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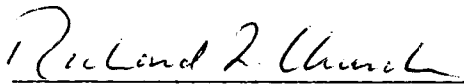
I am submitting herewith a thesis written by Gordon Innes entitled "Comparison of Infiltration Models on Disturbed Soils Using Parameter Optimization." I recommend that it be accepted in partial fulfillment of the requirements for the Master of Science Degree, with a major in Environmental Engineering.



Donald E. Overton, Major Professor

We have read this thesis
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COMPARISON OF INFILTRATION MODELS ON DISTURBED
SOILS USING PARAMETER OPTIMIZATION

A Thesis
Presented for the
Master of Science
Degree

The University of Tennessee, Knoxville

Gordon Innes

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ABSTRACT

The infiltration models of Horton, Green and Ampt, Philip and the SCS-CN method were reviewed and their parameters were optimized for a data set of 103 rainfall simulations. The parameters, after being fitted to simulate steady state storms, were related to soil characteristics, the most significant of which was the initial soil moisture. Results indicate that the goodness of fit is dependent upon the initial soil moisture. Some models fit well if the soil was wet; others fit well if the soil was dry. None fit all conditions well. The parameters of Philip's model and Green and Ampt's model were linearly related to the change in soil moisture. Good correlations occurred when the sample size was adequate.

The accuracy of the infiltration models was concluded to be dependent upon accuracy of the estimate of the time of ponding. Since Horton, Green and Ampt, and Philip do not give methods for estimating this time, however, another model with new parameters and assumptions would have to be used in conjunction with them. For this reason it is recommended that either the SCS-CN method or Mein and Larson's model be used because they are both capable of simulating the time prior to runoff and subsequent infiltration rate.

The results are applicable to disturbed denuded soils such as would be found on strip mined spoil banks, construction sites, and plowed fields. Infiltration information about soils in this condition is important for simulating the stormwater response and soil erosion of disturbed areas.

TABLE OF CONTENTS

CHAPTER	PAGE
I. INTRODUCTION	1
II. LITERATURE REVIEW.	2
Model Classification	2
Green and Ampt Model	2
Philip Model	4
Mein and Larson Model	9
SCS Curve Number	11
Horton Model	12
Holtan Model	13
III. METHOD AND PROCEDURES.	15
Data Collection	15
Method of Optimization	16
Parameter Regionalization.	17
IV. RESULTS	20
Green and Ampt Model.	20
Philip Model	31
SCS-CN	31
Horton Model	34
V. DISCUSSION	37
SCS-CN	37
Horton Model	39
Green and Ampt Model	41
Philip Model	43
Mein and Larson Model.	45

CHAPTER	PAGE
VI. CONCLUSIONS	47
VII. RECOMMENDATIONS	48
REFERENCES	49
APPENDICES	52
Appendix A Regression of Sorptivity Versus Change in Soil Moisture.	53
Appendix B Regression of α Versus Change in Soil Moisture	64
Appendix C Optimized Parameters	74
VITA	83

LIST OF TABLES

TABLE		PAGE
4.1	Statistical Analysis for Regression of $(\bar{\theta} - \theta_i)$ Versus $\underline{a}$	30
4.2	Maximum Difference Between Fitted and Actual Infiltration Rate at Intermediate Times for Dry Molokai-A Soils. . .	32
4.3	Statistical Analysis for Regression of $(\theta_s - \theta_i)$ Versus S_p	33
4.4	Average, Minimum, and Maximum Values for Potential Storage	35

LIST OF FIGURES

FIGURE	PAGE
2.1 Plot of Soil Moisture Versus Soil Depth	7
4.1 Typical Fit of Green and Ampt Model for a Dry Soil.	21
4.2 Typical Fit of Green and Ampt Model for a Wet Soil.	22
4.3 Typical Fit of Philip Model for a Dry Soil.	23
4.4 Typical Fit of Philip Model for a Wet Soil.	24
4.5 Typical Fit of SCS-CN Model for a Dry Soil.	25
4.6 Typical Fit of Horton Model for a Wet Soil.	26
4.7 Typical Fit of SCS-CN Model for a Dry Soil.	27
4.8 Typical Fit of SCS-CN Model for a Wet Soil.	28
5.1 Plot of SCS-CN Model with Varying $\underline{S}$	38
5.2 Plot of Horton Model with Varying $\underline{k}$	40
5.3 Plot of Green and Ampt Model with Varying $\underline{a}$	42
5.4 Plot of Philip Model with Varying S_p	44
A.1 Regression of Sorptivity Versus Change in Soil Moisture for Molokai-A Soils	54
A.2 Regression of Sorptivity Versus Change in Soil Moisture for Molokai-B Soils	55
A.3 Regression of Sorptivity Versus Change in Soil Moisture for Wahiawa Soils	56
A.4 Regression of Sorptivity Versus Change in Soil Moisture for Kawaihae Soils.	57
A.5 Regression of Sorptivity Versus Change in Soil Moisture for Hilo Soils	58
A.6 Regression of Sorptivity Versus Change in Soil Moisture for Kukaiau Soils	59
A.7 Regression of Sorptivity Versus Change in Soil Moisture for Waikane Soils	60

FIGURE	PAGE
A.8 Regression of Sorptivity Versus Change in Soil Moisture for Lualuale Soils	61
A.9 Regression of Sorptivity Versus Change in Soil Moisture for Naalehu Soils	62
A.10 Regression of Sorptivity Versus Change in Soil Moisture for Pakini Soils	63
B.1 Regression of α Versus Change in Soil Moisture for Molokai-A Soils.	65
B.2 Regression of α Versus Change in Soil Moisture for Molokai-B Soils	66
B.3 Regression of α Versus Change in Soil Moisture for Waikane Soils	67
B.4 Regression of α Versus Change in Soil Moisture for Lualuale Soils	68
B.5 Regression of α Versus Change in Soil Moisture for Kukaiau Soils	69
B.6 Regression of α Versus Change in Soil Moisture for Wahiawa Soils	70
B.7 Regression of α Versus Change in Soil Moisture for Kawaihae Soils	71
B.8 Regression of α Versus Change in Soil Moisture for Naalehu Soils	72
B.9 Regression of α Versus Change in Soil Moisture for Pakini Soils	73

CHAPTER I

INTRODUCTION

A major variable for estimating stormwater response and soil erosion is the soil infiltration rate. The infiltration rate controls the rate of overland flow and influences the rate of soil particle detachment, transport, and deposition. The ability to estimate soil erosion and stormwater response is therefore dependent upon the accuracy of the infiltration estimate.

This study is primarily concerned with estimating the infiltration rate on disturbed and denuded soils. Such soils can be found on construction sites, plowed field, strip mined areas, and spoil banks. These areas tend to have high rates of stormwater discharge and are sources of stormwater pollution because of their high sediment loads. Hence, activities which disturb large amount of soil often require an environmental assessment. Since the accuracy of the environmental assessment will be dependent upon the accuracy of the infiltration estimate, it is important to have an accurate method for simulating infiltration. This study was initiated to determine which infiltration model would be most applicable for these hydrologic studies and to determine model parameters.

In the present study, infiltration models reported in the literature were reviewed and the parameters of these models were optimized for a data set measured on Hawaiian soils. The models were then compared both theoretically and from a practical viewpoint as to their ability to simulate infiltration.

CHAPTER II

LITERATURE REVIEW

Model Classification

Infiltration models can be placed into two categories: 1) models derived from soil physics, 2) hydrologic models. The models derived from soil physics are deterministic models that relate infiltration rate to intrinsic characteristics of the soil. They relate infiltration rate to such properties as soil conductivity, capillary tension, and moisture content. However, since the soil characteristics upon which they are based vary spatially and temporally and are difficult to measure, application of these models in design involves substantial judgement and requires a very large amount of input information.

Hydrologic models are parametric models and utilize lumped characteristics of the soil to simulate infiltration rates. The parameters of these models must be determined by optimization.

Three models derived from soil physics will be reviewed, Philip's model, Mein and Larson's model, and Green and Ampt's model; and three hydrologic models will be reviewed, Horton's model, Holtan's model and the Soil Conservation Service Curve Number (SCS-CN) method.

Green and Ampt Model

Green and Ampt (1) simplified the infiltration problem by assuming a discontinuous moisture profile. They assumed that the initial soil moisture was homogeneous. They also assumed a defined wetting front above which the soil moisture would also be homogeneous but of a higher percent than the initial soil moisture. This is a reasonable assumption,

since there is usually a rapid change in soil moisture along a "wetting front" which moves down the soil column. Green and Ampt (1) stated that there are two important forces which control the infiltration rate: (1) capillary pressure drop at the wetting front, (2) hydraulic head. After assuming that Darcy's law is valid for unsaturated flow if a capillary pressure term is added, the problem was formulated as

$$f = K \frac{H_o + H_p + L_f}{L_f} \quad (2.)$$

where: K = soil conductivity
 H_o = depth of ponding
 L_f = distance of wetting front from surface
 f = infiltration rate

since moisture must be conserved

$$f = (\bar{\theta} - \theta_o) \frac{dL_f}{dt} = \Delta\theta \frac{dL_f}{dt} \quad (2.2)$$

where: $\bar{\theta}$ = moisture content behind the wetting front
 θ_o = initial moisture content

Combining equations 2.1 and 2.2 yields the differential equation.

$$\Delta\theta \frac{dL_f}{dt} = K \frac{H_o + H_p + L_f}{L_f} \quad (2.3)$$

Equation 2.3 has the solution

$$\frac{Kt}{\Delta\theta} = L_f - (H_o + H_p) \ln \left(1 + \frac{L_f}{H_o + H_p} \right) \quad (2.4)$$

If ponding is assumed to be negligible, equations 2.1 and 2.4 can be restated as

$$f = \frac{a}{F} + f_c \quad (2.5)$$

and

$$t = \frac{1}{f_c} \left[F - \frac{a}{f_c} \ln \left(1 + \frac{F}{a/f_c} \right) \right] \quad (2.6)$$

where

F = accumulated infiltration

$a = K H_p \Delta \theta$

$f_c = K$ = final infiltration rate

The parameters of the Green and Ampt model are difficult to measure. It is difficult to measure the capillary pressure drop at the wetting front. Brakensiek (2) reviewed several methods in 1977. Currently these methods require considerable field and/or laboratory effort. Bower (3) suggested that the conductivity, K , should not be the conductivity at full saturation. He suggested that it should be the conductivity at residual air saturation which he estimated to be $.5 K_s$, the saturated conductivity.

Philip Model

Philip (4,5,6,7,8,9,10) published a series of seven papers on infiltration in 1957. In this series he presents his method of solving Richard's equation for one dimensional vertical flow

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left(D \frac{\partial \theta}{\partial x} \right) - \frac{\partial K}{\partial x} \quad (2.7)$$

Subject to

$$\begin{aligned} \theta &= \theta_o & t &= 0 & x &> 0 \\ \theta &= \theta_s & x &= 0 & t &\geq 0 \end{aligned} \quad (2.8)$$

where:

θ = soil moisture

D = Soil diffusivity

K = Soil conductivity

X = distance from surface

θ_s = saturated moisture

θ_o = initial moisture

Philip (4) used a method of successive approximation to prove that for a semi-infinite medium a power series in $t^{1/2}$ is a solution to equation 2.7 subject to 2.8.

$$\chi = \lambda t^{1/2} + \chi t + \psi t^{3/2} + \dots + f_m(\theta) t^{m/2} \dots \quad (2.9)$$

The solution is an extension of Boltzman's transformation, $\chi = \lambda t^{1/2}$, which is used for solving for horizontal infiltration and diffusion. The coefficients of the series, λ , χ , ψ , etc., are single valued functions of θ and can be expressed as differential equations.

For example:

$$\chi = \frac{d}{d\theta} \left(D \left(\frac{d\theta}{d\chi} \right)^2 \frac{d\chi}{d\theta} \right) + \frac{dK}{d\theta} \quad (2.10)$$

The coefficients are functions of the diffusivity, conductivity, and Boltzman's transform which are all assumed to be single valued functions of θ .

Philip (4) obtained the cumulative increase in soil moisture, W_{inc} , by integrating $\theta_s - \theta_o$ over the column length

$$W_{inc} = \int_{x=0}^{\infty} (\theta_s - \theta_o) dx \quad (2.11)$$

and realizing that this value was equivalent to

$$W_{inc} = \int_{\theta_o}^{\theta_s} x d\theta \quad (2.12)$$

since both functions represent the same area under the θ vs x curve.

This is demonstrated in Figure 2.1.

Philip also realized that the amount of water that leaves the column, W_b , is equal to

$$W_b = K_o t \quad (2.13)$$

where:

K_o = conductivity of soil at the initial moisture content.

The equation is an application of Darcy's law where the hydraulic gradient is unity.

Since the cumulative infiltration must equal the change in soil moisture plus the moisture that leaves the column, the cumulative infiltration is the sum of these two terms.

$$F = \int_{\theta_o}^{\theta_s} x d\theta + K_o t \quad (2.14)$$

Philip substituted in equation 2.9 for x to obtain

$$F = t^{1/2} \int_{\theta_o}^{\theta_s} \lambda d\theta + K_o t + t \int_{\theta_o}^{\theta_s} x d\theta + t^{3/2} \int_{\theta_o}^{\theta_s} s d\theta + \dots + t^{m/2} \int_{\theta_o}^{\theta_s} f_m(\theta) d\theta \quad (2.15)$$

Since equation 2.15 converges rapidly for small t , it can be truncated to

$$F = S_p t^{1/2} + A t \quad (2.16)$$

where

$$S_p = \int_{\theta_o}^{\theta_s} \lambda d\theta$$

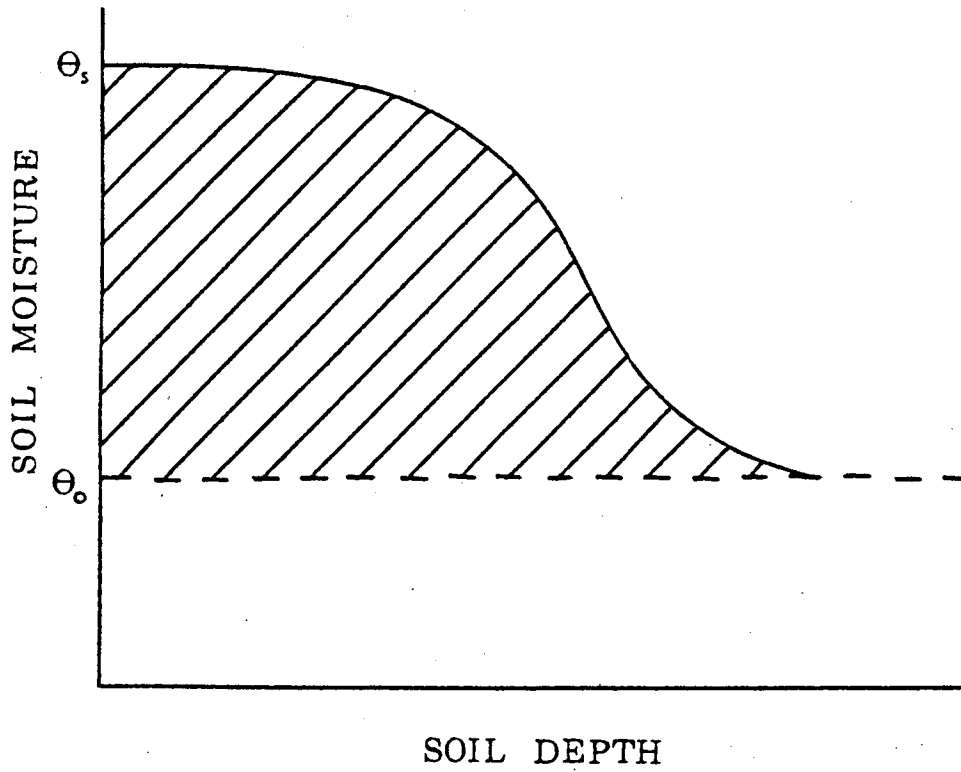


FIGURE 2.1
PLOT OF SOIL MOISTURE VERSUS SOIL DEPTH

$$A = K_0 + \int_{\theta_0}^{\theta_s} \chi d\theta$$

Equation 2.16 is known as Philip's infiltration equation. Since the solution to the horizontal problem is

$$F = S_p t^{1/2} \quad (2.17)$$

it can be readily observed that all terms to the right of the first term in equation 2.15 are gravity terms. Note that A is not equal to K_s , the saturated conductivity, as is often assumed.

In his paper Philip presents a numerical method for calculating $S_p(\theta_s, \theta_0)$ if $D(\theta)$ and $K(\theta)$ are known. The method requires detailed knowledge of the diffusivity and conductivity of the soil which is not ordinarily available and requires considerable laboratory effort to obtain.

Another approach is to assume a constant or weighted diffusivity. For a constant or weighted diffusivity

$$S_p = (\theta_s - \theta_0) \sqrt{\frac{\bar{D}}{\pi}} \quad (2.18)$$

where:

$\bar{D}$ = constant or weighted diffusivity

Since diffusivity varies widely with the moisture content equation 2.18 will only be an approximation of the sorptivity versus moisture relationship. Philip believed that a discontinuous moisture profile as was assumed by Green and Ampt would be a better approximation of the sorptivity versus moisture relationship. For such an assumption the diffusivity can be represented mathematically as a Dirac delta function. Philip solved equation 2.15 for a Dirac delta function and found the sorptivity to be proportional to the difference between the saturated

and the initial moisture.

$$S_p \propto (\theta_s - \theta_i)^{1/2} \quad (2.19)$$

Mein and Larson Model

Mein and Larson (11) expanded Green and Ampt's model to account for the influence of infiltration prior to runoff. The model of Mein and Larson simulates both the time of ponding and the subsequent decline in the infiltration rate.

To simulate the infiltration process Mein and Larson assume a wetting front. The wetting front that Mein and Larson conceptualize, however, is not distinct and precisely definable as was assumed by Green and Ampt. They visualize their wetting front as changing from the saturated moisture to the initial moisture over a constant depth. They define the volume of water in the wetting front to be F_s . This volume is equal to the amount of infiltration prior to runoff. They also define a length, L_s , which is equal to F_s divided by the change in soil moisture.

$$L_s = F_s / (\theta_s - \theta_i) \quad (2.20)$$

Mein and Larson calculated the average capillary suction over their wetting front and applied Darcy's law in the same manner as did Green and Ampt to develop the equation

$$q = K \frac{(S_{av} + L_s)}{L_s} \quad (2.21)$$

where:

q = rainfall intensity

K_s = saturated conductivity

S_{av} = average capillary suction

to describe the infiltration at the initiation of runoff. Substitution of the definition of F_s yields the equation

$$F_s = \frac{S_{av} (\theta_s - \theta_i)}{[(q/K_s) - 1]} \quad (2.22)$$

To simulate infiltration after runoff begins, Mein and Larson formulated their equation as

$$f = K_s \frac{(S_{av} + L_s + L)}{(L_s + L)} \quad (2.23)$$

where:

L = distance from the top of the wetting front to the surface

In terms of the accumulated infiltration equation 2.23 can be restated as

$$f = \frac{K_s S_{av} \Delta \theta}{F_s + F} + K_s \quad (2.24)$$

where:

F = accumulated infiltration after initiation of runoff

The Mein and Larson model has several advantages over the other algebraic infiltration models. Of the other infiltration models only Holton's and the SCS-CN method are capable of simulating infiltration prior to runoff. If the Philip, Green and Ampt, or Horton models are used, another method would have to be used to estimate the initial abstraction. Although this would be possible, it would require using two separate models with different parameters and assumptions.

Another advantage of the Mein and Larson model is that it is deterministic, yet not overly complex. Hence, it is possible to directly measure the parameters of the Mein and Larson model. These

parameters are the same ones that are used by Green and Ampt, however, and cannot be measured without considerable effort.

SCS Curve Number

The Soil Conservation Service curve number method (12) was developed in the early 1950's to predict storm runoff volume from rainfall. Although the method was originally developed to predict runoff volume, it has since been used to simulate infiltration.

The model is based on three assumptions: 1) there is a maximum amount of water, S , that a watershed can hold by depression and soil storage, 2) the ratio of the actual storage to the potential storage, S , is equal to the ratio of the runoff to the precipitation minus the initial abstraction, i.e.

$$\frac{F}{S} = \frac{Q}{P - I_a} \quad (2.25)$$

where:

F = accumulated infiltration

S = potential storage

Q = total runoff

P = precipitation

I_a = initial abstraction

and, 3) the initial abstraction and the potential storage are linearly related by the empirical relationship

$$I_a = .2 S \quad (2.26)$$

Upon substitution of the mass balance relationship

$$F = (P - I_a) - Q \quad (2.27)$$

and equation 2.26, equation 2.25 becomes

$$Q = \frac{(P - .2 S)^2}{(P + .8 S)} \quad (2.28)$$

Equation 2.28 was placed into graphical form by relating S to a curve number, CN ,

$$CN = \frac{1000}{S+10} \quad (2.29)$$

and plotting accumulated rainfall versus runoff for different curve numbers.

Because of its ease in application, the SCS curve number method has been widely used for simulating runoff. Several stormwater models incorporate it. The attractiveness of the model is that it has only one parameter and tables are available which estimate it (12).

The disadvantage of the model is that it predicts that the final infiltration rate is zero. This can be seen by substituting equation 2.28 into equation 2.27 and differentiating. The resulting equation is

$$f = rf (1-b)^2 \quad (2.30)$$

where:

$$b = \frac{(P - .2 S)}{(P + .8 S)}$$

rf = rainfall rate

As P goes to infinity, f goes to zero

Horton Model

Horton (13) proposed the equation

$$f = (f_0 - f_c) e^{-kt} + f_c \quad (2.31)$$

where:

k = decay coefficient

f_0 = capacity rate

f_c = final infiltration rate

Equation 2.31 was originally presented as an empirical equation (14) but Horton later derived it (13) by assuming that infiltration is an exhaustion process. The processes involved in the reduction of the infiltration rate were proposed to be rain packing, breaking down of the crumb structure, swelling of colloids, and the closing of sun checks. However, since these characteristics are not measureable, the equation is still thought of as being empirical.

The equation has the advantage of being able to predict a finite initial infiltration rate and a nonzero final infiltration rate. The equation accurately fits experimental data over a wide range of time. The disadvantage of the model is that it has three parameters that must be optimized by a nonlinear iterative method.

Holtan Model

Holtan (15) proposed a conceptual infiltration model in 1961. Holtan's model relates the infiltration rate to the unsaturated pore space remaining in the soil. He called this the remaining volume, F_p , and related it to the infiltration rate by the equation

$$f = a_h F_p^n + f_c \quad (2.32)$$

where:

F_p = unsaturated pore volume

f_c = final infiltration rate

The parameters a_h , n , and f_c were fitted to field data taken by the US Agricultural Research Service. The exponent, n , was found to be about 1.4 while the coefficient, a_h , varied widely. a_h was later related to the initial soil moisture.

Overton (16) obtained a closed form solution of equation 2.32 by assuming $n = 2$ and solving for f .

$$f = f_c \sec^2 \left[(a_h f_c)^{1/2} (t_c - t) \right]$$

A problem with Holtan's model is that it is difficult, if not impossible, to optimize its parameters for a variable n . Overton's model could be optimized more readily, but the solution is not theoretically pleasing. One would not expect the infiltration rate to equal f_c within a finite length of time.

CHAPTER III

METHOD AND PROCEDURES

Data Collection

The data set used for this study was taken by the Agricultural Research Services (ARS) and the University of Hawaii between July 1972 and March 1974 (17). The infiltration data collection was part of a joint research effort to characterize the erosion properties of Hawaiian soil. For the study a rainulator that produced a spray which approximated natural rainfall was adjusted to spray 2.5 inches of rainfall per hour over prepared plots. The plots were located on 10 Hawaiian soil groups.

Soil plots were prepared by first removing all vegetation. The corners of the plots were then staked and the rainulator was erected. A rotiller was then used to turn the soil over to a depth of 6 inches. Nine inches of corrugated steel siding was installed on the plot boundaries to prevent lateral water movement, and a through was placed at the lower boundary to collect runoff. Final plot preparation consisted of filling in depressions to obtain a uniform slope. Additional soil was added if necessary. Soil samples were then taken and spiked tooth harrow was pulled from bottom to the top of the plot. All plots were 12 ft. wide and were either 70 ft. or 35 ft. in length.

Field data collected before each experimental run consisted of measuring the plot profile and taking soil moisture samples at depths of 0-3, 3-6, 6-12, 12-18, and 18-24 inches. During the runs, runoff was collected from the through in two gallons containers. The time to fill

the containers were determined by stopwatch. Runoff and infiltration rates were calculated from this information. Within 30 minutes after each run soil moisture samples were taken. Bulk density and organic residue samples were taken several days later.

The soils consisted of ten different types. The characteristics of each type is given in the Agricultural Research Service report (17). The soils were of volcanic origin and had varying physical characteristics. The soil texture varied from clay to sandy loam to silty clay loam. Bulk densities varied from 1.22 gm/cm^3 to 0.42 gm/cm^3 .

The data set consisted of 103 infiltration tests taken at 42 sites. Each site usually contained two plots. The typical procedure was to have two storm simulations on each plot, one with dry soil and another run the following day on wet soil.

A computer program was used to calculate infiltration rate from runoff data. The program interpolated the data so as to give the infiltration rate at minute and half minute intervals.

Method of Optimization

The Philip Model and Green and Ampt model were fitted to the Hawaiian data by least square regression. Philip (equation 2.16) was first differentiated to obtain

$$f = 1/2 S_p t^{-1/2} + A$$

A linear least square regression was then used to optimize S_p and A , the independent variate being $t^{-1/2}$.

The differential form of the Green and Ampt model (equation 2.5) was used to optimize the parameters $\underline{a}$ and $\underline{f_c}$. The method of linear

least square regression fitted these parameters for the independent variate $1/F$. F was calculated by numerically integrating the infiltration rate.

It was not possible to transform the SCS-CN model or Horton model into a linear equation, so a nonlinear least square iterative optimization method was used. The method of nonlinear fitting was that of Gauss-Newton with the modification due to Harley (18).

No attempt was made to fit the Holtan or Overton models, since they are of such a form that their parameters would be difficult to optimize. Mein and Larson's model was not fitted to the data set because the author became aware of the model late in the study. Dangler et al., (17), however, did fit the Hawaiian data to the Mein and Larson model so comparison to the other models was possible.

SAS (19), the Statistical Analysis System, was used to fit the models to the ARS data. GLM, the general linear model procedure, was used for the linear regressions and NLIN, the nonlinear least squares procedure, was used for the nonlinear optimization.

Parameter Regionalization

After obtaining the fitted parameters, the parameters were related to soil characteristics. The most significant was found to be the initial moisture. This was expected, since the initial moisture content is a significant variable in most infiltration models including Green and Ampt's and Philip's.

According to Green and Ampt (1)

$$f = \frac{a}{F} + f_c \quad (2.5)$$

where

$$a = K H_p (\bar{\theta} - \theta_o)$$

$$f_c = K$$

F = accumulated infiltration

In order to test this theory, it was assumed that KH_p was constant for each soil type and was not a function of the initial soil moisture. The fitted values of a were then correlated with $(\bar{\theta} - \theta_o)$ and a fitted value of KH_p was obtained for each soil type. The values for KH_p were then divided by the average value of K for each soil type to obtain H_p . During this study, it was assumed that for a two hour storm simulation the depth of the wetting front would be below six inches and that the average of the final moisture contents between 0 to 3 and 3 to 6 inches would be a good approximation of $\bar{\theta}$.

Since Philip's model is more complex, it was more difficult to relate its parameters to the initial moisture content. Closed form solutions to sorptivity, S_p , are available only for certain functions of diffusivity. Of these solutions, only the ones for constant diffusivity and "Dirac delta function" diffusivity were found to be readily optimizable.

During the present study, the assumption of a constant diffusivity was explored. If the diffusivity is constant it follows that

$$S_p = (\theta_s - \theta_o) \sqrt{\bar{D}/\pi} \quad (2.18)$$

This equation was fitted to the Hawaiian data to obtain values of $\bar{D}$ for each soil type. The initial moisture, θ_o , was taken to be the average of initial moisture content between 0-3 and 3-6 inches. It was found that the average of the moisture contents at these two depths provided the best correlations.

There were difficulties in determining the saturated moisture, θ_s . Unfortunately, the saturated moisture content at each site was either not measured or never recorded. The only measurements reported were the final and initial moisture contents (17). The final moisture content within the first three inches of each plot was assumed to be approximately equal to θ_s . This is a reasonable approximation, since the moisture content within the first three inches should be nearly saturated after two hours of rain.

GLM was again used to correlate the parameters with the difference between the initial and final moisture contents. Both Green and Ampt's model and equation 2.18 were fitted with a non-intercept regression.

The Soil Conservation Service (SCS) has related their curve numbers to soil type, land use, hydrologic condition, and antecedent soil moisture (12). According to their classification scheme, the Hawaiian data was taken on fallow, straight row plots of hydrologic soil group C. The curve number, CN, for such plots is listed as being 91. The SCS-CN method classifies soil moisture into three groups, I, II, and III which corresponds to normal, wet, and dry, respectively.

During the present study, the runs were classified into two moisture groups, normal and wet. The average of the optimized storage potentials was calculated for each group and the values were compared to those found in the SCS Hydrology Guide (12). Following this comparison, the runs were classified according to soil type and the average storage potential for each group was again calculated and compared to SCS values.

The optimized parameters of Horton's model showed no relation to the initial moisture. Hence, it was not possible to relate its parameters to it.

CHAPTER IV

RESULTS

The parameters of Green and Ampt, Philip, Horton, and the SCS-CN models that were optimized on the Hawaiian data are presented in the appendix. Coefficients of determinations, R^2 , and in the case of Green and Ampt's and Philip's models, the conditional variance, is also given. Examples of typical fits for all four models on wet and dry soils are given in Figures 4.1 to 4.8. Note the negative R^2 values for some of the Horton and SCS-CN optimizations. This indicates that the data fit the models so poorly that they explain none of the original variance.

Green and Ampt Model

Green and Ampt's model fit the data the poorest of the four models tested. The conditional variance tended to be greater and the R^2 values tended to be lower than the others. Since some of the assumptions of linear regression have been violated, the R^2 values are but an indication of variance explained. In this case, there are errors in the independent variate, $1/F$. Linear regression assumes that there are errors only in the dependent variate, f . Also, note that low R^2 values were obtained for the wet runs although the conditional variance for these runs is not especially high. Since the infiltration rate dropped rapidly during these runs and then remained at a steady state, there was little total variance. The low R^2 value reflects a low total variance rather than a high error of fit.

The fitted Green and Ampt model had a tendency to over simulate

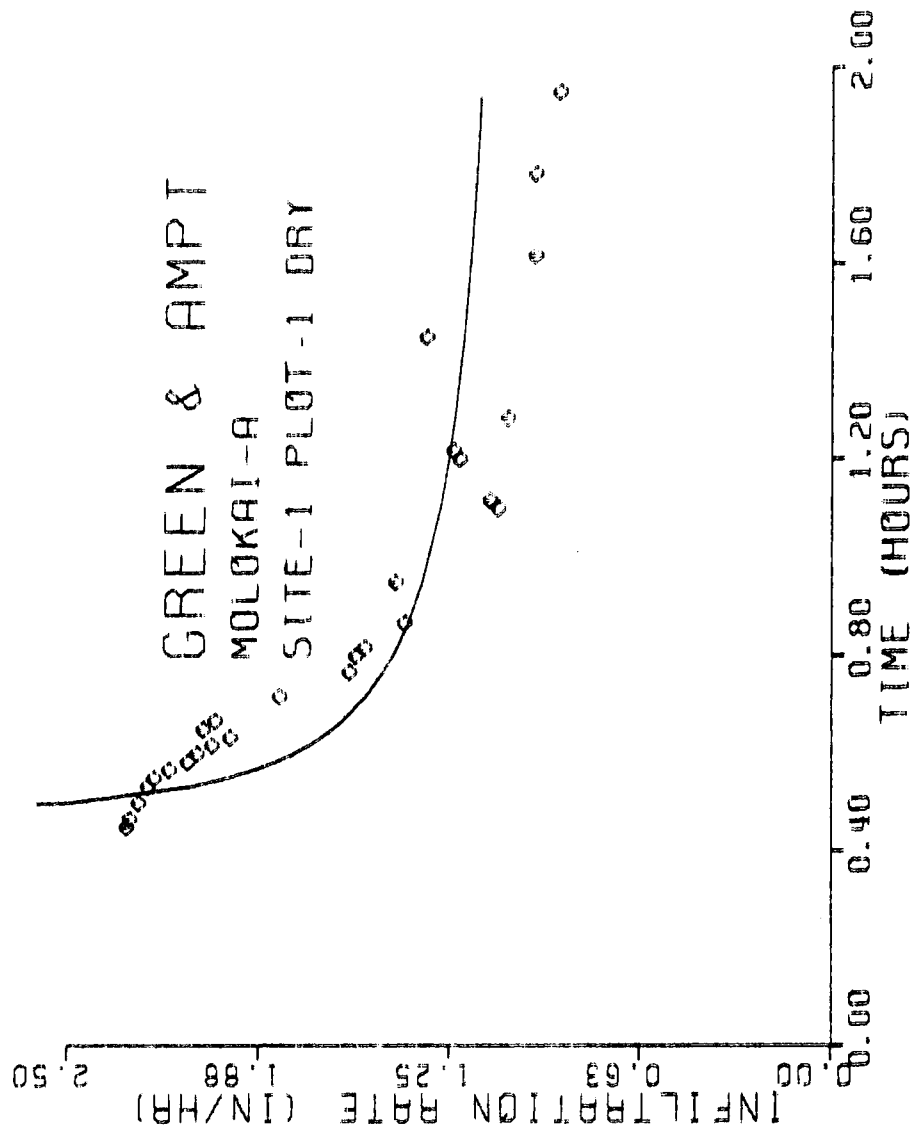


FIGURE 4.1

TYPICAL FIT OF GREEN AND AMPT MODEL FOR A DRY SOIL

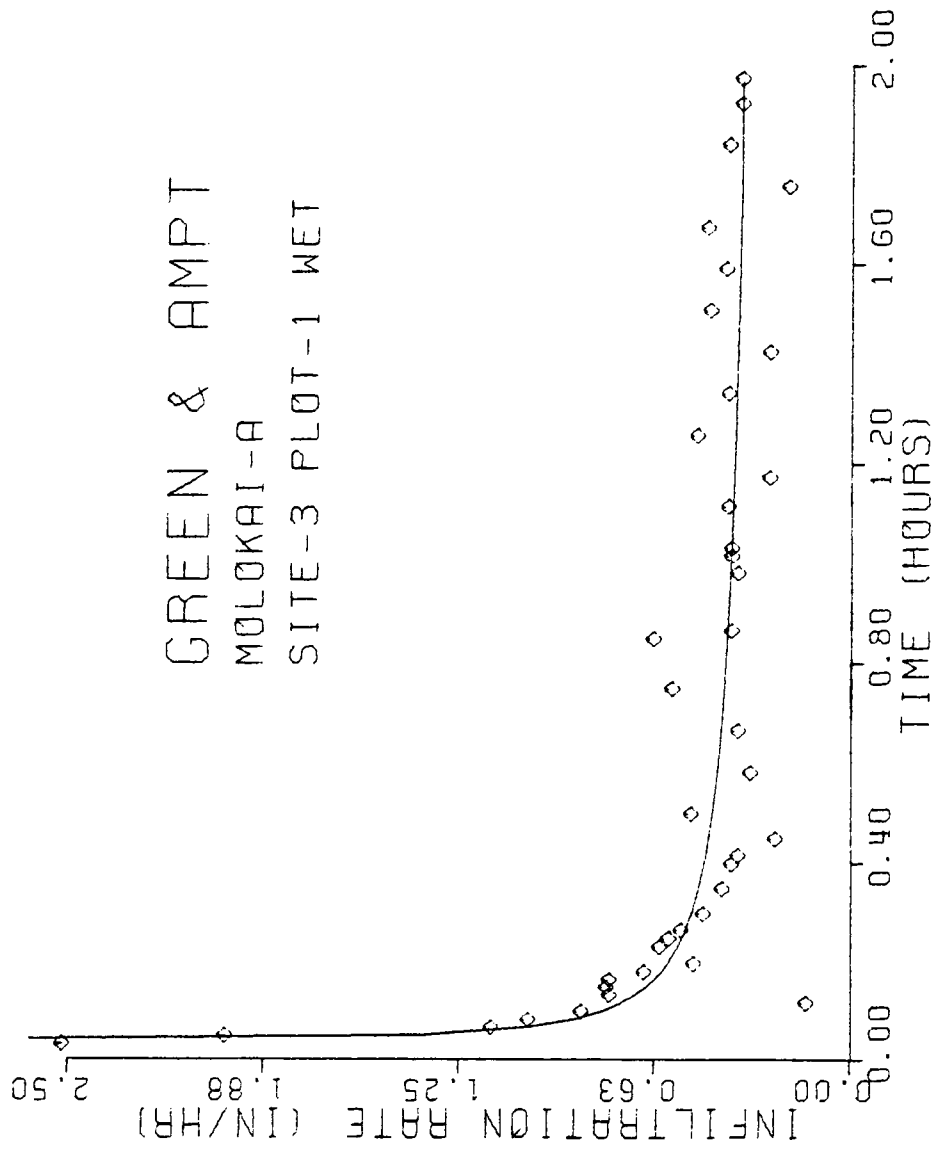


FIGURE 4.2

TYPICAL FIT OF GREEN AND AMPT MODEL FOR A WET SOIL

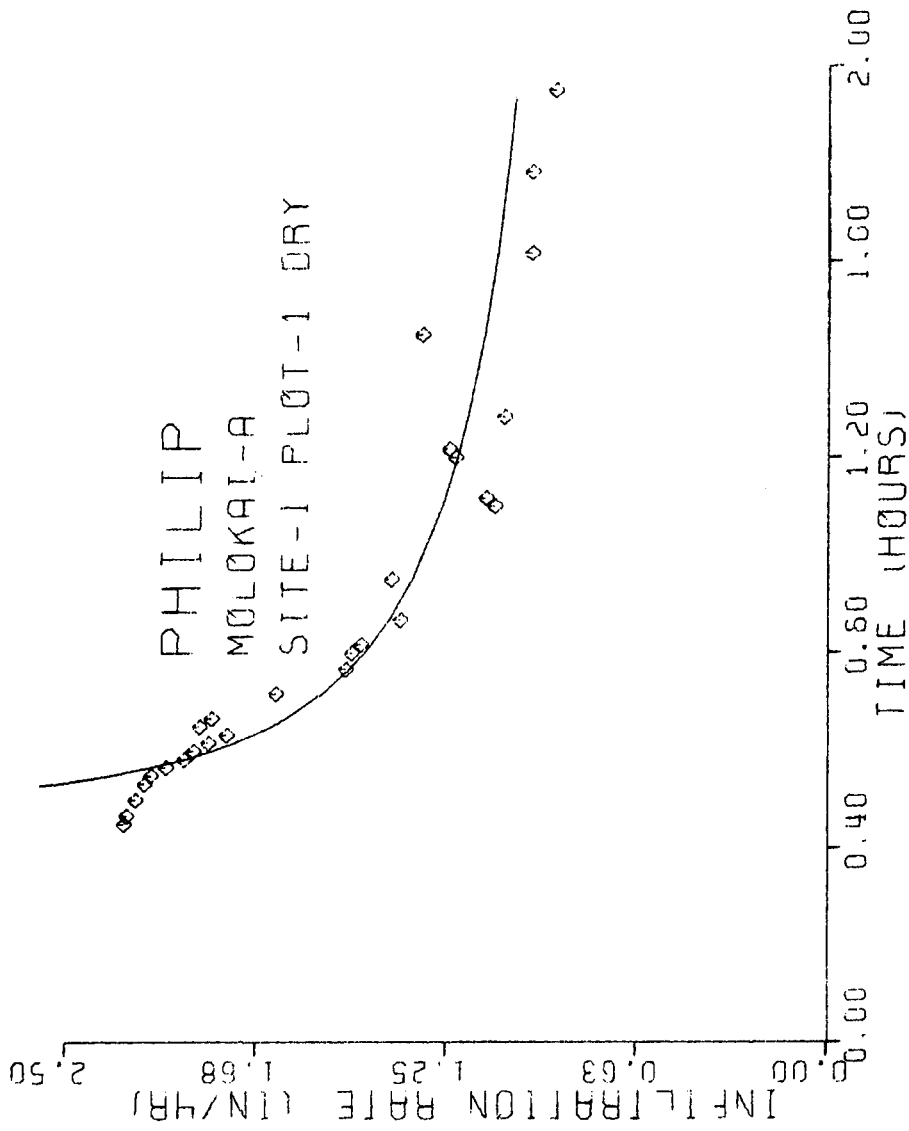


FIGURE 4.3

TYPICAL FIT OF PHILIP MODEL FOR A DRY SOIL

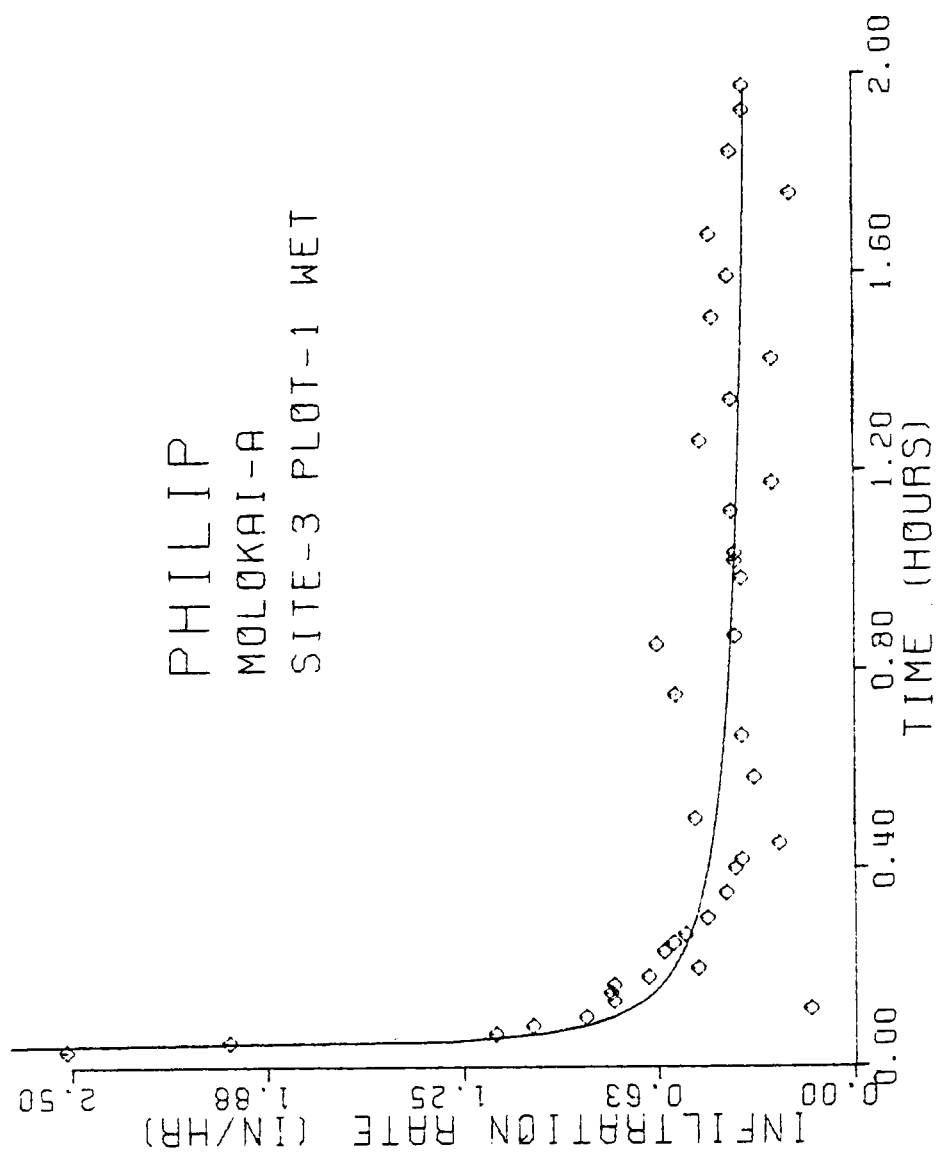


FIGURE 4.4

TYPICAL FIT OF PHILIP MODEL FOR A WET SOIL

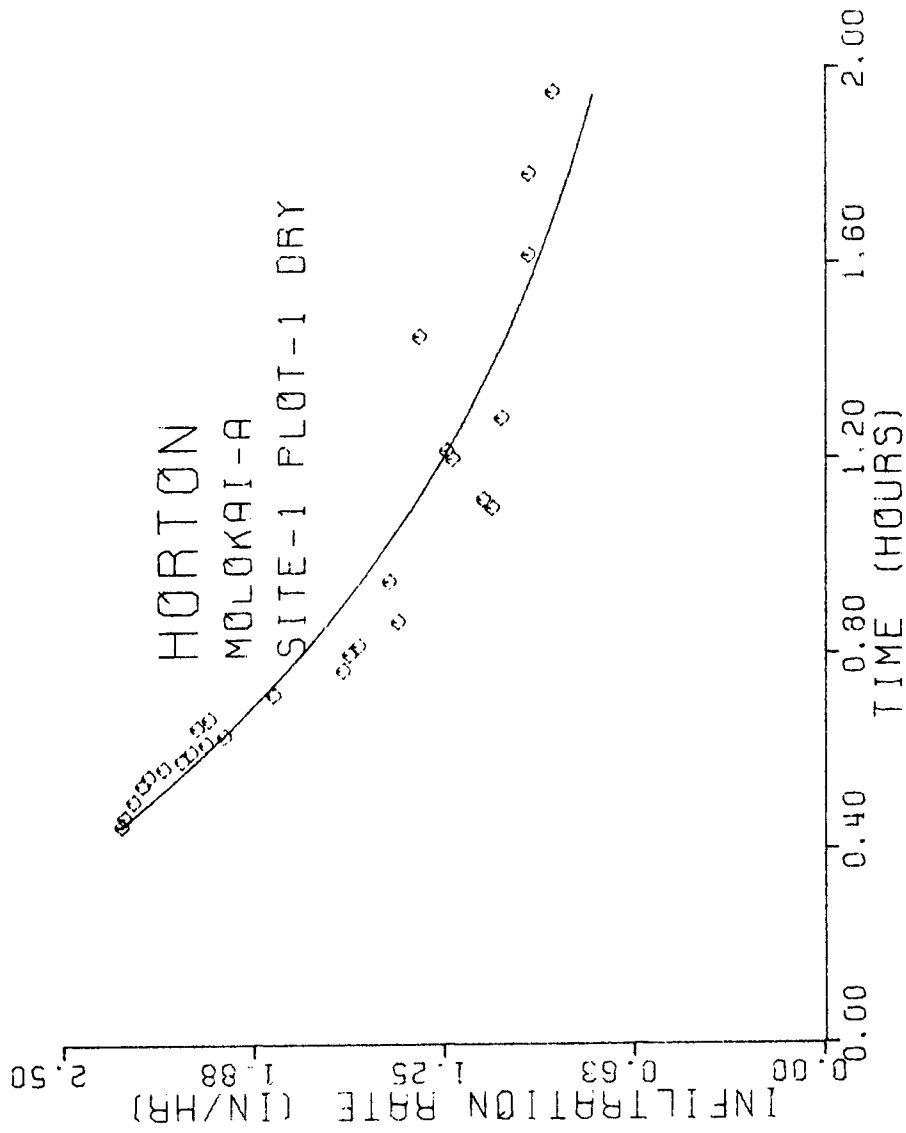


FIGURE 4.5

TYPICAL FIT OF HORTON MODEL FOR A DRY SOIL

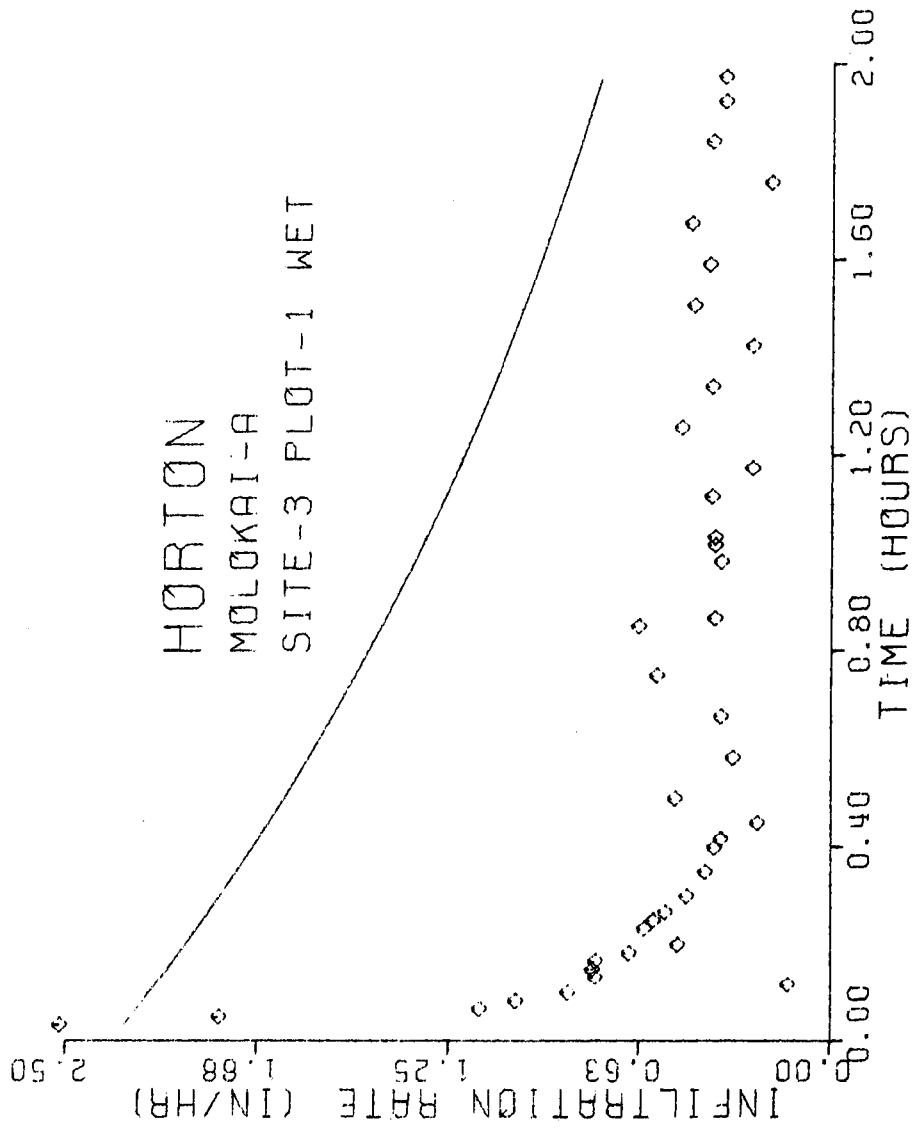


FIGURE 4.6

TYPICAL FIT OF HORTON MODEL FOR A WET SOIL

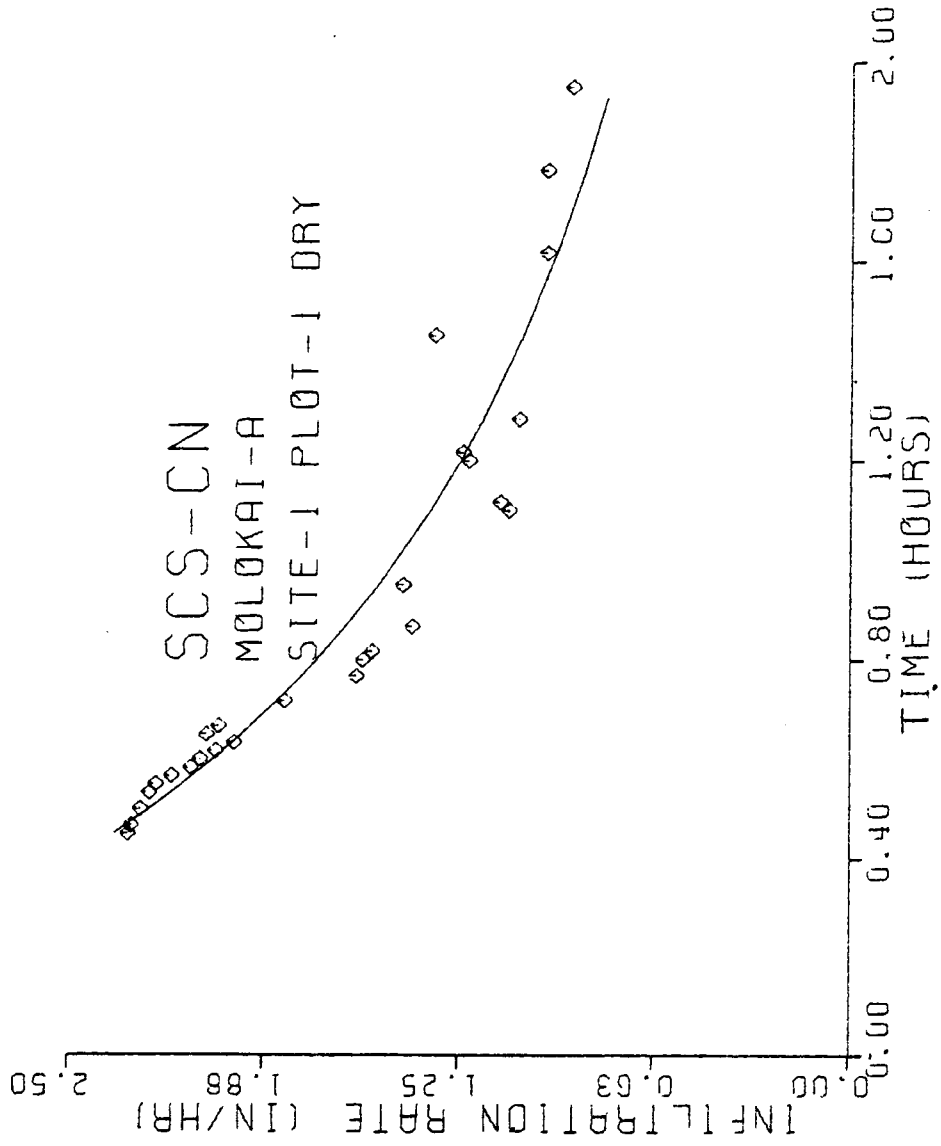


FIGURE 4.7

TYPICAL FIT OF SCS-CN METHOD FOR A DRY SOIL

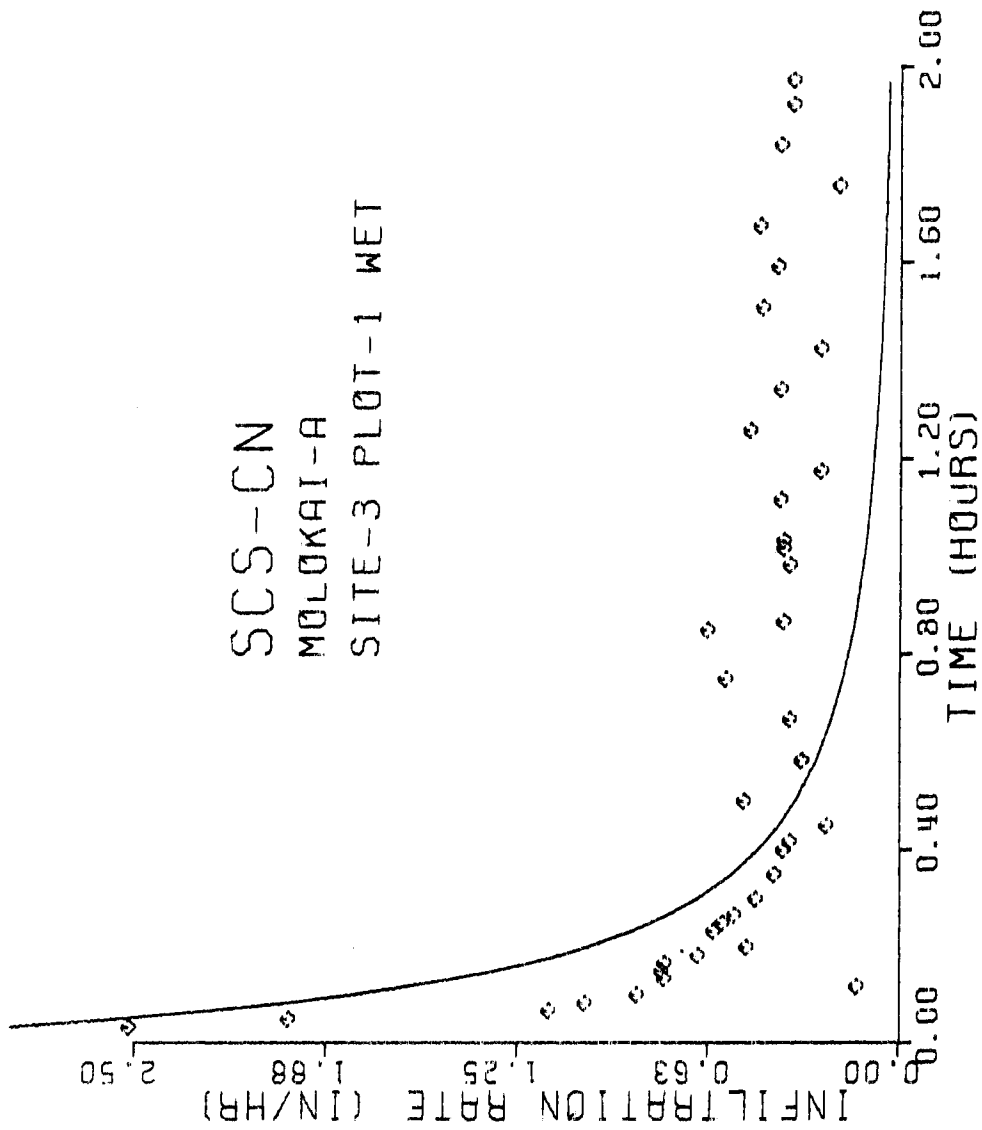


FIGURE 4.8

TYPICAL FIT OF SCS-CN METHOD FOR A WET SOIL

the final infiltration rate. The overestimation of the final infiltration rate could have been lessened if the runs included data points at times greater than two hours.

Better fits were obtained from the wet runs than the dry runs. This was because the infiltration rate dropped rapidly during these runs and more closely resembled the Green and Ampt curve. The better fit was not reflected by the R^2 value or conditional variance, however. This was because the data taken during these runs was not smooth and had considerable fluctuation.

As a result of the poor fit of the dry runs, the conductivity, K , was found to vary with the initial moisture. Higher values of K were determined from runs on dry soils.

The fitted values of $H_p K$ are listed in Table 4.1 and plots of the regressions are presented in the appendix. These values are recorded along with their R^2 value and standard error of estimates, SEE. By dividing $H_p K$ by the mean of the fitted conductivities, values of H_p were also calculated. The sample size for some of the soil types was quite small. Note that there are only two data points for Waipahu soils. Hence, the regression for Waipahu soils has a large R^2 value and high standard error of estimate.

The values $H_p K$ ranged between 0.631 in/hr for Lualuale soil to 2.42 in/hr for Naalahu soil. The average K for each soil was more variable and ranged from 0.245 in/hr for Hilo soil to 1.67 in/hr for Waipahu soil.

The fitted values of H_p seem low compared to measured values. Brakensiek (2) calculated the theoretical capillary pressure for five

TABLE 4.1

STATISTICAL ANALYSIS FOR
REGRESSION OF $(\theta - \theta_i)$ VERSUS $\underline{a}$

Soil	$\bar{a}^1$ (in ² /hr)	$\bar{f}_c^1$ (in/hr)	H_{pK} (in/hr)	H_D (in)	R^2	SEE (in/hr)	no. obs.
Molokai-A	.319	.734	.917	1.25	.78	.10	23
Waipahu	.127	1.676	2.230	1.33	.90	.74	2
Molokai-B	.157	.928	.934	1.01	.44	.37	9
Wahiawa	.203	.900	.987	1.10	.81	1.11	8
Lualualei	.351	.355	.631	1.78	.89	.11	5
Waikane	.173	1.644	.991	.60	.40	.60	5
Kukaiau	.243	1.008	1.079	1.07	.56	.21	20
Hilo	.464	.245	1.013	4.13	.43	.83	3
Kawaihae	.213	.451	1.931	4.23	.88	.27	8
Naalehu	.264	.330	2.422	7.34	.89	.37	6
Pakini	.194	.977	.847	.87	.91	.12	6

¹Average value of parameter

different types of soils. His values ranged from 4.8-5.7 inches for Plainfield sand to 9.0-9.3 inches for Yolo light clay. Only three of the values for H_p from this study were over 2.0 inches. The low values of H_p and high values of K indicate that the soils tested are very porous.

Philip Model

Philip's model achieved better fits than the Green and Ampt model. It generally had higher R^2 values and lower conditional variances. However, the fitted curves also tended to overestimate the initial infiltration rate, underestimate the intermediate infiltration rate, and overestimate the final infiltration rate. The maximum error at intermediate time for the Molokai A series is given for comparison of Green and Ampt's and Philip's model in Table 4.2. As can be seen Philip's model fits better. Philip's model also tended to overestimate the final infiltration rate for dry soils (Figure 4.3).

After applying the assumption of a constant diffusivity, an optimized value of $\bar{D}$ was determined for each soil type. The value of $1/2 \sqrt{\bar{D}/\pi}$, the standard error of estimate and the R^2 value are recorded along with $\bar{D}$ in Table 4.3. Diffusivity varies with the soil moisture so it is impossible to measure an "average" diffusivity in a soil. Hanks and Bower's (20) measurements of diffusivity for Geary silt loam ranged from 0.105 in²/hr for 5% moisture to 233 in²/hr for 41% moisture.

SCS-CN

The SCS curve number method fit the data well for the dry runs but fit poorly for the wet runs. The reason for this is the SCS-CN model

TABLE 4.2

MAXIMUM DIFFERENCE BETWEEN FITTED AND ACTUAL INFILTRATION RATE
AT INTERMEDIATE TIMES FOR DRY MOLOKAI-A SOILS

PLOT	SITE	GREEN & AMPT (in/hr)	PHILIP (in/hr)
1	1	-.34	-.24
1	2	-.36	-.21
2	1	-.39	-.24
2	2	-.35	-.19
3	1	-.40	-.25
3	2	-.34	-.25
4	1	-.28	-.60
4	2	-.77	-.60
5	1	-.33	-.18
5	2	-.25	-.11
6	1	-.32	-.21
6	2	-.48	-.40
7	1	-.24	-.16
7	2	-.38	-.25
8	1	-.21	-.13
8	2	-.47	-.48
9	2	-.37	-.19

TABLE 4.3

STATISTICAL ANALYSIS FOR
REGRESSION OF $(\theta_s - \theta_i)$ VERSUS S_p

Soil	S_p (in $hr^{-1/2}$)	A (in/hr)	$1/2 \sqrt{D/\pi} t^{1/2}$ (in $hr^{-1/2}$)	$\bar{D}$ (in ² hr)	R^2	SEE (in $hr^{-1/2}$)	no. obs.
Molokai-A	1.048	.420	1.58	31.4	.91	.10	23
Waipahu	.536	1.050	8.32	869.9	.76	4.65	2
Molokai-B	.506	.568	1.59	31.8	.46	.60	10
Wahiawa	.475	.427	2.25	63.6	.79	.43	8
Lualualei	.604	.059	1.07	14.4	.88	.20	5
Waikane	.300	1.439	1.78	39.8	.50	.90	5
Kukaiau	.430	.737	1.95	47.8	.66	.32	20
Hilo	.316	-.043	1.50	28.3	.58	.90	3
Kowaihae	.393	.258	3.38	143.6	.82	.44	8
Naalehu	.356	.188	3.35	141.0	.86	.60	6
Pakini	.337	.757	1.44	26.0	.90	.21	6

¹ Average value of parameter for soil type

predicts a less rapid decline in the infiltration rate at intermediate times. However, when the soil was wet the infiltration rate tended to drop rapidly and then remain at a steady state. The SCS-CN model could not fit this type of curve since it assumes that the infiltration rate goes to zero. Hence, negative R^2 values were calculated from the wet runs.

The soils from which the data were taken can be classified as C-type soils according to the SCS hydrologic classification scheme. The soil moisture condition could be classified as either I or II. I is normal; II is wet. The mean of the class I samples was 4.44 inches. This was equivalent to a CN of 69.2. The mean S of the class I samples was 3.06 inches which is equivalent to a CN of 76.6. These curve numbers are rather low and would not be expected for C type soils. This again indicates that the soils are rather porous.

The average was bloated by some very large S's. The largest S was 21.5 inches from the waikane site 23, plot 2 wet run. During this run 7.52 inches of rain fell, while only 0.13 inches ran off. During the dry run on this plot, no runoff occurred at all. The other runs on the Waikane soils also had large storage values. Since the soil type seemed to have more influence on determining S than the initial moisture, a soil by soil analysis was performed. The average S for each soil type is recorded in Table 4.4. The soil type with the lowest mean storage potential was Hilo with 1.24 inches. The soil type with the largest mean S was Waikane with 11.24 inches.

Horton Model

The fitted parameters of Horton's model were $f_0 - f_c$ and k . f_0 was

TABLE 4.4

AVERAGE, MINIMUM, AND MAXIMUM VALUES
FOR POTENTIAL STORAGE

Soil	Average (inches)	Minimum (inches)	Maximum (inches)	no. obs.
Molokai-A	3.88	.58	12.0	23
Waipahu	9.05	2.43	16.7	4
Molokai-B	2.28	.45	9.2	10
Wahiawa	4.50	.59	8.9	8
Lualualei	2.93	1.25	4.4	5
Waikane	11.23	3.40	21.5	5
Kukaiau	4.52	1.12	12.5	20
Hilo	1.24	.68	2.2	6
Kawaihae	1.73	.58	4.2	8
Naaiehu	1.95	.40	3.5	6
Pakini	2.70	1.70	3.4	6
Normal	4.44	.45	15.0	62
Wet	3.06	.40	21.5	39

fixed at the initial infiltration rate. As was the case with the curve number method, Horton's model had a tendency to fit the dry runs well but the wet runs poorly. Under dry conditions it usually fit better than all the other models. Under wet conditions it failed completely.

This may not be because of the model itself but because of the optimization scheme. Horton's model is highly flexible. By employing a large k it should be easy to fit a wet run with the model. It was common for $f_o - f_c$ to equal 2.50 and k to equal 0.50. The nonlinear least squares procedure used a grid search routine to find a starting point. Quite often it would locate the starting point of $f_o - f_c = 2.5$ and $k = 0.50$ then not go through any iterations. This indicated that the program may not be converging.

No further work was done to regionalize the parameters of Horton's model, because of a lack of confidence in the fitting procedure and the lack of a theory to relate Horton's parameters to the initial moisture.

CHAPTER V

DISCUSSION

The objective of this study was to determine which infiltration model reported in the literature would be best suited for simulating infiltration on disturbed soils. The results of this study indicates some definite preferences. The criteria for defining these preferences were: (1) the ability of the models to fit the data, (2) the sensitivity of the models to errors in parameter estimation, and (3) the accuracy of which the model's parameters can be estimated.

SCS-CN

The SCS-CN method fit dry runs well. However, the method fit wet runs very poorly. Since most erosion occurs during design storms in which the soil is usually initially wet, this is a major disadvantage. Figure 5.1 demonstrates the sensitivity of the infiltration rate to the storage potential, S . As can be seen a small error in estimating S will not grossly change the infiltration curve.

However, it is possible to grossly under estimate the CN. Such was the case with this study. For the dry soils the average fitted storage potential was over four times more than that suggested by the SCS Hydrology guide (11). The reason for this is probably that the soils were so turned over during site preparation that they were open and loose. The results was porous soils. This should be kept in mind when transferring the information from this study. The results are only applicable to disturbed soils.

Within each soil group there was also considerable variance in the

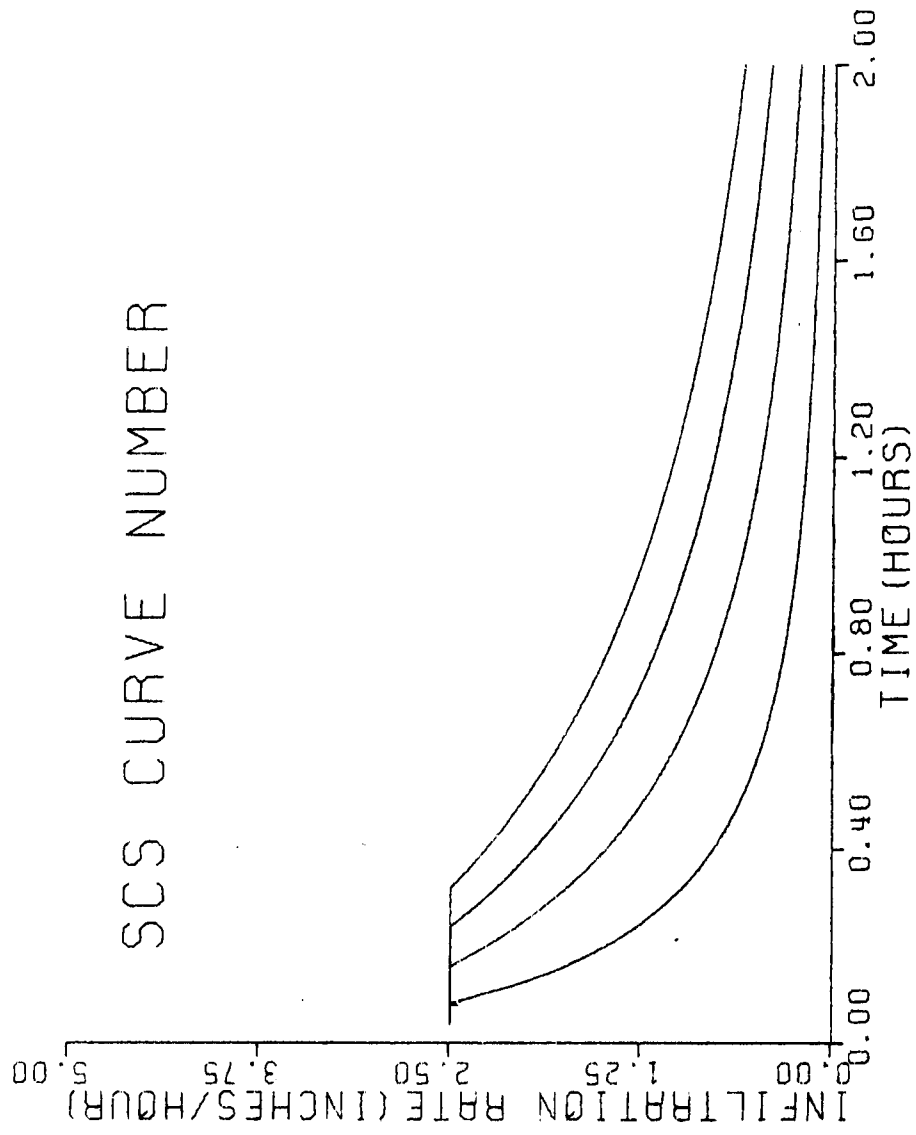


FIGURE 5.1

PLOT OF SCS-CN METHOD WITH VARYING S

storage potential. Some of the variance could be explained by considering the initial moisture. However, the sample size was so small that such an analysis was not done.

Since the SCS-CN model is the only infiltration model available which has regionalized parameters, it is the most commonly used method for simulating runoff today. If the method is used for simulating runoff from soil banks, good simulation will be obtained only if the soils are initially dry. Considerable judgement should be used if the soils are wet.

Horton Model

Horton's model also fit well. The model is quite flexible and fit well over all time periods. It has a finite initial infiltration rate, variable slopes at intermediate times, and nonzero final infiltration rate. However, the optimized parameters often made little sense. Sometimes the final infiltration rate was estimated as being below zero. The fitted parameters also show little relationship to the initial moisture.

Figure 5.2 demonstrates the sensitivity of the Horton model to the decay parameter k . The model is sensitive to k only when k is small. The lack of sensitivity to k was probably one of the reasons Horton's model was difficult to optimize.

Although an acceptable value for k can be estimated for the Horton model, values for the capacity rate, f_0 , and the final infiltration rate, f_c , are difficult to determine. The fitted values for f_c from this study were often physically incorrect. If extended runs of more than two hours were run better values for f_c would have been obtained.

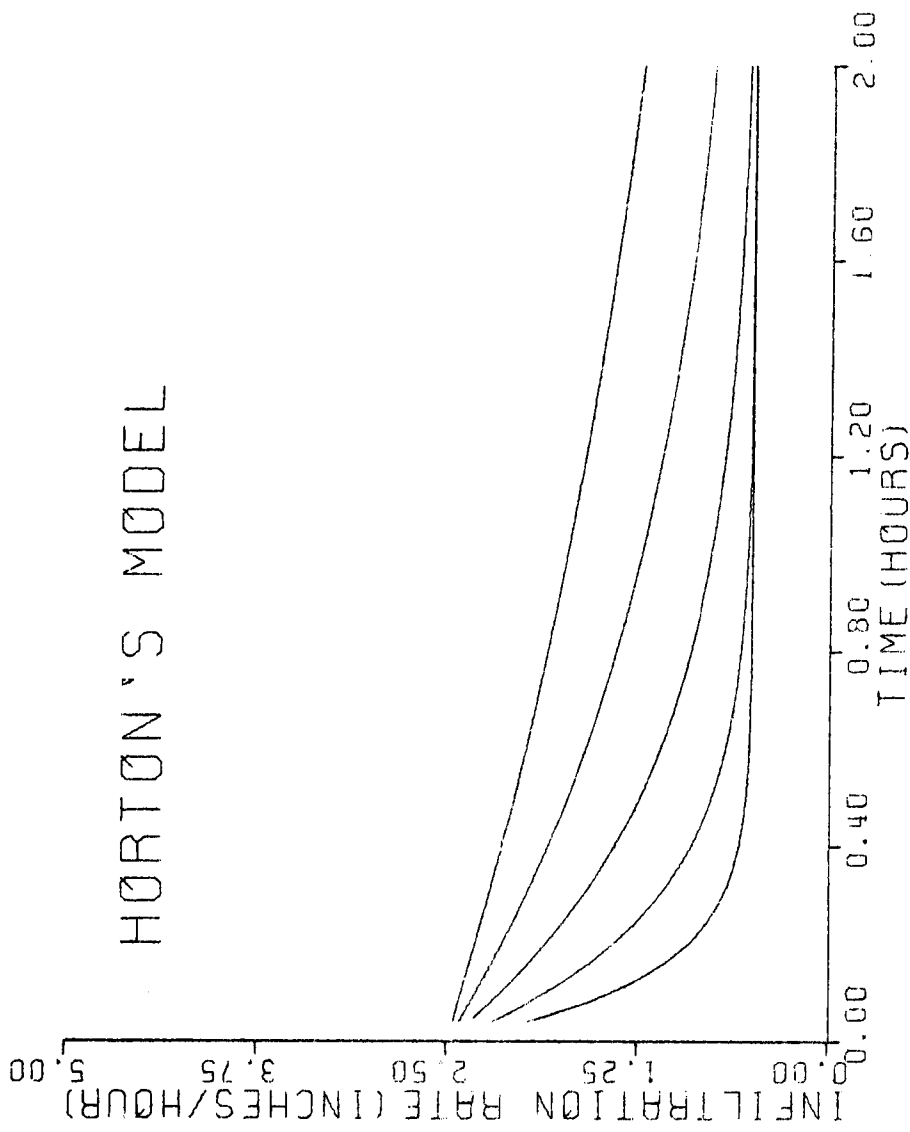


FIGURE 5.2

PLOT OF HORTON MODEL WITH VARYING k

However, this would not have cured the main problem with using Horton's model, determining the capacity rate. According to Horton, rainfall lowers the capacity rate until it is equal to the rainfall rate (13). Following this, the infiltration rate declines according to Horton's model. But if the rainfall rate is not steady, what is f_0 ? Are f_0 and k independent? The parameters of Horton's model vary from storm to storm.

The Horton model has little potential. It fits well but has parameters that are difficult to estimate. Since the model is empirical, it is difficult to relate the parameters to physical properties of the soil.

Green and Ampt Model

The Green and Ampt model fit poorest of the four models. The model consistently underestimated the infiltration rate at intermediate times. Acceptable fits occurred only for the wet runs. The lack of fit does not indicate that the assumptions of the model are poor or incorrect, however. The Green and Ampt model has accurately simulated infiltration in controlled laboratory experiments when the soil moisture profile was initially constant and the water supply at the surface was never exhausted. These assumptions were not followed during the experimental runs.

Figure 5.3 demonstrates the sensitivity of the Green and Ampt model to the parameter, $\underline{a}$. The model is more sensitive to $\underline{a}$ as the time approaches zero. Also note that the sensitivity of $\underline{a}$ increases as $\underline{a}$ becomes smaller.

A method for estimating $\underline{a}$ was developed during this study. Plots for estimating $\underline{a}$ given the soil type, initial moisture, and final moisture

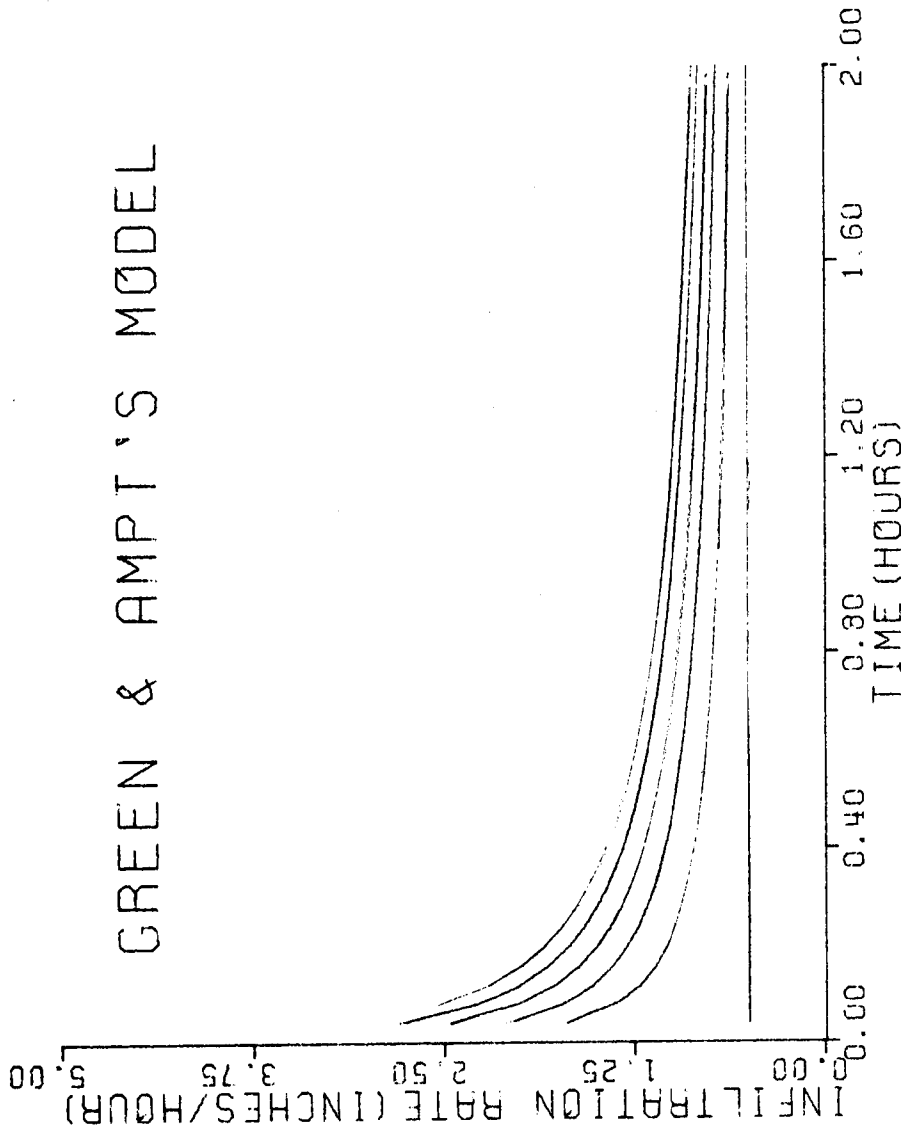


FIGURE 5.3

PLOT OF GREEN AND AMPT MODEL WITH VARYING a

are in the appendix. The confidence limits of the regressions are also given. The fit of the regressions is about the same as those which estimate the sorptivity of Philip's model.

Since Philip's model fits better than Green and Ampt's and has parameter which are just as predictable, Philip's model will simulate more accurately. Unless easier methods are developed which directly measure and calculate the parameters of the Green and Ampt model there is no advantage in using it over Philip's.

Philip Model

Philip's model fit acceptably. The model did not fit the dry runs as well as the SCS-CN model, but since most erosion occurs when the soil is already wet this is only a minor drawback.

As with the other models, the parameters of Philip's model did not show extreme sensitivity in any of its parameters. Figure 5.4 demonstrates the sensitivity of the model to the sorptivity, S_p . The model is sensitive to S_p when the time approaches zero.

The sorptivity for disturbed Hawaiian soils can be estimated from the plots in the appendix. The accuracy of the estimate will depend upon the sample size and how well the data fit. For some soils degree of confidence is quite small; for others it is good.

The diffusivities did not correspond well with soil textures. One would expect the sandy soils to have high diffusivities while the clays would have low ones. Of the sandy loams, Kawaihae had a high diffusivity, $143.6 \text{ in}^2/\text{hr}$, while Pakini had a low one, $260 \text{ in}^2/\text{hr}$. Lualuale, the clay soil, did have the lowest diffusivity, $14.4 \text{ in}^2/\text{hr}$, however. Other factors besides texture seem to be important. These could be bulk density or organic content.

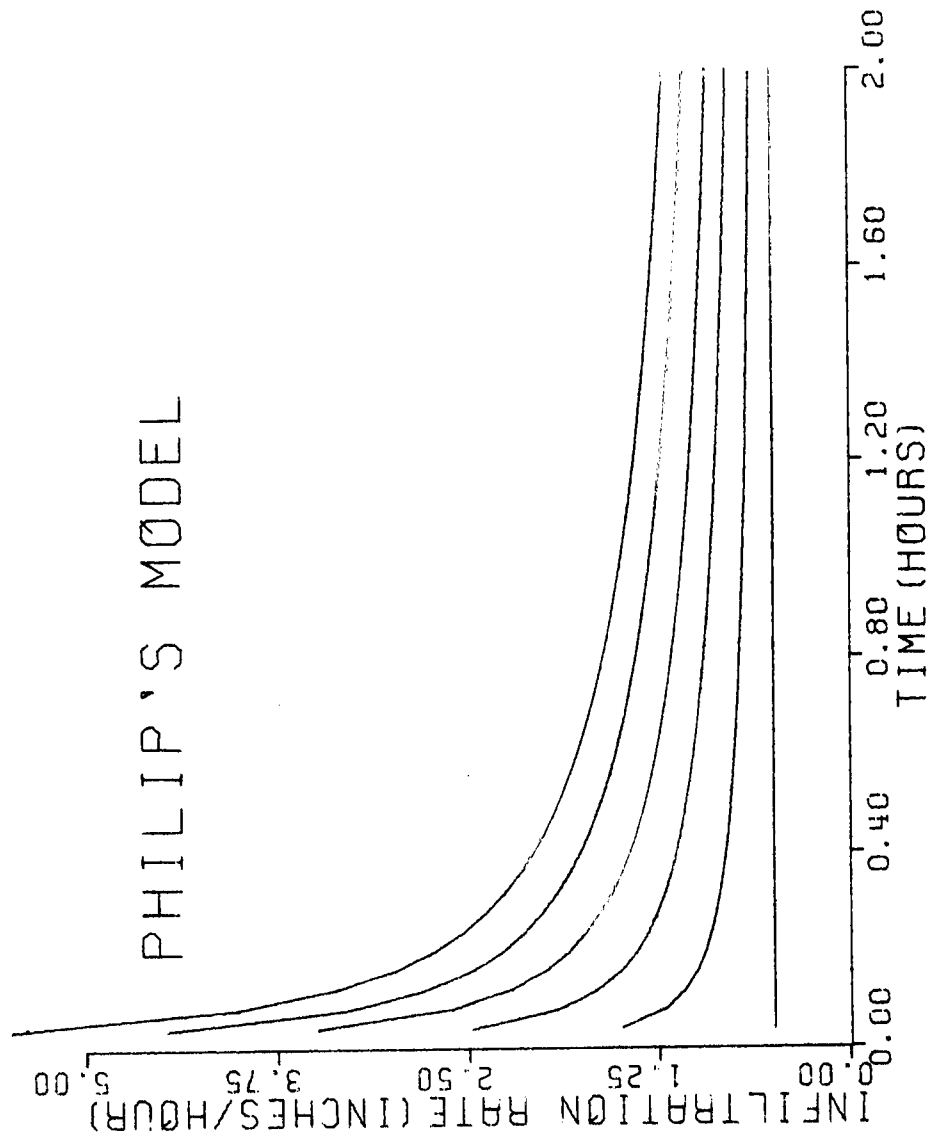


FIGURE 5.4

PLOT OF PHILIP MODEL WITH VARYING S_p

There is still some question as to whether the relationship between saturated moisture minus initial moisture and sorptivity is actually linear. Since the initial abstraction changes in the initial moisture profile, the relationship between the two is unclear. The relationship requires more study.

Philip's model would be a good model to use for simulating infiltration. It is theoretically sound, fits well, and has parameters that can be estimated. The model does not simulate the time of ponding, however. Unless a method is developed to simulate the initial abstraction, Philip's model will not be of much value.

Mein and Larson Model

The Mein and Larson model usually fit the Hawaiian data well (17). There was a tendency, however, for the optimized soil conductivities to be lower than expected. Often they were negative. Since there was no data at times greater than two hours, the parameters were optimized for infiltration rate at beginning and intermediate times. An evaluation of the model by Idike et al., (21) in which the parameters were physically measured indicated that the Mein and Larson model would underestimate the infiltration rate at intermediate times. If this is the case, parameters optimized for infiltration tests of less than two hours will give low values for conductivity and low values for capillary suction.

Since Dangler et al., (16) gave no indication of the goodness of fit of their optimized parameters, it is difficult to compare Mein and Larson to the other models. Plots presented by Dangler et al., show the fit to be better than Green and Ampt and Philip on dry soils and better than Horton and SCS-CN on wet soils.

Since the Mein and Larson model fits data well and also estimates the initial abstraction it is the infiltration model with the most potential for accurately simulating infiltration during a storm. Presently the parameters are difficult to measure and have not been regionalized. Hence, more research needs to be done before it is applicable for hydrologic studies.

CHAPTER VI

CONCLUSIONS

At the present time, the only method available for simulating infiltration rate which has regionalized parameters, is the SCS-CN method. The method gave good results for the dry soils but simulated the infiltration rate for the wet conditions poorly.

An alternative to this method is Philip's model. The model fit the wet rainfall simulations well and had parameters which are predictable. In the present study, it was found that a constant diffusivity model accounted for much of the variation in the sorptivity. Hence, the sorptivity could be linearly related to the saturated moisture minus the initial moisture. The Philip model, however, is quite sensitive to the time of ponding. Unless a method for simulating initial abstraction is developed, Philip's model will not be of much value for simulating infiltration during a storm.

The Horton model showed little potential. It was difficult to relate its parameters to soil characteristics and the model gave no method for simulating the initial abstraction.

The Green and Ampt model fit poorest of the four models. It consistently underestimated the infiltration rate at intermediate times. Since Mein and Larson's variation of the Green and Ampt model fits better than Green and Ampt, there is no advantage in using Green and Ampt over Mein and Larson.

The Mein and Larson model has much potential. It fits well and also simulates the time prior to runoff during a steady rainfall. Further research to develop procedures for estimating model parameters is recommended.

CHAPTER VII

RECOMMENDATIONS

1) The SCS-CN method and Mein and Larson's method should be compared to determine which method is more applicable for modeling stormwater runoff from small watersheds.

2) Easier methods to determine the parameters of Mein and Larson's model should be developed.

3) Methods to model stormwater runoff using Mein and Larson's model when the watershed is of more than one soil type should be explored.

4) The parameters of Mein and Larson's model should be determined for spoil banks on coal stripped watersheds. This will facilitate erosion simulation.

5) The limits of applicability of Mein and Larson's model should be explored. The loss of accuracy due to nonidealities such as non-uniform soils and slopes should be investigated.

6) An estimate of the accuracy of the SCS-CN method and Mein and Larson's method should be established. This will be helpful for estimating the accuracy of stormwater models.

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APPENDICES

APPENDIX A

Regression of Sorptivity Versus
Change in Soil Moisture

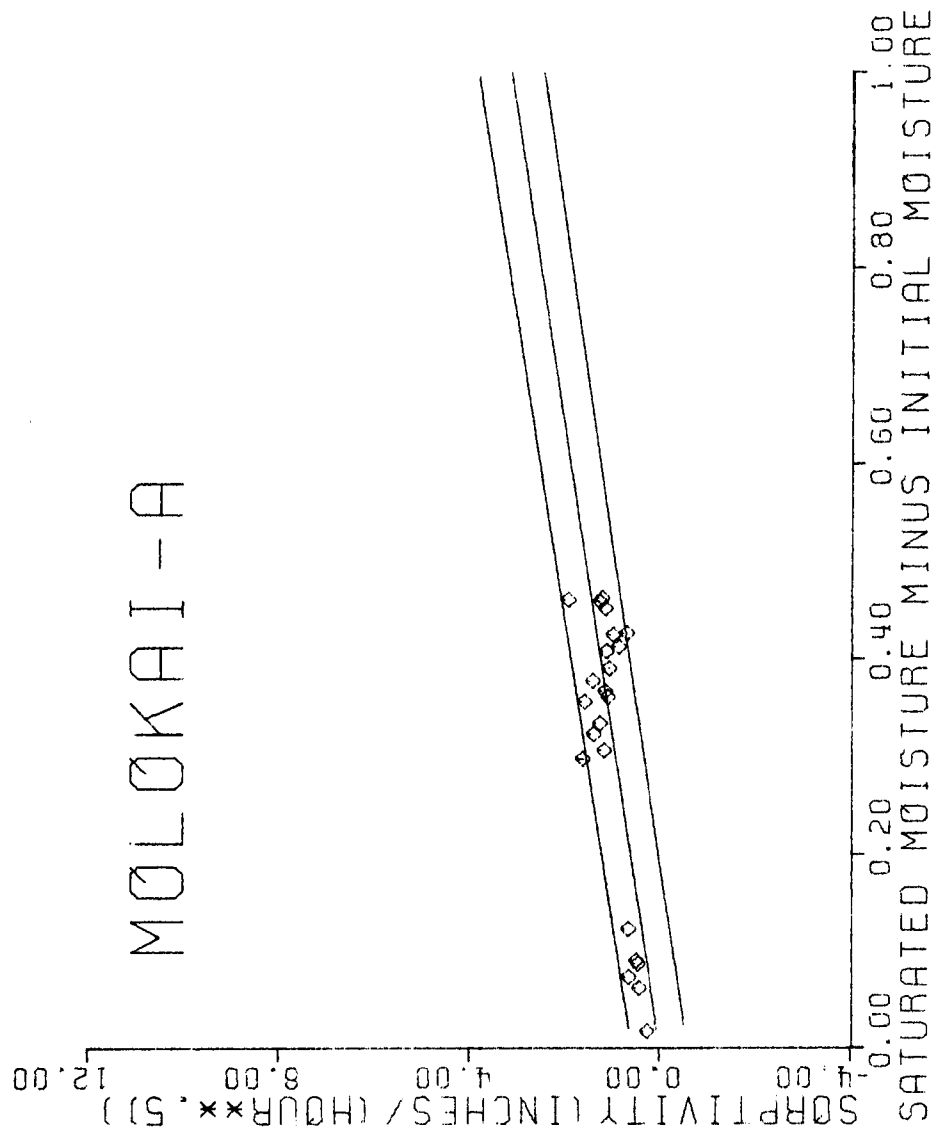


FIGURE A.1

REGRESSION OF SORPTIVITY VERSUS CHANGE IN SOIL
MOISTURE FOR MOLOKAI-A SOILS

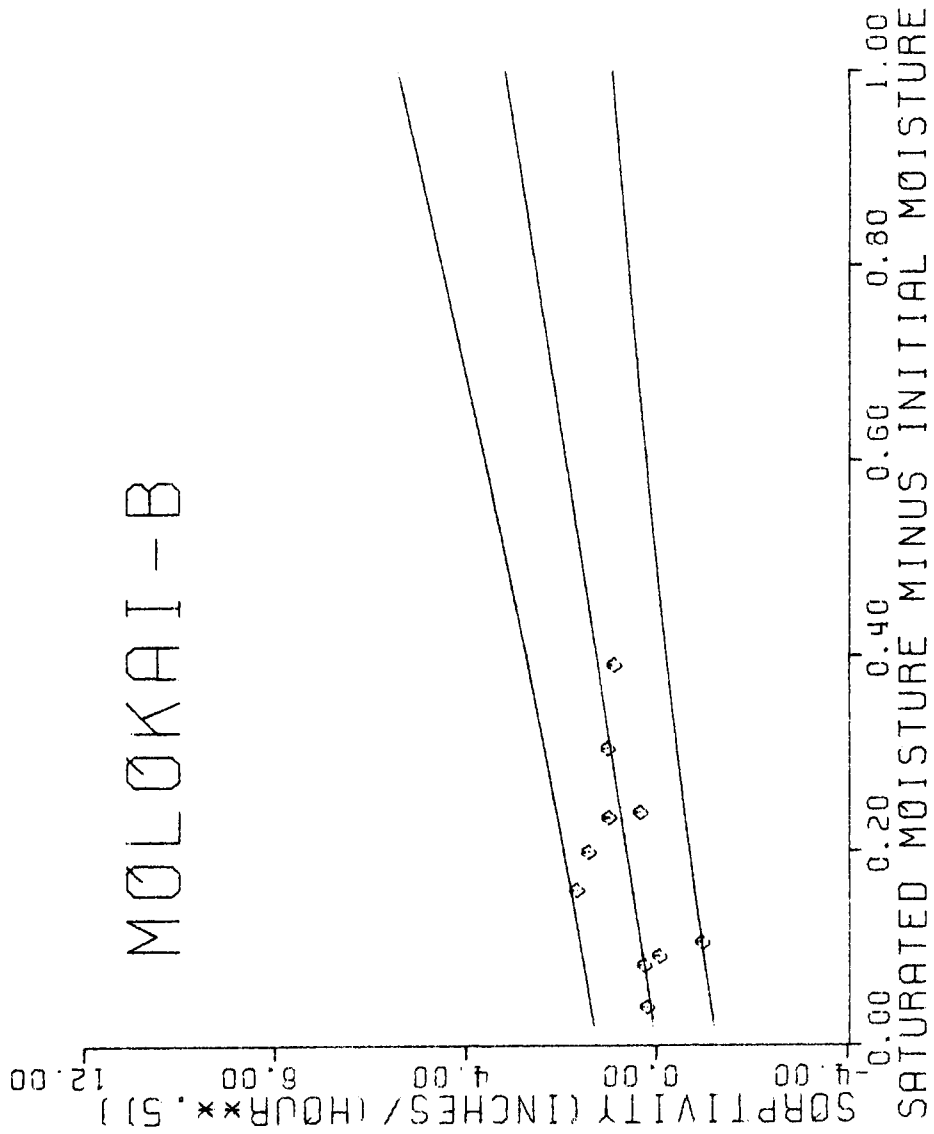


FIGURE A.2

REGRESSION OF SORPTIVITY VERSUS CHANGE IN SOIL
MOISTURE FOR MOLOKAI-B SOILS

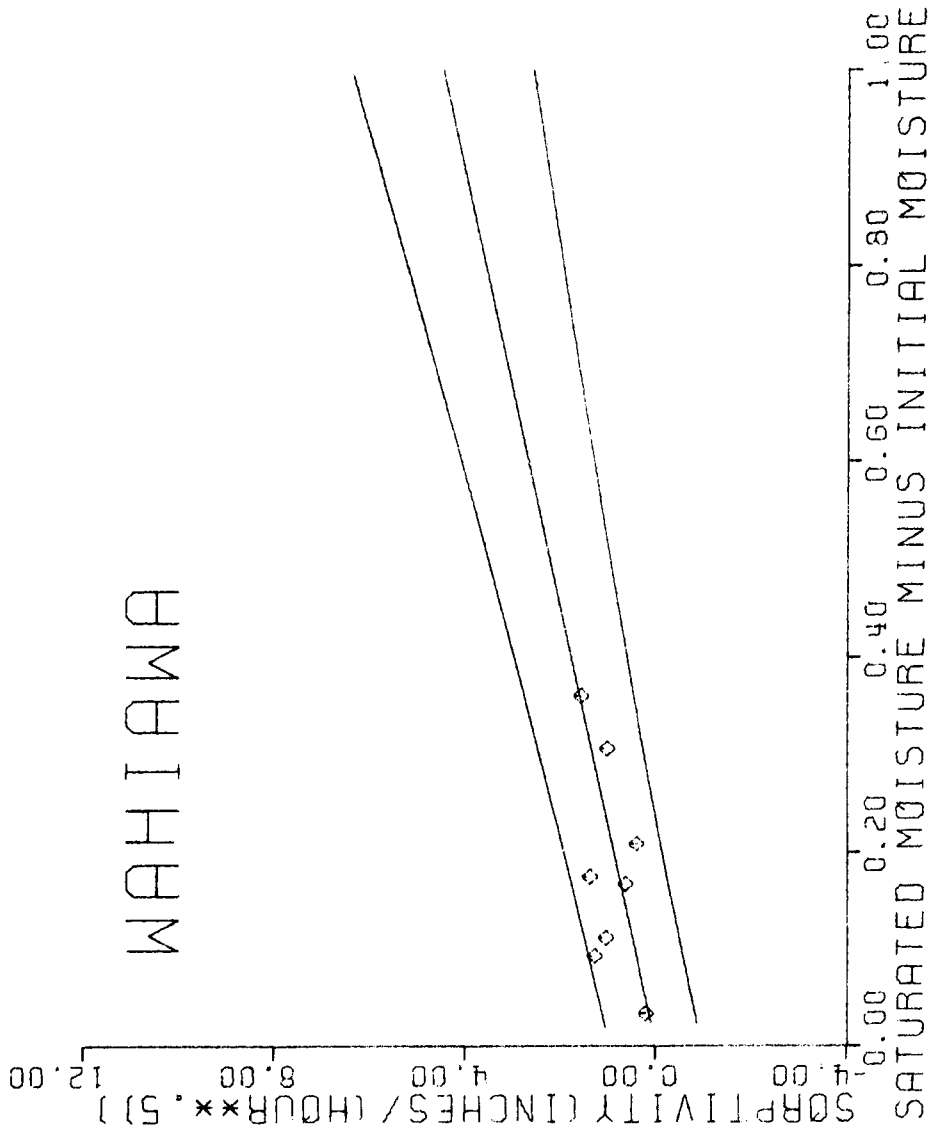


FIGURE A.3

REGRESSION OF SORPTIVITY VERSUS CHANGE IN SOIL
MOISTURE FOR WAHIAWA SOILS

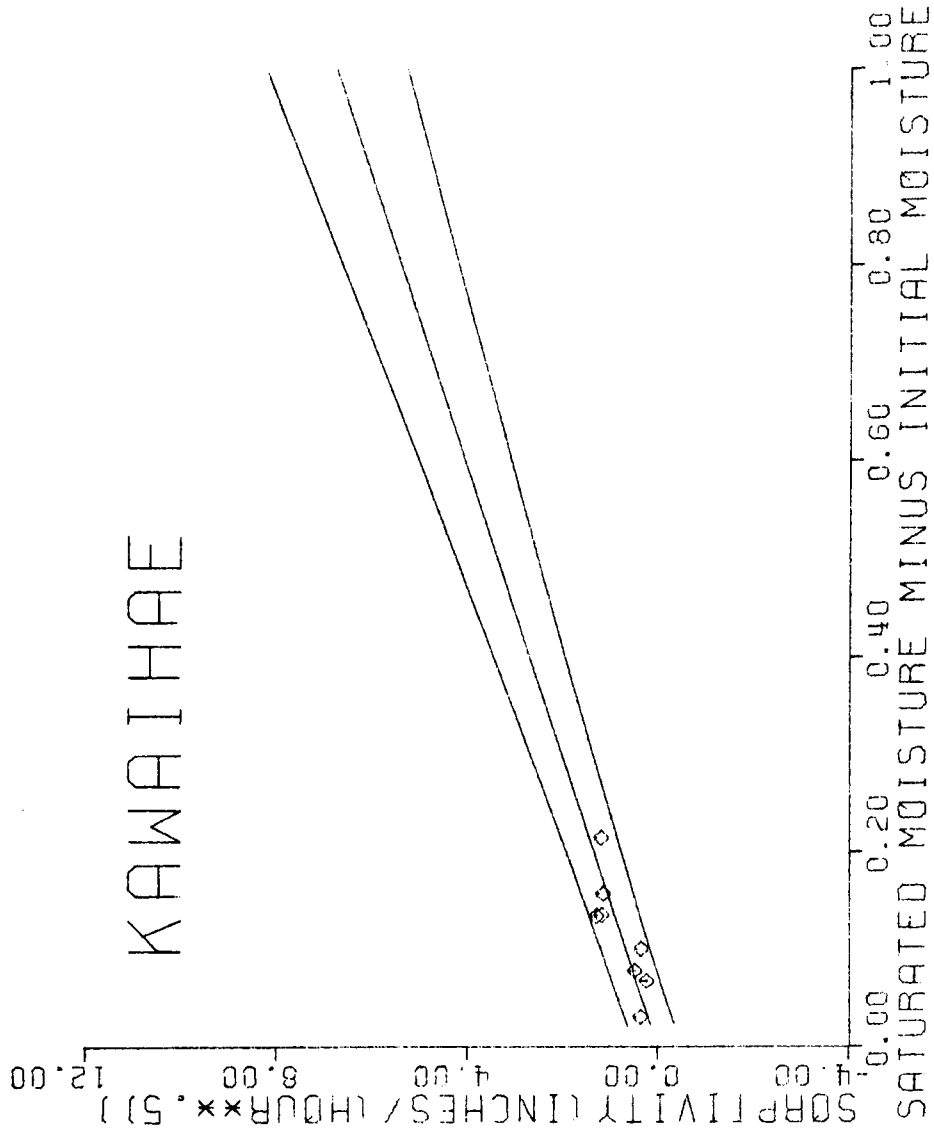


FIGURE A.4

REGRESSION OF SORPTIVITY VERSUS CHANGE IN SOIL
MOISTURE FOR KAWAIHAE SOILS

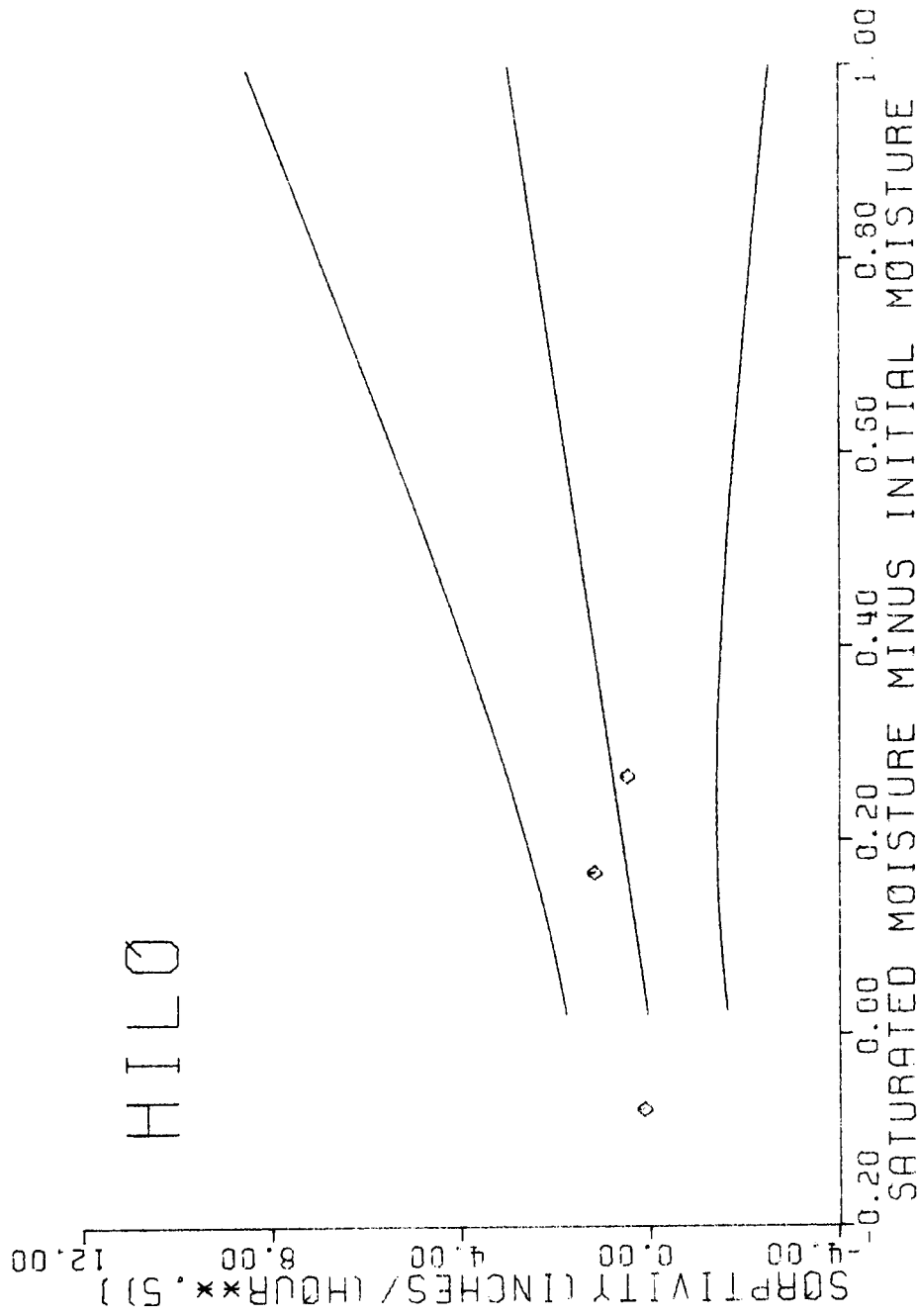


FIGURE A.5

REGRESSION OF SORPTIVITY VERSUS CHANGE IN SOIL
MOISTURE FOR HILO SOILS

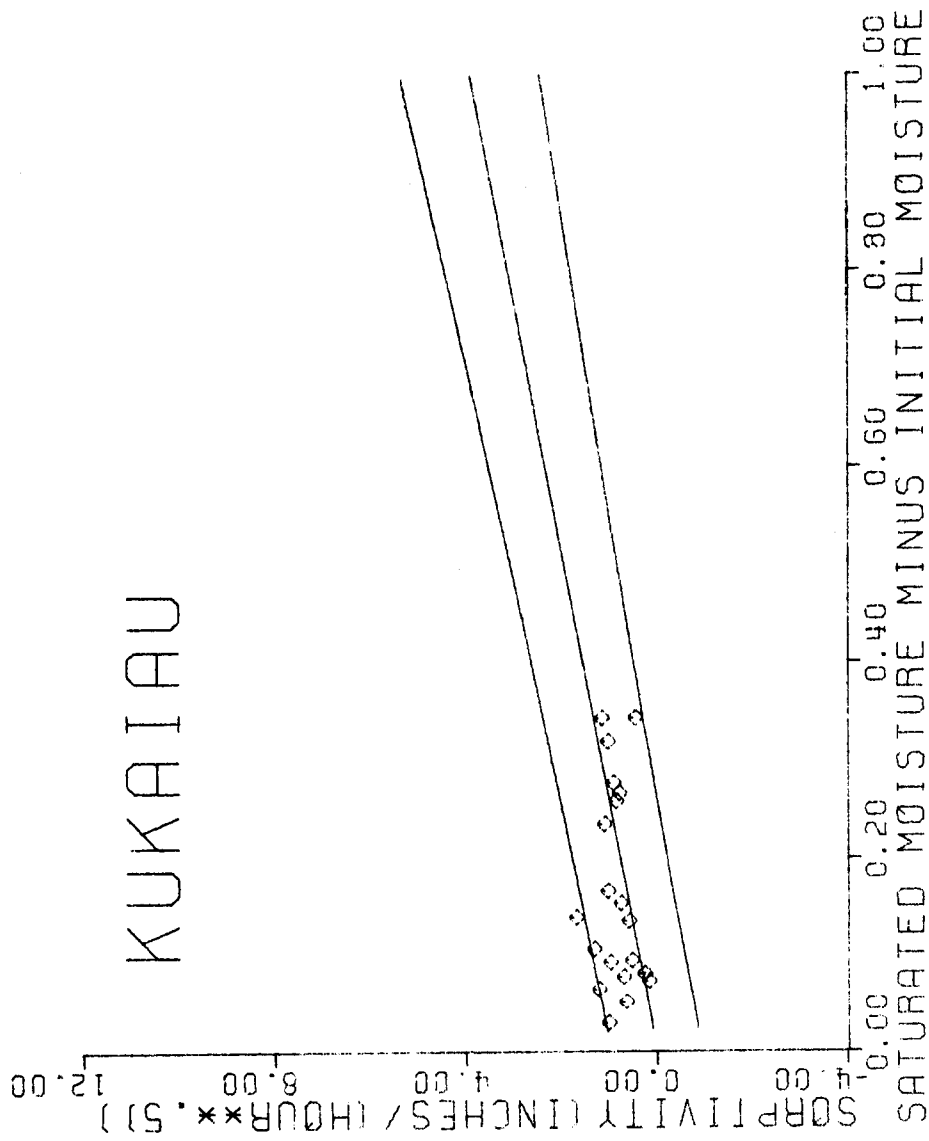


FIGURE A.6

REGRESSION OF SORPTIVITY VERSUS CHANGE IN SOIL
MOISTURE FOR KUKAIAU SOILS

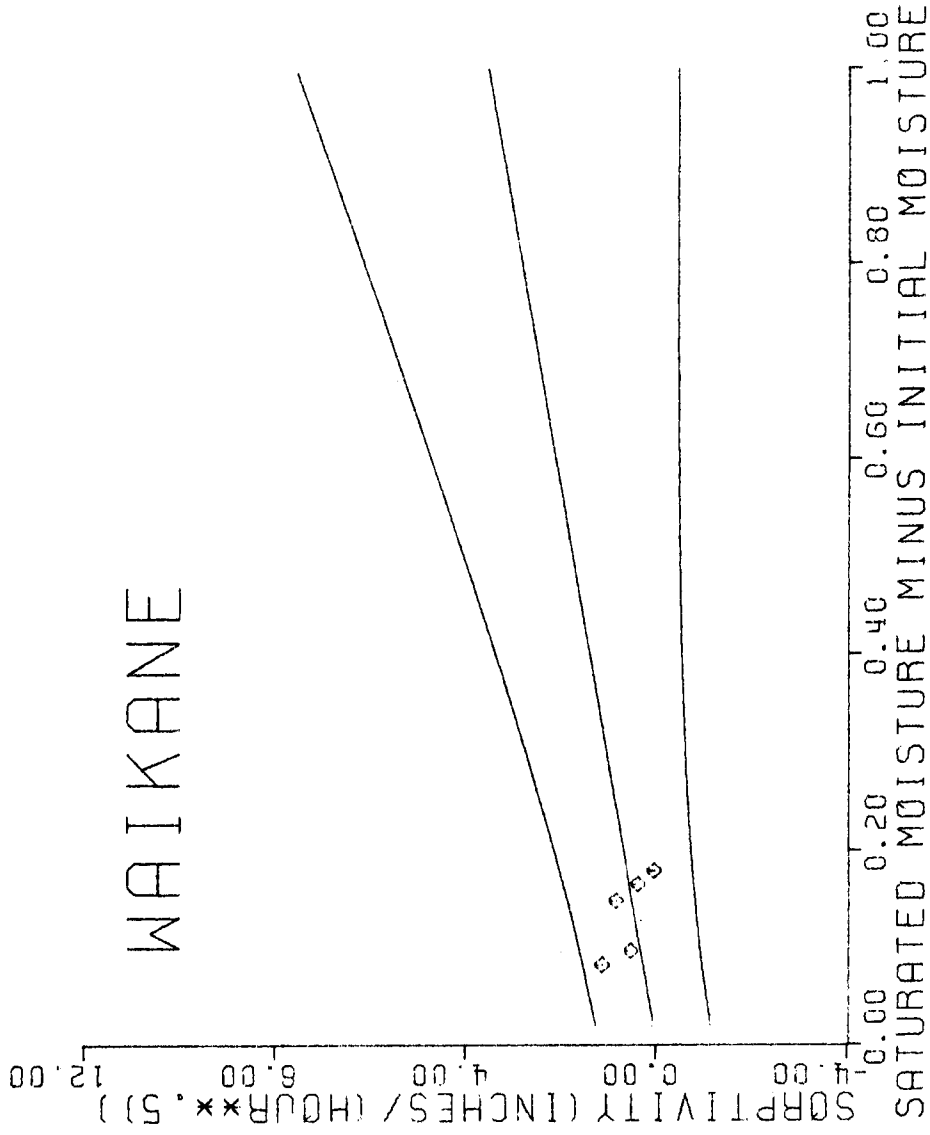


FIGURE A.7

REGRESSION OF SORPTIVITY VERSUS CHANGE IN SOIL
MOISTURE FOR WAIKANE SOILS

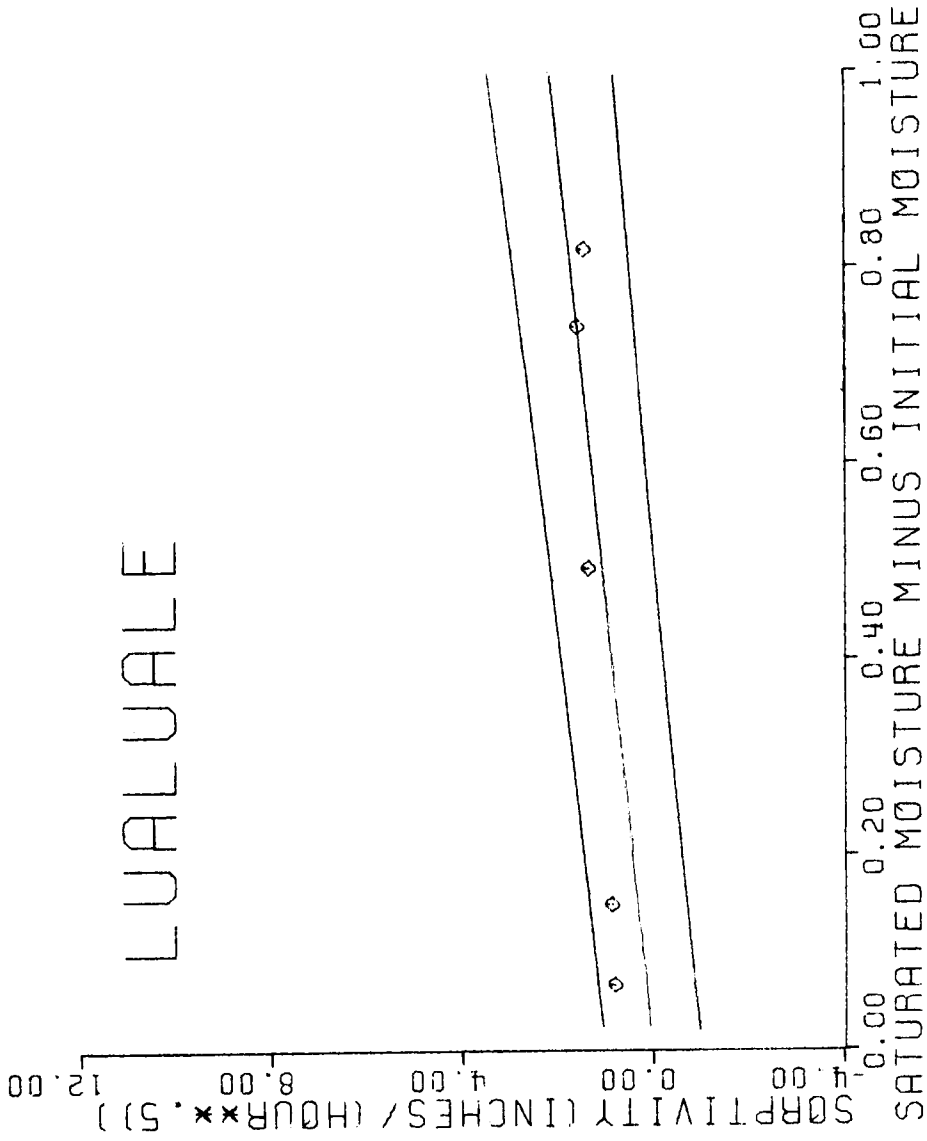


FIGURE A.8

REGRESSION OF SORPTIVITY VERSUS CHANGE IN SOIL
MOISTURE FOR LUALUALE SOILS

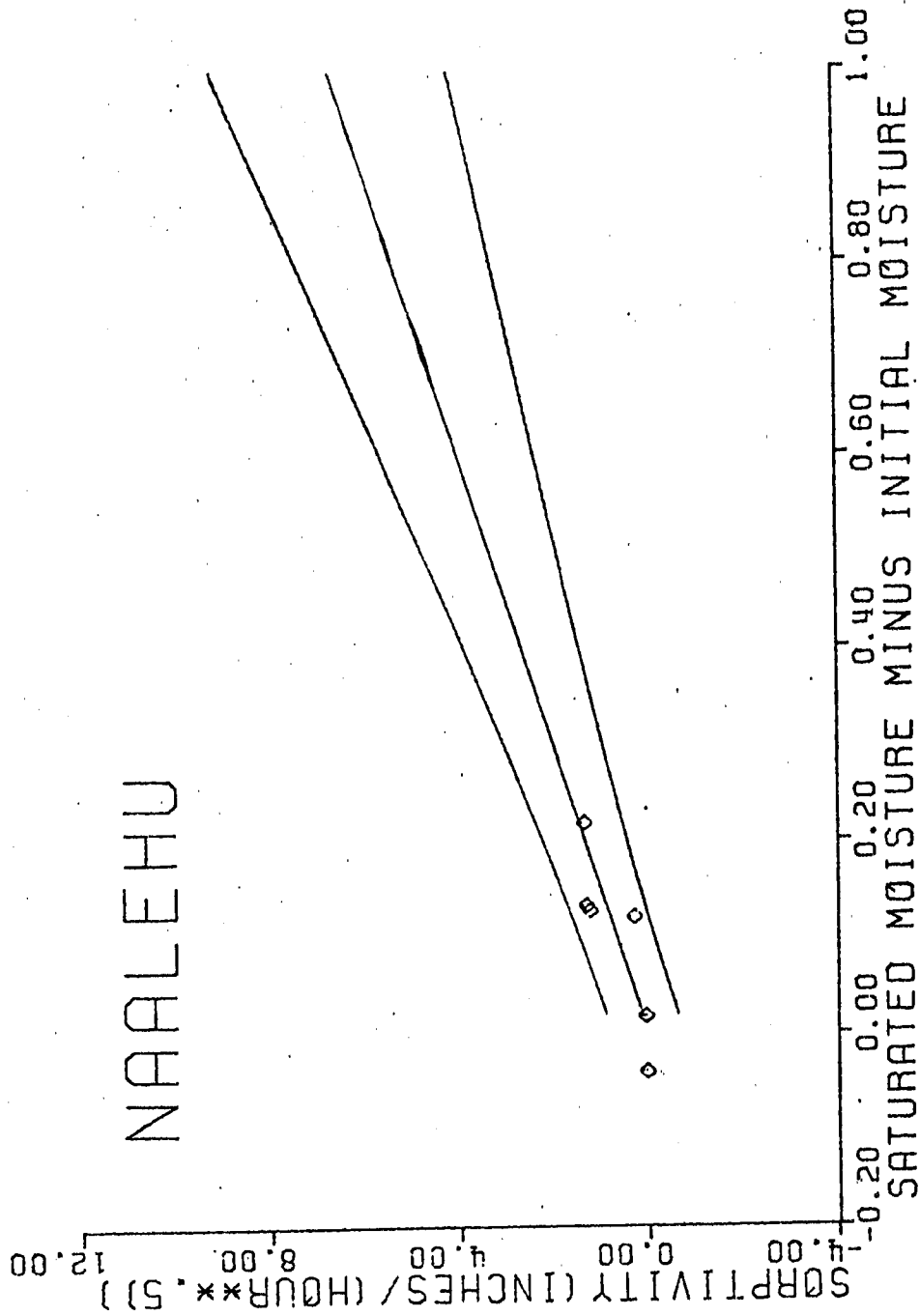


FIGURE A.9

REGRESSION OF SORPTIVITY VERSUS CHANGE IN SOIL
MOISTURE FOR NAALEHU SOILS

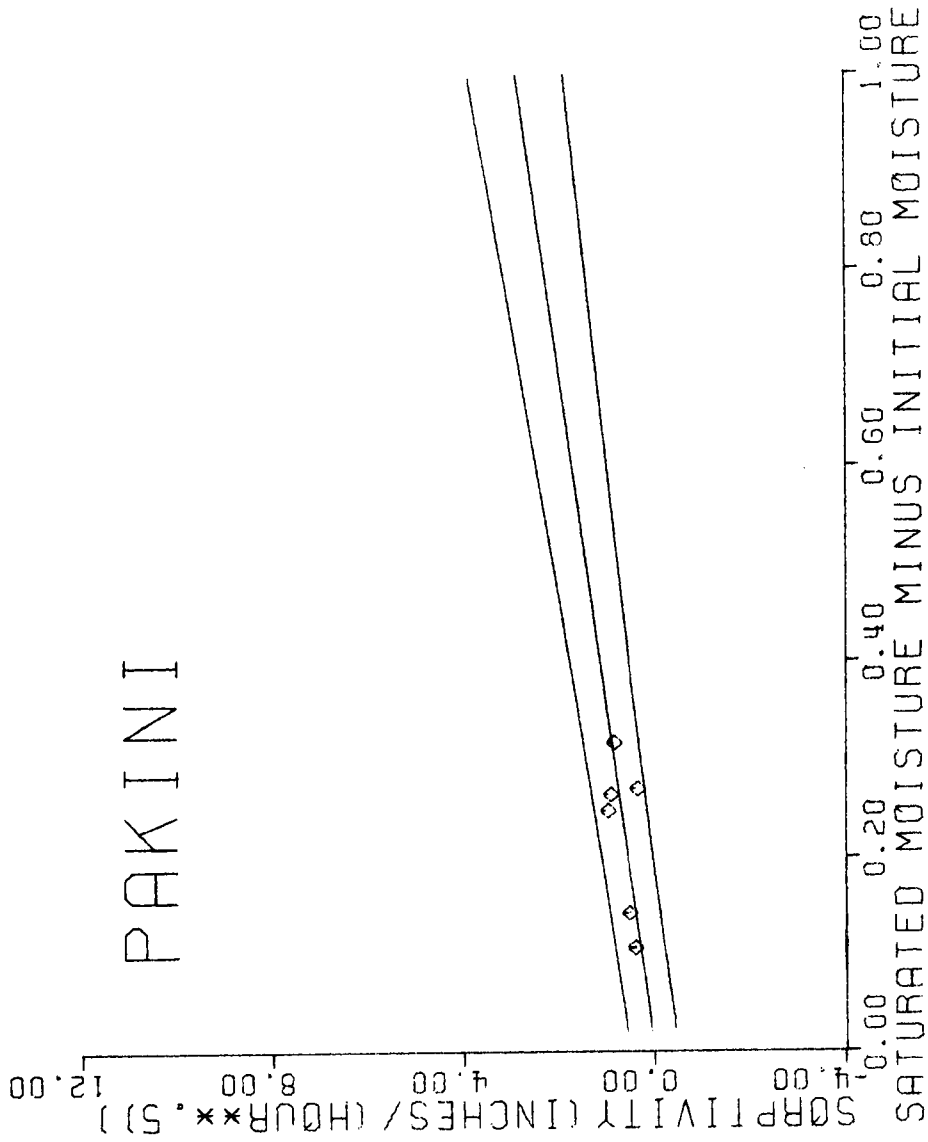


FIGURE A.10

REGRESSION OF SORPTIVITY VERSUS CHANGE IN SOIL
MOISTURE FOR PAKINI SOILS

APPENDIX B

Regression of a Versus
Change in Soil Moisture

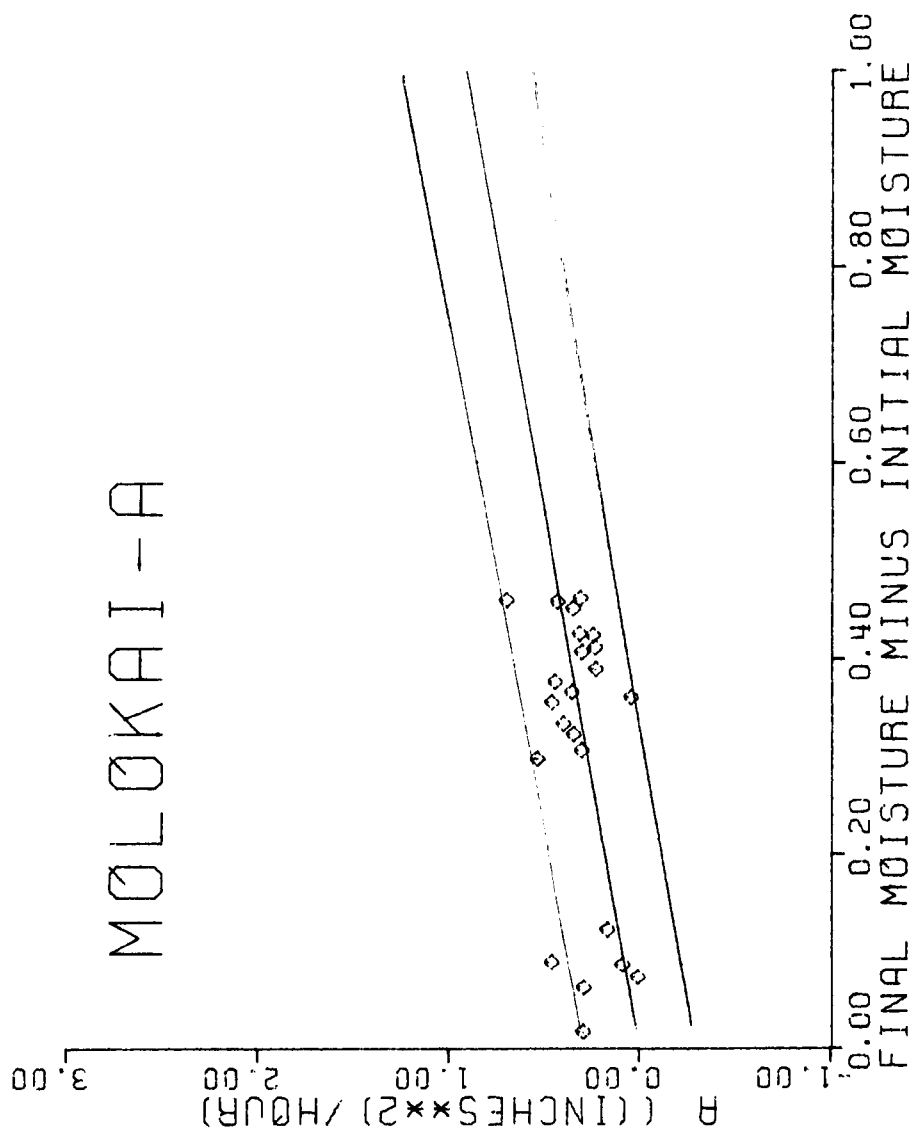


FIGURE B.1

REGRESSION OF a VERSUS CHANGE IN SOIL
MOISTURE FOR MOLOKAI-A SOILS

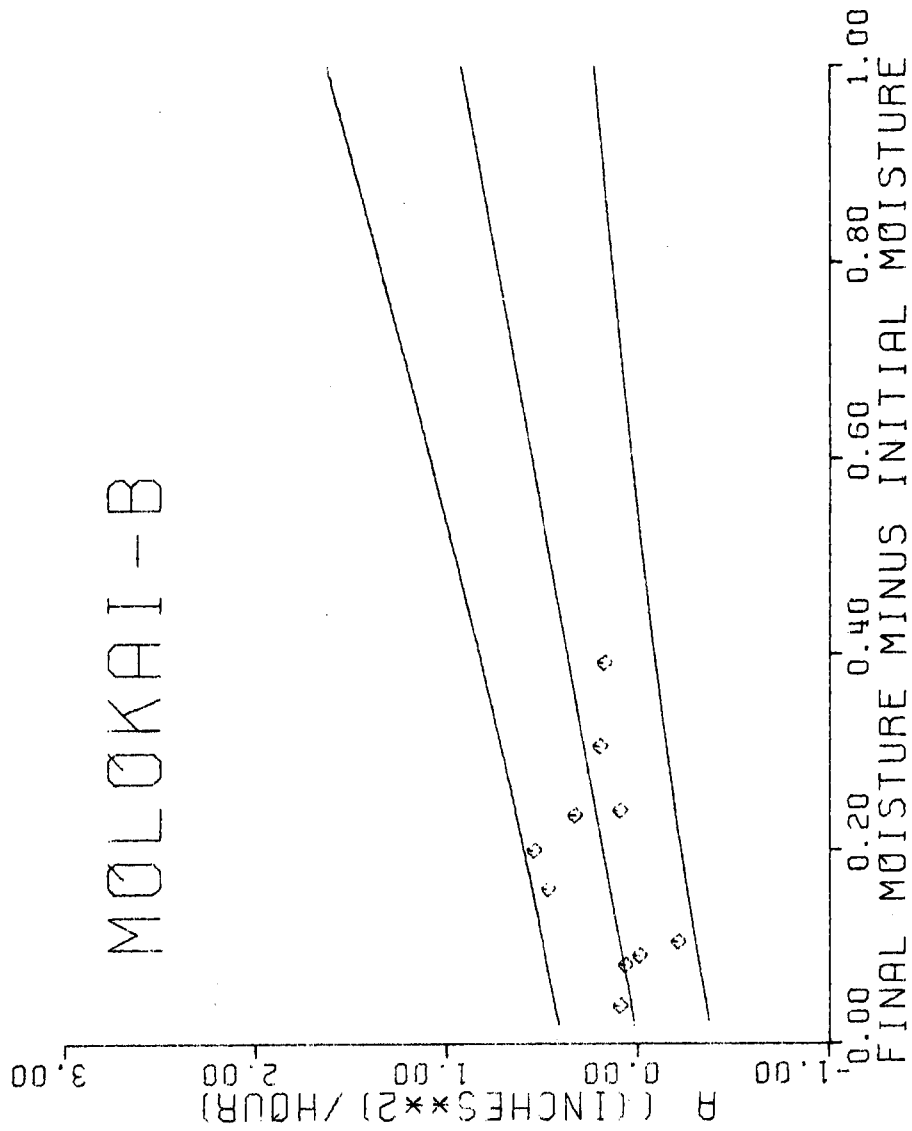


FIGURE B.2

REGRESSION OF $\bar{a}$ VERSUS CHANGE IN SOIL
MOISTURE FOR MOLOKAI-B SOILS

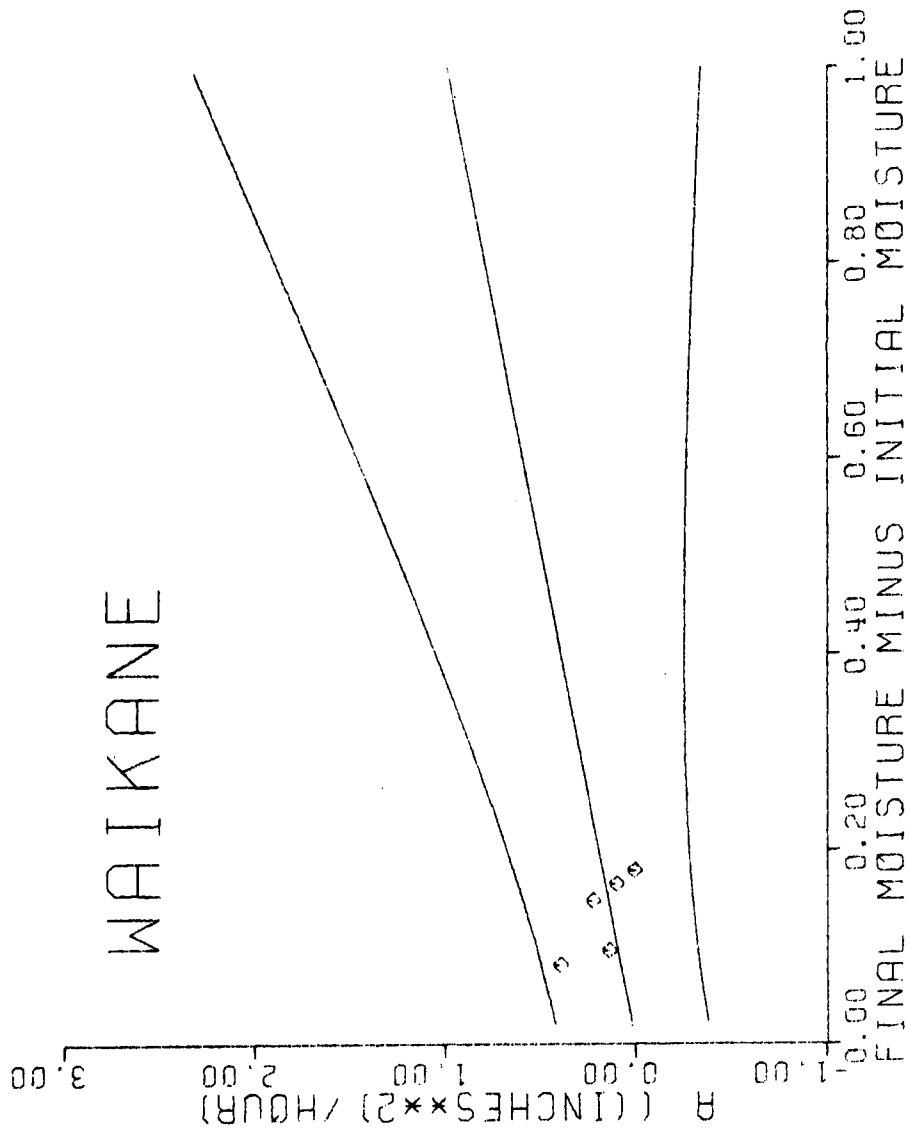


FIGURE B.3

REGRESSION OF a VERSUS CHANGE IN SOIL
MOISTURE FOR WAIKANE SOILS

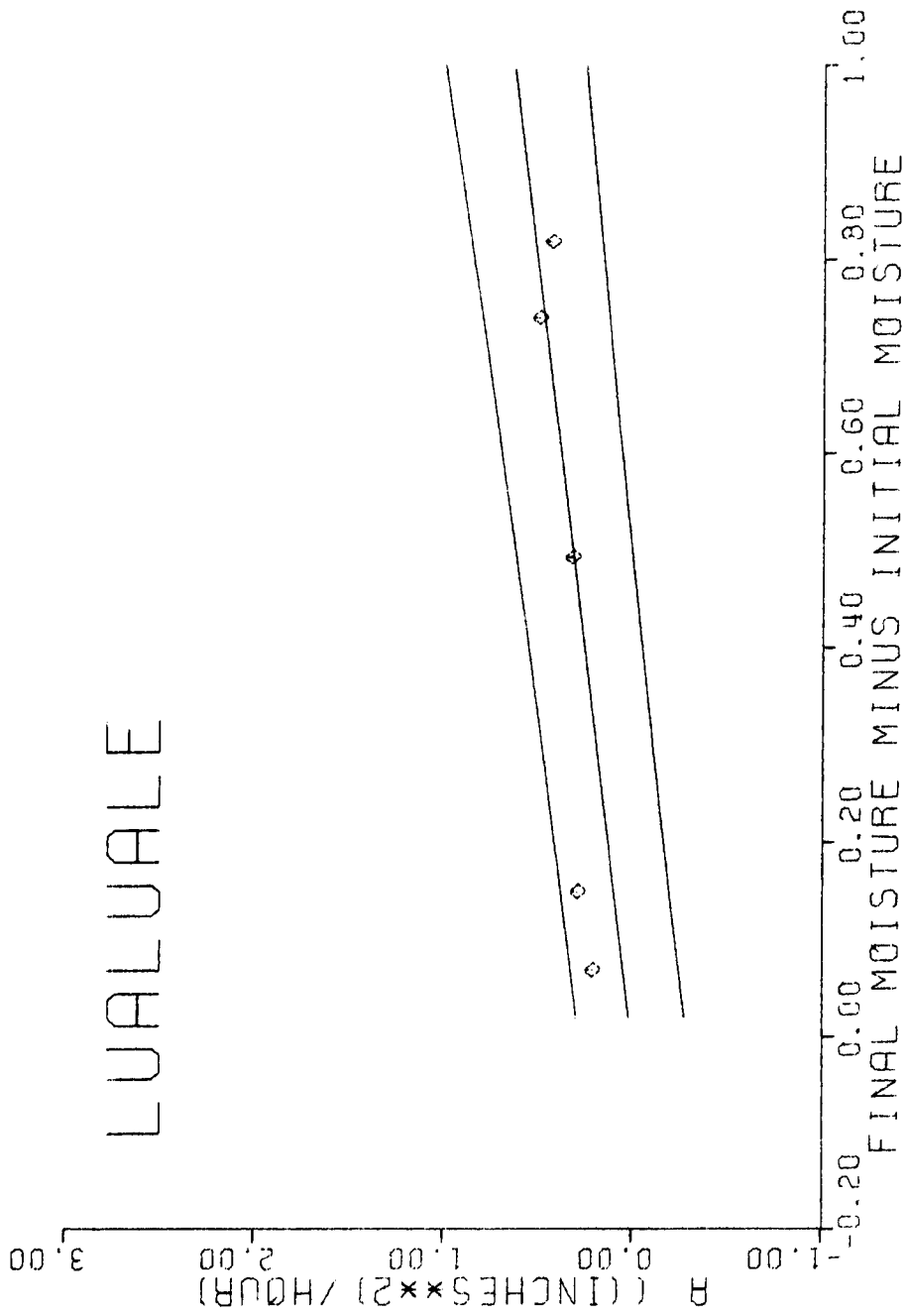


FIGURE B.4

REGRESSION OF a VERSUS CHANGE IN SOIL
MOISTURE FOR LUALUALE SOILS

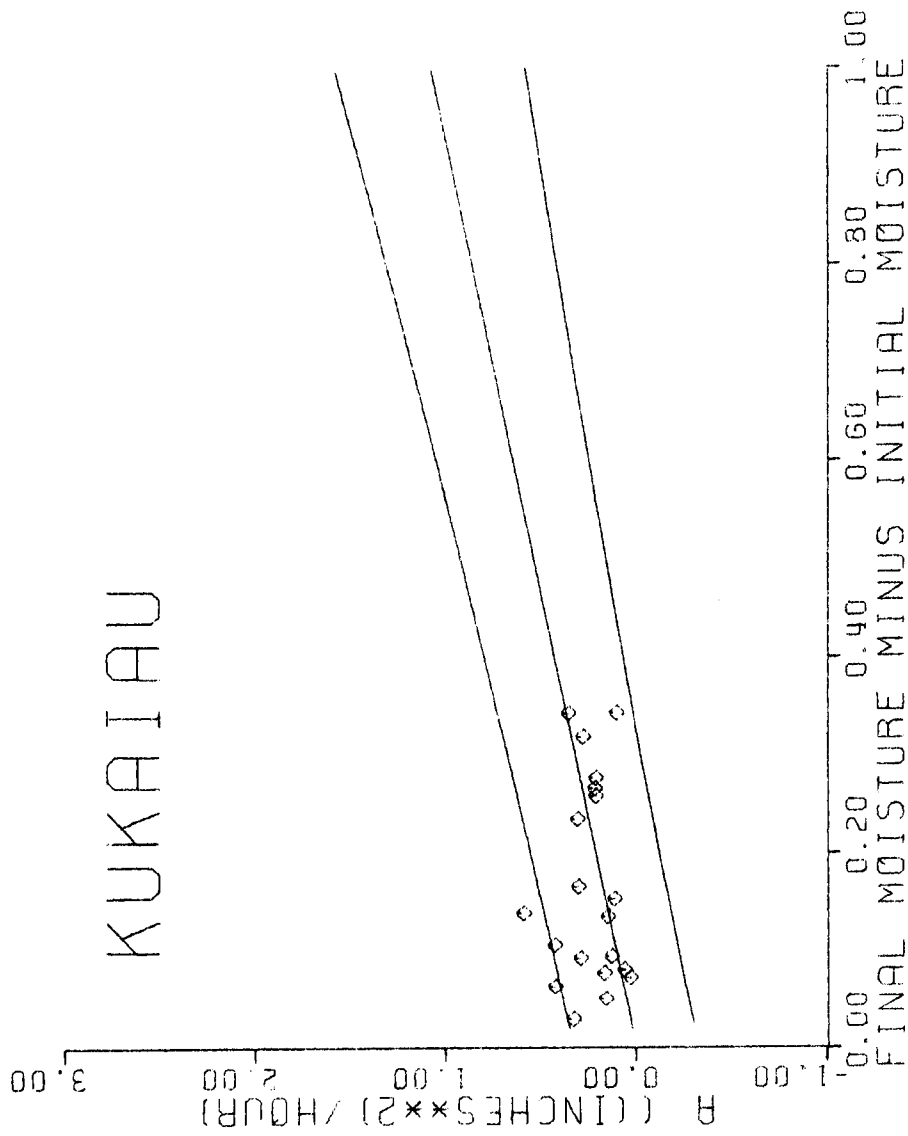


FIGURE B.5

REGRESSION OF a VERSUS CHANGE IN SOIL
MOISTURE FOR KUKAIAU SOILS

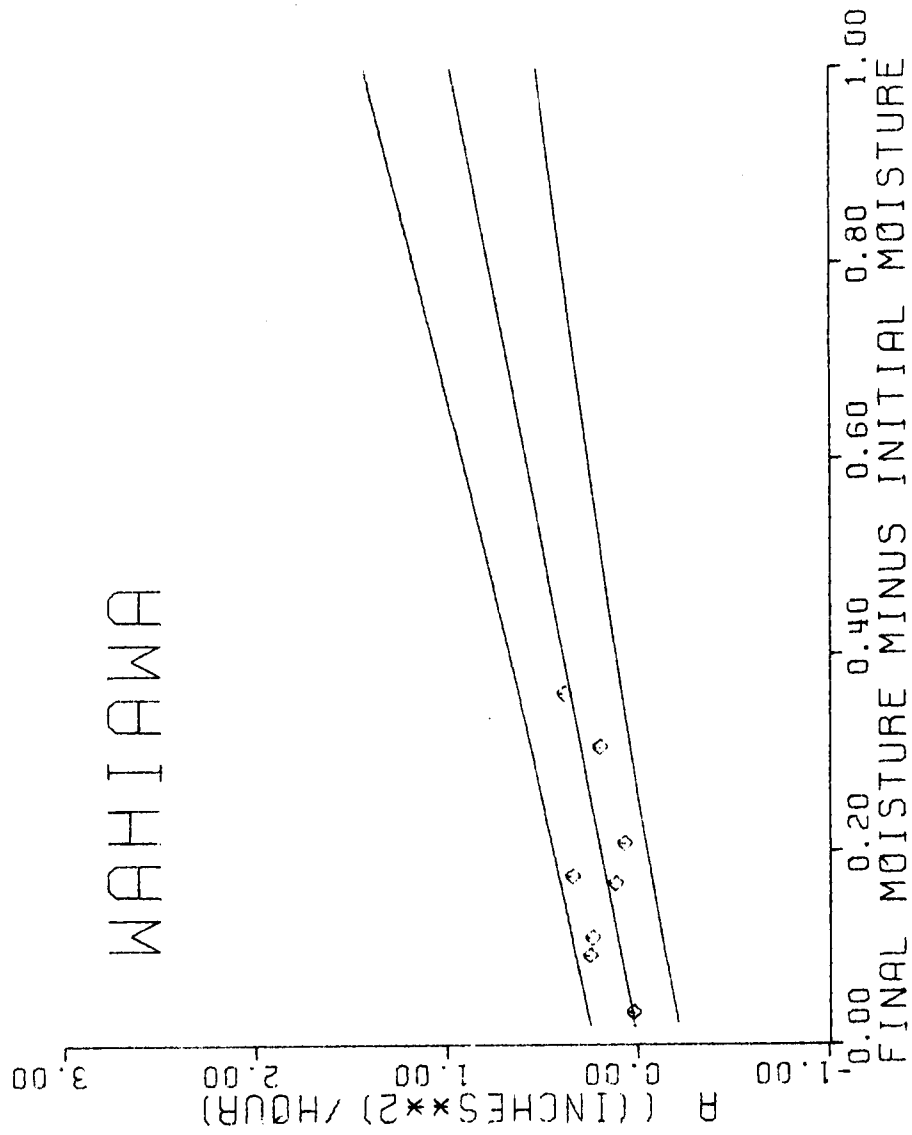


FIGURE B.6

REGRESSION OF a VERSUS CHANGE IN SOIL
MOISTURE FOR WAHIAWA SOILS

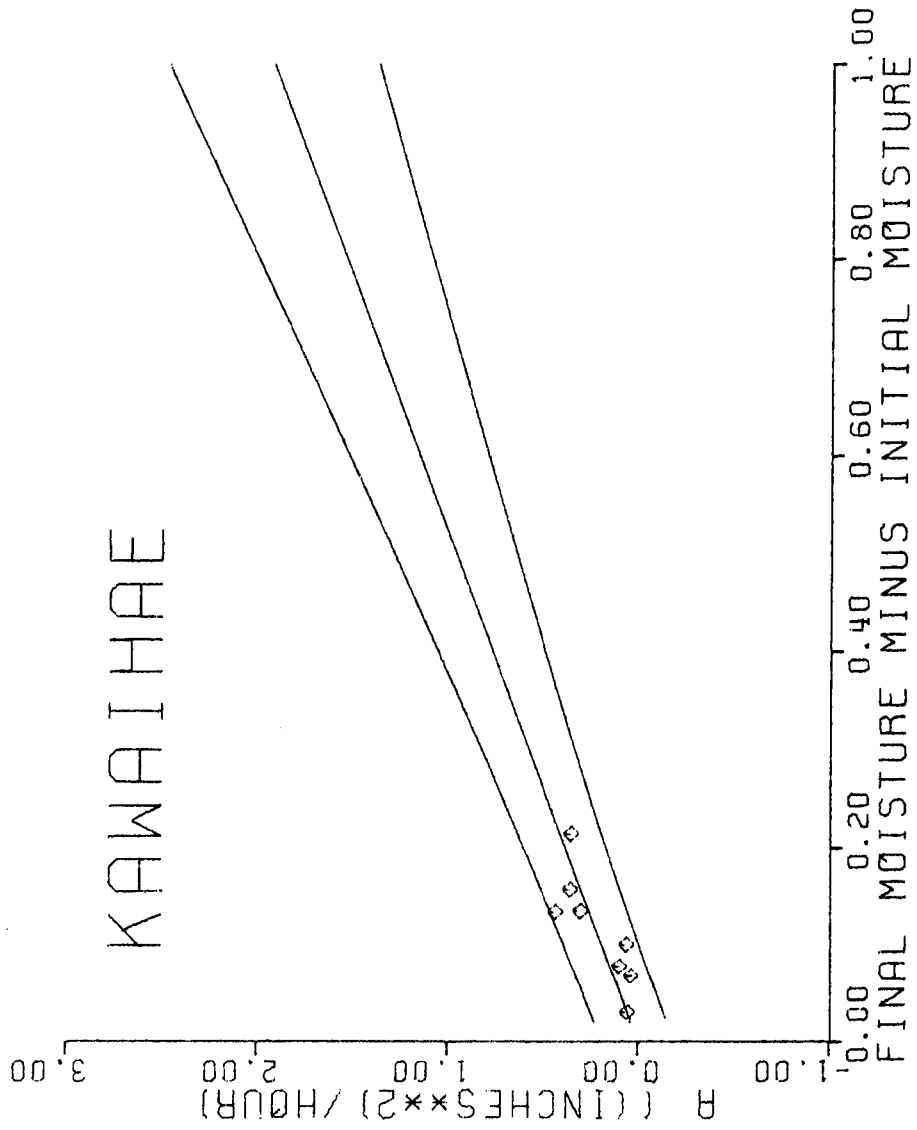


FIGURE B.7

REGRESSION OF a VERSUS CHANGE IN SOIL
MOISTURE FOR KAWAIIHAE SOILS

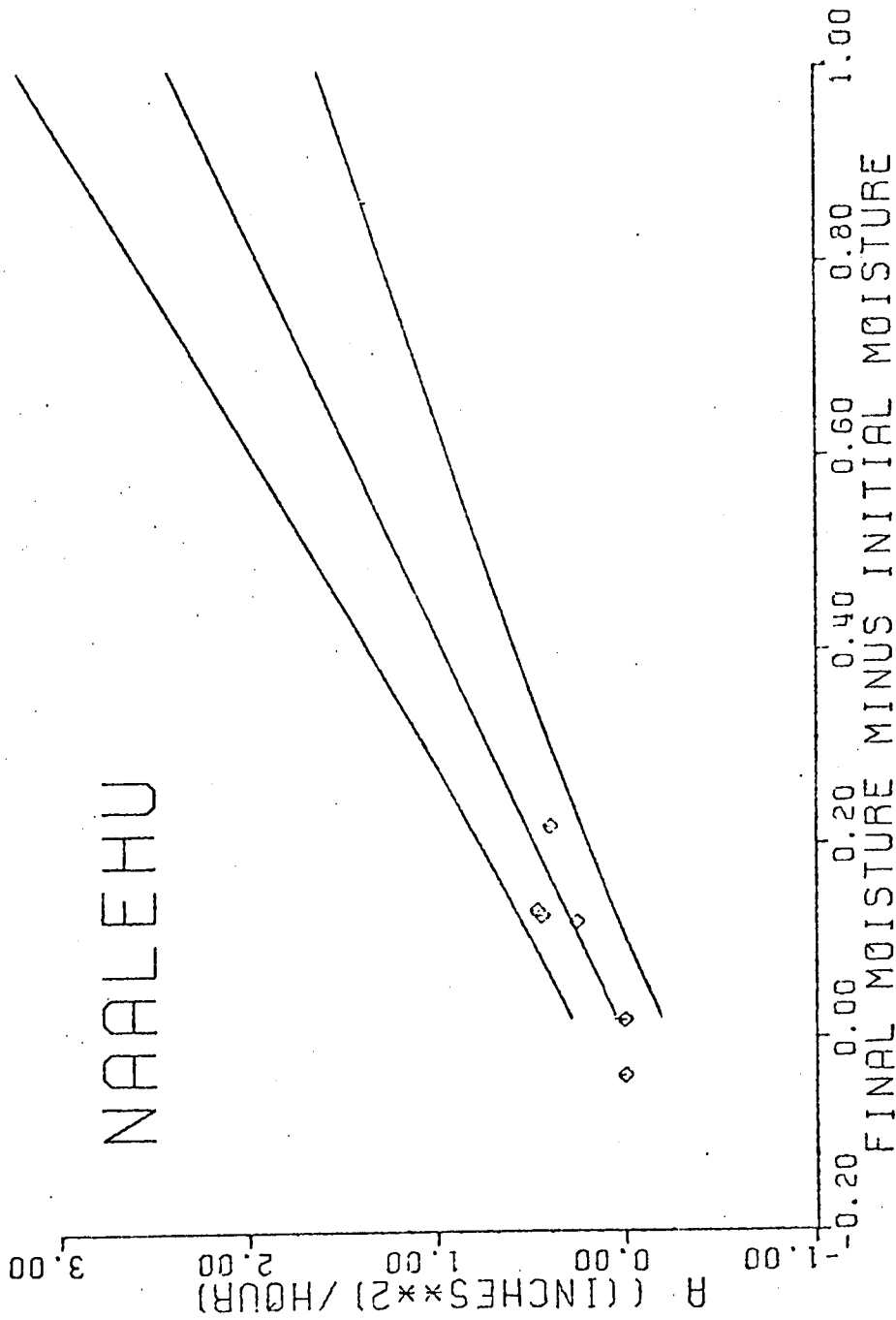


FIGURE B.8

REGRESSION OF a VERSUS CHANGE IN SOIL
MOISTURE FOR NAALEHU SOILS

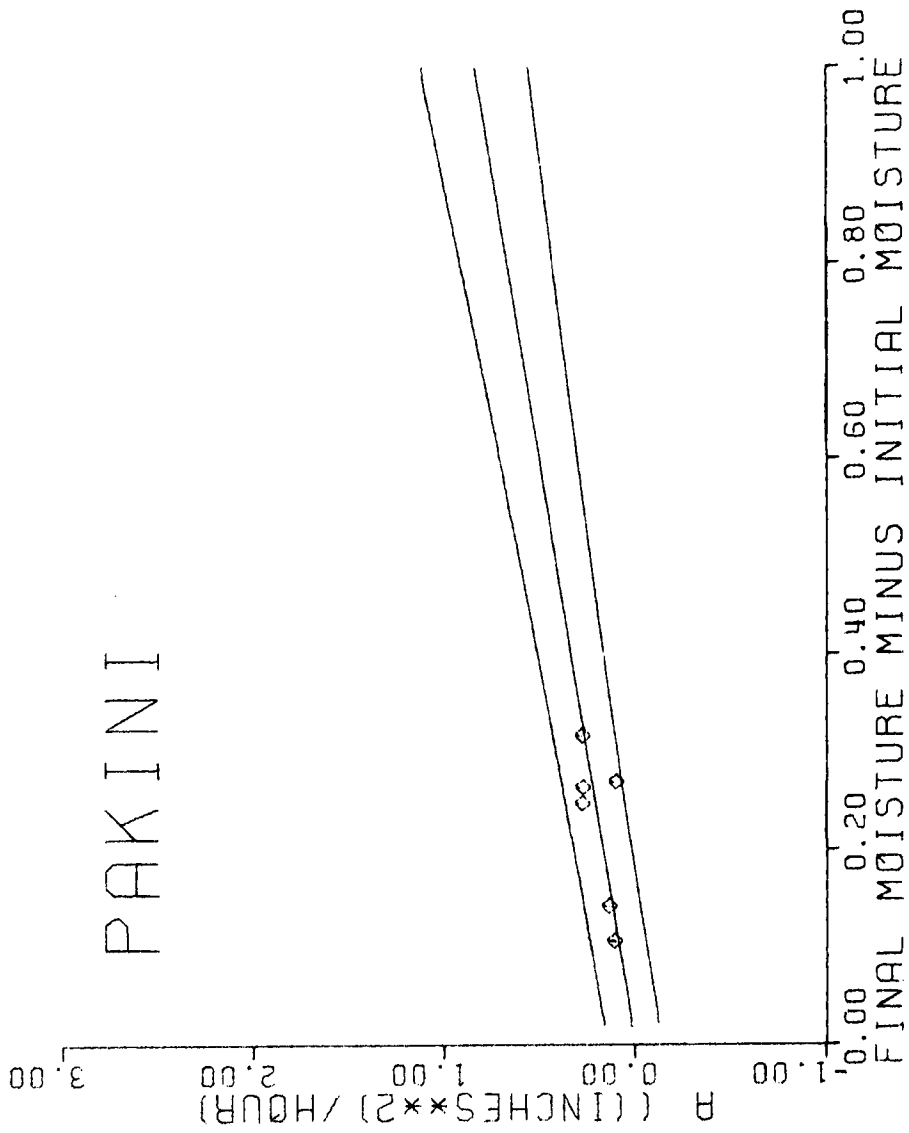


FIGURE B.9

REGRESSION OF a VERSUS CHANGE IN SOIL
MOISTURE FOR PAKINI SOILS

APPENDIX C

Optimized Parameters

OPTIMIZED PARAMETERS OF PHILIP'S MODEL

	SOIL	PLOT	SITE	SP IN/HR**0.5	A IN/HR	SEE IN/HR	R**2
1	MOLOKAI-A	1	1 DRY	.566	.561	.136	.92
2		1	2 DRY	.580	.323	.131	.92
3		2	1 DRY	.634	.355	.143	.94
4		2	2 DRY	.700	.237	.124	.96
5		3	1 DRY	.612	.410	.134	.92
6		3	2 DRY	.552	.973	.190	.80
7		3	1 WET	.135	.247	.141	.47
8		3	2 WET	.248	.045	.107	.85
9		4	1 DRY	.352	1.535	.203	.53
10		4	2 DRY	.797	.277	.304	.80
11		5	1 DRY	.633	.742	.166	.89
12		5	2 DRY	.710	.351	.156	.92
13		6	1 DRY	.576	.730	.128	.92
14		6	2 DRY	.494	1.151	.289	.67
15		6	1 WET	.233	.435	.124	.79
16		6	2 WET	.335	.288	.106	.91
17		7	1 DRY	.435	.501	.087	.95
18		7	2 DRY	.964	.170	.130	.95
19		7	1 WET	.328	.041	.112	.13
20		7	2 WET	.221	.235	.162	.60
21		8	1 DRY	.590	-.279	.127	.91
22		8	2 DRY	.537	.261	.271	.76
23		9	2 DRY	.814	.088	.175	.92
24	WAIPAHU	10	1 DRY	.454	.353	.095	.95
25		10	2 DRY	.277	1.694	.115	.75
26		11	1 DRY	.166	.631	.073	.97
27		11	2 DRY	.174	1.522	.112	.70
28	MOLOKAI-B	12	1 DRY	.502	-.014	.319	.74
29		12	2 DRY	.170	1.882	.037	.93
30		12	1 WET	.122	.307	.030	.91
31		12	2 WET	.132	.704	.040	.86
32		14	1 DRY	.446	.278	.125	.92
33		14	1 WET	.098	.311	.048	.80
34		15	2 DRY	.896	-.151	.271	.89
35		15	2 WET	-.028	.436	.088	.09
36		18	1 DRY	.721	.228	.188	.88
37		18	1 WET	-.482	1.701	.281	.57
38	WAHIAWA	16	1 DRY	.513	.420	.319	.64
39		16	2 DRY	.792	.309	.437	.65
40		17	1 DRY	.322	.810	.155	.84
41		17	2 DRY	.694	.617	.348	.66
42		17	1 WET	.524	.312	.204	.90
43		17	2 WET	.646	.222	.508	.62
44		19	1 DRY	.205	.517	.143	.51
45		19	1 WET	.107	.212	.052	.78
46	LUALUALEI	20	2 DRY	.788	.233	.210	.90
47		20	2 WET	.433	-.372	.258	.70
48		21	1 DRY	.719	.348	.224	.86
49		21	1 WET	.404	.039	.175	.83

50		22	2	DRY	2.40	2.00	.49	.96
51	WAIKANE	23	2	WET	2.51	.44	4.94	.22
52		24	2	DRY	2.64	2.64	3.98	.95
53		24	2	WET	2.65	1.50	.50	.24
54		25	1	DRY	2.43	1.50	.50	.78
55		25	1	WET	2.47	1.50	.50	.61
56		26	1	DRY	2.74	3.00	2.00	.83
57		26	2	DRY	2.71	2.36	1.55	.89
58		27	1	DRY	2.74	2.00	.50	.93
59		27	2	DRY	2.84	2.50	.50	.95
60	KUKUIAU	28	1	DRY	2.31	1.50	1.00	.82
61		28	2	DRY	2.46	1.46	.56	.96
62		29	1	DRY	1.99	1.35	.51	.83
63		29	2	DRY	2.48	2.01	.99	.89
64		30	1	DRY	2.51	1.50	.50	-.86
65		30	2	DRY	2.65	1.50	.50	.78
66		30	1	WET	2.37	2.50	.50	-2.20
67		30	2	WET	2.55	2.98	.53	-4.90
68		31	1	WET	2.34	2.50	1.00	.92
69		31	2	DRY	2.40	1.50	.50	.90
70		32	1	DRY	2.29	1.50	.50	.63
71		32	2	DRY	2.69	2.50	.50	.24
72		33	1	DRY	2.44	1.50	1.00	.92
73		33	2	DRY	2.49	3.00	3.00	.96
74		33	1	WET	2.45	2.00	.50	-31.90
75		33	2	WET	2.59	2.00	.50	-15.90
76	HILO	34	1	DRY	2.46	2.50	.50	-12.60
77		34	2	DRY	2.76	3.00	.50	-7.50
78		34	1	WET	2.35	2.50	.50	-148.20
79		34	2	WET	3.17	3.00	.50	-2.80
80		35	1	DRY	2.57	3.00	.50	-8.10
81		35	2	DRY	2.60	3.00	.50	-2.30
82	KAWAIIHAE	36	1	DRY	2.39	2.00	.50	.76
83		36	2	DRY	2.53	1.61	.38	.86
84		36	1	WET	2.35	2.00	.50	-8.90
85		36	2	WET	2.43	2.49	.52	-6.40
86		37	1	DRY	2.35	2.00	.50	.79
87		37	2	DRY	2.40	2.50	.50	.68
88		38	1	DRY	2.50	2.00	.50	.83
89		38	2	DRY	2.41	2.50	.50	.17
90		38	1	WET	2.40	2.50	.50	
91		38	2	WET	2.43	2.50	.50	-31.60
92	NAALEHU	39	1	DRY	2.75	2.50	.50	.23
93		39	2	DRY	2.43	2.00	.50	.96
94		40	1	DRY	2.44	2.00	.50	.71
95		40	2	DRY	2.44	2.00	.50	
96		40	1	DRY	2.47	2.50	.50	-48.50
97		40	2	DRY	2.44	3.00	.50	-63.50
98	PAKINI	41	1	DRY	2.63	1.50	.50	.73
99		41	2	DRY	2.70	2.00	.50	.51
100		42	1	DRY	2.73	1.50	.50	-.03
101		42	2	DRY	2.70	1.50	.50	-4.20
102		42	1	WET	2.60	2.50	.50	-3.60
103		42	2	WET	2.64	2.50	.50	-10.90

OPTIMIZED PARAMETERS OF GREEN AND AMPT'S MODEL

	SOIL	PLOT	SITE	A IN**2/HR	FG IN/HR	SEE IN/HR	R**2	
1	MOLOKAI-A	1	1	DRY	.303	.726	.214	.79
2		1	2	DRY	.356	.855	.242	.83
3		2	1	DRY	.433	.698	.221	.86
4		2	2	DRY	.347	.823	.214	.80
5		3	1	DRY	.312	1.425	.261	.62
6		3	2	DRY	.045	.295	.142	.47
7		3	1	WET	.295	.045	.142	.47
8		3	2	WET	.463	.874	.411	.63
9		4	1	DRY	.314	1.008	.202	.82
10		4	2	DRY	.463	.873	.411	.63
11		5	1	DRY	.400	1.209	.247	.75
12		5	2	DRY	.495	.845	.242	.81
13		6	1	DRY	.351	1.139	.190	.82
14		6	2	DRY	.244	1.618	.373	.47
15		6	1	WET	.089	.575	.140	.80
16		6	2	WET	.167	.444	.081	.95
17		7	1	DRY	.232	.784	.135	.88
18		7	2	DRY	.703	.775	.210	.84
19		7	1	WET	.011	.344	.112	.14
20		7	2	WET	.293	.293	.161	.61
21		8	1	DRY	.304	-.066	.160	.85
22		8	2	DRY	.231	.710	.350	.60
23		9	2	DRY	.539	.596	.272	.81
24	WAIPAHU	10	1	WET	.102	2.325	.157	.30
25		11	2	DRY	.135	1.177	.153	.56
26		11	2	WET	.209	.676	.152	.88
27	MOLOKAI-B	13	1	WET	.003	1.725	.140	.53
28		12	1	DRY	.327	.327	.334	.71
29		12	2	DRY	.093	2.029	.053	.86
30		12	1	WET	.025	.405	.036	.81
31		19	2	WET	.065	.777	.040	.86
32		14	1	DRY	.175	.637	.214	.76
33		14	1	WET	.092	2.029	.053	.86
34		15	2	DRY	.469	.480	.419	.68
35		15	2	WET	-.009	.435	.084	.14
36		18	1	DRY	.544	.615	.193	.87
37	WAHIAWA	18	1	WET	-.210	1.541	.236	.71
38		16	1	DRY	.198	.921	.386	.48
39		16	2	DRY	.386	1.023	.548	.44
40		17	1	DRY	.117	1.163	.213	.69
41		17	2	DRY	.342	1.305	.436	.46
42		17	1	WET	.237	.872	.308	.76
43		17	2	WET	.250	.994	.622	.43
44		19	1	DRY	.069	.653	.151	.46
45	LUALUALEI	19	1	WET	.024	.265	.052	.77
46		20	2	DRY	.498	.783	.320	.76
47		20	2	WET	.290	-.644	.236	.75
48		21	1	DRY	.433	.870	.308	.73
49		21	1	WET	.213	.182	.108	.84

50		22	2	DRY	.674	.048	.226	.89
51	WAIKANE	23	2	WET	.025	2.422	.023	.46
52		24	2	DRY	.196	2.202	.161	.69
53		24	2	WET	.272	1.162	.092	.87
54		25	1	DRY	.428	.805	.082	.91
55		25	1	WET	.577	.542	.216	.77
56		26	1	DRY	.550	1.183	.347	.61
57		26	2	DRY	.575	1.031	.217	.78
58		27	1	DRY	.660	.441	.134	.94
59		27	2	DRY	.847	-.077	.123	.96
60	KUKAIAU	28	1	DRY	.008	.630	.089	.93
61		28	2	DRY	.511	.783	.082	.95
62		29	1	DRY	.379	.603	.167	.79
63		29	2	DRY	.516	.906	.153	.85
64		30	1	DRY	.224	1.076	.145	.63
65		30	2	DRY	.395	.999	.082	.94
66		30	1	WET	.297	.399	.098	.82
67		30	2	WET	.263	.537	.062	.90
68		31	1	DRY	.454	.607	.131	.95
69		31	2	DRY	.424	.711	.071	.96
70		32	1	DRY	.513	.411	.180	.80
71		32	2	DRY	.491	.281	.095	.94
72		33	1	DRY	.348	1.183	.155	.77
73		33	2	DRY	.326	1.394	.141	.79
74		33	1	WET	.083	.733	.069	.50
75		33	2	WET	.133	.865	.075	.69
76	HILO	34	1	DRY	.221	.109	.098	.70
77		34	2	DRY	.242	.339	.085	.87
78		34	1	WET	.065	.196	.037	.59
79		34	2	WET	.479	-.148	.243	.75
80		35	1	DRY	.303	-.135	.084	.86
81		35	2	DRY	.588	-.616	.133	.81
82	KAWAIIHAE	36	1	DRY	.544	.220	.106	.93
83		36	2	DRY	.651	.478	.144	.91
84		36	1	WET	.177	.572	.070	.75
85		36	2	WET	.181	.575	.124	.61
86		37	1	DRY	.468	.437	.168	.77
87		37	2	DRY	.045	.084	.362	.65
88		38	1	DRY	.598	.129	.107	.95
89		38	2	DRY	.581	-.308	.171	.84
90		38	1	WET	.243	.120	.208	.41
91		38	2	WET	.122	.281	.077	.67
92	NAALEHU	39	1	DRY	.651	-.045	.254	.69
93		39	2	DRY	.143	.579	.181	.91
94		40	1	DRY	.674	-.068	.123	.94
95		40	2	DRY	.615	.080	.067	.97
96		40	1	WET	.022	.290	.118	.02
97		40	2	WET	.032	.292	.106	.07
98	PAKINI	41	1	DRY	.488	.739	.080	.90
99		41	2	DRY	.459	.745	.214	.67
100		42	1	DRY	.426	.854	.241	.52
101		42	2	DRY	.174	1.154	.131	.46
102		42	1	WET	.266	.420	.148	.60
103		42	2	WET	.206	.629	.065	.82

OPTIMIZED PARAMETERS OF HORTON'S MODEL

	SOIL	PLOT	SITE	FO IN/HR	FO-FC IN/HR	K 1/HR	R**2
1	MOLOKAI-A	1	1 DRY	2.31	2.00	1.00	.90
2		1	2 DRY	2.29	1.66	.47	.96
3		2	1 DRY	2.50	1.88	.59	.91
4		2	2 DRY	2.51	2.00	.50	.93
5		3	1 DRY	2.31	1.50	.50	.97
6		3	2 DRY	2.41	3.26	3.00	.97
7		3	1 WET	2.52	2.50	.50	-17.50
8		3	2 WET	2.39	2.50	.50	-5.90
9		4	1 DRY	2.36	2.50	4.50	.88
10		4	2 DRY	2.39	2.03	.97	.85
11		5	1 DRY	2.63	2.00	1.00	.94
12		5	2 DRY	2.51	2.40	1.05	.93
13		6	1 DRY	2.40	2.00	1.50	.84
14		6	2 DRY	2.59	3.06	2.49	.90
15		6	1 WET	2.40	2.00	.50	-3.06
16		6	2 WET	2.55	2.50	.50	-1.09
17		7	1 DRY	2.35	1.50	.50	.67
18		7	2 DRY	2.40	2.48	1.51	.93
19		7	1 WET	2.01	2.00	.50	-35.70
20		7	2 WET	2.39	2.50	.50	-4.81
21		8	1 DRY	2.18	2.47	.54	.85
22		8	2 DRY	2.23	2.47	1.01	.89
23		9	2 DRY	2.53	2.00	.50	.91
24	WAIPAHU	10	1 DRY	2.67	1.00	4.50	.26
25		10	2 DRY	2.57	2.00	2.00	.99
26		11	1 DRY	2.51	2.00	.50	.84
27	MOLOKAI-B	11	2 DRY	2.38	1.00	.50	.84
28		12	2 DRY	2.31	2.50	.50	.56
29		12	2 DRY	2.54	1.45	2.02	.69
30		12	1 WET	2.32	3.00	.50	-49.20
31		12	2 WET	2.56	3.00	.50	-32.10
32		14	1 DRY	2.12	1.50	.50	.79
33		14	1 WET	2.56	2.50	.50	-54.60
34		15	2 DRY	2.54	2.22	.48	.89
35		15	2 WET	2.54	3.00	.50	.55
36		18	1 DRY	3.39	3.00	.50	.34
37		18	1 WET	5.79	3.00	.50	-72.10
38	WAHIAWA	16	1 DRY	1.92	3.00	2.00	.82
39		16	2 DRY	2.31	3.28	1.94	.84
40		17	1 DRY	2.26	1.50	.50	.94
41		17	2 DRY	2.46	3.00	.50	.80
42		17	1 WET	2.42	2.05	.44	.94
43	LUALUALEI	17	2 WET	2.37	3.14	.94	.78
44		19	1 DRY	3.19	3.00	.50	-13.50
45		19	1 WET	2.75	3.00	.50	-79.20
46		20	2 DRY	2.58	2.48	1.01	.98
47		20	2 WET	2.43	3.00	.50	-1.30
48		21	1 DRY	2.52	2.31	1.08	.90
49		21	1 WET	2.56	2.50	.50	-.56

50		22	2	DRY	.322	.586	.372	.69
51	WAIKANE	23	2	WET	.006	2.450	.028	.21
52		24	2	DRY	.100	2.266	.131	.53
53		24	2	WET	.138	1.378	.128	.78
54		25	1	DRY	.225	1.257	.098	.88
55		25	1	WET	.397	.869	.221	.76
56		26	1	DRY	.307	1.689	.407	.46
57		26	2	DRY	.354	1.501	.282	.63
58		27	1	DRY	.427	.889	.211	.85
59		27	2	DRY	.589	.444	.226	.88
60	KUKAIAU	28	1	DRY	.424	.989	.127	.85
61		28	2	DRY	.329	1.120	.130	.86
62		29	1	DRY	.114	.983	.205	.69
63		29	2	DRY	.279	1.388	.207	.72
64		30	1	DRY	.102	1.264	.155	.57
65		30	2	DRY	.218	1.328	.126	.86
66		30	1	WET	.151	.556	.094	.83
67		30	2	WET	.129	.702	.067	.88
68		31	1	DRY	.212	1.015	.187	.79
69		31	2	DRY	.212	1.070	.120	.89
70		32	1	DRY	.304	.708	.191	.78
71		32	2	DRY	.292	.549	.129	.90
72		33	1	DRY	.107	1.419	.120	.62
73		33	2	DRY	.161	1.698	.189	.62
74		33	1	WET	.031	.782	.066	.55
75		33	2	WET	.064	.942	.068	.74
76	HILO	34	1	DRY	.110	.130	.100	.69
77		34	2	DRY	.097	.468	.085	.87
78		34	1	WET	.023	.200	.040	.52
79		34	2	WET	.371	-.192	.239	.76
80		35	1	DRY	.113	-.078	.103	.79
81		35	2	DRY	.493	-.970	.043	.95
82	KAWAIHAE	36	1	DRY	.303	.535	.155	.86
83		36	2	DRY	.435	.889	.195	.84
84		36	1	WET	.063	.691	.079	.69
85		36	2	WET	.058	.712	.131	.56
86		37	1	DRY	.207	.881	.203	.66
87		37	2	DRY	.281	.813	.411	.55
88		38	1	DRY	.353	.465	.170	.88
89		38	2	DRY	.357	-.191	.185	.81
90		38	1	WET	.099	.179	.210	.40
91		38	2	WET	.041	.329	.077	.66
92	NAALEHU	39	1	DRY	.469	.161	.250	.70
93		39	2	DRY	.263	.603	.305	.74
94		40	1	DRY	.400	.292	.179	.88
95		40	2	DRY	.444	.309	.072	.97
96		40	1	WET	.003	.307	.119	.01
97		40	2	WET	.005	.310	.106	.05
98	PAKINI	41	1	DRY	.276	1.119	.146	.88
99		41	2	DRY	.273	1.087	.235	.60
100		42	1	DRY	.276	1.112	.253	.47
101		42	2	DRY	.099	1.268	.138	.40
102		42	1	WET	.134	.545	.152	.58
103		42	2	WET	.108	.731	.062	.84

OPTIMIZED STORAGE POTENTIALS OF THE SCS-CN METHOD

	SOIL	PLOT	SITE	S (IN/HR)	R**2
1	MOLOKAI-A	1	1	DRY 4.87	.91
2		1	2	DRY 3.85	.95
3		2	1	DRY 4.08	.89
4		2	2	DRY 3.80	.95
5		3	1	DRY 4.31	.97
6		3	2	DRY 7.30	.98
7		3	1	WET .66	-4.90
8		3	2	WET .64	-.48
9		4	1	DRY 12.00	.82
10		4	2	DRY 4.75	.87
11		5	1	DRY 5.95	.92
12		5	2	DRY 5.09	.93
13		6	1	DRY 5.80	.90
14		6	2	DRY 7.30	.92
15		6	1	WET 1.33	-3.20
16		6	2	WET 1.30	-.95
17		7	1	DRY 3.62	.82
18		7	2	DRY 4.75	.97
19		7	1	WET .58	-13.90
20		7	2	WET .85	-2.40
21		8	1	DRY 2.26	.70
22		8	2	DRY 4.01	.85
23		9	2	DRY 3.27	.93
24	WAIPAHAU	10	1	DRY 16.73	-2.50
25		10	2	DRY 13.00	.98
26		11	1	DRY 2.43	.78
27		11	2	DRY 4.06	-1.10
28	MOLOKAI-B	12	1	DRY 3.48	.40
29		12	2	DRY 9.20	-1.80
30		12	1	WET .45	-1.80
31		12	2	WET .92	-14.60
32		14	1	DRY 2.77	.94
33		14	1	WET .65	-12.30
34		15	2	DRY 2.38	.91
35		15	2	DRY 2.60	-38.90
36		18	1	DRY 1.82	.09
37		18	1	WET .56	-3.80
38	WAHIAWA	16	1	DRY 5.08	.68
39		16	2	DRY 7.11	.68
40		17	1	DRY 6.54	.79
41		17	2	DRY 8.85	.61
42		17	1	WET 2.29	.96
43		17	2	WET 2.89	.75
44		19	1	DRY 2.66	-20.40
45		19	1	WET .54	-5.10
46	LUALUALEI	20	2	DRY 4.31	.98
47		20	2	WET 1.91	.71
48		21	1	DRY 4.37	.93
49		21	1	WET 1.25	.27

50		22	2	DRY	2.83	.95
51	WAIKANE	23	2	WET	21.50	-143.30
52		24	2	DRY	14.95	.92
53		24	2	WET	3.42	-6.60
54		25	1	DRY	12.84	-.48
55		25	1	WET	3.90	.17
56		26	1	DRY	9.45	.81
57		26	2	DRY	6.89	.88
58		27	1	DRY	3.85	.84
59		27	2	DRY	3.36	.92
60	KUKUIAU	28	1	DRY	3.97	.44
61		28	2	DRY	4.11	.27
62		29	1	DRY	3.85	.77
63		29	2	DRY	4.92	.91
64		30	1	DRY	12.51	-268.60
65		30	2	DRY	14.88	.77
66		30	1	WET	1.14	-.90
67		30	2	WET	1.12	-2.20
68		31	1	DRY	3.27	.97
69		31	2	DRY	2.89	.76
70		32	1	DRY	2.79	.33
71		32	2	DRY	2.28	.45
72		33	1	DRY	7.65	.95
73		33	2	DRY	8.70	.92
74		33	1	WET	1.26	-30.91
75		33	2	WET	1.62	-23.84
76	HILO	34	1	DRY	1.57	-1.34
77		34	2	DRY	2.15	.77
78		34	1	WET	.68	-15.16
79		34	2	WET	1.18	.46
80		35	1	DRY	.90	.62
81		35	2	DRY	.97	.57
82	KAWOIHOE	36	1	DRY	2.28	.60
83		36	2	DRY	4.17	.83
84		36	1	WET	1.16	-10.28
85		36	2	WET	1.10	-5.72
86		37	1	DRY	2.89	.78
87		37	2	DRY	3.30	.47
88		38	1	DRY	2.49	.86
89		38	2	DRY	1.35	1.00
90		38	1	WET	.67	
91		38	2	WET	.58	-9.39
92	NAALEHU	39	1	DRY	2.61	.57
93		39	2	DRY	2.62	.98
94		40	1	DRY	3.47	.80
95		40	2	DRY	2.18	
96		40	1	DRY	.43	-8.04
97		40	2	DRY	.40	-10.55
98	PAKINI	41	1	DRY	3.25	.45
99		41	2	DRY	2.67	-.31
100		42	1	DRY	3.44	-.99
101		42	2	DRY	3.38	-10.11
102		42	1	WET	1.70	-2.11
103		42	2	WET	1.77	-8.18

VITA

Gordon Innes was born in Stamford, Connecticut on January 20, 1954. After graduating from Upland High School, Upland, California in June 1972, he attended the University of California at Los Angeles. His bachelors degree in Environmental Engineering was completed at Humboldt State University, Arcat, California in December 1977.

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