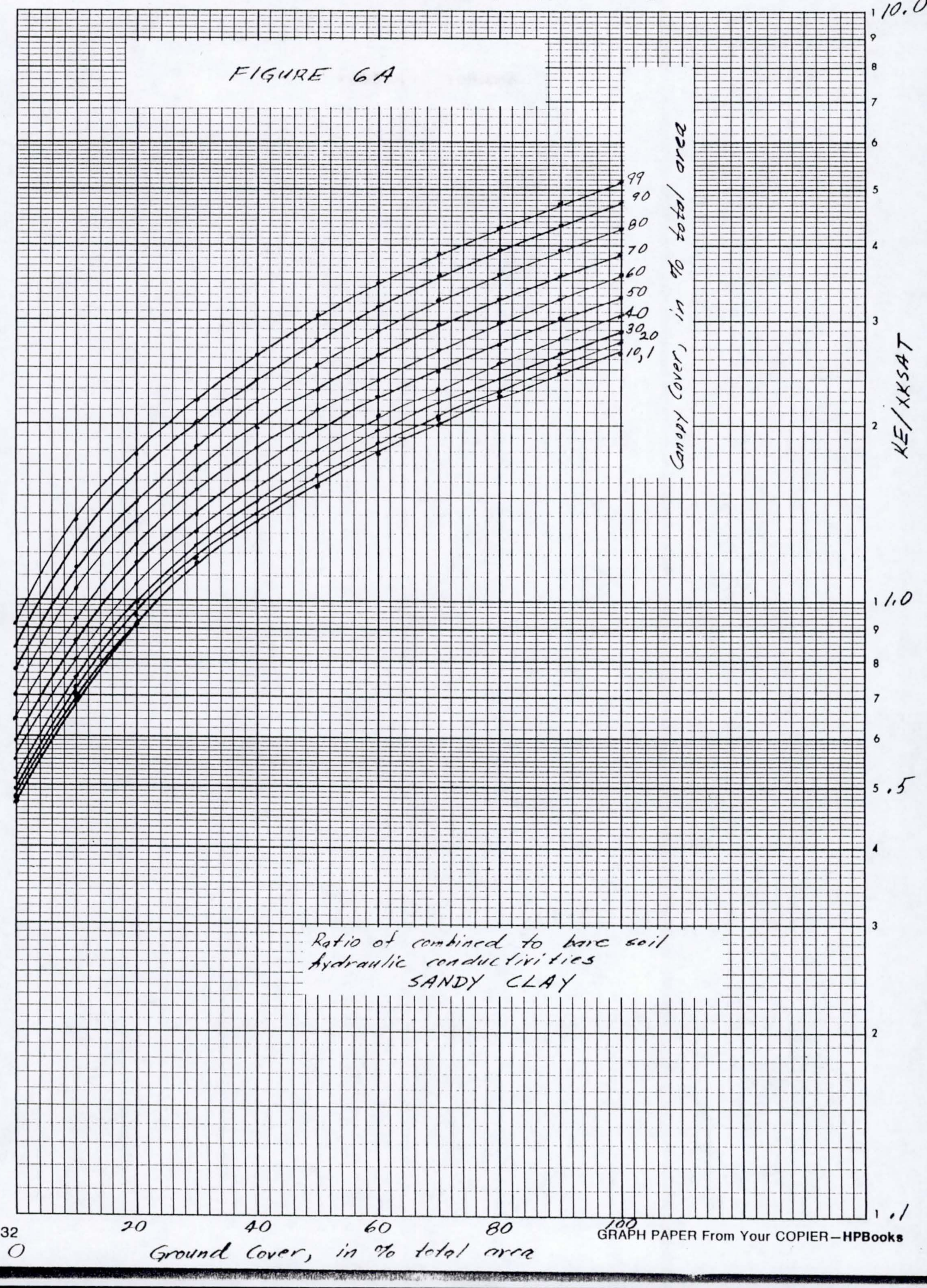


FIGURE 5A
Canopy Cover, in % total area
99
90
80
70
60
50
40
30
20%
1
KE/KKSAT
10.0
1.0
.5
.1
Ratio of combined to bare soil
hydraulic conductivities
SANDY CLAY LOAM
0
20
40
60
80
100
Ground Cover, in % total area

70 Divisions 5th, 10th Accent by 2 Cycle Semi-Log

27 April 89



28 April 87

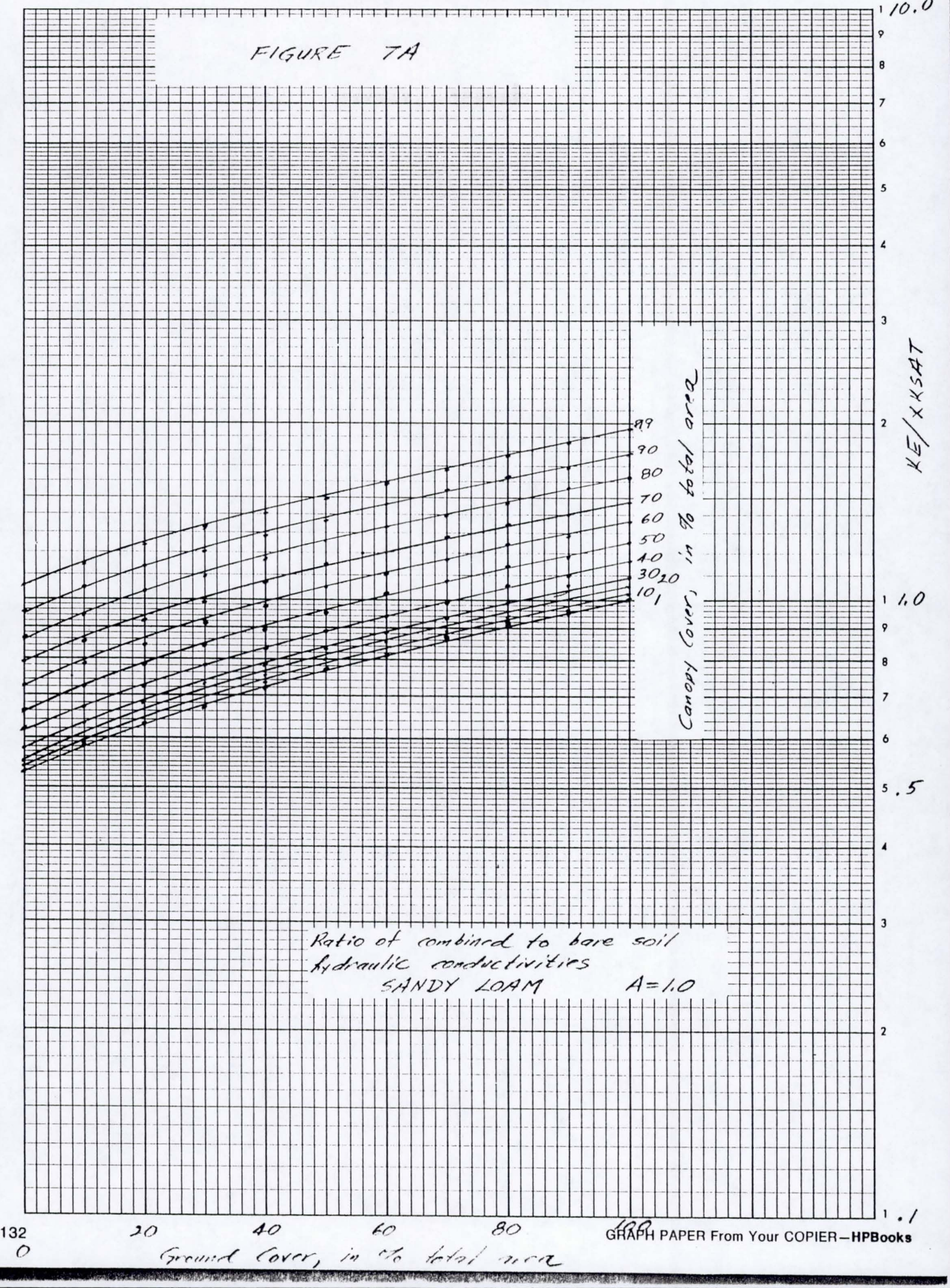


FIGURE 7A
Canopy Cover, in % total area
99
90
80
70
60
50
40
30
20
10
1
KE/XKSAT
10.0
1.0
.5
.1
Ratio of combined to bare soil
hydraulic conductivities
SANDY LOAM A=1.0
0
20
40
60
80
100
Ground Cover, in % total area

APPENDIX 6-M

TO: GEORGE SABOL RE HIS 28 APRIL CORRESPONDENCE

SUBJECT: PROPOSED FIGURE 7A AS A METHOD OF ADJUSTING VALUES OF BARE SOIL HYDRAULIC CONDUCTIVITY Ks0 TO REFLECT CANOPY COVER AND GROUND COVER

FROM: L. J. LANE

George:

I think we are close to solving the problem of how to derive simplified means of estimating Ks to use in the Green-Ampt infiltration equation.

I must confess, I am still somewhat confused by the complicated regression equations from Rawls, et al. But, I have a proposal for you which may help clear up the confusion.

If you could clean up and document a straight forward way to account for coarse fragments in the soil, crusting, and bulk density changes affecting Ks, I can take care of canopy cover and ground cover effects.

Consider an equation of the form:

Ks = Ks0*(exp(Acc*cc5))*(exp(Agc*gc%))

where:
- Ks = Adjusted Ks for use in Green-Ampt eq. (mm/h),
- Ks0 = Bare soil Ks incorporating coarse fragments in the profile, crusting, and changes in bulk density (mm/h),
- Acc = Coefficient expressing influence of canopy cover,
- cc% = Percent canopy cover (%),
- Agc = Coefficient expressing influence of ground cover, and
- gc% = Percent ground cover (%).

If you could develop procedures to get estimates of Ks0, I have some ideas for the canopy cover and ground cover effects.

In the following Analysis Notes, I derive first order estimates of Acc and Agc for data from 32 rainfall simulator plots in Arizona, Nevada, and New Mexico.

But first a question for you. In your Fig. 7A, why is the value of KE/XKSAT less than one (~0.53) for values of 0.0 ground cover and 0.0 canopy cover? I thought the bare soil Ks0 was the minimum value and Ks increased with addition of canopy cover and ground cover. This is why I do not understand why we don't require KE/XKSAT >=1.0?

In any event, please read through my Analysis notes and let me know what the next step is. Perhaps we should set down at a desk together for half to a full day together to clear up any misunderstandings, reach a decision on how to proceed, and to

The problem is my crazy schedule. I will be travelling to Kansas City, Honolulu, Newark, Edmonton, and West Lafayette over the next two and a half months. Following are some proposed dates should you agree on the need for some personal discussions. We should probably count on a full day to accomplish the tasks outlined above.

June: 1. Sat 6/17 (Note Sunday June 18 is Father's Day)

July: 1. Mon 7/3 (Note Tues is July 4)
2. Fri 7/7
3. Sat 7/8

Again, please consider the need for a meeting and let me know if any of the above dates would be convenient for you. You can call and leave a message on my machine at home (602-575-8009) if we wind up missing calls back and forth.

Thanks,

Leonard

Leonard J. Lane

ANALYSIS NOTES

Re: PROPOSED FIGURE 7A AS A METHOD OF ADJUSTING Ks IN THE GREEN-AMPT INFILTRATION EQUATION FOR THE MARICOPA COUNTY HYDROLOGY MANUAL

I. SELECTION AND PRELIMINARY ANALYSIS OF DATA

My personal library and the University of Arizona Science Library were consulted to find appropriate reports and papers meeting the following criteria.

1. Dealing with rainfall simulator studies in the Southwest
2. Studies reporting some soils information including surface soil texture, or providing sufficient information in the text to allow estimation of apparent surface soil texture.
3. Studies reporting percent canopy cover, percent ground cover, and measured final infiltration rate Kf as a statistic representing a field-measured estimate of Ks.

My quick literature search and quick trip to the library turned up four key references listing data on 32 experimental plots (Table 1). The soils on the sites listed in Table 1 were all poorly described in the text with textures given as sand, gravelly loamy sand, gravelly sandy loam, fine sandy loam, and sandy loam. From narrative descriptions given in the texts of the papers, I classified the soils as sand (Sa), Loamy Sand (LSa), Sandy Loam (SaL), and Loam (L) in the last column of Table 1. Those classified as Loam probably are Sandy Loam near the Sandy Loam--Loam border. In any event, my textural classifications are not rigorous but are more "apparent" based on my reading of the texts, my knowledge of the sites, and the grouping of the resulting Kf values. I am far from satisfied with these classifications or groupings. But, as long as our soils colleagues continue to use such descriptive and qualitative descriptions of soils and concentrate their efforts on profile properties as opposed to surface and near surface properties, we in the West will suffer from poor soils information.

The quantitative data from the publications are summarized in Table 2. Of the four textural classes in Table 2 (Sa, LSa, SaL, and L), LSa and SaL could probably be combined based on the statistics of the measured Kf values shown in the last column. But, I suggest we keep them separate for now as we don't know how really representative the values are of all possible Loamy Sands and Sandy Loams.

II. ANALYSIS & PREDICTION OF Ks FROM Ks0, CC%, AND GC%

An equation of the following form was hypothesized as a means of adjusting Ks0 for canopy and ground cover effects. Because I had trouble understanding how to get coarse fragments, crusting, etc. into the estimate of Ks0, I decided to get estimates of it by optimization.

The proposed equation is an exponential form which has some desirable properties such as robustness and known properties in the limits. The proposed equation is

$$Ks = Ks0*[exp(Acc*cc\%))*(exp(Agc*gc\%))] \quad (1)$$

where: Ks = Adjusted Ks value to use in Green-Ampt eq. (mm/h),
Ks0 = Bare soil Ks value adjusted for crusting, etc. (mm/h),
Acc = Coefficient for canopy cover effects,
cc% = Percent canopy cover,
Agc = Coefficient for ground cover effects, and
gc% = Percent ground cover.

A least squares program was written to read in observed Kf data from Table 2, assume initial values of Ks0, Acc, and Agc, calculate corresponding values of Ks from Equation 1, and find the least squares or best estimates of Ks0, Acc, and Agc. Except for the Sand, it looked like 0.01 provided a reasonable (not optimal as I have not done a complete analysis) value for Acc and Agc. For Sand, I assumed Acc = 0.005 because canopy effects seem to diminish for the sandier soils. Of course, these somewhat arbitrary selections for Acc and Agc no doubt affect the optimal value of Ks0. This is a problem for a subsequent multivariable optimization study. I do not have the appropriate software available. However if you have a statistical package which can do multiple regression, we could take the log transform of Equation 1 and estimate all three parameters by least squares regression. I did not think you wanted me to take the large amount of time to write such a program and, in fact, you probably already have one we can use if we get together.

Table 3 lists the Ks0, Acc, and Agc values used for each of the four apparent textural classes and the final column of table 3 shows the estimated Ks values. As you will see, these predictions are quite close to the measured Kf values considering the data were collected over a 20+ year period by a variety of investigators using many different techniques.

Table 4 contains data summarizing how well the Ks values correlate with the measured Kf values by class and for all data. The corresponding Kf and Ks values and the regression line between them is shown in Fig. 1. My conclusion is that if you can get the right Ks0 value, then the proposed equation and the parameter values shown in Table 4 can be used to estimate Ks values sufficiently accurate for practical applications.

Figure 2 shows Ks/Ks0 vs ground cover and canopy cover for the Sand and similar results are shown for the other texture classes in Figure 3.

If you compare Figure 3 with your Figure 7A, you will notice the following:

1. Fig. 3 suggests the range of influence of ground cover is from exp(0.0) = 1.0 to exp(1.0) = 2.718 as is the influence of canopy cover so long as Acc=Agc=0.01. Your Fig. 7A

suggests about a factor of 2 correction for canopy cover and also for ground cover. Again, I don't know why KE/XKSAT is not 1.0 when canopy cover and ground cover are both zero.

2. The corrections to Ks0 due to canopy cover and ground cover are exponential and thus transform to "nice" straight lines on semilog paper as shown in Fig. 3. This makes for easy interpolation.

3. Figure 3 incorporates optimal or least squares estimates for Ks0. How does Ks0 enter in your Fig. 7A?

III. SUGGESTIONS

1. Please go through my notes and analysis to make sure they are correct and that I did not misinterpret your results.

2. Assuming no problems from step 1, please consider combining your work on Ks0 and my work on canopy and ground cover influences as the first practical procedure to estimate Ks on sandy soils in the desert Southwest. We could propose it as a documented procedure, clearly explained, and thus amenable to further testing, evaluation, and refining. Perhaps we could suggest some carefully conducted experiments to evaluate Ks0, Acc, and Agc as well as the form of Eq. 1. In any event, Eq. 1 is the simplest I could come up with which is robust and has reasonable, easily apparent limits, yet fits the data so well. But again we need to use log transformations and a multiple regression program to find the true optimal values.

Please let me know what you think of these suggestions. I think we are getting close but are not quite there yet.

L. J. Lane
Tucson

Table 1. Selected referenced with data on canopy cover, ground cover, and final infiltration rates.

Reference	Plot Identification In Reference	Plot Identification Here
Bach, L. B. 1984. Determination of infiltration, runoff, and erosional characteristics of a small watershed using rainfall simulation data. Unpublished MS Thesis, New Mexico State Univ., Las Cruces, NM, 69 pp.	UV	Sa1
	UI	Sa2
	MV	Sa3
	MI	Sa4
	LI	SaL1
Kincaid, D. R., J. L. Gardner, and H. A. Schreiber. 1964. Soil and vegetation parameters affecting infiltration under semiarid conditions. Bull. IASH 65:440-453.	E3	LSa1
	E2	LSa2
	E4	LSa3
	LH-3	LSa4
	E1	LSa5
	K-10	SaL2
Lane, L. J., J. R. Simanton, T. E. HaKonson, and E. M. Romney. 1987. Large-plot infiltration studies in desert and semiarid rangeland areas of the Southwestern U.S.A. Proc. Intrl. Conf. on Infiltration Development and Application., Water Res. Res. Center, Univ. of Hawaii at Manoa, Honolulu, HI, pp.365-376.	BN	LSa6
	BC	LSa7
	BB	LSa8
	A11N	LSa9
	A11C	LSa10
	A11B	LSa11
	CN	SaL3
	CC	SaL4
	CB	SaL5
	HN	SaL6
	HC	SaL7
	HB	SaL8
	MN	L1
	MC	L2
	MB	L3
Ward, T. J. 1986. A study of runoff and erosion processes using large and small area rainfall simulators. New Mexico State Univ. Water Res. Res. Center, Report No. 215, 71p.	WS2	SaL9
	WS3	SaL10
	WS2	Sal11
	WS3	L4
	NMSU	LSa12
	NMSU	LSa13

Table 2. Summary of canopy cover, ground cover, and final infiltration rates for selected data in Table 1.

Plot ID	"Apparent" Textural Class of Surface Soil	% Canopy Cover (%)	% Ground Cover (%)	Final Infil. Rate Kf (mm/h)
Sa1	Sand or Loamy Sand	57.0	35.0	45.8
Sa2	"	25.0	70.4	60.7
Sa3	"	41.2	57.8	75.6
Sa4	"	17.0	82.7	81.0
LSa1	Loamy Sand or Gravelly	44.4	26.7	35.6e
LSa2	Loamy Sand	35.2	27.2	17.3
LSa3	"	32.1	10.5	20.3
LSa4	"	20.3	17.6	14.7
LSa5	"	26.0	14.7	17.0
LSa6	"	65.2	57.3	35.3
LSa7	"	0.0	62.4	21.0
LSa8	"	0.0	23.6	13.7
LSa9	"	21.2	78.4	33.7
LSa10	"	0.0	70.8	29.4
LSa11	"	0.0	16.8	16.3
LSa12	"	5.0	52.7	25.9
LSa13	"	12.0	50.0e	22.1
SaL1	Sandy Loam or Gravelly	23.5	1.9	12.0
SaL2	Sandy Loam	20.0e	17.7	13.2
SaL3	"	34.7	57.9	26.3
SaL4	"	0.0	59.4	15.0
SaL5	"	0.0	18.8	11.6
SaL6	"	48.7	63.9	31.6
SaL7	"	0.0	65.0	19.3
SaL8	"	0.0	21.9	12.4
SaL9	"	23.0	2.1	18.8
SaL10	"	12.0	1.2	14.7
SaL11	"	26.0	2.0e	16.0
L1	Sandy Loam to Loam	22.0	76.5	20.5
L2	"	0.0	78.1	7.3
L3	"	0.0	16.6	4.8
L4	"	22.0	1.0e	7.1

The symbol e represents estimated values using information from the text of the references cited in Table 1.

Table 3. Summary of Ks estimating equations, canopy cover, ground cover, measured final infiltration rates, and estimated Ks values. Estimating equation is Ks = Ks0(exp(Acc*cc%))*(exp(Agc*gc%)) where Ks0 is the bare soil Ks value, cc% is the percent canopy cover, and gc% is percent ground cover. The coefficients are Acc and Agc.

Plot ID	Parameters			% Canopy Cover	% Ground Cover	Final Infil. Rate	Est. Ks
	Ks0 (mm/h)	Acc (--)	Agc (--)	(%)	(%)	Kf (mm/h)	(mm/h)
Sa1	30.0	.005	.01	57.0	35.0	45.8	56.6
Sa2		"		25.0	70.4	60.7	68.7
Sa3		"		41.2	57.8	75.6	65.7
Sa4		"		17.0	82.7	81.0	74.7
LSa1	12.0	.01	.01	44.4	26.7	35.6e	24.4
LSa2		"		35.2	27.2	17.3	22.4
LSa3		"		32.1	10.5	20.3	18.4
LSa4		"		20.3	17.6	14.7	17.5
LSa5		"		26.0	14.7	17.0	18.0
LSa6		"		65.2	57.3	35.3	40.8
LSa7		"		0.0	62.4	21.0	22.4
LSa8		"		0.0	23.6	13.7	15.2
LSa9		"		21.2	78.4	33.7	32.5
LSa10		"		0.0	70.8	29.4	24.4
LSa11		"		0.0	16.8	16.3	14.2
LSa12		"		5.0	52.7	25.9	21.4
LSa13		"		12.0	50.0e	22.1	22.3
SaL1	10.3	.01	.01	23.5	1.9	12.0	13.3
SaL2		"		20.0e	17.7	13.2	15.0
SaL3		"		34.7	57.9	26.3	26.0
SaL4		"		0.0	59.4	15.0	18.7
SaL5		"		0.0	18.8	11.6	12.3
SaL6		"		48.7	63.9	31.6	31.8
SaL7		"		0.0	65.0	19.3	19.7
SaL8		"		0.0	21.9	12.4	12.8
SaL9		"		23.0	2.1	18.8	13.2
SaL10		"		12.0	1.2	14.7	11.8
SaL11		"		26.0	2.0e	16.0	13.6
L1	5.7	.01	.01	22.0	76.5	20.5	15.3
L2		"		0.0	78.1	7.3	12.4
L3		"		0.0	16.6	4.8	6.7
L4		"		22.0	1.0e	7.1	7.2

The symbol e represents estimated values using information from the text of the references cited in Table 1.

Table 4. Comparison of measured Kf and estimated Ks values for the four "apparent" textural classes shown in Tables 2 and 3.

Plot ID	"Apparent" Textural Class of Surface Soil	Regression Results for: Ks = A + B*Kf A	B	R Squared
Sa1	Sand or Loamy Sand	39.9	0.40	0.72
Sa2	"			
Sa3	"			
Sa4	"			
LSa1	Loamy Sand or Gravelly	5.1	0.75	0.68
LSa2	Loamy Sand			
LSa3	"			
LSa4	"			
LSa5	"			
LSa6	"			
LSa7	"			
LSa8	"			
LSa9	"			
LSa10	"			
LSa11	"			
LSa12	"			
LSa13	"			
SaL1	Sandy Loam or Gravelly	0.84	0.94	0.85
SaL2	Sandy Loam			
SaL3	"			
SaL4	"			
SaL5	"			
SaL6	"			
SaL7	"			
SaL8	"			
SaL9	"			
SaL10	"			
SaL11	"			
L1	Sandy Loam to Loam	5.6	0.49	0.70
L2	"			
L3	"			
L4	"			

For all data: N = 32, Ks = 1.3 + 0.94*Kf, R Squared = 0.93

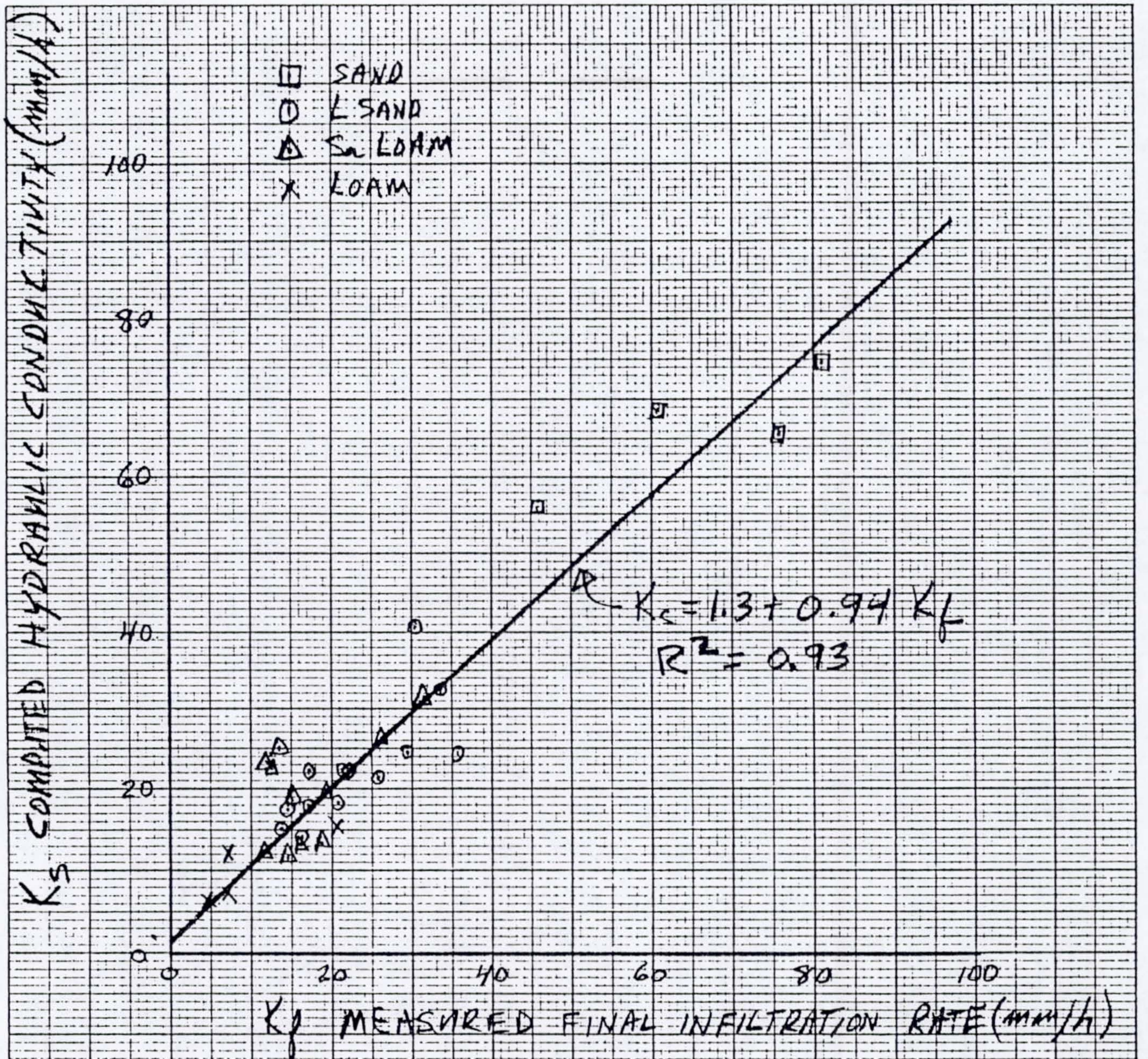


FIGURE 1. RELATIONSHIP BETWEEN MEASURED K_f AND COMPUTED K_s. DATA FROM TABLES 3 & 4.

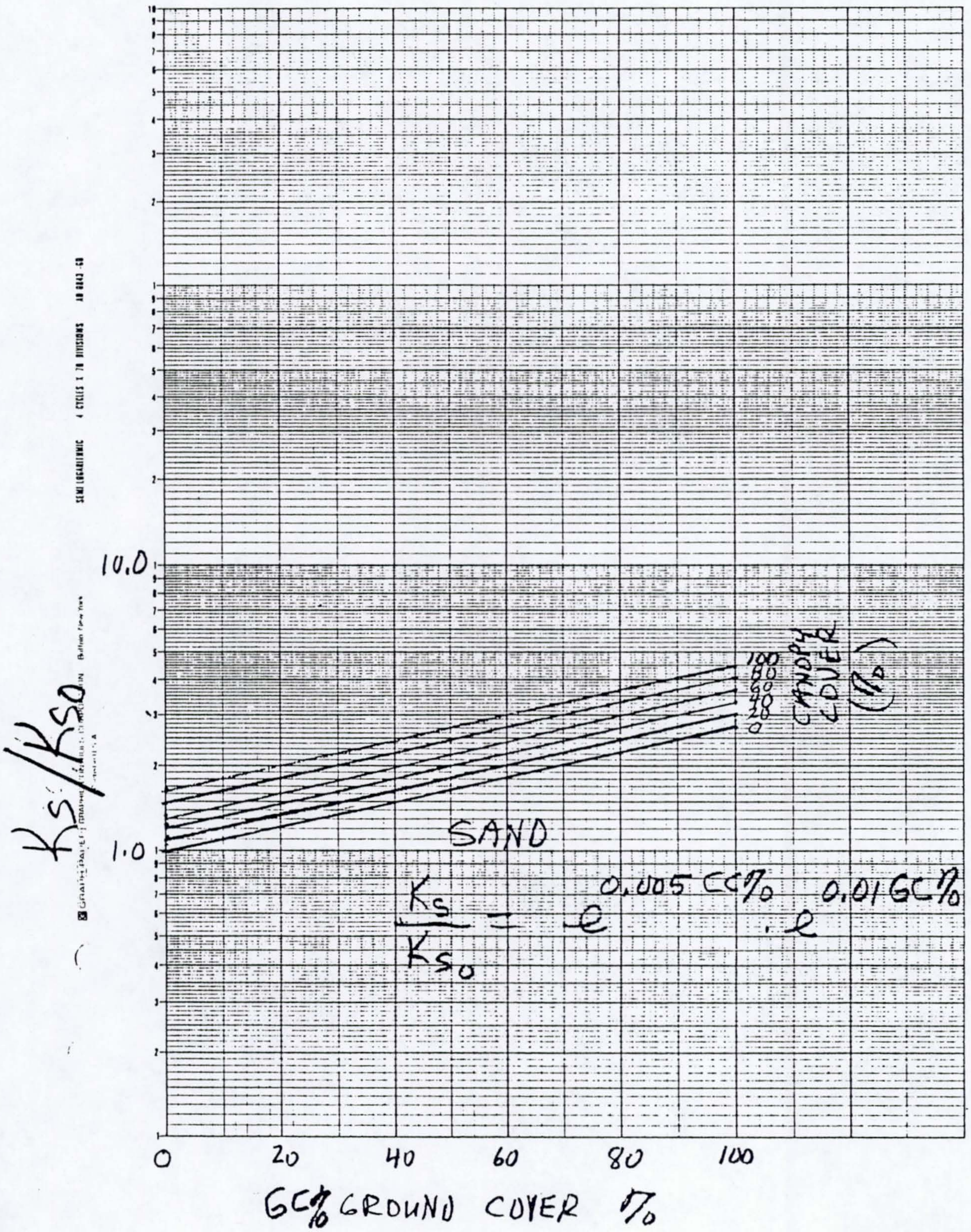


FIGURE 2. RELATIONSHIP BETWEEN CANOPY COVER, GROUND COVER AND ADJUSTMENT IN K_s FOR TEXTURAL CLASS "SAND."

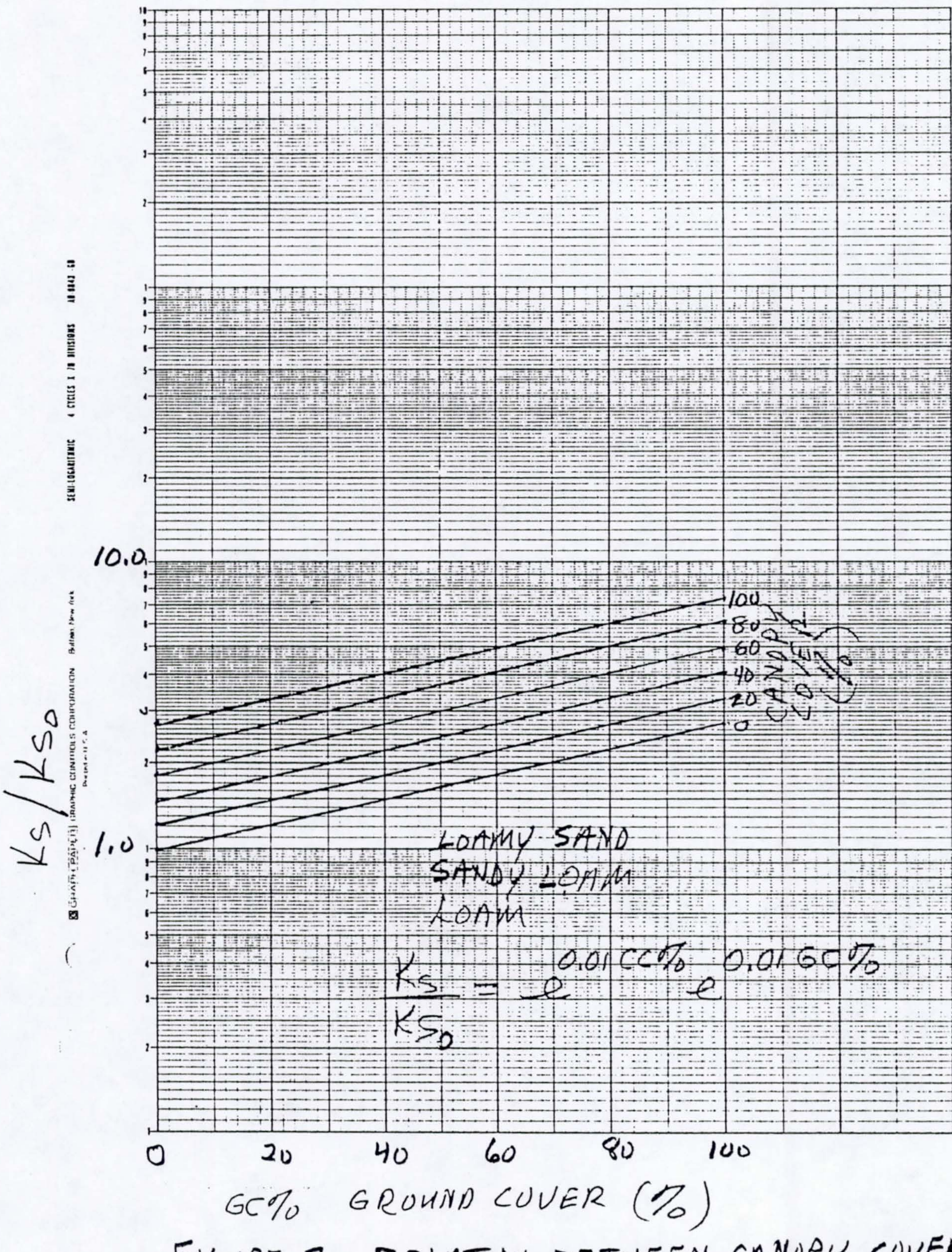


FIGURE 3. RELATION BETWEEN CANOPY COVER, GROUND COVER, AND ADJUSTMENT IN K_S FOR LOAMY SAND, SANDY LOAM, & LOAM

L. J. Lane
Hydrologist
411 E. Suffolk Dr.
Tucson, AZ 85704
602-575-8009

DATE: August 13, 1989

TO: Dr. George V. Sabol
1351 East 141st Ave.
Brighton, CO 80601
303-457-0989

SUBJECT: Report on Analyses of Infiltration Data

Enclosed is a report on my subsequent analyses of the infiltration data as suggested during your visit here on July 7, 1989.

I think I have done about all I can do with the basic data set (which is enclosed in hard copy and on a disk). Please examine the material carefully and let me know how you decide to proceed. I suggest you look at Table 4 and 4a enclosed and consider a procedure such as this.

Enclosed are the following documents/items:

1. Invoice for June, July and August
2. The interpreted infiltration data
3. Listings of the raw data files which I used in the 2 variable regression through the origin analyses
4. Listings of the regression results
5. Documentation and a listing of the 2 variable regression program
6. A disk containing the input and regression output data, source and exe code for the regression program, the program documentation, and a read.me file to help you sort out the information on the disk.

With the enclosed information and invoice, I will not do any more work on the project until you have had a chance to examine the enclosed material in detail and until we have discussed the project.

Leonard

Leonard J. Lane

enclosures

(2) INTERPRETED DATA

Table 1. Selected referenced with data on canopy cover, ground cover, and final infiltration rates.

Reference	Plot Identification In Reference	Plot Identification Here
Bach, L. B. 1984. Determination of infiltration, runoff, and erosional characteristics of a small watershed using rainfall simulation data. Unpublished MS Thesis, New Mexico State Univ., Las Cruces, NM, 69 pp.	UV	LSa1
	UI	LSa2
	MV	LSa3
	MI	LSa4
	LI	SaL1
Kincaid, D. R., J. L. Gardner, and H. A. Schreiber. 1964. Soil and vegetation parameters affecting infiltration under semiarid conditions. Bull. IASH 65:440-453.	E3	SaL2
	E2	SaL3
	E4	SaL4
	LH-3	SaL5
	E1	SaL6
	K-10	SaL7
Lane, L. J., J. R. Simanton, T. E. Hakonson, and E. M. Romney. 1987. Large-plot infiltration studies in desert and semiarid rangeland areas of the Southwestern U.S.A. Proc. Intrl. Conf. on Infiltration Development and Application., Water Res. Res. Center, Univ. of Hawaii at Manoa, Honolulu, HI, pp.365-376.	BN	LSa5
	BC	LSa6
	BB	LSa7
	A11N	LSa8
	A11C	LSa9
	A11B	LSa10
	CN	SaL8
	CC	SaL9
	CB	SaL10
	HN	SaL11
	HC	SaL12
	HB	SaL13
	MN	L1
	MC	L2
	MB	L3
Ward, T. J. 1986. A study of runoff and erosion processes using large and small area rainfall simulators. New Mexico State Univ. Water Res. Res. Center, Report No. 215, 71p.	WS2	SaL14
	WS3	SaL15
	WS2	SaL16
	WS3	L4
	NMSU	LSa11
	NMSU	LSa12
Ward, T. J. and S. B. Bolin. 1989. Determination of hydrologic parameters for selected soils in Arizona and New Mexico utilizing rainfall simulation. New Mexico State Univ. Water Res. Center, Report No. 243, 84p.	BH3B	LSa13
	BH6L	LSa14
	BH6H	LSa15
	HB2B	LSa16
	HB4L	LSa17
	HB4H	LSa18
	LK2L	LSa19
	LK2H	LSa20

Table 2. Summary of canopy cover, ground cover, and final infiltration rates for selected data in Table 1.

Plot ID	"Apparent" Textural Class of Surface Soil	% Canopy Cover (%)	% Ground Cover (%)	Final Infil. Rate Kf (mm/h)
LSa1	Loamy Sand or Gravelly	57.0	35.0	45.8
LSa2	Loamy Sand	25.0	70.4	60.7
LSa3	"	41.2	57.8	75.6
LSa4	"	17.0	82.7	81.0
LSa5	"	65.2	57.3	35.3
LSa6	"	0.0	62.4	21.0
LSa7	"	0.0	23.6	13.7
LSa8	"	21.2	78.4	33.7
LSa9	"	0.0	70.8	29.4
LSa10	"	0.0	16.8	16.3
LSa11	"	5.0	52.7	25.9
LSa12	"	12.0	50.0e	22.1
LSa13	"	0.0	0.0	16.3
LSa14	"	9.3	78.9	18.3
LSa15	"	19.6	78.5	33.3
LSa16	"	0.0	0.0	6.4
LSa17	"	18.0	59.7	23.2
LSa18	"	12.3	69.0	25.3
LSa19	"	36.7	67.4	31.2
LSa20	"	39.3	76.6	27.9
SaL1	Sandy Loam or Gravelly	23.5	1.9	12.0
SaL2	Sandy Loam	44.4	26.7	35.6e
SaL3	"	35.2	27.2	17.3
SaL4	"	32.1	10.5	20.3
SaL5	"	20.3	17.6	14.7
SaL6	"	26.0	14.7	17.0
SaL7	"	20.0e	17.7	13.2
SaL8	"	34.7	57.9	26.3
SaL9	"	0.0	59.4	15.0
SaL10	"	0.0	18.8	11.6
SaL11	"	48.7	63.9	31.6
SaL12	"	0.0	65.0	19.3
SaL13	"	0.0	21.9	12.4
SaL14	"	23.0	2.1	18.8
SaL15	"	12.0	1.2	14.7
SaL16	"	26.0	2.0e	16.0
L1	Loam or Loam near	22.0	76.5	20.5
L2	Sandy Loam	0.0	78.1	7.3
L3	"	0.0	16.6	4.8
L4	"	22.0	1.0e	7.1

The symbol e represents estimated values using information from the text of the references cited in Table 1.

Table 3. Summary of Ks0 base values, canopy cover, ground cover, measured final infiltration rates, and normalized, Kf/Ks0, values.

Plot ID	Base Ks0 Values (mm/h)	% Canopy Cover (%)	% Ground Cover (%)	Final Infil. Rate Kf (mm/h)	Normalized Kf/Ks0 (--)
LSa1	30.	57.0	35.0	45.8	1.52
LSa2	"	25.0	70.4	60.7	2.02
LSa3	"	41.2	57.8	75.6	2.52
LSa4	"	17.0	82.7	81.0	2.70
LSa5	"	65.2	57.3	35.3	1.18
LSa6	" 1.2 in/hr	0.0	62.4	21.0	0.70
LSa7	"	0.0	23.6	13.7	0.46
LSa8	"	21.2	78.4	33.7	1.12
LSa9	"	0.0	70.8	29.4	0.98
LSa10	"	0.0	16.8	16.3	0.54
LSa11	"	5.0	52.7	25.9	0.86
LSa12	"	12.0	50.0	22.1	0.74
LSa13	"	0.0	0.0	16.3	0.54
LSa14	"	9.3	78.9	18.3	0.61
LSa15	"	19.6	78.5	33.3	1.11
LSa16	"	0.0	0.0	6.4	0.21
LSa17	"	18.0	59.7	23.2	0.77
LSa18	"	12.3	69.0	25.3	0.84
LSa19	"	36.7	67.4	31.2	1.04
LSa20	"	39.3	76.6	27.9	0.93
SaL1	10.	23.5	1.9	12.0	1.20
SaL2	"	44.4	26.7	35.6	3.56
SaL3	"	35.2	27.2	17.3	1.73
SaL4	"	32.1	10.5	20.3	2.03
SaL5	"	20.3	17.6	14.7	1.47
SaL6	" .4 in/hr	26.0	14.7	17.0	1.70
SaL7	"	20.0	17.7	13.2	1.32
SaL8	"	34.7	57.9	26.3	2.63
SaL9	"	0.0	59.4	15.0	1.50
SaL10	"	0.0	18.8	11.6	1.16
SaL11	"	48.7	63.9	31.6	3.16
SaL12	"	0.0	65.0	19.3	1.93
SaL13	"	0.0	21.9	12.4	1.24
SaL14	"	23.0	2.1	18.8	1.88
SaL15	"	12.0	1.2	14.7	1.47
SaL16	"	26.0	2.0	16.0	1.60
L1	6.4 .25 in/hr	22.0	76.5	20.5	3.20
L2	"	0.0	78.1	7.3	1.14
L3	"	0.0	16.6	4.8	0.75
L4	"	22.0	1.0	7.1	1.11

Table 3a. Summary of Ks0 base values, canopy cover, ground cover, measured final infiltration rates, and normalized, Kf/Ks0, values. Ks0 values adjusted for gravel in profile by Ks0adj = Ks0*(1.0 - fraction of gravel in profile).

Plot ID	Base Ks0 Values (mm/h)	% Canopy Cover (%)	% Ground Cover (%)	Final Infil. Rate Kf (mm/h)	Normalized Kf/Ks0 (--)
LSa1	30.	57.0	35.0	45.8	1.52
LSa2	30.	25.0	70.4	60.7	2.02
LSa3	30.	41.2	57.8	75.6	2.52
LSa4	30.	17.0	82.7	81.0	2.70
LSa5	17.	65.2	57.3	35.3	2.08
LSa6	17.	0.0	62.4	21.0	1.24
LSa7	17.	0.0	23.6	13.7	0.81
LSa8	27.	21.2	78.4	33.7	1.25
LSa9	27.	0.0	70.8	29.4	1.09
LSa10	27.	0.0	16.8	16.3	0.60
LSa11	25.	5.0	52.7	25.9	1.04
LSa12	25.	12.0	50.0	22.1	0.88
LSa13	24.	0.0	0.0	16.3	0.68
LSa14	23.	9.3	78.9	18.3	0.80
LSa15	22.	19.6	78.5	33.3	1.51
LSa16	18.	0.0	0.0	6.4	0.36
LSa17	16.	18.0	59.7	23.2	1.45
LSa18	17.	12.3	69.0	25.3	1.49
LSa19	22.	36.7	67.4	31.2	1.42
LSa20	22.	39.3	76.6	27.9	1.27
SaL1	10.	23.5	1.9	12.0	1.20
SaL2	6.1	44.4	26.7	35.6	5.84
SaL3	6.1	35.2	27.2	17.3	2.84
SaL4	6.1	32.1	10.5	20.3	3.33
SaL5	6.1	20.3	17.6	14.7	2.41
SaL6	6.1	26.0	14.7	17.0	2.79
SaL7	8.6	20.0	17.7	13.2	1.53
SaL8	5.0	34.7	57.9	26.3	5.26
SaL9	5.0	0.0	59.4	15.0	3.00
SaL10	5.0	0.0	18.8	11.6	2.32
SaL11	4.0	48.7	63.9	31.6	7.90
SaL12	4.0	0.0	65.0	19.3	4.82
SaL13	4.0	0.0	21.9	12.4	3.10
SaL14	10.0	23.0	2.1	18.8	1.88
SaL15	10.0	12.0	1.2	14.7	1.47
SaL16	10.0	26.0	2.0	16.0	1.60
L1	5.8	22.0	76.5	20.5	3.53
L2	5.8	0.0	78.1	7.3	1.26
L3	5.8	0.0	16.6	4.8	0.83
L4	6.4	22.0	1.0	7.1	1.11

Table 4. Summary of regression results for influence of percent canopy cover (cc%) and percent ground cover (gc%) on hydraulic conductivity.

Model: y = (Kf/Ks0) - 1 = a*cc% + b*gc%
or
Kf/Ks0 = 1.0 + a*cc% + b*gc%
Where: Kf = measured final infiltration rate in mm/h
Ks0= base value of hydraulic conductivity in mm/h

Soil Texture	N	Coefficient a	Coefficient b	R**2
Loamy Sand	20	0.011	0.0	0.17
Sandy Loam	16	0.028	0.011	0.72
Loam	4	0.036	0.009	0.60

Table 4a. Summary of regression results for influence of percent canopy cover (cc%) and percent ground cover (gc%) on hydraulic conductivity.

Model: y = (Kf/Ks0adj) - 1 = a*cc% + b*gc%
or Kf/Ks0adj = 1.0 + a*cc% + b*gc%
Where: Kf = measured final infiltration rate in mm/h
Ks0adj = base value of hydraulic conductivity in mm/h adjusted for gravel content in the profile

Soil Texture	N	Coefficient a	Coefficient b	R**2
Loamy Sand	20	0.013	0.003	0.42
Sandy Loam	16	0.043	0.055	0.78
Loam	4	0.039	0.012	0.62

ORIGINAL DATA LSAND.DAT

(3) DATA FILES (INPUT DATA)

	K_{S0}	CC%	GC%	K_f	$\frac{K_f}{K_{S0}} - 1$
LSa1	30.	57.0	35.0	45.8	0.52
LSa2	"	25.0	70.4	60.7	1.02
LSa3	"	41.2	57.8	75.6	1.52
LSa4	"	17.0	82.7	81.0	1.70
LSa5	"	65.2	57.3	35.3	0.18
LSa6	"	0.0	62.4	21.0	-0.30
LSa7	"	0.0	23.6	13.7	-0.54
LSa8	"	21.2	78.4	33.7	0.12
LSa9	"	0.0	70.8	29.4	-0.02
LSa10	"	0.0	16.8	16.3	-0.46
LSa11	"	5.0	52.7	25.9	-0.14
LSa12	"	12.0	50.0	22.1	-0.26
LSa13	"	0.0	0.0	16.3	-0.46
LSa14	"	9.3	78.9	18.3	-0.39
LSa15	"	19.6	78.5	33.3	0.11
LSa16	"	0.0	0.0	6.4	-0.79
LSa17	"	18.0	59.7	23.2	-0.23
LSa18	"	12.3	69.0	25.3	-0.16
LSa19	"	36.7	67.4	31.2	0.04
LSa20	"	39.3	76.6	27.9	-0.07

DATA ADJUSTED FOR GRAVEL IN PROFILE LSANDA.DAT

	K_{S0} ADJ				$\frac{K_f}{K_{S0}\text{ADJ}} - 1$
LSa1	30.	57.0	35.0	45.8	0.52
LSa2	"	25.0	70.4	60.7	1.02
LSa3	"	41.2	57.8	75.6	1.52
LSa4	"	17.0	82.7	81.0	1.70
LSa5	17.	65.2	57.3	35.3	1.08
LSa6	"	0.0	62.4	21.0	0.24
LSa7	"	0.0	23.6	13.7	-0.19
LSa8	27.	21.2	78.4	33.7	0.25
LSa9	"	0.0	70.8	29.4	0.09
LSa10	"	0.0	16.8	16.3	-0.40
LSa11	25.	5.0	52.7	25.9	0.04
LSa12	"	12.0	50.0	22.1	-0.12
LSa13	24.	0.0	0.0	16.3	-0.32
LSa14	23.	9.3	78.9	18.3	-0.20
LSa15	22.	19.6	78.5	33.3	0.51
LSa16	18.	0.0	0.0	6.4	-0.64
LSa17	16.	18.0	59.7	23.2	0.45
LSa18	17.	12.3	69.0	25.3	0.49
LSa19	22.	36.7	67.4	31.2	0.42
LSa20	22.	39.3	76.6	27.9	0.27

FORMAT

(20X, 2F11.1, 11X, F11.1) FOR CC%, GC% & $\frac{K_f}{K_{S0}} - 1$

ORIGINAL DATA SALOAM.DAT

SaL1	10.	23.5	1.9	12.0	0.20
SaL2	"	44.4	26.7	35.6	2.56
SaL3	"	35.2	27.2	17.3	0.73
SaL4	"	32.1	10.5	20.3	1.03
SaL5	"	20.3	17.6	14.7	0.47
SaL6	"	26.0	14.7	17.0	0.70
SaL7	"	20.0	17.7	13.2	0.32
SaL8	"	34.7	57.9	26.3	1.63
SaL9	"	0.0	59.4	15.0	0.50
SaL10	"	0.0	18.8	11.6	0.16
SaL11	"	48.7	63.9	31.6	2.16
SaL12	"	0.0	65.0	19.3	0.93
SaL13	"	0.0	21.9	12.4	0.24
SaL14	"	23.0	2.1	18.8	0.88
SaL15	"	12.0	1.2	14.7	0.47
SaL16	"	26.0	2.0	16.0	0.60

DATA ADJUSTED FOR GRAVEL IN PROFILE SALOAMA.DAT

SaL1	10.	23.5	1.9	12.0	0.20
SaL2	6.1	44.4	26.7	35.6	4.84
SaL3	"	35.2	27.2	17.3	1.84
SaL4	"	32.1	10.5	20.3	2.33
SaL5	"	20.3	17.6	14.7	1.41
SaL6	"	26.0	14.7	17.0	1.79
SaL7	8.6	20.0	17.7	13.2	0.53
SaL8	5.0	34.7	57.9	26.3	4.26
SaL9	"	0.0	59.4	15.0	2.00
SaL10	"	0.0	18.8	11.6	1.32
SaL11	4.0	48.7	63.9	31.6	6.90
SaL12	"	0.0	65.0	19.3	3.82
SaL13	"	0.0	21.9	12.4	2.10
SaL14	10.0	23.0	2.1	18.8	0.88
SaL15	"	12.0	1.2	14.7	0.47
SaL16	"	26.0	2.0	16.0	0.60

ORIGINAL DATA

LOAM.DAT

L1	6.4	22.0	76.5	20.5	2.20
L2	"	0.0	78.1	7.3	0.14
L3	"	0.0	16.6	4.8	-0.25
L4	"	22.0	1.0	7.1	0.11

DATA ADJUSTED
FOR GRAVEL IN PROFILE

LOAMA.DAT

L1	5.8	22.0	76.5	20.5	2.53
L2	"	0.0	78.1	7.3	0.26
L3	"	0.0	16.6	4.8	-0.17
L4	6.4	22.0	1.0	7.1	0.11

Loamy sand data, 8/13/89, x1=cc%, x2=gc%, y = (Kf/KS0) - 1 (4) REGRESSION RESULTS

Regression through the origin for
y = a*x1 + b*x2

a = .011 b = -.000

$\frac{K_f}{K_{s0}} = 1 + 0.011\ CC\%$

With Rsquared = .172

Data Listing

i	x1(i)	x2(i)	y(i)	ypred(i)
1	57.000	35.000	.520	.599
2	25.000	70.400	1.020	.244
3	41.200	57.800	1.520	.422
4	17.000	82.700	1.700	.155
5	65.200	57.300	.180	.680
6	.000	62.400	-.300	-.021
7	.000	23.600	-.540	-.008
8	21.200	78.400	.120	.201
9	.000	70.800	-.020	-.024
10	.000	16.800	-.460	-.006
11	5.000	52.700	-.140	.036
12	12.000	50.000	-.260	.112
13	.000	.000	-.460	.000
14	9.300	78.900	-.390	.073
15	19.600	78.500	.110	.184
16	.000	.000	-.790	.000
17	18.000	59.700	-.230	.173
18	12.300	69.000	-.160	.109
19	36.700	67.400	.040	.371
20	39.300	76.600	-.070	.396

-----End of Data Listing-----

Sandy loam data, 8/13/89, x1=cc%, x2=gc%, y = (Kf/KS0) -1

Regression through the origin for
y = a*x1 + b*x2

a = .028 b = .011

$$\frac{Kf}{KS_0} = 1.0 + 0.028\,CC\% + 0.011\,GC\%$$

With Rsquared = .720

Data Listing

i	x1(i)	x2(i)	y(i)	ypred(i)
1	23.500	1.900	.200	.679
2	44.400	26.700	2.560	1.547
3	35.200	27.200	.730	1.295
4	32.100	10.500	1.030	1.018
5	20.300	17.600	.470	.769
6	26.000	14.700	.700	.895
7	20.000	17.700	.320	.761
8	34.700	57.900	1.630	1.631
9	.000	59.400	.500	.678
10	.000	18.800	.160	.215
11	48.700	63.900	2.160	2.091
12	.000	65.000	.930	.742
13	.000	21.900	.240	.250
14	23.000	2.100	.880	.667
15	12.000	1.200	.470	.349
16	26.000	2.000	.600	.750

-----End of Data Listing-----

25x

Loam data, 8/13/89, x1=cc%, x2=gc%, y = (Kf/KS0) -1

Regression through the origin for
y = a*x1 + b*x2

$\frac{Kf}{Ks_0} = 1.0 + 0.036\ CC\% + 0.009\ GC\%$

a = .036 b = .009

With Rsquared = .605

Data Listing

i	x1(i)	x2(i)	y(i)	ypred(i)
1	22.000	76.500	2.200	1.506
2	.000	78.100	.140	.725
3	.000	16.600	-.250	.154
4	22.000	1.000	.110	.804

-----End of Data Listing-----

Loamy sand data, 8/13/89, adj for gravel, x1=cc%, x2=gc%, y=Kf/KS0 -1

Regression through the origin for
y = a*x1 + b*x2

a = .013 b = .003

$\frac{K_f}{K_{SOADJ}} = 1.0 + 0.013\,CC\% + 0.003\,GC\%$

With Rsquared = .420

Data Listing

i	x1(i)	x2(i)	y(i)	ypred(i)
1	57.000	35.000	.520	.878
2	25.000	70.400	1.020	.556
3	41.200	57.800	1.520	.735
4	17.000	82.700	1.700	.486
5	65.200	57.300	1.080	1.058
6	.000	62.400	.240	.194
7	.000	23.600	-.190	.073
8	21.200	78.400	.250	.529
9	.000	70.800	.090	.220
10	.000	16.800	-.400	.052
11	5.000	52.700	.040	.231
12	12.000	50.000	-.120	.317
13	.000	.000	-.320	.000
14	9.300	78.900	-.200	.370
15	19.600	78.500	.510	.508
16	.000	.000	-.640	.000
17	18.000	59.700	.450	.428
18	12.300	69.000	.490	.380
19	36.700	67.400	.420	.704
20	39.300	76.600	.270	.768

-----End of Data Listing-----

Sandy loam data, 813/89, adj for gravel, x1=cc%, x2=gc%, y=Kf/KS0 -1

Regression through the origin for
y = a*x1 + b*x2

a = .043 b = .055

$\frac{Kf}{KS0\ ADJ} = 1.0 + 0.043\,CC\% + 0.055\,GC\%$

With Rsquared = .783

Data Listing

i	x1(i)	x2(i)	y(i)	ypred(i)
1	23.500	1.900	.200	1.121
2	44.400	26.700	4.840	3.385
3	35.200	27.200	1.840	3.014
4	32.100	10.500	2.330	1.965
5	20.300	17.600	1.410	1.843
6	26.000	14.700	1.790	1.931
7	20.000	17.700	.530	1.836
8	34.700	57.900	4.260	4.675
9	.000	59.400	2.000	3.256
10	.000	18.800	1.320	1.030
11	48.700	63.900	6.900	5.610
12	.000	65.000	3.820	3.562
13	.000	21.900	2.100	1.200
14	23.000	2.100	.880	1.111
15	12.000	1.200	.470	.585
16	26.000	2.000	.600	1.235

-----End of Data Listing-----

Loam, 8/13/89, adj for gravel, x1=cc%, x2=gc%, y = Kf/KS0 - 1

Regression through the origin for
y = a*x1 + b*x2

a = .039 b = .012

With Rsquared = .625

Data Listing

i	x1(i)	x2(i)	y(i)	ypred(i)
1	22.000	76.500	2.530	1.765
2	.000	78.100	.260	.921
3	.000	16.600	-.170	.196
4	22.000	1.000	.110	.875

-----End of Data Listing-----

(5) PROGRAM DOCUMENTATION & PROGRAM LISTING

PROGRAM DOCUMENTATION

```
PROGRAM: REGORGN2

PURPOSE: Two perform regression through the origin for two
         independent variables:

         Model:    y = a*x1 + b*x2
         Solution: Estimates of a and b and  R squared

LANGUAGE: FORTRAN 77

      Input units: * keyboard, 1 input files
      Output Units: * screen, 99 output file

      Input Information: 1. title, FORMAT 510
                         2. fmt,    FORMAT 510
                            fmt is the variable format for
                            the input data.
                         3. filen, FORMAT 510
                            filen is the filename for the
                            input data x1(i) x2(i) y(i) read
                            in under the format fmt
                         4. fname, FORMAT 510
                            fname is the filename for all
                            file output
                         5. temp1,temp2,temp3  FORMAT fmt
                            x1(i) = temp1
                            x2(i) = temp2
                            y(i)  = temp3
                            for i = 1 to i = nx

      Output Information: 1. title, FORMAT 510
                             Output to screen and fname
                          2. Heading, FORMAT 600
                             Output to screen and fname
                          3. Equation, FORMAT 610
                             Output to screen and fname
                          4. a and b, FORMAT 620
                             Output to screen and fname
                          5. rsqrd, FORMAT 630
                             Output to screen and fname
                          6. Heading, FORMAT 635
                             Output to fname only
                          7. Heading, FORMAT 640
                             Output to fname only
                          8. i,x1(i),x2(i),y(i),yhat(i)
                                  FORMAT 650
                             Output to fname only
                          9. Heading, FORMAT 660
                             Output to fname only
```

EXAMPLE:

Suppose you have a problem with the following.

```
Title: Test run for two vars
fmt: (20x,3f10.2)  This is the format for the x1,x2,y data
filen: test1.dat   This is file name for input data
fname: test1.out   This is file name for output data
```

To run the program you would enter the following data in response to the program prompts.

Prompt	User Input
Enter Job Title	Test run for two vars
Enter format for data (?x,fnn.n,fnn.n,fnn.n)	(20x,3f10.2)
Enter file name for input data	test1.dat
Enter file name for output	test1.dat

At this point the program will read in the data from the file called test1.dat. The file test1.dat looks like this: Note that the first three rows below are for illustrative purposes and are not in the data file. The data file would only contain the lines labeled actual data below. That is, the data file test1.dat would consist of six rows of data.

```
Column in data file
123456789112345678921234567893123456789412345678951234567 89
         0         0         0         0         0
   actual data             1.20      2.22      3.55
   actual data             3.33      4.44      7.32
   actual data             8.00    100.50    125.90
   actual data             0.50      0.50      1.10
   actual data             3.21     55.90     75.00
   actual data            50.00      1.95     82.00
```

The output data (in file fname) would look like the following.

```
 Test run for two vars


      Regression through the origin for
      y = a*x1 + b*x2

      a =         1.588  b =        1.154

   With Rsquared =          .997

   Data Listing

   i          x1(i)         x2(i)        y(i)        ypred(i)

   1          1.200         2.220       3.550          4.469
   2          3.330         4.440       7.320         10.415
   3          8.000       100.500     125.900        128.733
   4           .500          .500       1.100          1.371
   5          3.210        55.900      75.000         69.635
   6         50.000         1.950      82.000         81.660

-----End of Data Listing-----
```

```
      program regorgn2
c           Program to perform regression analysis
c           through the origin for two independent variables
c           y = ax1 + bx2
c     L. J. Lane, July 1989

c
            character*80 title
            character*80 fmt
            character*1 ans1
            character*12 filen
            character*12 fname
            common x1(1000),x2(1000),y(1000),yhat(1000)

c    section to input job info

            write (*,500)
500         format(' Enter Job Title ')
            read (*,510) title
510         format(a)
            write (*,505)
505     format(' Enter format for data (?x,fnn.n,fnn.n,fnn.n) ')
            read(*,510)fmt
            write(*,520)
520         format(' Enter file name for input data ')
            read (*,510) filen
            open(1,file=filen,status='old')
c
            write(*,560)
560         format(' Enter file name for output ')
            read(*,510)fname
            open(unit=99,file=fname,status='new')
            nx = 0
c
c           read in data x1(i),x2(i),y(i), i=1 to nx
c
10          read(1,fmt,end=20) temp1,temp2,temp3
            nx = nx + 1
            x1(nx) = temp1
            x2(nx) = temp2
            y(nx)  = temp3
            go to 10
20          rewind 1
            nx = nx
            xnum = nx
c
c           initialize variables
c
          sumx1 = 0.0
          sumx2 = 0.0
          sumy  = 0.0
          sumx1y = 0.0
          sumx1x2 = 0.0
          sumx2y = 0.0
          sumx1sq = 0.0
          sumx2sq = 0.0
```

```
c
         do 30 i =1,nx
           sumx1 = sumx1 + x1(i)
           sumx2 = sumx2 + x2(i)
           sumy = sumy + y(i)
           sumx1y = sumx1y + x1(i)*y(i)
           sumx1x2 = sumx1x2 + x1(i)*x2(i)
           sumx2y = sumx2y + x2(i)*y(i)
           sumx1sq = sumx1sq + x1(i)*x1(i)
           sumx2sq = sumx2sq + x2(i)*x2(i)
30       continue
c
c          calculate regression coefficients
c
           b = sumx1y*sumx1x2 - sumx1sq*sumx2y
           b = b/((sumx1x2*sumx1x2) - sumx1sq*sumx2sq)
           a = (sumx2y - b*sumx2sq)/(sumx1x2)
c
c          calculate estimated y values
c
          sse = 0.0
          ssy = 0.0
          ybar = sumy/nx
        do 40 i = 1,nx
          yhat(i) = a*x1(i) + b*x2(i)
          sse = sse + (y(i)-yhat(i))*(y(i)-yhat(i))
          ssy = ssy + (y(i)-ybar)*(y(i)-ybar)
40      continue
          rsqrd = 1.0 - (sse/ssy)
c
c         section to write out results
c
        write(*,510)title
        write(99,510)title
        write(*,600)
        write(99,600)
600     format(//,5x,' Regression through the origin for ')
        write(*,610)
        write(99,610)
610     format(5x,' y = a*x1 + b*x2 ')
        write(*,620)a,b
        write(99,620)a,b
620     format(/,'       a = ',f10.3,'  b = ',f10.3)
        if((rsqrd.gt.0.0).and.(rsqrd.le.1.0)) then
        write(*,630)rsqrd
        write(99,630)rsqrd
        else
        endif
630     format(/,'     With Rsquared = ',f10.3,)
c
        write(99,635)
635     format(/,'     Data Listing ')
        write(99,640)
```

```
 0       format(/,'     i          x1(i)          x2(i)          y(i)
     1   ypred(i)     ',/)
         do 50 i=1,nx
          write(99,650)i,x1(i),x2(i),y(i),yhat(i)
 50      continue
 650     format(i5,4x,f10.3,3x,f10.3,1x,f10.3,7x,f12.3)
         write(99,660)
 660     format(/,'-----End of Data Listing-----',///)
         end
```

L. J. LANE 1/
JULY 8, 1989

$$y = ax_1 + bx_2$$

$$G = \sum \left[y - (ax_1 + bx_2) \right]^2$$

$$G = \sum y^2 - 2y(ax_1 + bx_2) + (ax_1 + bx_2)^2]$$

$$G = \sum \left[y^2 - 2ax_1y - 2bx_2y + a^2x_1^2 + 2abx_1x_2 + b^2x_2^2 \right]$$

$$\frac{\partial G}{\partial a} = \sum \left[-2x_1y + 2ax_1^2 + 2bx_1x_2 \right]$$

$$\frac{\partial G}{\partial a} = -2\sum x_1y + 2a\sum x_1^2 + 2b\sum x_1x_2 = 0$$

$$\frac{\partial G}{\partial a} = -\sum x_1y + a\sum x_1^2 + b\sum x_1x_2 = 0$$

$$\frac{\partial G}{\partial b} = \sum \left[-2x_2y + 2ax_1x_2 + 2bx_2^2 \right]$$

$$\frac{\partial G}{\partial b} = -2\sum x_2y + 2a\sum x_1x_2 + 2b\sum x_2^2 = 0$$

$$\frac{\partial G}{\partial b} = -\sum x_2y + a\sum x_1x_2 + b\sum x_2^2 = 0$$

$$\begin{cases} a\sum x_1^2 + b\sum x_1x_2 - \sum x_1y = 0 & (1) \\ a\sum x_1x_2 + b\sum x_2^2 - \sum x_2y = 0 & (2) \end{cases}$$

FROM (2)

$$a \Sigma x_1 x_2 = \Sigma x_2 y - b \Sigma x_2^2$$

$$\Rightarrow \boxed{a = \frac{\Sigma x_2 y - b \Sigma x_2^2}{\Sigma x_1 x_2}}$$

SUBSTITUTE INTO (1)

$$\Sigma x_1^2 \left(\frac{\Sigma x_2 y - b \Sigma x_2^2}{\Sigma x_1 x_2} \right) + b \Sigma x_1 x_2 - \Sigma x_1 y = 0$$

$$\Sigma x_1^2 \ \Sigma x_2 y - \Sigma x_1^2 b \Sigma x_2^2 + b \Sigma x_1 x_2 \Sigma x_1 x_2 - \Sigma x_1 y \Sigma x_1 x_2 = 0$$

$$\Rightarrow b \left((\Sigma x_1 x_2)^2 - \Sigma x_1^2 \Sigma x_2^2 \right) + \Sigma x_1^2 \Sigma x_2 y - \Sigma x_1 y \Sigma x_1 \Sigma x_2 = 0$$

$$\Rightarrow b \left(\qquad \qquad \right) = \Sigma x_1 y \Sigma x_1 \Sigma x_2 - \Sigma x_1^2 \Sigma x_2 y$$

$$\Rightarrow \boxed{\begin{aligned} b &= \frac{\Sigma x_1 y \Sigma x_1 \Sigma x_2 - \Sigma x_1^2 \Sigma x_2 y}{(\Sigma x_1 x_2)^2 - \Sigma x_1^2 \Sigma x_2^2} \\ a &= \frac{\Sigma x_2 y - b \Sigma x_2^2}{\Sigma x_1 x_2} \end{aligned}}$$

APPENDIX 6-N

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George V. Sabol Consulting Engineers, Inc.

CLIENT ______ SHEET ____ OF ____

PROJECT ______ DATE ______

SUBJECT ______ BY ______

PROJECT NO. ______

Comparison of Effective Impervious Area, in percent

Land-Use (1)	TR-55 (2)	Alley & Veenhuis (1983)* Mean (3)	Alley & Veenhuis (1983)* Range (4)	Selected Values Mean (5)	Selected Values Range (6)
Residential (Lot size, in acres)					
1/4	38	23	18-32	30	23-38
1/3	30	15	11-19	22	15-30
1/2	25	8.5	7-10	17	9-25
1	20	8.5	7-10	14	8-20
2	12			12	7-20
Multi-family Residential	65	42	33-52	54	42-65
Commercial	85	83	51-98	85	51-98
Industrial	72	46	—	59	46-72

* Ref. - Effective Impervious Area in Urban Runoff Modeling, W.M. Alley & J.E. Veenhuis, ASCE, Journal of Hyd. Engrg., Vol. 109, no. 2, Feb 1983.

APPENDIX 6-Q

Figure 4.1

Percent of Impervious Area vs. Dwelling Units/Acre

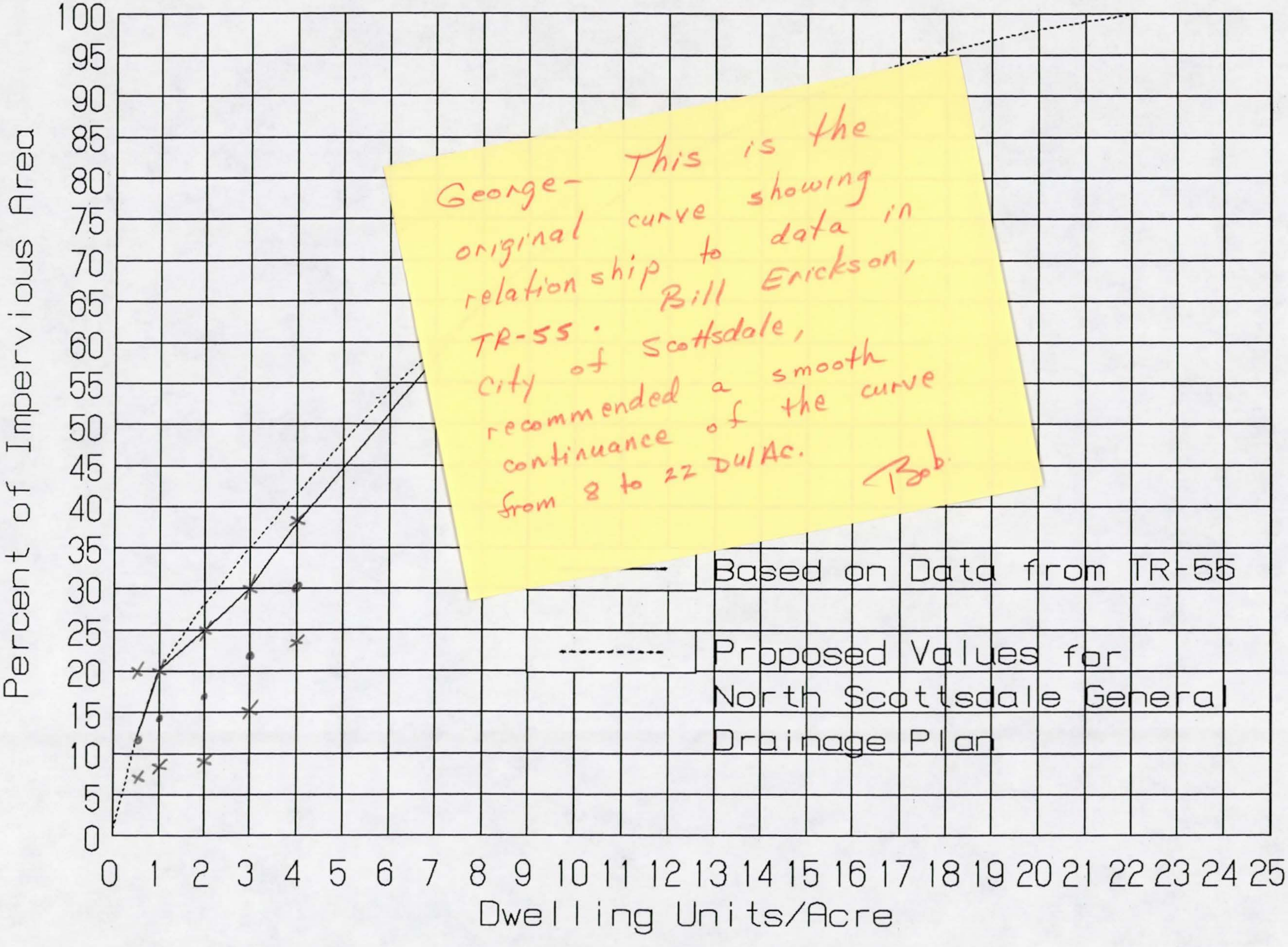
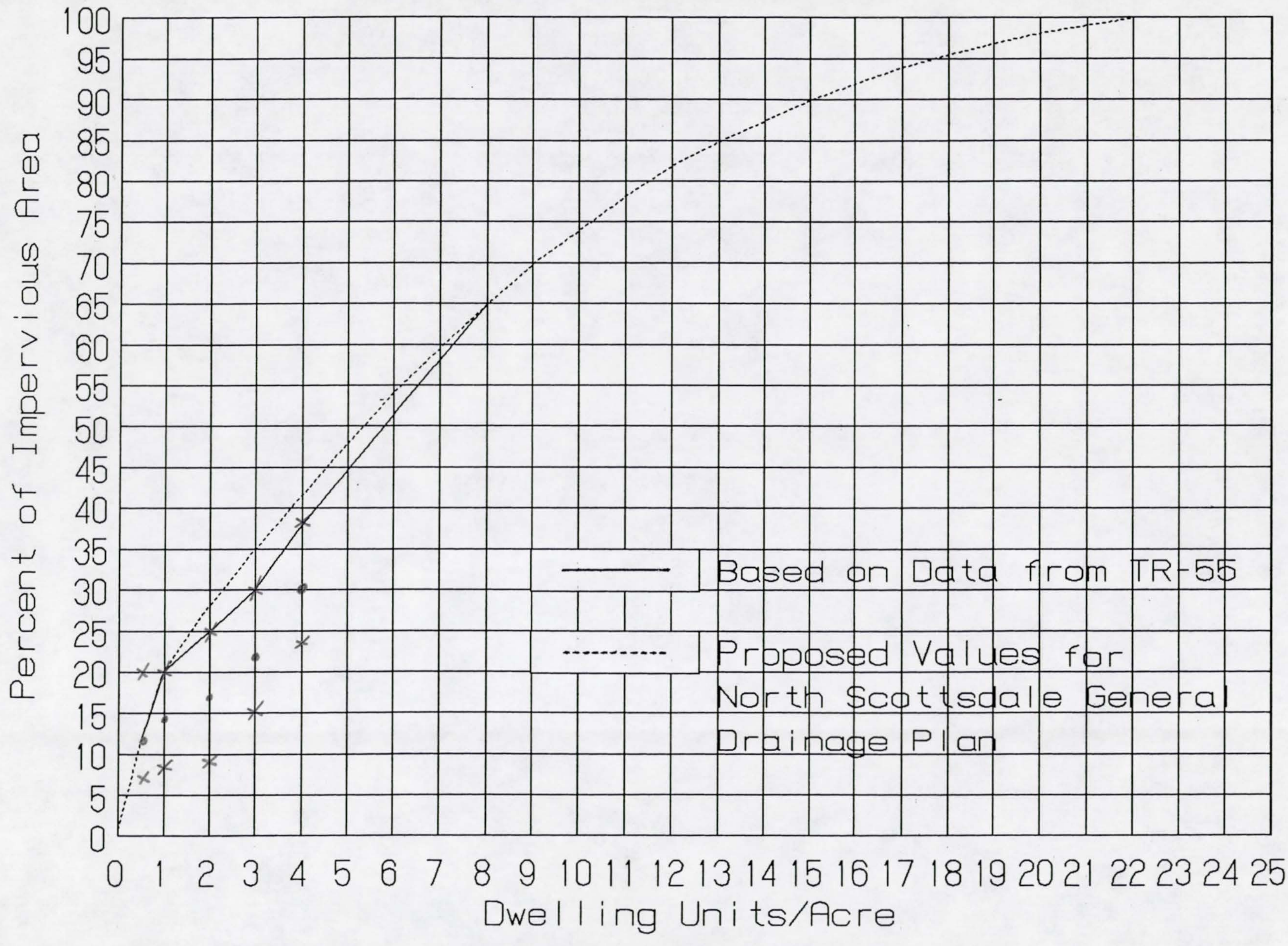


Figure 4.1

Percent of Impervious Area vs. Dwelling Units/Acre



CITY OF SCOTTSDALE

DEVELOPMENT DESIGN GUIDELINES
FOR
ENVIRONMENTALLY SENSITIVE LANDS

JULY 1989

DEVELOPMENT DESIGN GUIDELINES
FOR
ENVIRONMENTALLY SENSITIVE LANDS

PREPARED

FOR THE

CITY OF SCOTTSDALE

BY

TARANTO, STANTON & TAGGE, CONSULTING ENGINEERS
748 WHALERS WAY, BUILDING D
FORT COLLINS, COLORADO 80525

In Association With:

WATER RESOURCE ASSOCIATES, INC.
2702 NORTH 44TH STREET, SUITE 101-B
PHOENIX, ARIZONA 85008

&

ROBERT WARD P.E., CONSULTING ENGINEER
706 N. GENTRY CIRCLE
MESA, ARIZONA 85203

July 1989

Table C300-3

Summary of Curve Numbers
for Use in the 1989 City HEC-1 Model
(undeveloped Desert Shrub, 15% Cover Density)

Hydrologic Soil Group	Curve Numbers 24-Hour	Curve Numbers 6-Hour
A	60	66
B	74	78
C	82	85
D	86	89

Table C300-4

Percent of Impervious Area
for Land-Use Classification

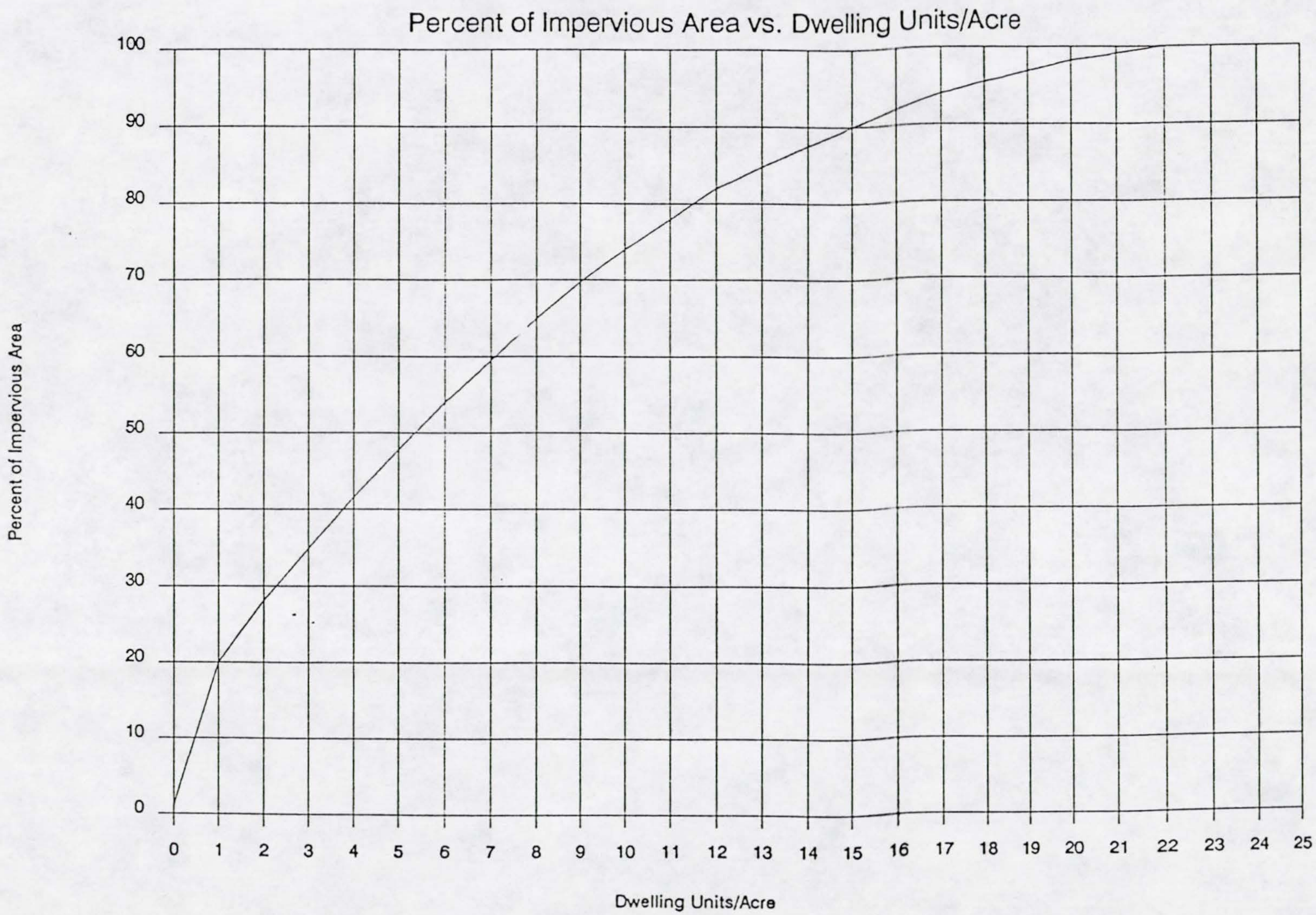
Land-Use Classification	Percent Impervious Area
Residential	See Figure C300-1
Tourist Accommodations	85.0
Low Intensity Resort	85.0
Support Commercial	85.0
General Commercial	85.0
Cultural/Institutional	85.0
Minor Office	85.0
Major Office	85.0
Light Industrial	72.0
Open Space	1.0

From TR-55

use Fig. C300-1 for residential land-use.

FIGURE C300 - 1

Adjustments to % Impervious Area to Reflect Urbanized Conditions



developed areas. The values of imperviousness used for this study are given in Table 4-1.

The soil types used in this study were furnished by the Los Angeles County Department of Public Works which is currently in the process of refining the soils types north of Avenue S. As this updated information becomes available, it should be used to revise the hydrologic calculations.

TABLE 4-1

LAND USE VS. IMPERVIOUSNESS

Land Use Designation	Density	Percent Impervious
NU, RU	1 Du/10 Acre, 1 Du/5 Acre	10
SR	2 Du/Acre	40
UR	5 Du/Acre	45
UMR	8 Du/Acre	50
UMHR	15 Du/Acre	65
UHR	> 18 Du/Acre	75
COM, LI, MI	Commercial/Industrial	90

This is from a study by BSI for Palmdale, Ca.

4.5 TIME OF CONCENTRATION

A major premise of the Modified Rational Method is that the greatest discharge from an area occurs when runoff from the entire area is contributing to the flow passing the selected point of concentration. Since the rainfall intensity is decreasing with respect to duration, the maximum discharge occurs at the shortest time period required for water to travel from the furthest point of the drainage area. That time period is identified as the "time of concentration".

Times of concentration are computed for each subarea. The selection of subareas can have a significant effect on the computed times of concentration, particularly with respect to the subareas at the upstream end of each drainage basin. The size and configuration of these upstream areas determines the "initial" time of concentration for the basin. Since the initial time of concentration determines the rainfall

APPENDIX 6-R

MEMORANDUM

TO: Project Committee Members

FROM: George V. Sabol

DATE: 20 April 1992

SUBJECT: Working Paper No. 3, Rainfall Losses

Attached is a revision to the Working Paper incorporating the procedure to be used to determine area weighted average of Green and Ampt parameter values. Figure 3-3 was added. Example No. 2 is included to illustrate this procedure.

A new Figure 3-1 is provided.

RESEARCH PROJECT NO. HPR-PL-1(31)281

ADOT HIGHWAY DRAINAGE DESIGN MANUAL

HYDROLOGY

GEORGE V. SABOL CONSULTING ENGINEERS, INC.
PHOENIX, ARIZONA
and
DENVER, COLORADO

SUBCONTRACTOR TO:
NBS/LOWRY ENGINEERS & PLANNERS
PHOENIX, ARIZONA

16 April 1992

WORKING PAPER NO. 3

RAINFALL LOSSES

PREPARED FOR

ARIZONA TRANSPORTATION RESEARCH CENTER

PHOENIX, ARIZONA

RAINFALL LOSSES

INTRODUCTION

General Discussion

Rainfall excess is that portion of the total rainfall depth that drains directly from the land surface by overland flow. By a mass balance, rainfall excess plus rainfall losses equals precipitation.

This section is only applicable when performing rainfall-runoff modeling with the HEC-1 program. The design rainfall is determined from the procedures in the Rainfall section, and this section provides procedures to estimate the runoff from the applied rainfall. When using the Rational Method, it is not necessary to estimate rainfall losses by the procedures in this section because the "C" factor accounts for the effect of rainfall loss on the peak discharge and runoff volume.

Two methods are provided to estimate rainfall losses; the first method is the normal one that is to be used for the majority of cases, and the second method is to be used only for special cases when it is determined that the normal method is inappropriate. The normal method requires the estimation of the surface retention loss (Table 3-1) and the estimation of the rainfall infiltration loss by the Green and Ampt equation. The Green and Ampt equation parameters are estimated as a function of soil texture (Table 3-2). This classification system places soil into one of 12 classes based on the size gradation of the soil according to percentage sand, silt, and clay (Figure 3-1). One of the Green and Ampt equation parameters (hydraulic conductivity) can be adjusted for the effects of vegetation ground cover (Figure 3-2). Correction for vegetation ground cover is not to be made if the soil is either sand or loamy sand, and this is because the use of such a correction could result in overestimation of the losses due to infiltration.

The second (special) method requires the estimation of the initial loss and an uniform loss rate (IL + ULR method). The special method is to be used for watersheds or subbasins where rainfall losses are known to be controlled by factors other than soil texture and vegetation cover, or for watersheds that are predominantly of sand. For example, the land surface of upland watersheds of Humphrey Mountain near Flagstaff are generally composed of volcanic cinder overlain by forest duff. Infiltration is not controlled by soil texture in these watersheds and infiltration rates may be as high as 5 inches per hour or more. Use of the special method requires adequate data or adequate studies to verify the IL+ULR parameters or to calibrate the model of the watershed.

Both the normal and the special methods require the estimation of the impervious area of the watershed. Impervious area (or nearly impervious area) is composed of rock outcrop, paved roads, parking lots, roof tops, and so forth. When performing watershed modeling with the HEC-1 program, the impervious area is to be the effective (directly connected) impervious area (see definitions). For urbanized areas, the effective impervious area should be estimated from aerial photographs with guidance as provided in Table 3-3. For areas that are presently undeveloped but for which flood estimates are desired for future urbanized conditions, estimates of effective impervious area should be obtained based on regional planning and land-use zoning as determined by the local jurisdiction. Estimates of the effective impervious area for urbanizing areas should be selected from local guidance, if available, along with the general guidance that is provided in Table 3-3. For undeveloped areas, the effective impervious area is often 0 percent. However, in some watersheds there could be extensive rock outcrop that would greatly increase the imperviousness of the watershed. Care must be exercised when estimating effective impervious area for rock outcrop. Often the rock outcrop is relatively small (in terms of the total drainage area) and is of isolated units surrounded by soils of relatively high infiltration capacities. Relatively small, isolated rock outcrop should not be considered as effective impervious area because runoff must pass over pervious surfaces before reaching the point of discharge concentration. For watersheds that have significant, contiguous rock outcrop, it may be necessary to establish those areas as subbasins so that the direct runoff can be estimated and then routed (with channel transmission losses, if appropriate) to the point of interest. Paved roads through undeveloped watersheds will not normally contribute to effective impervious area unless the road serves as a conveyance to the watershed outlet.

<u>Definitions</u>

rainfall excess - The equivalent uniform depth of runoff, in inches, that drains from the land surface. Rainfall excess equals rainfall minus rainfall losses.

rainfall losses - The sum of rainfall that is lost to surface runoff due to interception, depression storage, evaporation, infiltration, and other mechanisms. Rainfall loss is expressed as an equivalent uniform depth, in inches.

infiltration - The rate of movement, in inches per hour, of rainfall from the land surface into and through the surface soil.

percolation - The rate of movement, in inches per hour, of water through the underlying soil or geologic strata subsequent to infiltration.

surface retention loss - The depth of rainfall loss, in inches, due to all factors other than infiltration.

initial abstraction - The accumulative loss, due to all mechanisms, of all rainfall from the start of rainfall to the point in time when surface runoff begins. This is equivalent to the initial loss (STRTL) in the IL+ULR method.

drainage area - The total area contributing to surface runoff at a point of interest (flow concentration point).

subbasin - A portion of a drainage area that is determined according to the internal surface drainage pattern. A drainage area can often be divided into subbasins for modeling purposes.

subarea - A portion of a drainage area or subbasin that is delineated according to a physical feature such as soil texture or land-use.

impervious area - The portion of a land area, expressed in percent of total land area, that has a negligible infiltration rate. Impervious area can be natural, such as rock outcrop and the surface of permanent water bodies; or man-made, such as paved areas, roofs, and so forth.

effective impervious area - The portion of a land area, expressed in percent of total land area, that will drain directly to the outlet of the drainage area without flowing over pervious area. This is often called directly connected impervious area.

soil - The layer of inorganic particulate matter covering the earth's surface. It can and does contain organic matter and often supports vegetation. For the purpose of estimating rainfall losses, only the upper horizon (generally about the top 6 inches of soil) will be considered. Underlying soil horizons or other strata will generally not affect rainfall losses in Arizona for storms of 100 year magnitude or less.

soil texture - The classification of soil into groups according to percentage of sand, silt, and clay, as used by the U.S. Department of Agriculture (Figure 3-1).

sand - Soil composed of particles in the 2.0 mm to 0.05 mm size range.

silt - Soil composed of particles in the 0.05 mm to 0.002 mm size range.

clay - Soil composed of particles smaller than 0.002 mm.

hydrologic soil group - A classification system developed by the SCS to place soils into one of four groups based on runoff potential.

vegetation cover - The percentage of land surface that is covered by vegetation. Vegetation cover is evaluated on plant basal area for grasses and forbs, and on canopy cover for trees and shrubs.

PROCEDURE

General Considerations

1. Infiltration is the movement of water from the land surface into and through the upper horizon of soil. Percolation is the movement of water through the underlying soil or geologic strata subsequent to infiltration. Infiltration can be controlled by percolation if the soil does not have a sustained drainage capacity to provide access for more infiltrated water. However, the extent by which percolation can restrict infiltration for design rainfalls in Arizona needs to be carefully considered. For example, shallow soils with high infiltration rates that overlay nearly impervious material can be placed in hydrologic soil group D in SCS soil surveys. The soil texture, vegetation cover, and depth of the surface horizon of soil and the properties of the underlying horizons of soil need to be considered when estimating the infiltration rate. Surface soils that are more than 6 inches thick should generally be considered adequate to contain infiltrated rainfall for up to the 100-year event in Arizona without the subsoil restricting the infiltration rate. This is because most common soils have porosities that range from about 25 to 35 percent, and therefore 6 inches of soil with a porosity of 30 percent can absorb about 1.8 inches (6 inches times 30 percent) of rainfall infiltration and it is unlikely that more soil moisture storage is needed for storms up to the 100-year event in Arizona. In estimating the Green and Ampt infiltration parameters in Arizona for up to the 100-year rainfall, the top 6 inches of soil should be considered. If the top 6 inch horizon is uniform soil or nearly uniform, then select the Green and Ampt parameters (Table 3-2) for that soil texture. If the top 6 inch horizon is

layered with different soil textures, then select the Green and Ampt parameters (Table 3-2) for the soil texture with the lowest hydraulic conductivity (XKSAT).

2. Parameter values for design should be based on reasonable estimates of watershed conditions that would minimize rainfall losses. The estimate of impervious area (RTIMP) for urbanizing areas should be based on ultimate development in the watershed.

3. Two sources of information are to be used to classify soil texture for the purpose of estimating Green and Ampt infiltration equation parameters. The primary source that is to be used for the watershed, when it is available, are the detailed soil surveys that are prepared by the USDA, Soil Conservation Service (SCS). When detailed soil surveys are not available for the watershed, then the general soil maps and accompanying reports by the SCS for each county in Arizona are to be used.

4. Most drainage areas or modeling subbasins will be composed of several subareas containing soils of different texture; and therefore, there may be the need to determine composite values for the Green and Ampt parameters to be applied to the drainage areas or each modeling subbasin. The procedure that is to be used is to average the area weighted logarithms of the individual subarea XKSAT values and to select the PSIF and DTHETA values from a graph.

The composite XKSAT is calculated by Equation 3-1:

$$\overline{XKSAT} = antilog \left[\frac{\Sigma \, A_i \log XKSAT_i}{A_T} \right] \qquad (3\text{-}1)$$

where $\overline{XKSAT}$ = composite hydraulic conductivity (XKSAT), in inches/hour,

$XKSAT_i$ = hydraulic conductivity (Table 3-2) of the soil in a subarea, in inches/hour.

A_i = size of a subarea, and

A_T = size of the drainage area or modeling subbasin.

After $\overline{XKSAT}$ is calculated, the values of PSIF and DTHETA (normal or dry) are selected from Figure 3-3 at the corresponding value of $\overline{XKSAT}$.

5. Correction of XKSAT for vegetation cover (Figure 3-2) is made after the composite value of XKSAT is determined (Equation 3-1). The composite values for PSIF and DTHETA (Figure 3-3) are determined from the composite value of XKSAT prior to making the correction of XKSAT for vegetation cover.

6. There are conceptual and computational differences between the Green and Ampt infiltration equation method and the IL+ULR method for estimating rainfall losses. When using the IL+ULR method, the initial loss (STRTL) is defined as the sum of surface retention loss (IA) plus initial infiltration loss that accrues before surface runoff is produced, and this is equivalent to initial abstraction (see definitions). When using the Green and Ampt infiltration equation method, the initial abstraction is calculated based on the input of both the surface retention loss (IA) and the infiltration parameters (XKSAT, PSIF, and DTHETA).

7. When using the IL+ULR method both the initial loss (STRTL) and the uniform loss rate (CNSTL) must be estimated. Because this method is to be used for special cases where infiltration is not controlled by soil texture or for drainage areas and subbasins that are predominantly sand, the estimation of the parameters will require model calibration, results of regional studies, or other

valid techniques. It is not possible to provide complete guidance in the selection of these parameters, however, some general guidance is provided.

a. Because this method is only to be used for special cases, the uniform loss rate (CNSTL) will either be very low for nearly impervious surfaces or possibly quite high for exceptionally fast draining (porous) land surfaces. For land surfaces with very low infiltration rates, the value of CNSTL will probably be 0.05 inches per hour or less. For sand, a CNSTL of 0.5 to 1.0 inch per hour or larger would be reasonable. Higher values of CNSTL for sand and other surfaces are possible, however use of high values of CNSTL will require special studies.

b. The selection of the initial loss (STRTL) can be made on the basis of calibration or special studies at the same time that CNSTL is estimated. Alternatively, since STRTL is equivalent to initial abstraction, STRTL can be estimated by use of the SCS CN equations for estimating initial abstraction, written as:

$$STRTL = \frac{200}{CN} - 2 \qquad (3\text{-}2)$$

Estimates of CN for the drainage area or subbasin should be made by referring to various publications of the SCS, particularly TR-55. Equation 3-2 should provide a fairly good estimate of STRTL in many cases, however its use will have to be judiciously applied and carefully considered in all cases.

Applications and Limitations

The Green and Ampt infiltration equation, along with an estimate of the surface retention loss can be used to estimate rainfall losses for most areas of Arizona with confidence. Most soils in Arizona are loamy sand, sandy loam, loam, or silt loam for which the Green and Ampt infiltration equation parameters from Table 3-2 should apply. Silt, as a soil texture, is relatively rare and it is not expected that significant areas will be encountered. The finer soil textures (those with "clay" in the classification name) occur in Arizona but not usually over large areas; however, these soils have relatively low infiltration rates (XKSAT). Use of the Green and Ampt infiltration equation parameters for the finer soil textures may be somewhat conservative, and therefore their use should be appropriate for most design flood estimation purposes. Sand, as a soil texture, is also relatively rare and it has a very high infiltration rate (XKSAT). Therefore, when encountering large areas that have soils that are classified as sand, it is possible that estimates of rainfall losses with the Green and Ampt equation would be too large and the IL+ULR method should be used. Ideally, rainfall-runoff data or streamgage data would be available for model calibration of loss rate parameters in those cases. Alternatively, regional studies or extrapolation of results from similar watersheds can be used to estimate the IL+ULR parameters for sand.

In general, the Green and Ampt infiltration equation with an estimate of the surface retention loss should be used for most drainage areas in Arizona. The IL+ULR method should be used for drainage areas where soil texture does not control the infiltration rate (such as volcanic cinder) or where the soil texture of the drainage area is predominantly sand. Calibration data or results of regional studies are necessary to justify the selection of parameters for the IL+ULR method.

Determination of Soil Texture

The normal method to estimate infiltration losses requires the classification of soil according to soil texture (Figure 3-1). Two sources of information are available in Arizona to determine the soil texture. The following procedure should be applied when determining soil texture from these sources.

SCS Soil Survey - For limited areas of Arizona:

1. Locate the watershed boundaries and subbasin boundaries on the detailed soil maps.
2. List the map symbol and soil name for each soil that is contained within the watershed boundaries.

3. Read the description of each of the soil series and each mapping unit. Try to identify the soil texture that best describes each soil (or the top 6 inches of layered soils).
4. Consult soil properties tables of the soil survey, and from the columns for soil depth and dominant texture, make the final selection of soil texture that will control the infiltration rate. The size gradation data that is provided in the tables can also be used to assist in selecting the soil texture. Many of the soils in Arizona contain significant quantities of gravel, and the adjective "gravelly," when used in conjunction with the soil texture, can either be disregarded when it is used in conjunction with "sandy," that is, gravelly sandy loam can be taken as equivalent to sandy loam; or "gravelly" can be used as a replacement for "sandy" when used alone, that is, gravelly clay can be taken as equivalent to sandy clay. Similarly, adjectives such as "very fine" and "very coarse," usually used in association with sand, can be disregarded in determining soil texture classification.

General Soil Map - For each County in Arizona:

1. Locate the watershed boundaries and subbasin boundaries on the general soil map. (Since these maps are 1:500,000 scale, it may only be possible to locate the watershed.)
2. Identify the soil association(s) from the map.
3. Read the description of each soil which will identify the soil texture and soil depths.
4. Consult the soil properties tables of the general soils report, and from the columns for soil depth and texture make the final selection of soil texture that will control the infiltration rate. Comments regarding the use of adjectives such as "gravelly," and "very fine" or "very course" are the same as item 4 above.

INSTRUCTIONS

Green and Ampt Infiltration Equation based on Soil Texture

1. Prepare a base map of the drainage area delineating modeling subbasins, if used.
2. Delineate subareas of different soils on the base map. Determine the soil texture for each subarea and also assign a land-use or surface cover to each subarea.
3. Determine the size of each subbasin and size of each subarea within each subbasin.
4. Estimate the impervious area (RTIMP) for each subarea (Table 3-3).
5. Calculate the area weighted RTIMP for the drainage area or each subbasin.
6. Estimate the surface retention loss (IA) for the drainage area or each subarea (Table 3-1).
7. Calculate the area weighted value of IA for the drainage area or each subbasin.
8. If the drainage area or subbasin consists of soil of the same textural class, then select XKSAT, PSIF, and DTHETA for that soil texture (Table 3-2). Proceed to Step 10.
9. If the drainage area or subbasin consists of subareas of different soil textural classes, then calculate the composite value of XKSAT (Equation 3-1), and select the composite values of PSIF and DTHETA (Figure 3-3).
10. Estimate the percent vegetation cover and determine the hydraulic conductivity (XKSAT) correction factor (Ck) (Figure 3-2).
11. Apply correction factors (Ck) from Step 10 to the value of XKSAT from either Step 8 or Step 9.
12. The area weighted values of RTIMP, IA, XKSAT, PSIF, and DTHETA for the drainage area or each subbasin are entered on the LG record of the HEC-1 input file.

Initial Loss plus Uniform Loss Rate (IL + ULR)

The following method can be used only when it is known that soil texture does not control infiltration rate. This method must be used with adequate calibration or verification to justify the use of uniform loss rates that may exceed the hydraulic conductivities shown in Table 3-2.

1. Prepare a base map of the drainage area delineating modeling subbasins, if used.
2. Delineate subareas of different infiltration rates (uniform loss rates) on the base map. Assign a land-use or surface cover to each subarea.
3. Determine the size of each subbasin and size of each subarea within each subbasin.
4. Estimate the impervious area (RTIMP) for the drainage area or each subarea (Table 3-3).
5. Estimate the initial loss (STRTL) for the drainage area or each subarea by regional studies or calibration. Alternatively, Equation 3-2 can be used to estimate or to check the value of STRTL.
6. Estimate the uniform loss rate (CNSTL) for the drainage area or each subarea by regional studies or calibration.
7. Calculate the area weighted values of RTIMP, STRTL, and CNSTL for the drainage area or each subbasin.
8. The area weighted values of RTIMP, STRTL, and CNSTL for the drainage area or each subbasin are entered on the LU record of the HEC-1 input file.

TABLE 3-1

Surface retention loss for various land surfaces in Arizona
(To be used with the Green and Ampt Infiltration Equation for estimating rainfall losses.)

Land-use and/or Surface Cover (1)	Surface Retention Loss (IA) inches (2)
Natural	
Desert and rangeland, flat slope	.35
Desert and rangeland, hill slopes	.15
Mountain, with vegetated surface	.25
Developed (Residential and Commercial)	
Lawn and turf	.20
Desert Landscape	.10
Pavement	.05
Agricultural	
Tilled fields and irrigated pasture	.50

TABLE 3-2

Green and Ampt Infiltration Equation loss rate parameter values for bare ground

Soil Texture Classification (1)	XKSAT in/hr (2)	PSIF inches (3)	DTHETA[a] Dry (4)	DTHETA[a] Normal (5)	DTHETA[a] Saturated (6)
sand[b]	4.6	1.9	.35	.30	0
loamy sand	1.2	2.4	.35	.30	0
sandy loam	.40	4.3	.35	.25	0
loam	.25	3.5	.35	.25	0
silt loam	.15	6.6	.40	.25	0
silt	.10	7.5	.35	.15	0
sandy clay loam	.06	8.6	.25	.15	0
clay loam	.04	8.2	.25	.15	0
silty clay loam	.04	10.8	.30	.15	0
sandy clay	.02	9.4	.20	.10	0
silty clay	.02	11.5	.20	.10	0
clay	.01	12.4	.15	.05	0

[a] Selection of DTHETA:
Dry - for nonirrigated lands such as desert and rangeland
Normal - for irrigated lawn, turf, and permanent pasture
Saturated - for irrigated agricultural lands

[b] The use of the Green and Ampt Infiltration Equation for drainage areas or subbasins that are predominantly sand should be avoided and the IL+ULR should be used.

TABLE 3-3

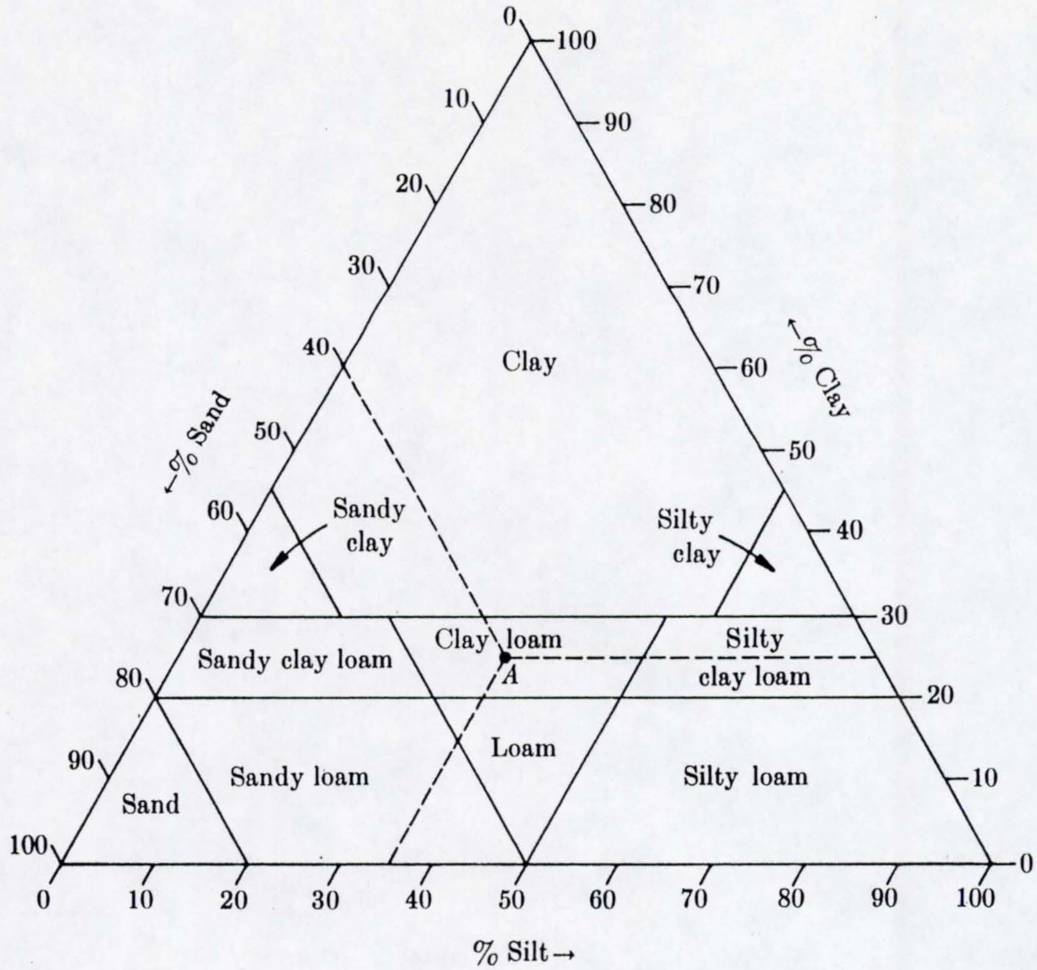
General guidance for selecting Effective Impervious Area (RTIMP)

Land-Use	Effective Impervious Area, in percent	
	Mean	Range
(1)	(2)	(3)
Single-Family Residential		
1/4 acre	30	23-38
1/3 acre	22	15-30
1/2 acre	17	9-25
1 acre	14	8-20
2 acres	12	7-20
Multi-Family Residential	54	42-65
Commercial	85	51-98
Industrial	59	46-72

FIGURE 3-1

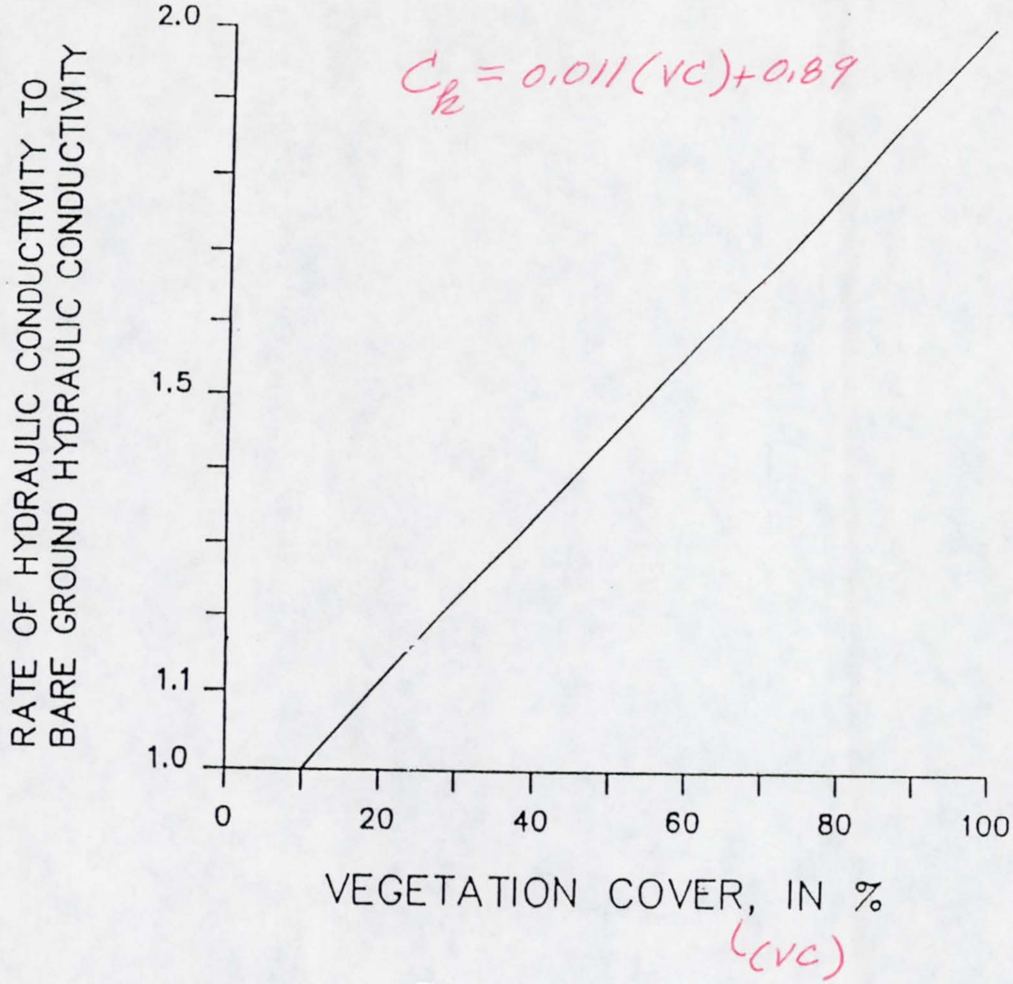
SOIL TEXTURE CLASSIFICATION

TRIANGLE



Definitions: Clay - mineral soil particles less than 0.002 mm in diameter.
Silt - mineral soil particles that range in diameter from 0.002 mm to 0.05 mm.
Sand - mineral soil particles that range in diameter from 0.05 mm to 2.0 mm.

Example: Point A is a soil composed of 40% sand, 35% silt, and 25% clay. It is classified as a clay loam.



Effect of Vegetation Cover on Hydraulic Conductivity
For Hydraulic Soil Groups B, C, and D, and
For all Soil Textures ~~other than~~ except
Sand and ~~Sandy Loam~~ Loamy Sand

(Reference – Drainage Design Manual for Maricopa County, Arizona, Volume 1, Hydrology)

Figure 3-2

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CLIENT ________ SHEET ____ OF ____

PROJECT ________ DATE ________

SUBJECT ________ BY ________

PROJECT NO. ________

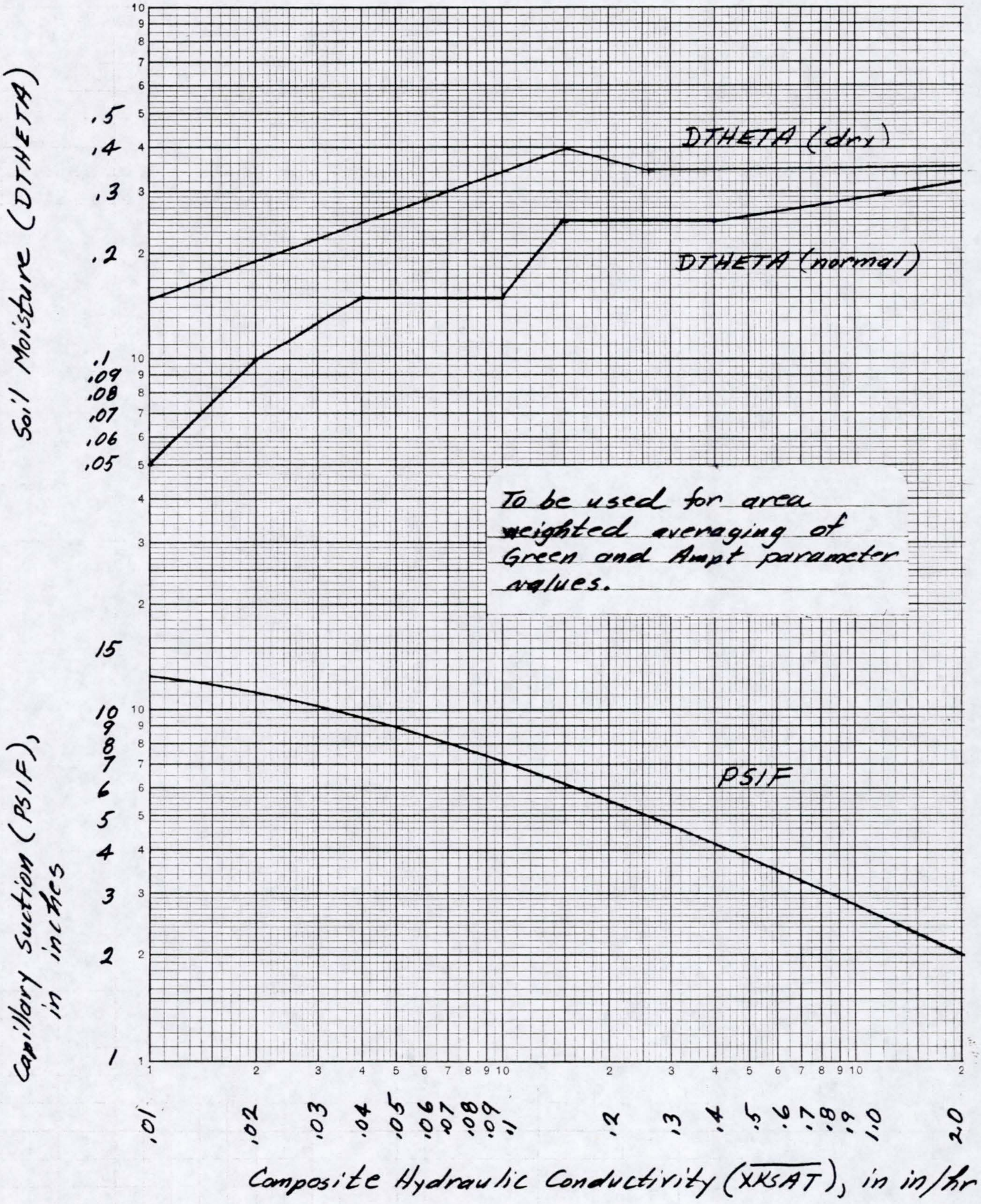


FIGURE 3-3

Composite values of PSIF and DTHETA as a function of $\overline{XKSAT}$.

EXAMPLE No. 1

Estimate the Rainfall Loss Parameters for Agua Fria River Tributary, Youngtown, Arizona

The rainfall loss parameters are estimated for a 0.13 square mile drainage area in Youngtown, Arizona. A drainage area is delineated on a topographic map, as shown in Figure 3-4. From the SCS Soil Survey of Maricopa County, Arizona, Central Part, September 1977, the soil series is Perryville (PeA), described as a gravelly loam in hydrologic soil group B. Particle size gradation of this soil from the soil survey is as follows:

Sieve No.	Particle Size, mm	% Passing Sieve
4	4.76	80-90
10	2.00 (sand)	55-75
40	.42	40-55
200	.074 (silt and clay)	30-40

From this size gradation data it is noted that 25 to 45 percent of this soil is coarser than sand, 15 to 25 percent is sand, and 30 to 40 percent is silt and clay. Data are not normally provided in the SCS soil surveys to estimate the percentage clay. From this information, it is concluded that the soil texture classification is best described as a sandy loam (SL).

The drainage area is nearly all single-family residential with about 1/4 acre or slightly smaller lot size. About 50 percent of the residential lots are irrigated turf, although some lawns are in poor condition and the vegetation cover is estimated as 75 percent. The other 50 percent of the residential lots are desert landscaped.

The loss parameters are estimated as follows:

IA	= 0.10 inch	Table 3-1	Residential, Desert Landscape
	0.20 inch	Table 3-1	Residential, Lawn and Turf
DTHETA	= 0.35	Table 3-2	Desert Landscape
	0.25	Table 3-2	Irrigated Lawn
PSIF	= 4.3 inches	Table 3-2	Sandy Loam
XKSAT	= 0.40 in/hr	Table 3-2	Sandy Loam (bare ground)
C_k	= 1.72	Figure 3-2	XKSAT correction factor at 75 percent ground cover

XKSAT = 0.40 for Desert Landscape

XKSAT = (1.72)(.40) = 0.69 in/hr for Lawn

RTIMP = 30 percent — Table 3-3 — Single-Family Residential, 1/4 acre

The area weighted parameters are calculated as follows:

IA = .50(.10) + .50(.20) = 0.15 inch

DTHETA = .50(.35) + .50(.25) = .30

PSIF = 4.3 inches

XKSAT = .50(.40) + .50(.69) = 0.54 in/hr

RTIMP = 30 percent

The LG record is coded as follows:

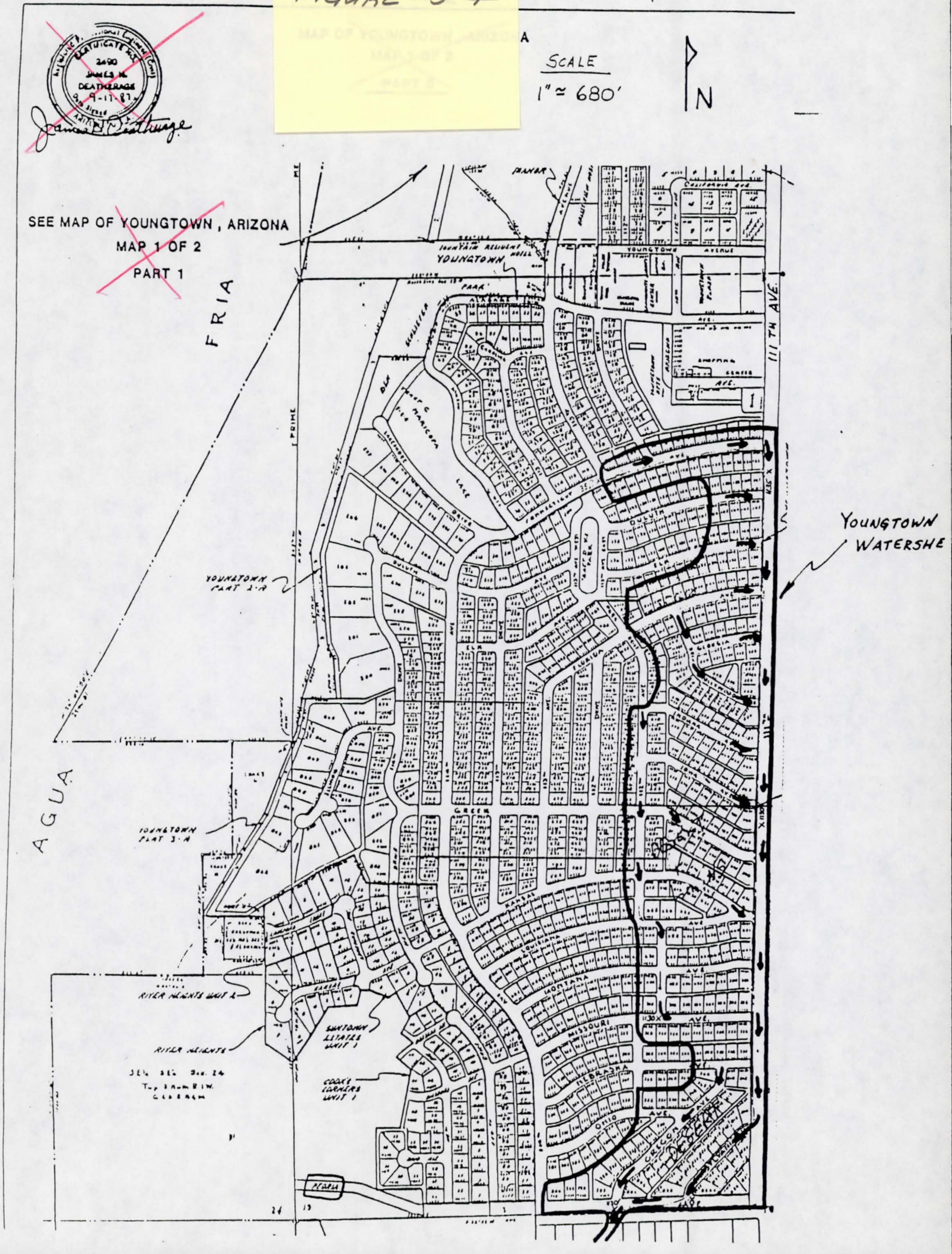
LG, IA, DTHETA, PSIF, XKSAT, RTIMP

LG, .15, .30, 4.3, .54, 30

FIGURE 3-4

SCALE

1" ≈ 680'



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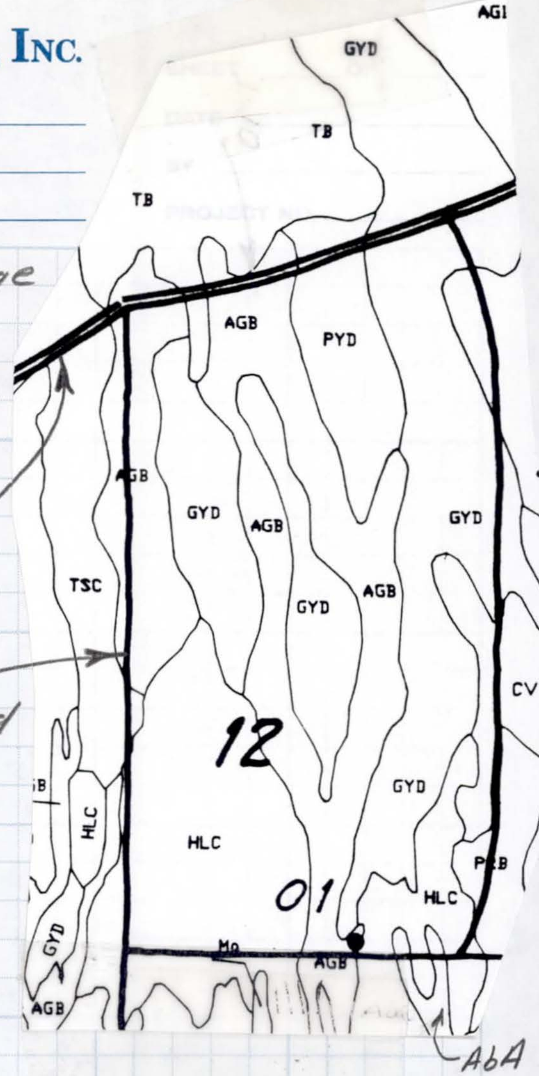
PROJECT

SUBJECT EXAMPLE No. 2

Determine the area weighted average Green and Ampt parameters for the subbasin near Buckeye, Arizona. Adjust XKSAT for 20% vegetation cover.



Use of the SCS Soil Survey of Maricopa County, Arizona, Central Part and planimetering of subareas results in the following:

Soil Symbol	Soil Name	Textural Class	XKSAT in/hr (Table 3-2)	Area sq. mi.
GYD	Gunsight-Rillito Complex	sandy loam	.40	.32
AGB	Antho-Carrizo Complex	sandy loam	.40	.29
HLC	Harqua-Gunsight Complex	clay loam	.04	.24
PYD	Pinamt-Tremant Complex	sandy clay loam	.06	.07
CV	Coolidge-Laveen Association	sandy loam	.40	.02
TSC	Tremant-Rillito Complex	sandy clay loam	.06	.02
PRB	Perryville-Rillito Complex	sandy loam	.40	.01
TB	Torrifluvents	loamy sand	1.2	.01
AbA	Antho sandy loam	sandy loam	.40	.01
				.99

Area of sandy loam (XKSAT=.40) = .65
Area of sandy clay loam (XKSAT = .06) = .09
Area of clay loam (XKSAT = .04) = .24
Area of loamy sand (XKSAT = 1.2) = .01

$$\overline{XKSAT} = \text{antilog}\left[\frac{.65(\log .40) + .09(\log .06) + .24(\log .04) + .01(\log 1.2)}{.99}\right] = .20 \text{ in/hr}$$

PSIF = 5.5 inches
DTHETA (dry) = .37 } Figure 3-3

XKSAT (adjusted) = .20[.011(20) + .89] = .22 in/hr

APPENDIX 6-S

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