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Oxic soils on Oahu were studied to develop and test simplified methods of determining the hydraulic conductivity of unsaturated soils, to test some simple infiltration models, and to assess the utility of soil survey mapped units in defining hydrologically similar soils. Field measurements of water infiltration and redistribution were accomplished on 21 sites located on the Lahaina, Molokai, and Wahiawa soil series. Water retention curves measured on undisturbed soil cores from the Ap1, Ap2, and B horizons of each site provided a means of determining the downward flux of water during redistribution from soil water suction measurements over time. These data allowed calculation of hydraulic conductivities (by a detailed Darcy analysis) of soil at various depths in the soil profile and for a range of water contents and suctions. The detailed analysis and field infiltration data provided a means of evaluating two new simplified methods of determining hydraulic conductivity functions of well-drained soils; the new methods are sufficiently accurate and economical to be used in watershed characterization. Also, field measured sorptivity and water redistribution data were used to successfully predict cumulative infiltration with the Talsma-Parlange and Green-Ampt equations, respectively. Statistical analysis of field and laboratory data suggested that soil maps of central Oahu would not be particularly useful in delineating soil areas of relative homogeneity with respect to hydrologic properties. These results further emphasize the need for simple methods to characterize hydrologic properties of importance.

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WATER CONDUCTION IN HAWAI'I OXIC SOILS

Richard E. Green
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Technical Report No. 143

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for
Characterization of Water-Conducting and Water-Storage Properties
of Hawaii's Watershed Soils for Watershed Modeling, Phases 1, 2

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ABSTRACT

Oxic soils on O'ahu were studied to develop and test simplified methods of determining the hydraulic conductivity of unsaturated soils, to test some simple infiltration models, and to assess the utility of soil survey mapped units in defining hydrologically similar soils.

Field measurements of water infiltration and redistribution were accomplished on 21 sites located on the Lahaina, Molokai, and Wahiawa soil series. Water retention curves measured on undisturbed soil cores from the Ap1, Ap2, and B horizons of each site provided a means of determining the downward flux of water during redistribution from soil water suction measurements over time. These data allowed calculation of hydraulic conductivities (by a detailed Darcy analysis) of soil at various depths in the soil profile and for a range of water contents and suctions. The detailed analysis and field infiltration data provided a means of evaluating two new simplified methods of determining hydraulic conductivity functions of well-drained soils; the new methods are sufficiently accurate and economical to be used in watershed characterization. Also, field measured sorptivity and water redistribution data were used to successfully predict cumulative infiltration with the Talsma-Parlange and Green-Ampt equations, respectively.

Statistical analysis of field and laboratory data suggested that soil maps of central O'ahu would not be particularly useful in delineating soil areas of relative homogeneity with respect to hydrologic properties. These results further emphasize the need for simple methods to characterize hydrologic properties of field soils.

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The authors are grateful for the assistance of several individuals whose contributions were important to the successful completion of the project: Charles Ellingson, Bradley Miyasato, and Lynn Onouye, student helpers, assisted in field and laboratory measurements and in data analysis; Saku Nakamura, U.S. Soil Conservation Service, described soil profiles at each field location; Michael Furukawa, Oahu Sugar Company, assisted in site selection and made arrangements for measurements on a number of Oahu Sugar Company fields; Faith N. Fujimura, Administrative Assistant and Editor, Water Resources Research Center, provided continuous encouragement and unlimited editorial assistance during the preparation of journal papers and the final report resulting from this research.

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INTRODUCTION

The hydraulic conductivity and retentivity (water storage function) of a soil are fundamental soil characteristics which specify the soil's contribution to important hydrologic phenomena, such as water infiltration, drainage, and groundwater recharge. These properties vary in space in the vertical and horizontal dimensions, and thus must often be measured at various depths and locations in a field to adequately characterize the soil for hydrologic calculations. In Hawai'i, mathematical modeling of specific groundwater and watershed cases holds promise for the future as a means of finding solutions to practical water transport and storage problems. The theory of water flow in soils has been recently applied to practical agricultural problems, such as the design of trickle irrigation systems (Bresler 1978) and the management of water and nitrogen fertilizer in such systems (Khan, Green, and Cheng 1981). Detailed deterministic models require that soil hydraulic functions be specified mathematically; this necessitates measurements of hydraulic conductivity on field-structured soils, preferably in situ. Measurement methods must be sufficiently simple and rapid to be practically useful for characterization of field soils at many locations.

Additionally, simple soil criteria must be established to identify reasonably homogeneous soil areas for hydrologic modeling before detailed plans of measuring hydraulic conductivity at several field sites in an area of interest are implemented.

OBJECTIVES

Project objectives included: (1) developing and field testing of simplified techniques of determining water conductivity of well-drained soils of Hawai'i, (2) developing and field testing of simplified infiltration models incorporating measured soil-water properties, and (3) assessing the variability in pertinent soil-water properties on selected soil survey mapped units and developing criteria for delineating "homogeneous soil units".

PREVIEW OF REPORT

The two major output categories from the project include: (1) description and assessment of methods developed and/or tested and (2) presentation of data (measured and derived) describing the soil properties of hydrologic significance for the soils included in the study. Some of the results in the first category have been submitted for publication in scientific journals and will be summarized in this report rather than given in their entirety. Other method-oriented results are presented in greater detail in this report than would be possible in journal papers. The second output category from the project includes data obtained from in situ field measurements and laboratory measurements on soil cores from each site of the three Oxisols studied, and a statistical analysis of these data to determine the nature of variability in properties between soil taxonomic units. Morphological descriptions of soil profiles are also included. The analysis in the first section of Part I includes the Tantalus and Panoche soils for which data had been obtained in other field studies.

O'ahu field site locations on which the various measurements were made are shown in Figure 1. The shaded area in central O'ahu includes the major part of soils classified as Oxisols on the island; most of this area is cropped with sugarcane and pipeapple. These Oxisols are principally derived from basaltic rocks of alluvium and are primarily composed of kaolinite and the oxides of iron and aluminum. Although the clay content of these soils is very high, up to 90% in some soils, they are highly structured and, thus, are quite permeable and generally well drained. The soil profile usually exceeds one meter in depth, but crop rooting is sometimes limited principally to the plow layer (about 45 cm) due to the combination of low macroporosity in the B horizon and the development of tillage pans.

In field aspects of this study, the three Oxisols included the Wahiawa, Lahaina, and Molokai series, which constitute the principal cropped soils of the Wahiawā plateau. The taxonomic classification of each soil, and location of field sites, and the site designations used in Part II of the report are given in Table 1. All sites were located on cultivated fields. Site W1 had been in grass and was cleared and rototilled shortly before the study. Site W2 was in a recently abandoned pineapple field. All other sites were located in sugarcane fields.

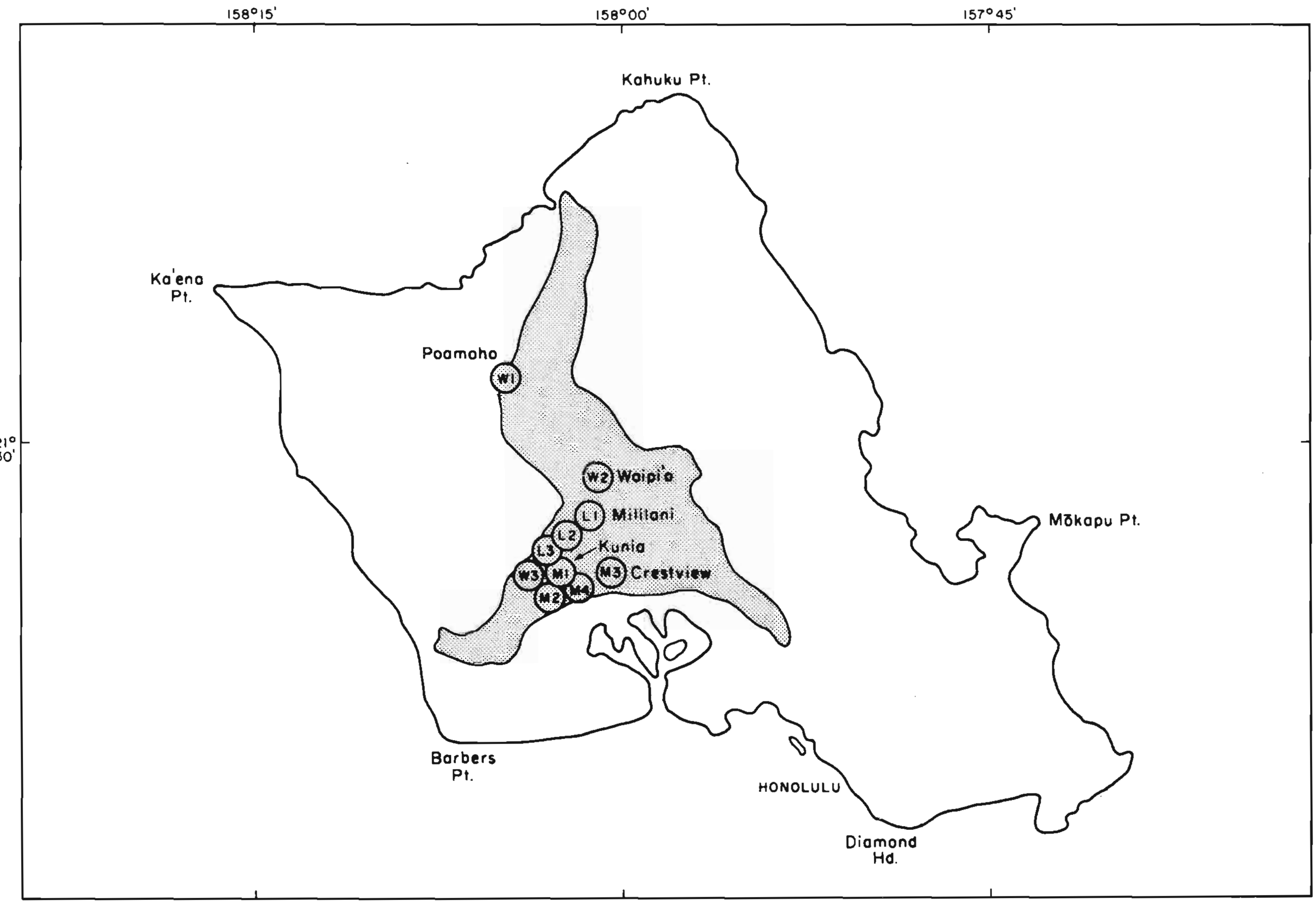


Figure 1. Field measurement sites within an Oxisols area, O'ahu, Hawai'i

TABLE 1. SOILS, TAXONOMY, STUDY SITES, REPLICATES, AND SITE DESIGNATIONS

Soil Series	Family (Subgroup)	Study Site	Replicate	Site Desig.
Wahiawa	Clayey, kaolinitic, isohyperthermic (Tropeptic Eutrustox)	U.H. Experiment Farm, Poamoho	Lower	W1-1
			Upper	W1-2
		Pineapple Research Institute, Waipi'o	North	W2-1
			South	W2-2
		OP* 157, Kunia	Plot 1	W3-1
			Plot 2	W3-2
			Plot 3	W3-3
			Plot 4	W3-4
Lahaina	Clayey, kaolinitic, isohyperthermic (Tropeptic Haplustox)	OP 246, Mililani (Sewage effluent experiment site)	West	L1-1
			East	L1-2
		OP 221, Kunia	East	L2-1
			West	L2-2
		OP 146, Kunia	West	L3-1
			East	L3-2
Molokai	Clayey, kaolinitic, isohyperthermic (Typic Torrox)	OP 146, Kunia	North	M1-1
			South	M1-2
		HSPA Experiment Station, Field C, Kunia	North	M2-1
			South	M2-2
		OP 410, Crestview	East	M3-1
			West	M3-2
		HSPA Experiment Station, Field L, Kunia	A	M4-1
			B	M4-2
			C	M4-3

*Refers to Oahu Sugar Plantation field.

I. DEVELOPMENT AND TESTING OF SIMPLIFIED METHODOLOGY

SOIL HYDRAULIC CONDUCTIVITY AND WATER CHARACTERISTICS DETERMINED FROM MINIMUM FIELD DATA

Application of the soil water-flow theory for describing infiltration and drainage in a watershed requires the determination of the soil's hydraulic conductivity-water content and suction-water content (soil-water characteristic) relationships and their spatial variability. To accomplish this, the most important range of determinations is the wet region of water contents at a suction of less than one bar. Perhaps the most reliable method for determining the field conductivity for saturated (or nearly-saturated) soil, as well as the unsaturated hydraulic conductivities in this region, is the Darcian analysis of in situ tensiometric measurements during steady-state infiltration and subsequent drainage, by using soil-water characteristics to calculate water fluxes (Richards, Gardner, and Ogata 1956; Ogata and Richards 1957; Nielsen et al. 1964; Rose, Stern and Drummond 1965; van Bavel, Stirk, and Brust 1968). The soil-water characteristics can be obtained by periodic measurement of soil-water content during the drainage phase by soil sampling, neutron meter or gamma-ray attenuation techniques. The water characteristics are more commonly measured in the laboratory on undisturbed soil cores. These methods of measuring the soil hydraulic properties are time consuming and tedious. Simplified time-saving approaches for obtaining one or both of the soil-water properties (Nielsen, Bigger, and Erh 1973), although somewhat approximate, will encourage their use for large-scale field application.

The objective of this study was to investigate the possibility of determining the hydraulic conductivity as well as the soil-water characteristics from minimum field measurements, by assuming that these functions can be represented by some simplified forms whose parameters can be estimated from less data. Earlier work with this general approach applied to a soil core wetting process (Ahuja 1975) provided encouragement for this study. The minimum field data considered necessary were the field-saturated hydraulic conductivities of the soil profile during infiltration, and numerous tensiometric readings and one soil moisture sampling during the subsequent

NOTE: The first section in Part I is the basis for an article by Ahuja, Green, Chong, and Nielsen (1980).

drainage.

Theory and Method of Computation

The theory of the method involves taking the hydraulic conductivity and the soil-water content as functions of the soil-water suction (negative of soil-water matric potential). These two functions are assumed to be described by the following piecemeal simplified forms over two subranges of the tensiometric soil-water suction range for a given depth interval:

$$K(\tau) = c_1\tau^{-n_1}$$
$$\theta(\tau) = a_1 - b_1\tau \qquad 0 < \tau \leqslant \tau_1 \qquad (1)$$

and

$$K(\tau) = c_2\tau^{-n_2}$$
$$\theta(\tau) = a_2 - b_2\ln\tau \qquad \tau > \tau_1 \;; \qquad (2)$$

where $K(\tau)$ is the hydraulic conductivity function, $\theta(\tau)$ is the soil-water content function, and c_1, c_2, n_1, n_2, a_1, a_2, b_1, b_2, and τ_1 are constants. The function forms for $K(\tau)$ suggested above are the types proposed and used by several other investigators for suctions greater than the air-entry value (Wind 1955; Brooks and Corey 1964; Brutsaert 1967). The τ_1 in equations (1) and (2) is used in the same sense as the air-entry value, but may not be equal to it. The $K(\tau)$ form of (1) allows K to be constant for $\tau < \tau_1$. The $\theta(\tau)$ function form of (2) has also been used before for suctions greater than the air-entry value (McQueen and Miller 1974). In the wet range of $\tau < \tau_1$, we found a linear $\theta(\tau)$ function of (1) to be better and more generally applicable than the constant θ assumption often used. The function provides for the latter as a special case. Substitution of the above functional forms into the Richards equation of unsaturated flow during the process of drainage from the soil results in

$$-b_1 \frac{\partial}{\partial t} \int_0^{z_1} \tau dz = -\left[c_1\tau^{-n_1}\left(\frac{\partial\tau}{\partial z} + 1\right)\right]_{z_1} \quad 0 < \tau \leqslant \tau_1 \qquad (3)$$

$$-b_2 \frac{\partial}{\partial t} \int_0^{z_1} \ln\tau \, dz = -\left[c_2\tau^{-n_2}\left(\frac{\partial\tau}{\partial z} + 1\right)\right]_{z_1} \quad \tau > \tau_1 \qquad (4)$$

where t is the time variable, z is the soil-depth variable, and z_1 is the soil depth considered. Rearranging these equations results in the following:

$$\left(\frac{\partial}{\partial t} \int_0^{z_1} \tau \, dz\right) \Big/ \left(\frac{\partial\tau}{\partial z} + 1\right) = \frac{c_1}{b_1}\tau^{-n_1}, \quad 0 < \tau \leqslant \tau_1 \qquad (5)$$

$$\left(\frac{\partial}{\partial t}\int_0^{z_1} \ln\tau \; dz\right) \Big/ \left(\frac{\partial\tau}{\partial z} + 1\right) = \frac{c_2}{b_2}\,\tau^{-n_2}, \quad \tau > \tau_1 \; . \tag{6}$$

The left-hand sides of these equations have terms that can be calculated from the field tensiometric data taken for the soil profile. By plotting the left-hand side of each equation against τ on a log-log plot, we can determine the limits of the subranges over which equations (5) and (6) hold adequately (and, hence, the τ_1) and then the values of n_1, n_2, c_1/b_1, and c_2/b_2. The constant c_1, of equation (1), is the saturated K determined in the field during steady-state infiltration prior to drainage. If the steady-state K is not the nearly saturated value, a proper c_1 can be derived from that value and the c_2 obtained by invoking continuity of $K(\tau)$ at τ_1. Thus, the constants b_1 and b_2 will also be available. With b_2 known, the constant a_2 of equation (2) can be determined from one field sampling of soil moisture content, corresponding to a recorded tension and a_1 obtained by invoking continuity at τ_1.

The method described above determines the $K(\tau)$ for a certain soil depth z_1, but $\theta(\tau)$ for a depth interval 0 to z_1. The method requires that the soil depth interval from 0 to z_1 be more or less uniform in $\theta(\tau)$. Experience of working with the method has, however, indicated that for a layered soil one may assume that an average $\theta(\tau)$ applicable to a layered soil profile exists during the drainage process. The method is first applied to the top soil layer, say 0 to z_1, and $\theta(\tau)$ for this layer determined. Then by applying the method to the first two soil layers, say 0 to z_2, an average $\theta(\tau)$ for the two layers will be found. From the two $\theta(\tau)$ determinations and the known soil-water suctions in the two layers at different times, $\theta(\tau)$ for the second layer can be estimated. However, for practical purposes of predicting drainage and water storage in the profile, an average $\theta(\tau)$ function may be adequate, or even an attractive feature, inasmuch as the prediction calculations are simplified.

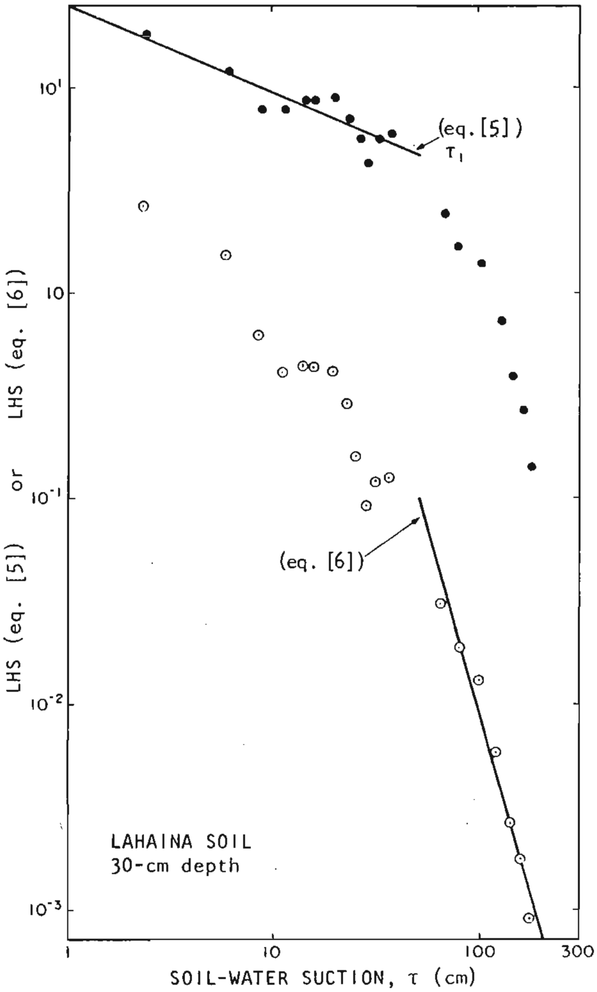
Experimental and Testing Procedure

The method described above was tested on field data for five soils: the three Hawai'i Oxisols (Lahaina, Molokai, and Wahiawa), a Hawai'i type Dystrandept (Tantalus), and one California soil, a Typic Torriorthents (Panoche series). Field data from previous studies were available for the Tantalus soil (Ahuja, El-Swaify, and Rahman 1976) and Panoche (Nielsen, Biggar, and Erh

1973). For Hawai'i soils, the data were obtained by a double-ring infiltrometer with multiple-depth tensiometers (Ahuja, El-Swaify, and Rahman 1976). The diameters of the inner ring were 30 cm and the outer ring, 120 cm. Field-saturated hydraulic conductivities were determined from the steady ponded-water infiltration rates and from tensiometer readings at the vertical axis of the axisymmetric flow system. During the subsequent drainage, transient readings for different depths at the vertical axis as well as at a location in the middle of the buffer area were periodically recorded for 10 to 25 days. For two of the four soils, soil moisture samples representing 0 to 30 cm and 30 to 60 cm depths were taken in the buffer area at three to four different times as the soil drained. Only one of the soil moisture samplings is needed for the simplified method being investigated; the additional measurements are used here for testing the results. Undisturbed soil cores, 10 cm in diameter and 7.5 cm long, were taken for comparison purposes from three or more depths in all the soils to determine suction-water content relations in the laboratory. Hanging water columns and air pressure were combined to determine these relations between 10 and 1000 cm water suctions. Values for less than 10-cm suction were linearly obtained by back-extrapolations from 10- and 25-cm values. These water characteristics were then utilized in the more rigorous Darcian analysis of the drainage tensiometric data (Nielsen, Biggar, and Erh 1973) to obtain unsaturated hydraulic conductivities for comparisons. The latter were also obtained by using the field soil moisture samplings in two of the soils. For computing hydraulic gradients, integrals, and time derivatives of equations (5) and (6) from field tension-depth-time data—as well as for the more detailed Darcian analysis, the least-squares cubic spline fittings (de Boor and Rice 1968) were employed. For the California soil (Panoche clay loam), the data for plot 1 of Nielsen, Biggar, and Erh (1973) were utilized.

Results and Discussion

Experimental results of plotting the left-hand sides of equations (5) and (6), respectively, versus the soil-water suction τ_1 for Lahaina soil to 30-cm depth, z_1 are presented in Figure 2. The straight line segments in the plots are least-squares fits to the data subranges over which equations (5) and (6), respectively, seem to be applicable. The slope of these lines



NOTE: LHS = Left-hand side.
NOTE: Straight lines are least-squares fits to the data for the subranges.

Figure 2. Plots of eqq. (5) and (6) showing subranges of their respective applicability for Lahaina soil

give n_1 = 0.415 and n_2 = 3.54, respectively, with the intercepts c_1/b_1 = 23.49 and c_2/b_2 = 1.04 × 10^5. The value of τ_1 indicated by the plots is 50 cm of water.

The constant c_1, taken as the field-saturated hydraulic conductivity at the 30-cm depth determined during the ponded-water infiltration, was found to be 0.042 cm/min. Using this c_1, with n_1, n_2, and τ_1 determined above, the unsaturated hydraulic conductivity (K) calculated as a function of soil-water suction (τ) is presented as straight line segments on a logarithmic plot (Fig. 3). The figure also shows $K(\tau)$ values calculated from the more detailed, and well established, Darcian analysis of the drainage tensiometric data, using the $\theta(\tau)$ function measured on soil cores or using the field soil moisture samplings. The three sets of $K(\tau)$ function agree very well in this case.

The constant c_2 of equation (2) obtained by invoking continuity of $K(\tau)$ at τ_1 = 50 cm is 8716.6; the constants b_1 and b_2 are respectively 1.79 × 10^{-3} and 0.8363. With this b_2 and a measured field moisture content in the 0 to 30 cm soil layer of 0.375, corresponding to an average suction of 90.5 cm (at 1548 min after the start of drainage), the constant a_2 of equation (2) is 0.7518. The soil-water characteristic $\theta(\tau)$ computed from these parameters represents an average function for the surface soil (Fig. 4). The $\theta(\tau)$ determined by three additional field moisture samplings

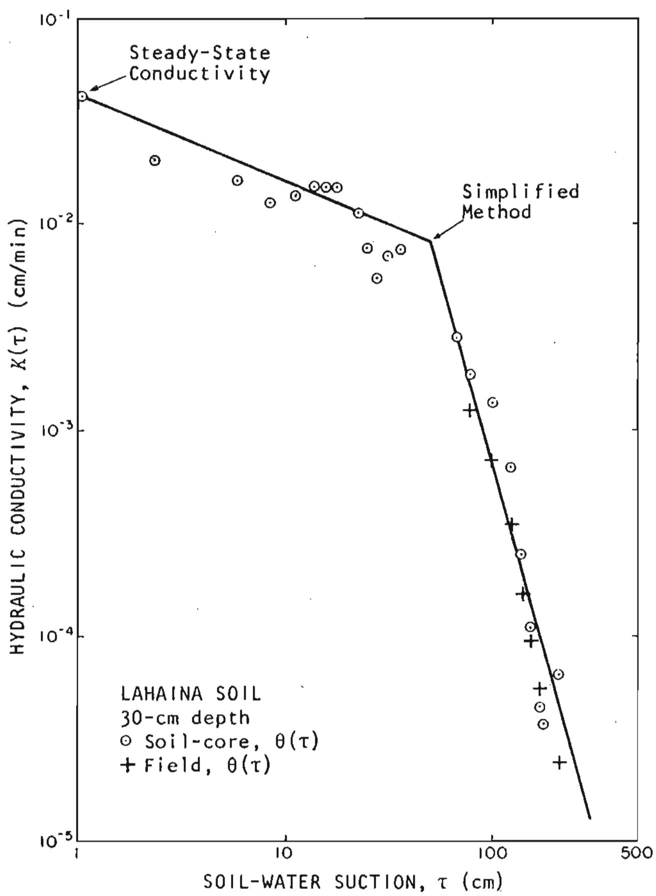


Figure 3. Hydraulic conductivity as function of soil-water suction of Lahaina soil determined by detailed Darcian analysis and simplified method

and by the soil-core method (for two different soil depths within the 0- to 30-cm layer) are given for comparisons. The core values shown are the average of two replicates, with a maximum difference in θ values of any two cores of 0.045 cm^3/cm^3. While the agreement between the simplified method and the three additional field-measured values is fairly good, the difference between the field and core data is noteworthy. This difference cannot be explained, except as a possible result of air entrapment during infiltration under field conditions. It is interesting that this difference in soil-core $\theta(\tau)$ and field $\theta(\tau)$ did not change the $K(\tau)$ values determined by using these functions in the analysis (Fig. 3). This is probably due to the two $\theta(\tau)$ functions being approximately parallel, which then gives about the same amount of water draining for flux calculations between any two suctions. The hydraulic conductivities expressed as a function of θ will be different for the two $\theta(\tau)$ functions.

Plots of equations (5) and (6), the $K(\tau)$ functions, and the $\theta(\tau)$ functions of the above Lahaina soil down to the 60-cm depth are respectively presented in Figures 5, 6, and 7. The results for $K(\tau)$ in Figure 6 indicate a disagreement between the simplified method and the detailed analysis using soil-core $\theta(\tau)$ at suctions less than 20 cm, even though the slope of the two $K(\tau)$ plots is about the same. The difference does not seem to be the result of simplifying assumptions involved in equations (1) and (2) or of the re-

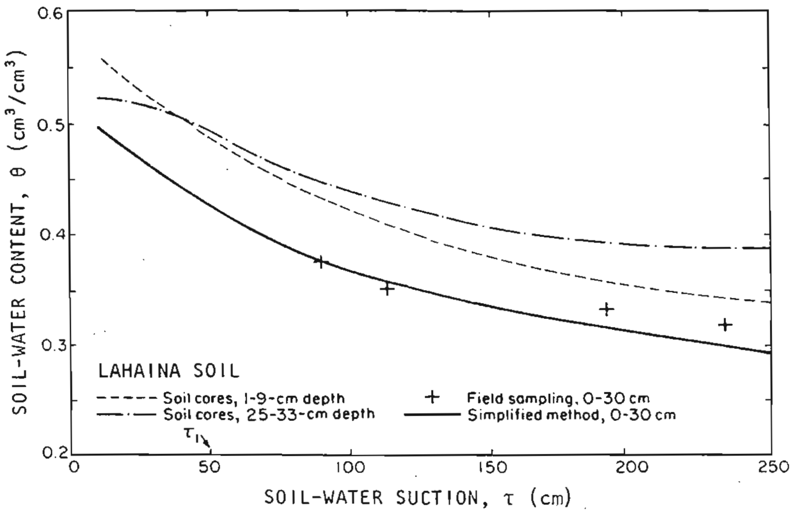
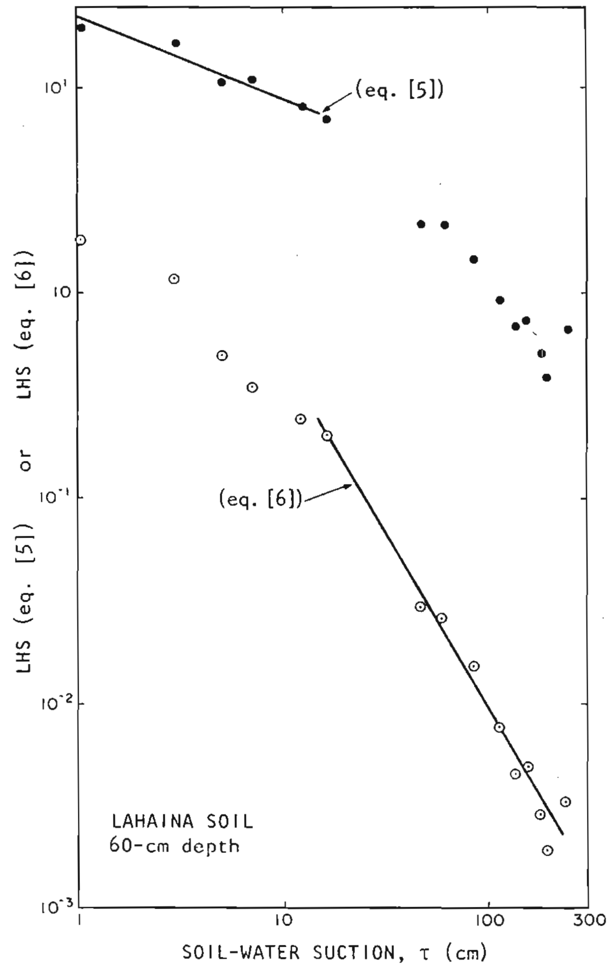


Figure 4. Soil-water characteristics of Lahaina soil determined by soil cores, field sampling, and simplified method



NOTE: LHS = Left-hand side.

Figure 5. Plots of equations (5) and (6) showing subranges of their respective applicability for Lahaina soil

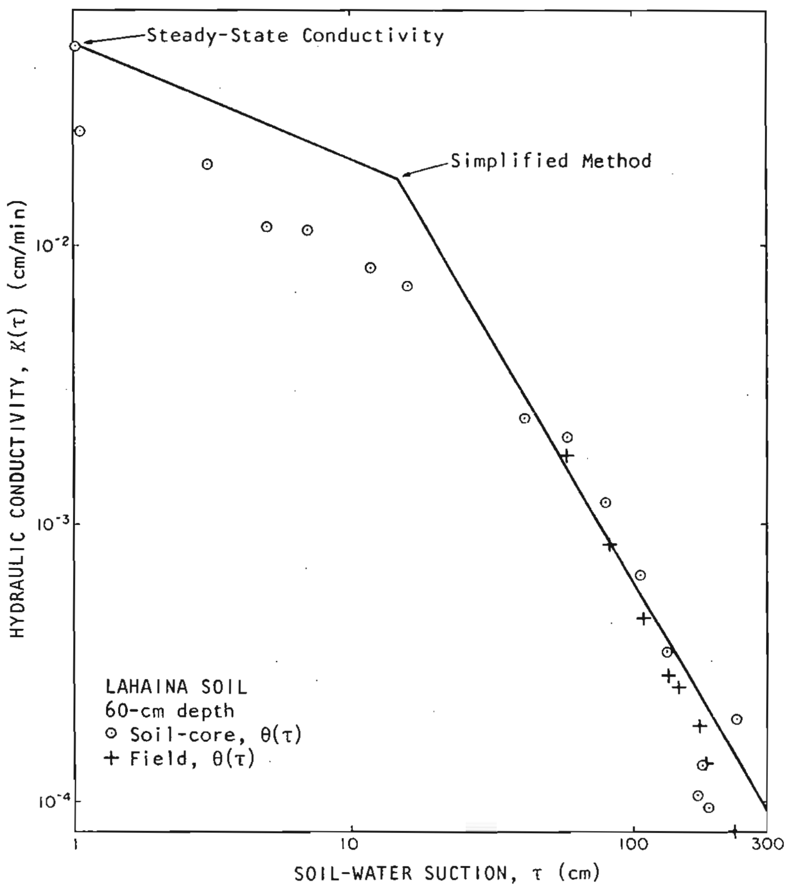


Figure 6. Hydraulic conductivity as function of soil-water suction of Lahaina soil determined by detailed analysis and simplified method

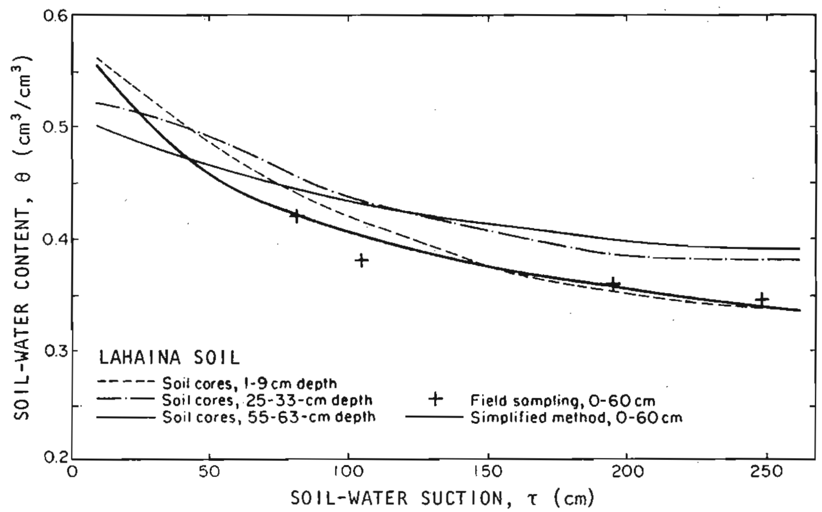


Figure 7. Soil-water characteristics of Lahaina soil determined by soil cores, field sampling, and simplified method

quirement that an average $\theta(\tau)$ applicable to soil between the 0- and 60-cm depths exists for the drainage process. The discrepancy appears more likely due to one or a combination of the following.

1. An error occurs in measuring the steady-state hydraulic conductivity during ponded-water infiltration when a multiple-depth tensiometer in the center of a double-ring infiltrometer is used. The error could be caused by the channeling of water along the tensiometer walls, which may affect the measured hydraulic gradients. However, the horizontal gradients at 60 cm measured between the inner ring and the middle of the buffer zone were practically negligible; thus, no lateral flow was suspected.
2. An error occurred in determining $K(\tau)$ by the detailed method in the very wet region (suctions <20-cm water) due to the errors in the $\theta(\tau)$ values for this region used in the analysis. The $\theta(\tau)$ in the very wet region may be unstable or not unique due to the dynamic nature of air entrapment. The $\theta(\tau)$ measured on soil cores in the very wet region may not represent the field situation.
3. The wet region is basically very difficult to characterize, and our linear back-extrapolation for obtaining $\theta(\tau)$ for suctions less than 10 cm may not be good enough in all cases.
4. The process of calculating water fluxes from time derivatives of soil water-storage integrals involves very steep slopes in the latter at small times (small suctions). An error is bound to occur and can be appreciable in determining slopes in this region by any method of fitting. The 0- to 60-cm average $\theta(\tau)$ obtained by the simplified method (Fig. 7) agrees quite well with additional field samplings. The field sampling values of $\theta(\tau)$ in this case are closer to the soil-core values than in the case of the 0- to 30-cm depth range in Figure 4.

The results of $K(\tau)$ and $\theta(\tau)$ calculations for Molokai soil, depth z_1 = 30 cm, are respectively presented in Figures 8 and 9. While the $K(\tau)$ of the simplified method is fairly close to that of the detailed method, the $\theta(\tau)$ evaluation is very poor. The data for z_1 = 60 cm (Figs. 10, 11) indicate a better $\theta(\tau)$ evaluation, but a discrepancy between $K(\tau)$ of the simplified method and that of the detailed analysis using soil-core $\theta(\tau)$ at low

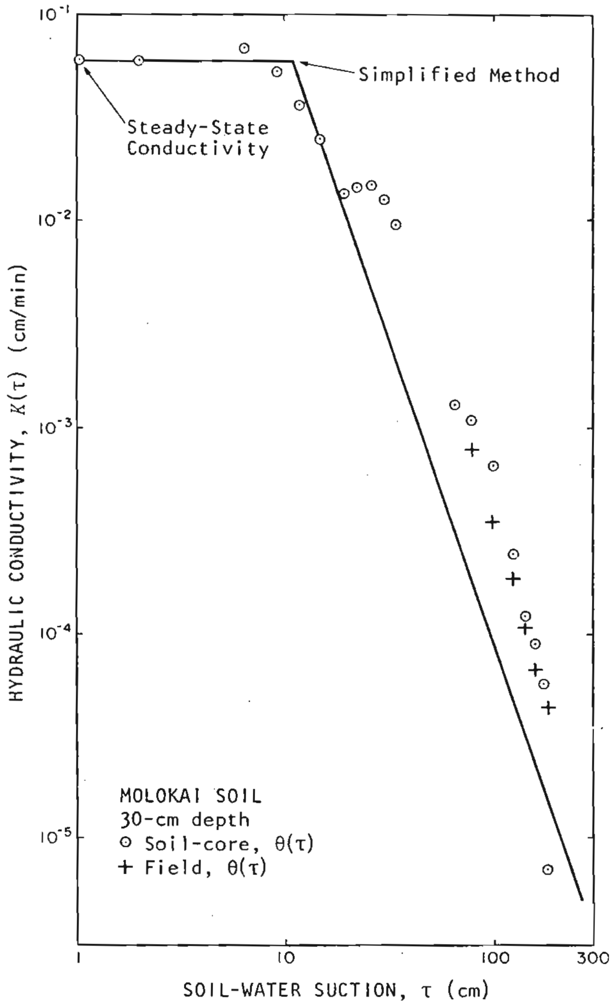


Figure 8. Hydraulic conductivity as function of soil-water suction of Molokai soil determined by detailed analysis and simplified method

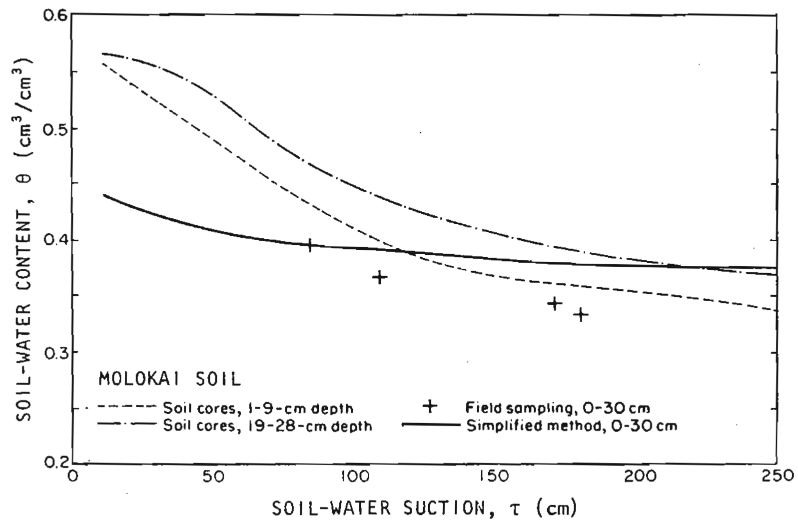


Figure 9. Soil-water characteristics of Molokai soil determined by soil cores, field sampling and simplified method

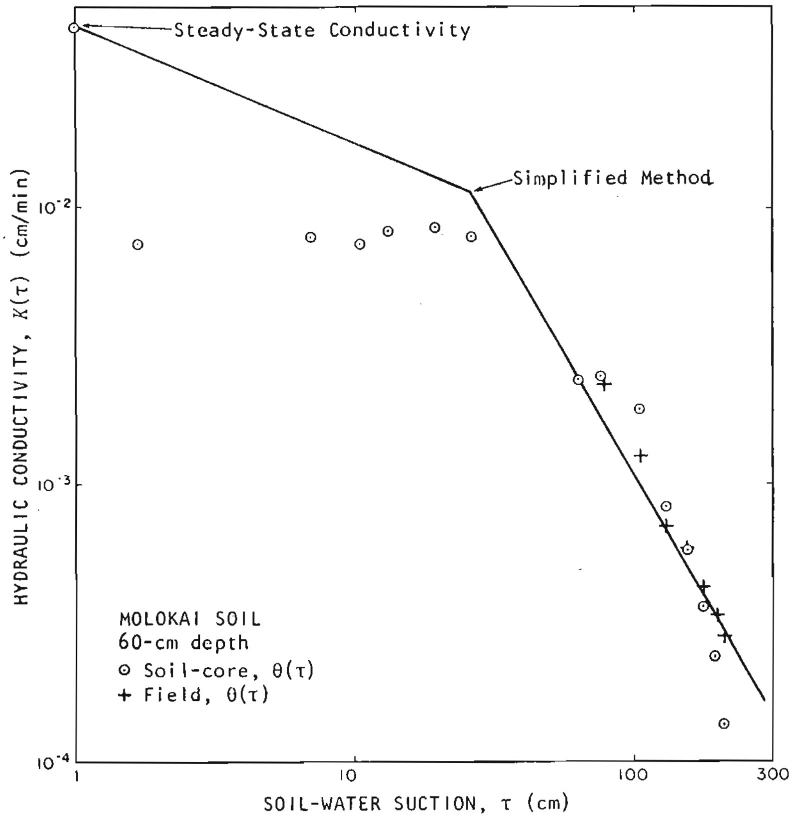


Figure 10. Hydraulic conductivity as function of soil-water suction of Molokai soil determined by detailed analysis and simplified method

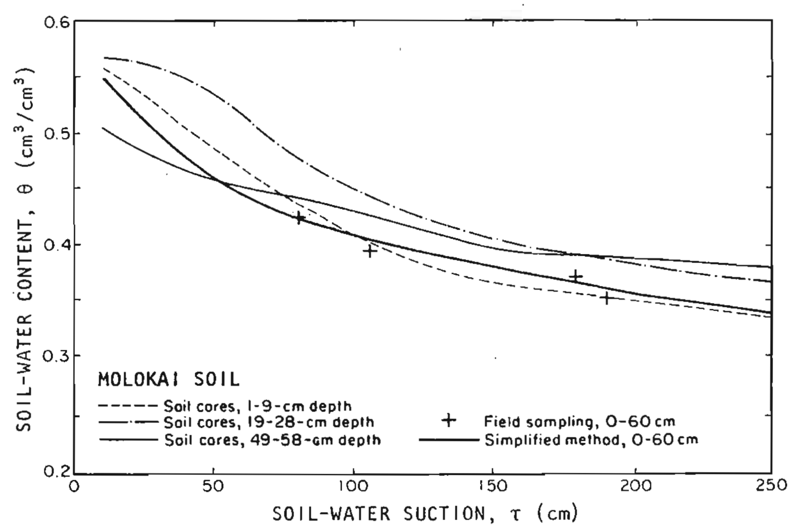


Figure 11. Soil-water characteristics of Molokai soil determined by soil cores, field sampling, and simplified method

suctions, as in the case of the 60-cm functions of Lahaina soil described above.

For Wahiawa soils, the analysis was extended to soil depths of 90 and 120 cm. The results for all four depths are presented in Figures 12 to 19. No field soil samples were taken during the process of drainage; therefore, for estimating the constant a_2 of equation (2) by the simplified method, an appropriate average soil-water content corresponding to 100-cm suction from soil-core data was utilized. For the 30-cm position, the hydraulic conductivity values at suctions less than 10 cm determined by the detailed analysis are higher than the steady-state conductivity, causing a discrepancy between them and the estimated simplified function in that region. For the 60-, 90- and 120-cm positions, quite the opposite is observed: the $K(\tau)$ values at low suctions determined by the detailed analysis are smaller than those estimated by the simplified method. Possible reasons for these discrepancies are given earlier in the case of Lahaina soil. When the 10-cm suction is exceeded there is fairly good agreement between the two methods. The $\theta(\tau)$ estimation by the simplified method is not satisfactory for the 30-cm position, but improves as the depth z_1 increases.

The analysis results for Tantalus soil are presented in Figures 20 and 21 for depth z_1 = 30 cm. The tensiometric data, the detailed-analysis $K(\tau)$, and the soil-core $\theta(\tau)$ data were from an earlier study (Ahuja and El-Swaify 1975). The plot of equation (6) described the experimental data in the complete range. The estimation of $K(\tau)$ by the simplified method, shown in Figure 20, agrees with that by the detailed analysis for suctions between 5 and 70 cm. For suctions less than 5 cm, the $K(\tau)$ by the latter method was not determined in the earlier work (Ahuja and El-Swaify 1975). The determination of $\theta(\tau)$ (Fig. 21) with the constant a_2 of equation (2) obtained by matching at average 0 to 30 cm water content for 100-cm suction of soil cores (since no field soil moisture samplings during the drainage were conducted), agrees well with the soil-core data. The results for the depth z_1 = 60 cm of this soil (Figs. 22, 23) are similar to the above for the 30-cm depth.

The simplified analysis of the field tensiometric data of Nielsen, Biggar, and Erh (1973) for Panoche soil, plot 1, is presented in Figures 24 to 27. The plot of equation (6) for depth z_1 = 30 cm (not presented here) indicated that while this equation described the points for suctions greater

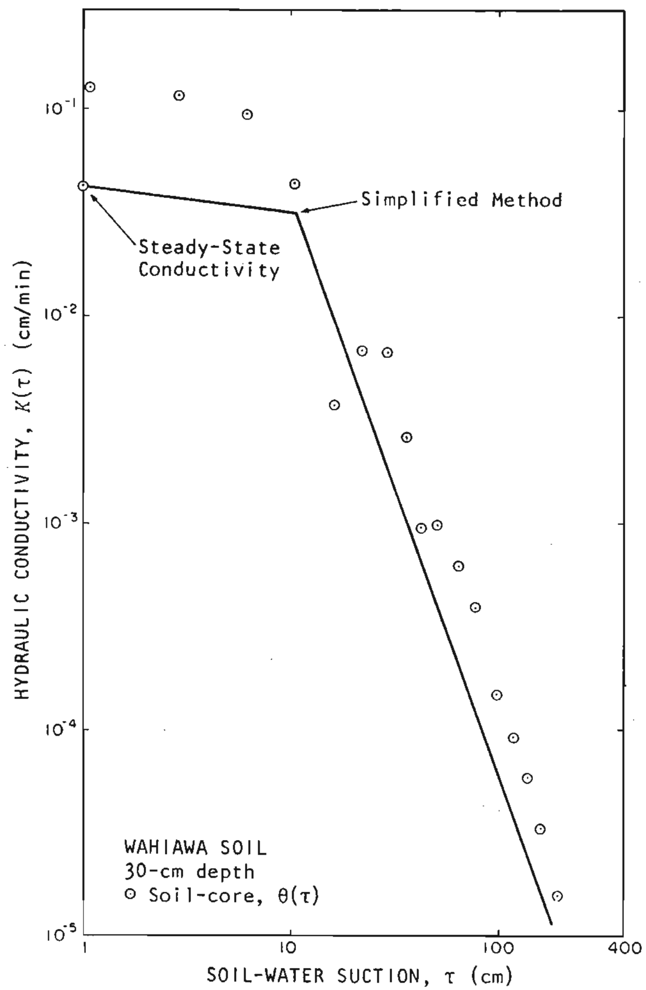


Figure 12. Hydraulic conductivity as function of soil-water suction of Wahiawa soil determined by detailed analysis and simplified method

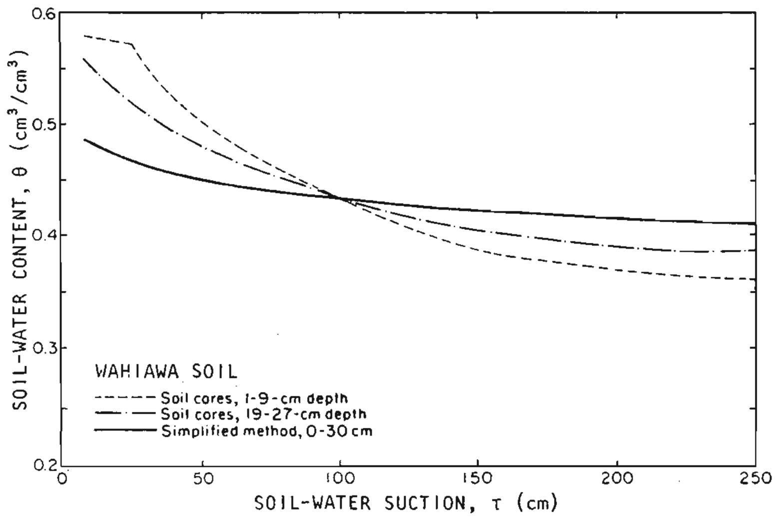


Figure 13. Soil-water characteristics of Wahiawa soil determined by soil cores and simplified method

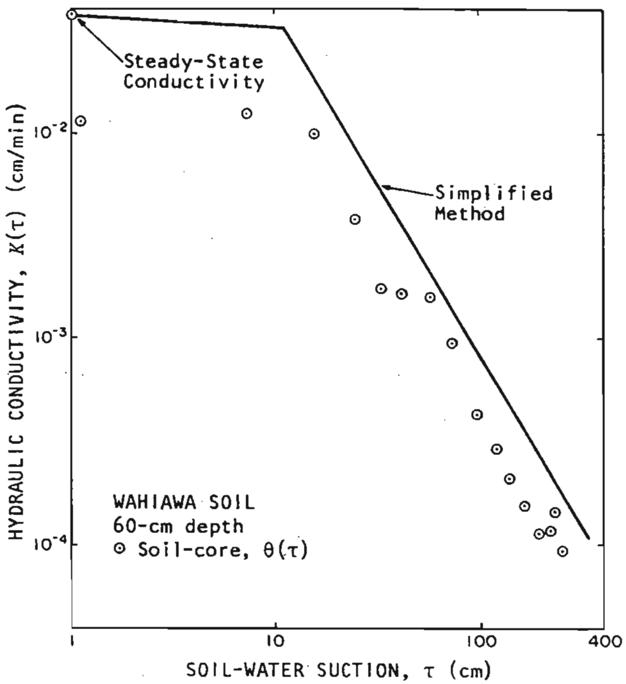


Figure 14. Hydraulic conductivity as function of soil-water suction of Wahiawa soil determined by detailed analysis and simplified method

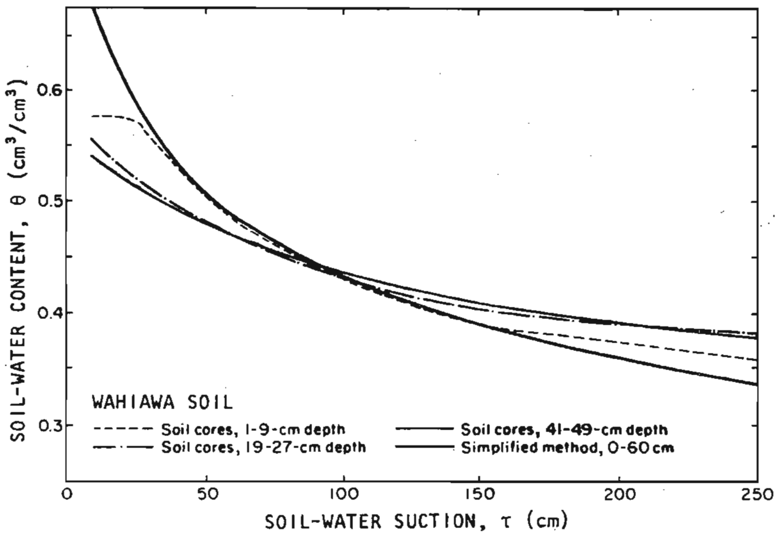


Figure 15. Soil-water characteristics of Wahiawa soil determined by soil cores and simplified method

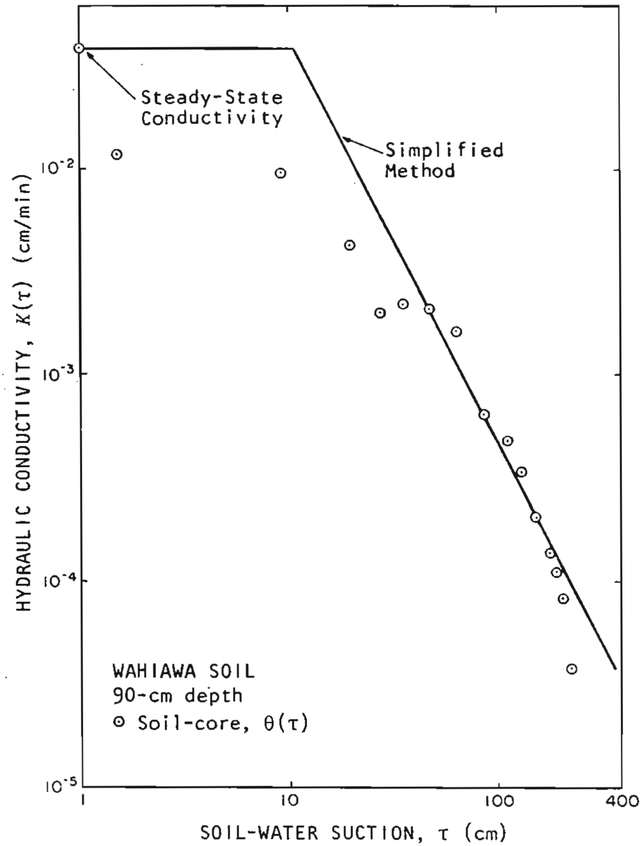


Figure 16. Hydraulic conductivity as function of soil-water suction of Wahiawa soil determined by detailed analysis and simplified method

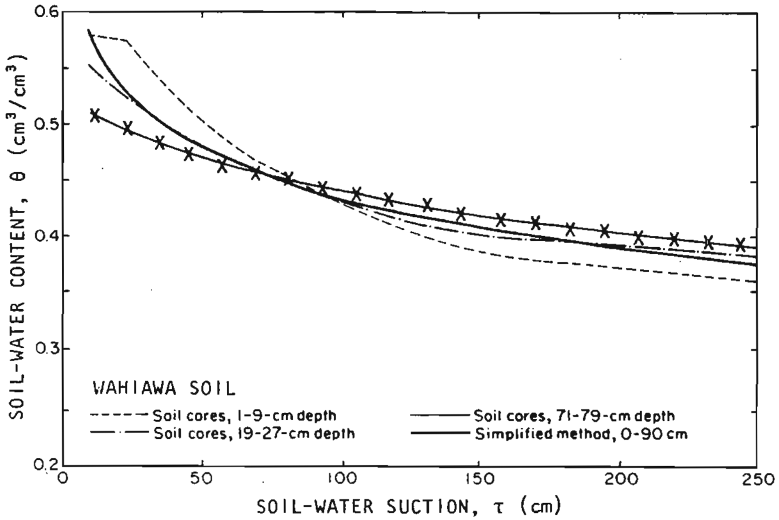


Figure 17. Soil-water characteristics of Wahiawa soil determined by soil cores and simplified method

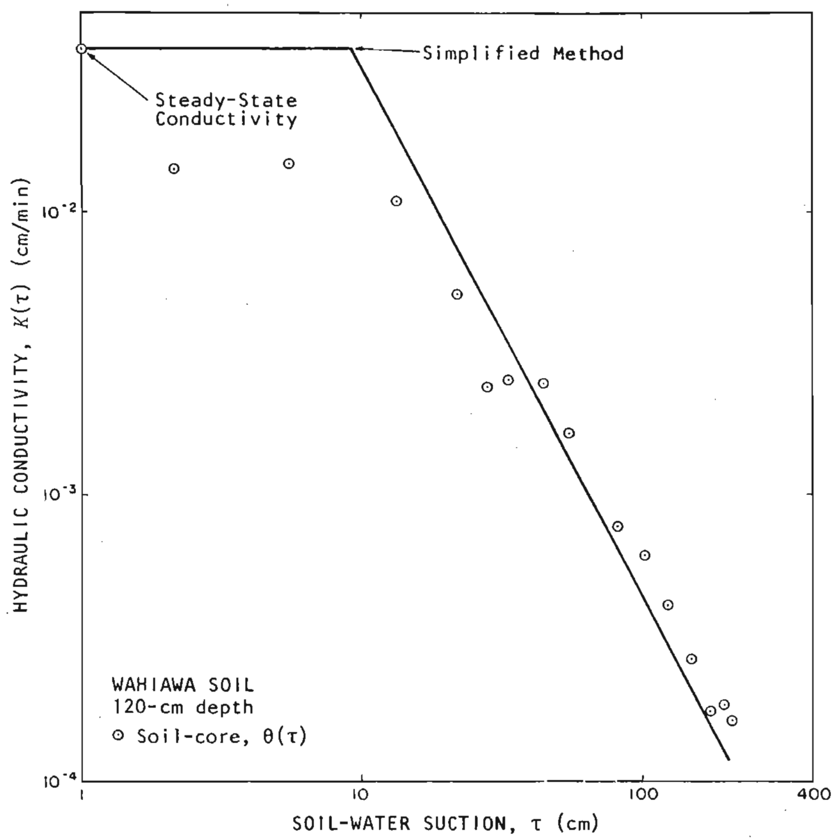


Figure 18. Hydraulic conductivity as function of soil-water suction of Wahiawa soil determined by detailed analysis and simplified method

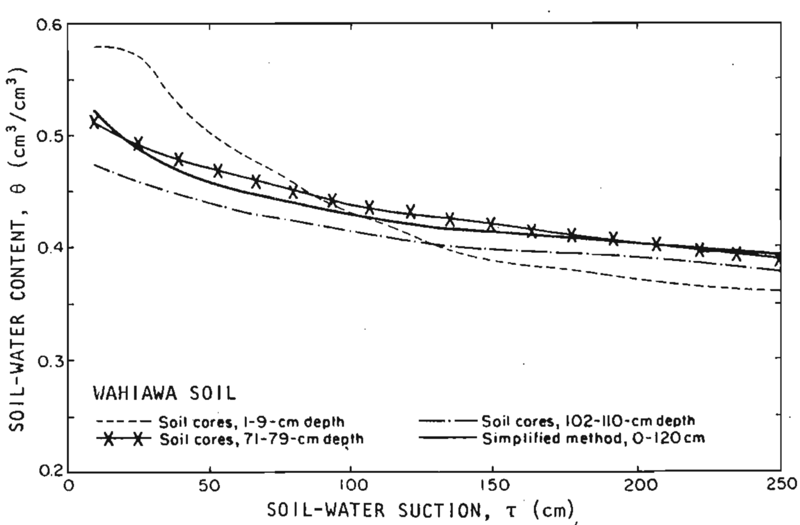


Figure 19. Soil-water characteristics of Wahiawa soil determined by soil cores and simplified method

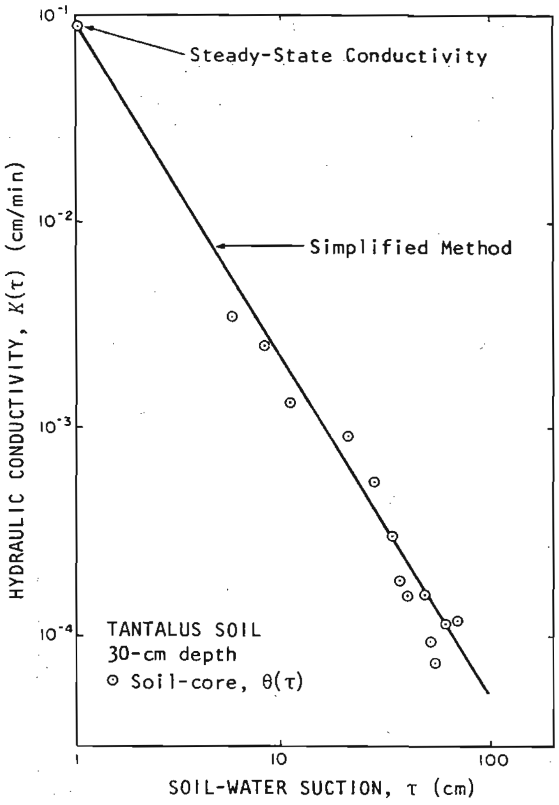


Figure 20. Hydraulic conductivity as function of soil-water suction of Tantalus soil determined by detailed analysis and simplified method

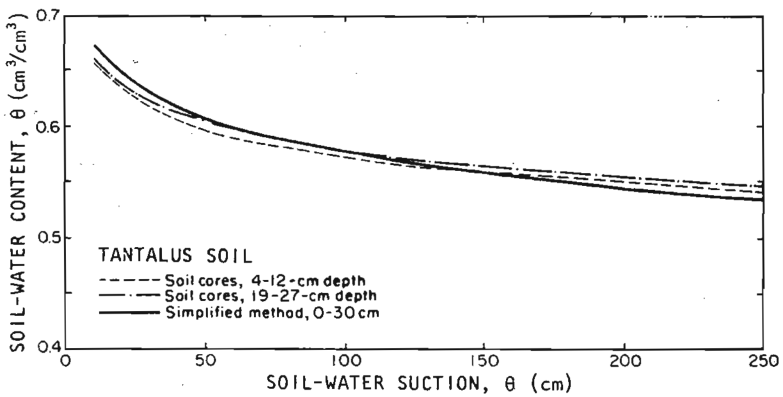


Figure 21. Soil-water characteristics of Tantalus soil determined by soil cores and simplified method

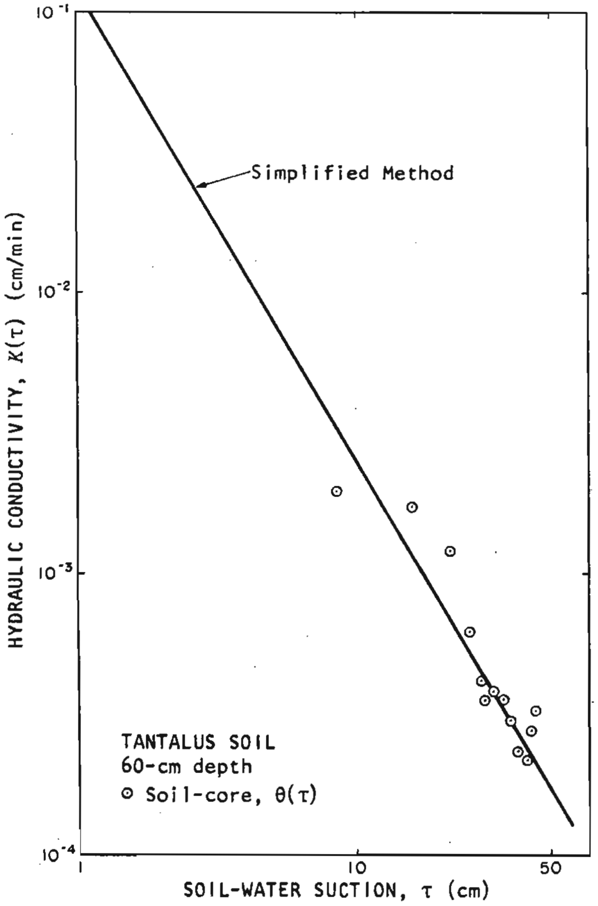


Figure 22. Hydraulic conductivity as function of soil-water suction of Tantalus soil determined by detailed analysis and simplified method

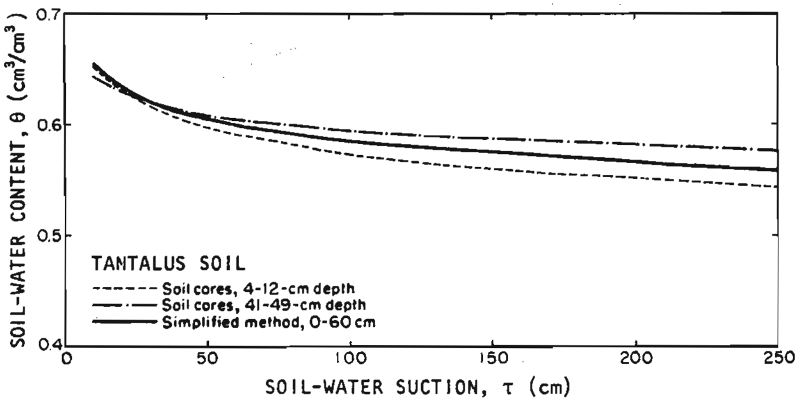


Figure 23. Soil-water characteristics of Tantalus soil determined by soil cores and simplified method

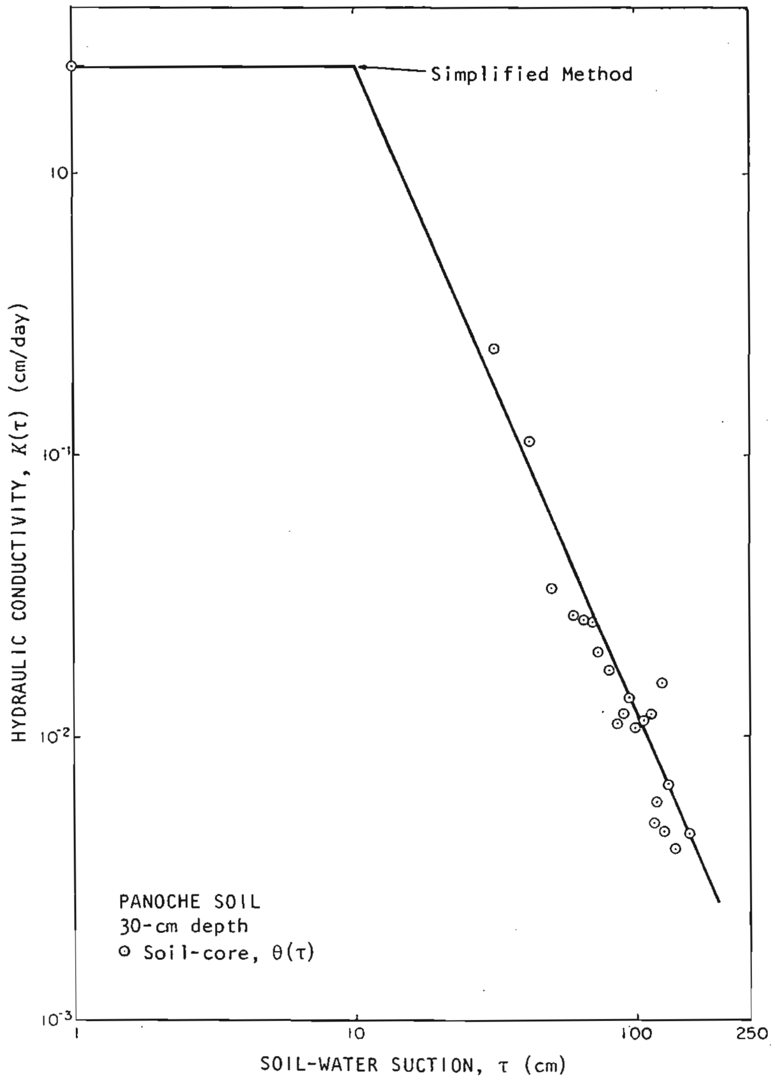
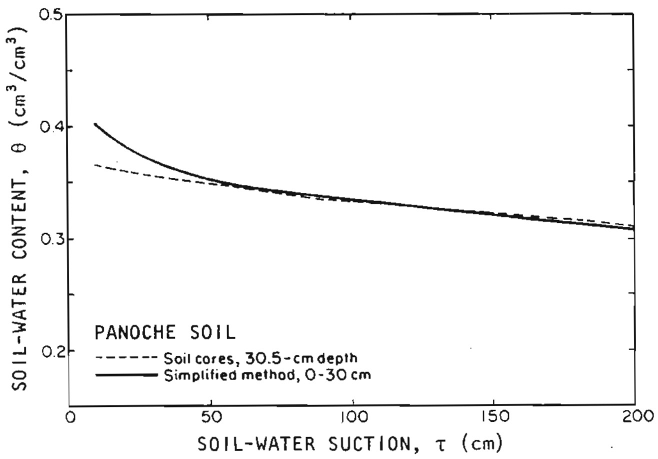


Figure 24. Hydraulic conductivity as function of soil-water suction of Panoche soil determined by detailed analysis and simplified method



NOTE: Vertical bars represent standard deviation of core data.

Figure 25. Soil-water characteristics of Panoche soil determined by soil cores and simplified method

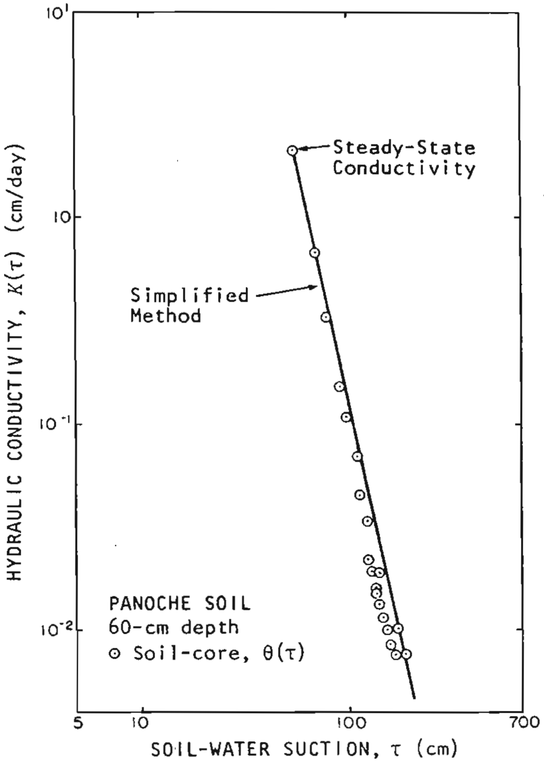


Figure 26. Hydraulic conductivity as function of soil-water suction of Panoche soil determined by detailed analysis and simplified method

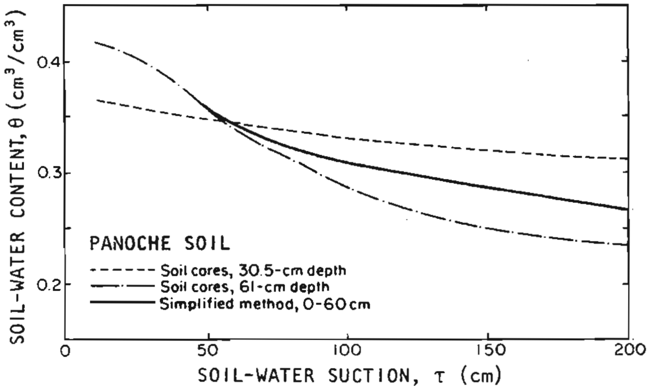


Figure 27. Soil-water characteristics of Panoche soil determined by soil cores and simplified method

than 30 cm, a lack of data points between 1.7 and 30 cm suction values prevented the determination of τ_1 in the normal way. The τ_1 was approximated by back-extrapolation of the least-squares line through points for 30 cm and higher suctions to the suction value where the ordinate value was equal to that of the data point at 1.7-cm suction. In spite of this somewhat crude approximation, the $K(\tau)$ obtained by the simplified method (Fig. 24), agrees quite well with the detailed analysis values. This is also true of the $\theta(\tau)$ determination for 0 to 30 cm (Fig. 25). The simplified calculations for soil depth z_1 = 60 cm of Panoche soil (Figs. 26, 27) also show good results.

Conclusions and Discussion

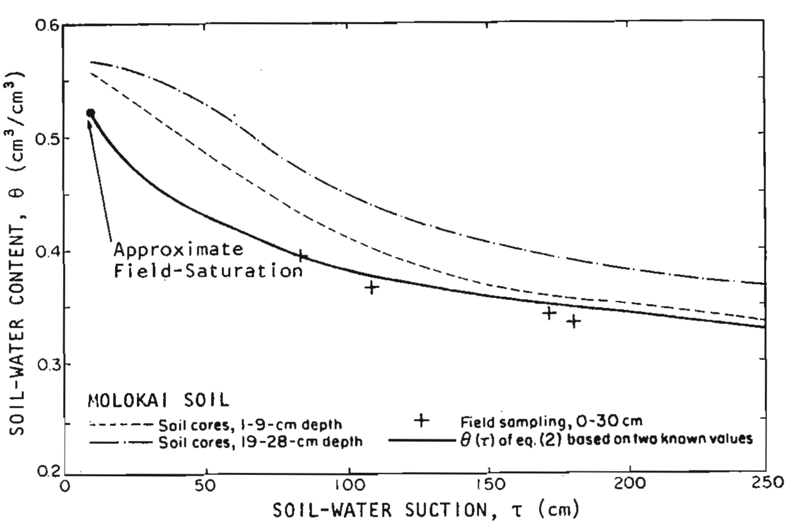
The following conclusions are drawn from the results and discussion of the preceding section.

1. The determination of the $K(\tau)$ by the simplified method of equations (1) to (6), especially at very small suctions between 0 and 20 cm of water, is affected by errors in the determination of field-saturated hydraulic conductivity, which is required as an input parameter. The deviations between the simplified method and the detailed Darcian analysis method in the very wet region will mostly disappear if an unsaturated $K(\tau)$ value obtained from the latter method were to be used as a parameter instead of the field-saturated conductivity. However, one should keep in mind that the calculation of $K(\tau)$ in the very wet region by the detailed method is also subject to appreciable uncertainties and errors in measurement of $\theta(\tau)$ of the field conditions as well as in calculation of slopes in the steep regions of the data involved. Overall, the mechanism of the simplified method for estimating $K(\tau)$ seems to work fairly well. The field-saturated conductivity is very important physically and its direct measurement is very desirable, in spite of some problems.

2. The determination of $K(\tau)$ by the simplified method does not require prior knowledge of the soil's $\theta(\tau)$ function, as is the case in the detailed Darcian analysis method. This is an attractive and useful feature, especially in view of the reason that the $\theta(\tau)$ determined on soil cores may not represent the actual field situation, as seen in Figures 4, 7, 9, and 11. The simplified method $K(\tau)$ would presumably be based on the actual field situation.

3. The estimation of the constant b_2 of the $\theta(\tau)$ function of equation

(2) seems to be somewhat more sensitive than that of the n_2 of the $K(\tau)$ function to scatter in the field and secondary data points, especially when the n_2 value is large (Figs. 8, 9, 12, 13). The procedure of obtaining b_2 from the ratio c_2/b_2 (eq. [6]) also makes it sensitive to the errors in the c_2 estimate, which in turn depends upon the field-saturated conductivity c_1. Large inaccuracies in the $\theta(\tau)$ obtained by the simplified method may be detected by comparing the estimated saturated value of θ with that obtained from the porosity (calculated from bulk density and particle density) along with a reasonable estimate for percent field saturation of porosity. For example, the Molokai soil had a bulk density of 1.09 g/cm^3 for 0 to 30 cm depth range, its measured particle density was nearly 2.85, which gave porosity = 0.618. Assuming field saturation of approximately 85% will give field-saturated θ = 0.525 cm^3/cm^3. Compared with this, the estimated $\theta(\tau)$ in Figure 9 is obviously quite a bit off. Of course, if two values of $\theta(\tau)$ are known both parameters b_2 and a_2 of the function of equation (2) can be directly determined. We did this for the Molokai soil case of 0 to 30 cm (Fig. 9), using one field-sampled value and the approximate field-saturated θ calculated above. The $\theta(\tau)$ thus obtained (Fig. 28) was closer to the three additional field-sampled values of $\theta(\tau)$. It should be noted that the knowledge of the position of τ_1 = 11 and b_1 = 0 (eq. [1]) in the above case from plots in Figure 7 was utilized in the process.



NOTE: See Fig. 9.

Figure 28. Soil-water characteristics of Molokai soil determined by soil cores, field sampling, and simplified method

In spite of some limitations, the $\theta(\tau)$ results for five different soils indicate that the estimations are fairly good in most cases. It is interesting that an average $\theta(\tau)$ for the soil profile (0 to 60 cm or deeper) can be assumed for the process of drainage.

$\theta(\tau)$ is obtained as a by-product of the measurements required for a simplified $K(\tau)$ determination, with one additional measurement for field-moisture content, which could correspond to the physically important field capacity point (about 100-cm suction in Hawai'i soils).

HYDRAULIC CONDUCTIVITY AND DIFFUSIVITY DETERMINED FROM SOIL WATER-REDISTRIBUTION MEASUREMENTS[1]

A simplified field method for measuring hydraulic conductivity, $K(\theta)$, and diffusivity, $D(\theta)$, was developed by Nielsen, Biggar, and Erh (1973) by assuming a unit hydraulic gradient in the soil profile during the redistribution period. On the average, the results obtained by this simple field method compared favorably with the detailed Darcian analysis. A limitation of this simple method is that hydraulic conductivity and diffusivity are determined only within the range of soil-water contents measured during drainage of a field plot after wetting of the soil profile. Extension of the method to provide a characterization of water conducting and water-storage properties of soils over a wider range of water contents requires some modification. Additionally, for the tilled soils of immediate concern to us, the possible errors introduced by the assumption of unit hydraulic gradient need to be evaluated. The subsurface horizons of Oxisols are generally denser and less permeable than the tilled surface horizon, a situation which might be expected to result in a nonunit gradient during drainage. A severe departure from unit gradient might invalidate the method for such soils.

Thus, we developed a procedure which would allow estimation of $K(\theta)$ and $D(\theta)$ over a wider range of water contents than provided by the method of Nielsen, Biggar, and Erh (1973) and determined the applicability of the simple field method for some important irrigated Oxisols in Hawai'i.

Theory

The assumption of a unit hydraulic gradient for water distribution, after steady infiltration in a uniform soil profile without evaporation, was introduced by Black, Gardner, and Thurtell (1969). With this assumption, the rate of change of soil-water content in the profile can be used to calculate

[1]This section contains material from a paper by Chong, Green, and Ahuja (1981) and from a Ph.D. dissertation by Chong (1979).

hydraulic conductivity, $K(\theta)$, as shown by Nielsen, Biggar, and Erh (1973):

$$K_L(\theta) = -L\frac{d\bar{\theta}}{dt} , \tag{7}$$

where

L = soil depth under consideration, cm

$K_L(\theta)$ = hydraulic conductivity at depth L, cm/min

$\bar{\theta}$ = average soil water content in the soil profile to depth L, cm^3/cm^3

t = time, min.

Furthermore, following Gardner (1970) and Nielsen, Biggar, and Erh (1973), if we assume that an average soil water-characteristic curve holds for the entire soil layer under consideration, along with the assumption of unit gradient, then the diffusivity of the soil profile at depth L, can be expressed as

$$D_L(\theta) = -L\frac{dh}{dt} , \tag{8}$$

where

$D_L(\theta)$ = soil-water diffusivity at depth L, cm^2/min

h = soil water-pressure head at L, cm of water.

Extension of this simplified method to allow calculation of K and D at water contents higher or lower than those measured during drainage requires the development of mathematical expressions which describe adequately θ and h vs. time during drainage. Following Richards, Gardner, and Ogata (1956) and Gardner, Hillel, and Benjamini (1970), the water content in the soil profile during the postinfiltration redistribution process is assumed to diminish with time in such a manner that

$$\theta = at^b \tag{9}$$

where a and b are constants. The relationship of (9) is assumed to be approximately applicable starting from $\bar{\theta}$ = field-saturated value $\bar{\theta}_s$, even though some discrepancy may occur near the point $\bar{\theta}_s$, and the effect of this assumption on the calculation of $K_L(\theta_s)$ will be tested. It is also assumed that the soil water-pressure head during the redistribution period can be similarly expressed as a power function of time, that is

$$h = mt^n \tag{10}$$

where m and n are constants. We assume that (10) is applicable starting from h = air entry pressure, h_a, which corresponds to the point $\bar{\theta}_s$ in (9).

Substituting equations (9) and (10) into (7) and (8), respectively, equations (11) and (12) are obtained in which K and D are both expressed as functions of t, where $t = 0$ corresponds to the initiation of drainage after the soil profile has been thoroughly wetted, as follows:

$$K_L(t) = -L\,abt^{b-1} \tag{11}$$

and

$$D_L(t) = -L\,mnt^{n-1} \ . \tag{12}$$

Furthermore, if we substitute equation (9) into (11) and (12), K and D can be expressed in terms of θ, such that

$$K_L(\theta) = -L\,ba^{(1/b)}\,\theta^{[(b-1)/b]} \tag{13}$$

$$D_L(\theta) = -L\,mna^{-[(n-1)/b]}\,\theta^{[(n-1)/b]} \ . \tag{14}$$

Thus, hydraulic conductivity and diffusivity of the soil profile at depth L can be calculated with (13) and (14) for a wide range of soil-water contents, if the constants a, b, m, and n can be determined. Similarly, K and D can be expressed as functions of h instead of θ when equation (10) is substituted in (11) and 12). For example, hydraulic conductivity as a function of soil water-pressure head is given by

$$K_L(h) = -L\,abm^{-[(b-1)/n]}\,h^{[b-1)/n]} \tag{15}$$

The reliability of (9) and (10) for describing soil-water behavior in the field is readily verified by experimental results. The accuracy of the simplified method is tested by comparisons of conductivities calculated with (15) and (13), with conductivities obtained by the detailed Darcy analysis of transient drainage data and by surface flux and gradient measurements during steady infiltration.

Experimental Procedures

Field infiltration and redistribution data used for this analysis included those from Molokai and Lahaina soil sites used for the work reported in the previous section of this report plus three additional Molokai soil sites located at the Hawaiian Sugar Planters' Association (HSPA) Kunia Substation. Detailed soil descriptions are given in Part II. Infiltration measurement procedures are described in the previous section.

After the water supply was cut off, zero time for redistribution corresponded to the time when water in the inner ring had just disappeared from the ground surface. The soil water-pressure heads during the redistribution period were obtained from the multiple tensiometer readings. The soil-water contents were gravimetrically obtained from soil samples obtained between the inner and the outer rings; duplicate samples were taken to depth L at each sampling time. The time period over which h and θ were measured varied for the different locations. The soil water-pressure head was measured at increasing time intervals throughout the drainage period, from initially every few minutes to daily near the end of the several days of measurement. Soil-water content, on the other hand, was measured less frequently: seven times over a 14-day period at the HSPA sites and only four or five times over a 5- to 8-day period at the other sites. The earliest θ measurement varied between 1 hr (HSPA sites) and 24 hr (other sites).

Results and Discussion

EVALUATION OF EQUATIONS (9) AND (10). The power functions provided an excellent description of the water redistribution data for all seven sites. Results from the regression of (9) and (10) on experimental data for each plot are tabulated in Table 2. The absolute value of the correlation coefficient, r, between regressed and measured results for θ vs. t exceeded 0.95 for all plots, and the standard deviation of the residual, s_θ, is less than 1% of soil-water content by volume. For h vs. t, the absolute value of r is always larger than 0.98, and s_h is less than 4.5 cm of water in all but one case. Thus, for the soils included in this study, equations (9) and (10) are very good empirical equations describing changes of θ and h with time during postinfiltration redistribution of water in the soil profile. The experimental water contents, from which the parameters in (9) were obtained, ranged from field saturation (about 50% water content) to 34% for the HSPA sites, and from about 40 to 34% for the other sites. Pressure values from which the parameters in (10) were obtained ranged from h = -25 cm to h = -250 cm water.

The appropriateness of (9) has been demonstrated also by Libardi et al. (1980) with an analysis of drainage data from six depths of the Panoche soil profile at 20 sites (data of Nielsen, Biggar, and Erh [1973]). Although the Panoche soil (a California Entisol) and the Hawai'i Oxisols included in this study are well drained, the California and Hawai'i soils differ considerably in soil structure, bulk density, and related physical properties. For example, the bulk density in the Panoche profile decreased with depth from

TABLE 2. WATER REDISTRIBUTION PARAMETERS (EQQ. [9], [10]) DETERMINED BY REGRESSION WITH EXPERIMENTAL DATA FROM SEVEN SITES, O'AHU, HAWAI'I

SOIL AND SITE	$\bar{\theta} = at^b$ (eq. [9])				$h = mt^n$ (eq. [10])			
	a	b	r*	s_θ†	m	n	r*	s_h‡
MOLOKAI SOIL								
HSPA A	0.6079	-0.0595	-0.9949	0.0058	-8.5570	0.3259	-0.9986	2.77
B	0.6602	-0.0633	-0.9928	0.0073	-1.1095	0.5505	-0.9903	14.50
C	0.6071	-0.0611	-0.9913	0.0071	-4.8220	0.3807	-0.9967	4.36
OP410E	0.7058	-0.0797	-0.9871	0.0053	-5.8426	0.3718	-0.9996	1.15
W	0.6110	-0.0601	-0.9944	0.0030	-12.1452	0.2761	-0.9990	2.09
LAHAINA SOIL								
OP221E	0.5895	-0.0601	-0.9874	0.0075	-6.6110	0.3555	-0.990	1.75
W	0.7132	-0.0769	-0.9965	0.0028	-8.1103	-.3446	-0.9959	2.94

*Correlation coefficient.
†Standard deviation of residual θ.
‡Standard deviation of residual h.

1.47 g/cm³ at the 30-cm depth to 1.31 g/cm³ at 180 cm (Nielsen, Biggar, and Erh 1973), while the Oxisols in our study evidenced an increase in bulk density with depth, from 1.00 g/cm³ at the surface to 1.30 g/cm³ at a depth of 52 cm. Thus, equation (9) appears to be applicable to a wide range of well-drained soils.

DETERMINATION OF θ AT "FIELD SATURATION" AND CALCULATION OF K AND D. Hydraulic conductivity and diffusivity of the soil profile can be calculated either from equations (11) and (12) or from (13) and (14). No matter which set of equations is used for calculating K and D, either the water content θ or the appropriate t has to be determined for the condition of field saturation. Unfortunately, when t is equal to zero, K in (11) is undefined because b always has a negative value. An arbitrary choice of a small value of t to satisfy (11) near zero time was considered as unsatisfactory.

On the other hand, if (13) and (14) are used, θ instead of t has to be determined. At the fully saturated condition, θ should be equal to the total porosity of the soil. However, reports from numerous studies state that even though a soil is submerged in water, the soil is not fully saturated due to air entrapment. For example, Jackson (1963) found that for loam soils only 79 to 91% of total porosity was fillable by water. In a previous field study* at a site near our HSPA site, soil water contents were measured by neutron probe at the time when the ponded water had just disappeared from the ground surface. The results showed saturation percentages of 75 to 86% with a median value of about 85%—a saturation percentage very close to the average value obtained by Jackson. Thus, 85% of total porosity is used as an estimate of the field-saturated, soil-water content in this study.

Since in (13) and (14) field saturation can be thus determined, $K(\theta)$ and $D(\theta)$ for any soil-water content of interest can be calculated by the equations. For using equation (15), the air-entry pressure h_a corresponding to field saturation θ_s can be obtained by solving (10) for the t value that gives θ_s when inserted in (9).

EVALUATION OF SIMPLIFIED METHOD. A comparison of estimated and measured values is provided in Figure 29. The diagonal line represents a one-to-one correspondence between calculated and measured K values. Vertical deviations from the diagonal line indicate the extent to which the simplified method yielded conductivity values which approached the measured values. Conductivity values calculated with equation (15), for OP221 and OP410, range from about 5×10^{-5} cm/min (corresponding to a pressure head of about -170 cm water) to about 3×10^{-2} cm/min (corresponding to a pressure head of about -30 cm water). The detailed analysis was not accomplished for the HSPA sites, so no $K(h)$ comparisons were possible for these sites. Saturated onductivities calculated with equation (13) for all seven sites are noted by K_s in Figure 29, these values are compared with measured conductivities obtained from surface flux and gradient measurements near the end of the infiltration measurements.

The comparisons in Figure 29 indicate that the simplified method was quite satisfactory for the soils included in this study despite the existence of nonunit gradients in some cases. The reasonably good prediction of conductivity at field saturation (Fig. 29) encourages the use of eq. (13) for the entire water content range between field saturation and water contents corresponding to about h = -170 cm water.

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*Green, Rao, and Balasubramanian (1972): unpublished data.

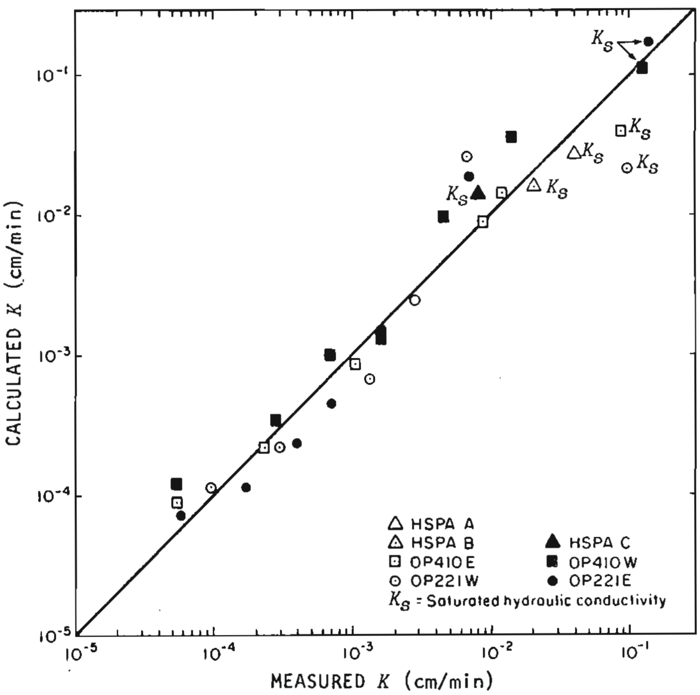


Figure 29. Hydraulic conductivies calculated by simplified method compared with measured conductivities at seven sites

Use of tensiometers in this study allowed calculation of $D(\theta)$ and $K(\theta)$ and also the evaluation of the simplified method by comparison of results with measurements of conductivity obtained by the standard detailed analysis. For field measurement of $K(\theta)$, however, tensiometers are not needed as only equations (9) and (13) are used.

Summary

A simplified method was sought to calculate hydraulic conductivity $K(\theta)$ and diffusivity $D(\theta)$ of the plow layer of well-drained agricultural soils from in situ measurements of infiltration and redistribution. Simple equations for calculating $K(\theta)$ and $D(\theta)$ were derived with the assumption of unit hydraulic gradient, following the approach of Nielsen, Biggar, and Erh (1973); the derivation employed power functions to describe the change of water content, θ, and pressure head h, with time during the redistribution period. For well-drained soils the resulting equations for $K(\theta)$ and $D(\theta)$ are expected to be applicable for the θ-range in which the power functions adequately represent redistribution data. There was some uncertainty, however, as to the validity of the assumption of unit hydraulic gradient—especially for tilled surface soils with less permeable B horizons—and the extent to which departures from unit gradient would diminish the accuracy of the simplified method. Measured transient pressure profiles during drainage showed that the total hydraulic gradient varied from extremes of about 0.3 in the early stage of drainage to 2.0 after several days; unit gradient was most frequently approached in the intermediate stages of drainage. Thus, $K(\theta)$ and $D(\theta)$ values obtained with the simplified method should be most reliable at intermediate water contents; this expectation was confirmed by comparison of $K(\theta)$ values from the simplified method with unsaturated K values measured by the detailed Darcy method. The simplified method appears to provide a practical means of characterizing $K(\theta)$ and $D(\theta)$ for the A horizon of well-drained soils, even when the surface is tilled and the conductivity at high-water contents decreases with depth. Such methods are needed to adequately characterize large areas for which hydrologic models, which require $K(\theta)$ and $D(\theta)$ functions, are to be applied.

FIELD-MEASURED SORPTIVITY APPLICATION FOR INFILTRATION PREDICTION

In watershed simulation, a major hindrance in predicting runoff from a watershed is the uncertainty in characterizing infiltration. The difficulty of predicting infiltration is mainly due to the variation of infiltration-related soil physical properties from site to site in the field. Thus, the use of analytical or numerical solutions of the theoretical flow equation for unsaturated conditions to describe water infiltration (Green, Hanks, and Larson 1964) is unsatisfactory for watershed prediction because of the difficulty of adequately characterizing the hydraulic conductivity-water content, $K(\theta)$, and pressure-water content, $h(\theta)$, which are functions needed for such calculations. These hydraulic properties are difficult and expensive to measure on field soils (Klute 1973) at even a few locations, let alone at the large number of locations that would be required to adequately characterize the spatial variability in $K(\theta)$ and $h(\theta)$ that is anticipated in most watersheds.

To simplify the infiltration prediction problem, researchers have introduced a number of simple algebraic infiltration equations (Green and Ampt 1911; Kostiakov 1932, Horton 1940; Philip 1957; Holtan 1961; Talsma and Parlange 1972; Collis-George 1977). These simple algebraic equations are either physically based or empirical. To apply these equations, one must first determine the equations parameters. Some of the physically based

[1]This section is abstracted from a paper by Chong and Green (1979).

parameters can be measured in the field, e.g., the saturated hydraulic conductivity, K_s, in the Green-Ampt equation, or the sorptivity, S, in the Philip and the Talsma-Parlange equations. But most of the empirical equation parameters are determined from a regression of the infiltration equation on the experimental data. In general, the regressed parameters are good only for the particular set of data from which they originated and cannot be used with confidence for other cases. This implies that most of the simple algebraic equations are not adequate for infiltration prediction on a range of soils for which both spatial and temporal variability will be encountered.

In short, in watershed infiltration analysis, a reasonably accurate prediction equation that can accommodate variability is needed. The method of determining equation parameters should also be simple and relatively inexpensive, and the parameters should be sufficiently sensitive to represent significant variations in infiltration associated with soil differences in a watershed.

The Talsma-Parlange equation, applicable for the case of immediate ponding on the soil surface, is used to predict infiltration. The parameters S and K_s in the equation were directly obtained in the field. The nature of the statistical distribution of the measured sorptivities is tested by the Kolmogorov-Smirnov method. Because sorptivity varies with antecedent water content, θ_n, a linear approximation of the S-θ_n relation is assumed for infiltration prediction. The method was tested on the Molokai (Typic Torrox) and Lahaina (Tropeptic Haplustox) soil series of the Oxisols order at seven soil locations with 26 infiltration measurements. All experimental sites are located on cultivated soils on the island of O'ahu, Hawai'i.

Description of a Theory-Based Equation

Much attention has been given to the Philip two-term equation,

$$I = St^{\frac{1}{2}} + At ,$$

in which cumulative infiltration I, is related to time, t, by two parameters, the sorptivity, S, and the coefficient A. Sorptivity is the single most important quantity governing the early portion of infiltration (Philip

1957); it varies for different soils as it depends on the structure and the pore-size distribution of the soil, and is also influenced by antecedent water content (Bouwer 1978). A problem in using Philip's equation is the uncertainty in estimation of the parameter A (Youngs 1968; Swartzenruber and Youngs 1974; Parlange 1975).

An infiltration equation which is similar to the Philip equation was recently developed and tested in a series of studies by Talsma and Parlange (1972) and Parlange (1971, 1975, 1977). This new equation will be subsequently referred to as the Talsma-Parlange equation. Cumulative infiltration is given by

$$I = St^{\frac{1}{2}} + \frac{1}{3}K_s t + \frac{1}{9}\frac{K_s^2}{S}t^{\frac{3}{2}} \tag{16}$$

in which I is the cumulative infiltration (in m/s) corresponding to $t(s)$ in a soil having a sorptivity S (m/s$^{\frac{1}{2}}$), at a specified antecedent soil-water content, and hydraulic conductivity K_s (m/s) at water saturation. The corresponding infiltration rate, i, is given as

$$i = \frac{1}{2}St^{-\frac{1}{2}} + \frac{1}{3}K_s + \frac{1}{6}\frac{K_s^2}{S}t^{\frac{1}{2}} . \tag{17}$$

Equation (16) is the working equation for calculating cumulative infiltration in this study. The similarity between equation (16) and the time expansion solution by Philip (1957) is notable. Even though the Talsma-Parlange equation contains three terms, it requires only two parameters which characterize the soil, the sorptivity, S, and the saturated hydraulic conductivity, K_s.

Equations (16) and (17) thus are promising equations for practical infiltration prediction. They are physically based, having physically meaningful parameters, S and K_s, which can be independently measured in the field with relative ease. The equations appear to predict infiltration with sufficient accuracy for moderate times in most practical cases (Talsma and Parlange 1972). Equation (16) has two principal advantages over the Philip two-term equation: (a) it avoids the need for $K(\theta)$ and $D(\theta)$, which are required to calculate the parameter A in the Philip equation, and (b) it appears to be more accurate for longer times than the Philip equation.

Procedures

At each experimental site the field measurements included cumulative infiltration versus time and also independent measures of sorptivity within a few meters of the infiltration site. Measured cumulative infiltration data were used to assess the accuracy of infiltration predictions with equation (16) and also provided the estimate of K_s needed for each site. All sites were in sugarcane fields with tilled Ap horizons 0.30 to 0.40 m deep.

INFILTRATION MEASUREMENT AND ESTIMATION OF K_s. Infiltration measurements were conducted with a double-ring infiltrometer in a manner similar to that described by Ahuja, El-Swaify, and Rahman (1976), but with only a 0.02-m head maintained by controlling water flow to the inner and outer rings. The rings were inserted 0.15 to 0.20 m into the soil. Cumulative infiltration over time was measured in the 0.30 m diameter inner ring while a buffer zone was provided by the 1.20 m outer ring. Initial wetting of the profile was accomplished with an infiltration run on dry soil (dry-run), after which the soil surface was covered and insulated to reduce evaporation during a 3-day redistribution period. Subsequently, infiltration measurements were accomplished on the moist soil (wet-run). Measurements were continued until an apparent steady intake rate was sustained for about 1 hr. The total period of infiltration was generally 3 to 5 hr.

The apparent steady infiltration rate was used as an estimate of the saturated conductivity, K_s. The rationale for this approximation is given in the Results and Discussion section.

FIELD SORPTIVITY MEASUREMENT. At six of the seven soil locations, infiltration sites were duplicated, and duplicate sorptivity measurements were made near each infiltration measurement site. A more thorough evaluation of sorptivity variation was conducted on the Molokai soil at the Hawaiian Sugar Planters' Experiment Station at Kunia. Infiltration was measured at three sites about 10 m apart. Each infiltration site was located in the center of a 5.4-m × 5.4-m area (29.16 m^2) which was divided into nine square subareas, each having an area 1.8 m × 1.8 m (3.24 m^2). A sorptivity measurement was taken at the center of each of the eight squares surrounding the infiltration rings.

Sorptivity was measured essentially as described by Talsma (1969). The method is based on the assumption that, for the very early portion of infiltration, the second term of the right-hand side of Philip's two-parameter equation can be neglected. Therefore, if one plots the early portion of experimental cumulative infiltration versus the square root of the elapsed time on normal scale paper, the sorptivity for the existing antecedent soil conditions can be obtained from the slope of the curve. Since this method is simple and rapid, many measurements can be made with limited funds and labor for watershed characterization.

The site preparation for sorptivity measurement was the same as that for infiltration measurement: it involved leveling the soil surface, followed by shallow hoeing and final leveling. The single infiltrometer ring (0.30-m diam) was inserted about 0.15 m into the soil. The soil was prewetted 4 to 5 days before sorptivity was measured. Just prior to the sorptivity measurement, a composite gravimetric antecedent soil-water sample was obtained from the soil (to about 0.06 m deep) within the sorptivity ring with a cork borer (0.015-m diam). After sampling, soil from outside the ring was placed in the hole and compacted.

A porous, fibrous packing material was placed on a portion of the soil surface to reduce disturbance of the soil when water was rapidly applied into the ring at zero time. A known volume of water (0.0016 m^3) was then ponded in the ring, giving an initial water depth of about 0.02 m. The subsequent drop in water level was read from a graduated capillary tubing which was inclined at a 9.5° angle to the water surface, giving a six-fold amplification in depth changes with time. The time corresponding to each water-level reading was recorded using a hand-carried digital electronic stopwatch. Normally, the measurement required two people; however, if a tape recorder is used, one person can handle the entire operation.

The soil sample for bulk density and particle density was taken within the sorptivity plot after completion of the measurement. The initial volumetric soil water content for the sorptivity measurement was calculated from the measured gravimetric water content and bulk density. The particle density was determined by the pycnometer method described by Blake (1965).

APPROXIMATION OF SORPTIVITY-WATER CONTENT RELATION. A single, field sorptivity measurement as described above results in a single value of S at a given antecedent soil water content, θ_n. For other antecedent water contents, corresponding values of S must be obtained either by measurement or by some method of estimation. Unstable soil, such as in a recently tilled surface layer, tends to consolidate with repeated application of water;

thus, measurements of sorptivity at different soil water contents within the same infiltration ring can seldom be accomplished without confounding the effects of soil structure and soil water content on sorptivity. It would be desirable, therefore, to estimate the entire $S(\theta_n)$ relationship from a single field measurement. In a related study, Chong (1979) found that the $S(\theta_n)$ relation was almost linear in several cases. This suggested approximating $S(\theta_n)$ by a linear function, i.e., by passing a straight line from $S = 0$ at saturation through the S value measured in the field at the existing antecedent water content. The sorptivity function derived in this way can then be used to obtain an estimate of S at any antecedent water content for the soil on which the sorptivity was measured, assuming that the pore-size distribution of the soil is essentially invariant with changes in water content. A similar linear approximation was previously used by Chapman (1970), who assumed that the sorptivity at a given water content was a function of the soil-water deficit and the sorptivity at zero water content.

STATISTICAL ANALYSIS. To determine a representative value for a given hydrological parameter in a large watershed, it is necessary to first determine the form of the statistical distribution of the parameter. For example, if the parameter observations are normally distributed, an arithmetic mean is used. On the other hand, a geometric mean is suggested if the parameter observations are from a log-normal population. In this study we assumed that K_s was log-normally distributed; however, the distribution of S data was tested as there are no published studies establishing the nature of S distribution.

There are a number of equations which can be used for calculating the empirical cumulative distribution function (Chow 1964; Haan 1977). In this study, the Kolmogorov-Smirnov test was employed for a goodness-of-fit test, and the California method was used to calculate the sample cumulative distribution (Benjamin and Cornell 1970). Detailed procedures for the Kolmogorov-Smirnov test are given by Lilliefors (1967). A 5% level of significance was used in our tests.

Results and Discussion

CALCULATION OF SORPTIVITY AND PREDICTION OF INFILTRATION. A method of obtaining S versus θ_n by linear approximation has been described and an example is shown in Figure 30. In this case, eight sorptivity measurements

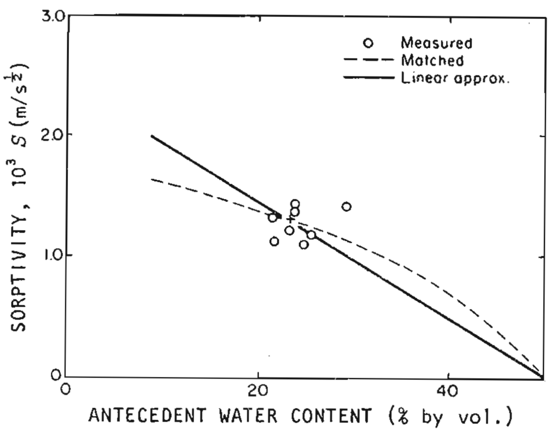


Figure 30. Sorptivity as function of antecedent water content

were made at one site, and the geometric mean of sorptivities and the arithmetic mean of water contents were used to obtain the linear approximation of $S(\theta_n)$ shown by the solid line. For comparison, another $S(\theta_n)$ curve was calculated from the water flow theory using $K(\theta)$ and $D(\theta)$ for the Molokai soil from field soil-water redistribution measurements. The computed $S(\theta_n)$ function was matched to the measured value to give the dashed curve in Figure 30 (Chong 1979). The comparison suggests that the linear approximation can be expected to yield values of S which are too large at low water contents and too small at water contents above that of the measured S; however, the error in S introduced by the approximation does not appear large relative to the sorptivity measurement error.

In the calculation of infiltration, K_s in equation (16) is approximated by the geometric mean value of field-measured "steady" flux, i_s, which is essentially the field-measured "steady" infiltration rate. To obtain K_s = i_s requires the assumption of unit hydraulic gradient with depth in the profile during the infiltration measurement. There are two reasons for using the "steady" flux to approximate K_s. First, because a determination of the true value of K_s requires a measurement of soil-water pressure during infiltration with one or more tensiometers installed at each site, it is more convenient and economical, especially in characterizing an entire watershed, if tensiometers can be eliminated in the method. Second, the maximum difference between K_s and i_s for our field measurements was about two-fold (Chong 1979). The error thus contributed to the calculated cumulative infiltration due to using i_s in place of K_s in the third term of the right-hand side of equation (16) is essentially zero (squaring of K_s reduces the error). In the second term of the right-hand side of equation (16), the error associated with the estimate of K_s is also relatively small, but depends more upon the magnitude of t. Using the HSPA A site as an example, i_s and S values used to calculate I are respectively 3.133×10^{-6} m/s and

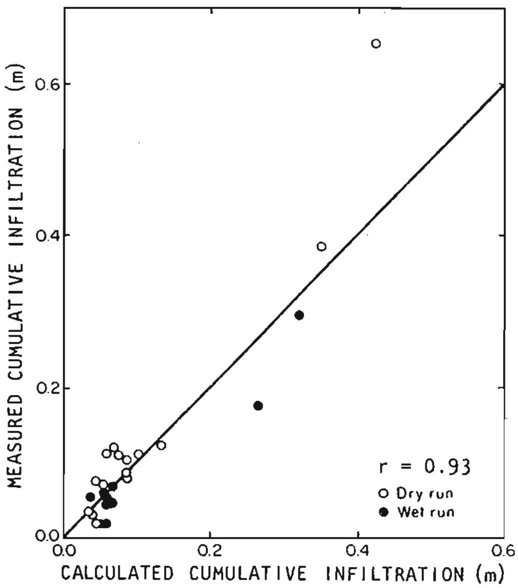


Figure 31. Comparison of cumulative infiltration calculated by Talsma-Parlange equation and measured in the field

1.356×10^{-3} m/s . If is calculated using $K_s = i_s$, $I = 0.0853$ m of water when t = 3600 s, and if $K_s = 2i_s$, I = 0.0896 m. Therefore, the difference between the two computed results is about 5%, which constitutes a reasonable small error for a field method.

Figure 31 shows a comparison of calculated (eq. [16]) and measured cumulative infiltration for elapsed times of 300 s to the time, t, when the wetting front is estimated to have reached the B horizon of the profile. The horizontal distance of a data point from the diagonal line is an indication of the absolute error in calculated cumulative infiltration for a field site. Cumulative infiltration results predicted by equation (16) are generally good, although a few predictions exhibit considerable error. The relative error in each calculated value can be obtained by dividing the absolute difference between calculated and measured values for each site by the measured value; expressed as percentages, the relative errors ranged from 4.7 to 175% with a median of 19% and mean of 37%. The three lowest measured cumulative infiltration values had much higher percentage errors than all other values (130, 141, 176%); therefore, if these three sites are omitted the mean error is 23%. The calculated and measured values are reasonably well correlated (r = 0.93).

While the prediction method examined in the present paper may sacrifice accuracy in relation to more detailed methods, it is extremely simple, requiring only two parameters which are easily measured in the field. The steady state infiltration measurement, which is used to estimate the saturated hydraulic conductivity, is more difficult to measure than sorptivity, and thus would not be characterized at as many sites in a watershed as the sorptivity. In most field situations, infiltration rates for storms of relatively short duration (<3 600 s) will be mroe sensitive to variations in S than to variations in K_s, so that the greater ease of measuring S is advantageous. A single sorptivity measurement, including site preparation on tilled soils, takes less than 1 800 s. The method should allow infiltration prediction at a greater number of sites in a watershed and thus provide a means of characterizing spatial variability of infiltration.

Summary and Conclusion

The sorptivity of cultivated surface soils was measured using Talsma's method. The statistical distribution of field-measured sorptivity in a large area was found to be log-normal by the Kolmogorov-Smirnov test. A linear relation between S and θ was assumed to predict infiltration, and was obtained from the geometric mean of the field-measured sorptivity and the sorptivity at saturation (assumed to be zero). The infiltration equation of Talsma and Parlange, which requires only the $S(\theta_n)$ relation and saturated hydraulic conductivity, was used to predict infiltration.

The method was tested on two soil series at seven soil locations, for a total of 26 infiltration measurements, including both "dry" and "wet" antecedent conditions. Predictions of cumulative infiltration by this method were reasonably good, considering the simplicity of the method. The method proposed here should provide a practical means of predicting infiltration in field soils, but will require testing on other soils to determine the appropriateness of the linear approximation of $S(\theta_n)$.

II. HYDROLOGIC PROPERTIES OF THREE OXISOLS OF THE WAHIAWĀ PLATEAU, O'AHU, HAWAI'I

FIELD-MEASURED PROPERTIES AND RELATED DERIVED FUNCTIONS

Several operations were performed over a period of several days at each of the field sites shown on the map in Figure 1. The approximate sequence of operations was as follows:

Day	Sequence of Operations
1	Preparation of soil surface for two or more replicate measurements of infiltration
1	Installation of infiltration rings and final leveling of soil surface within rings
1	Preparation of soil surface and installation of sorptivity rings near each infiltration ring
1 or 2	Sampling of soil for determination of antecedent water content at infiltration and sorptivity measurement sites
2	Measurement of water infiltration at existing antecedent soil water content, the dry run
2	Measurement of sorptivity near infiltration sites for dry antecedent conditions while infiltration measurements were proceeding
3	Installation of multiple tensiometers in inner and outer rings of each infiltrometer 1 day after first infiltration measurements
5	Sampling of soil for antecedent water content at infiltration and sorptivity sites 3 days after initial infiltration measurements
5	Measurement of infiltration for wet antecedent condition and simultaneous monitoring of soil water pressure at various depths over time
5	Measurement of sorptivity with wet antecedent condition
5 to 10-12	Measurements of soil water content and soil water pressure at increasing time intervals throughout 5 to 7 day water redistribution period
10-12	Removal of infiltrometer, tensiometers, and sorptivity rings from site; sampling of soil cores from three depths at each site
	Description of soil profile at each infiltration site, using pits dug during core sampling.

In Part II, the methods used are either described herein or referenced in the literature, and measured or derived values of various hydrologic properties of soils are presented with only cursory discussion of the data.

Cumulative Infiltration and Infiltration Rate

MATERIALS AND METHODS. The determination of infiltration rate with elapsed time was not required to meet the objectives of this study; only the steady infiltration rate was needed. An extension of this study, however, involved the prediction of infiltration rates over time by various methods, and the data obtained in the experiments reported here provided a means of evaluating predictions of infiltration for various sites.

Infiltration with time was measured for the ponded case, with a constant head being maintained in the inner and outer rings of a double-ring infiltrometer by control of water flow into each ring. The inner and outer ring diameters were respectively 30 cm and 120 cm. The head was maintained at 2 ± 0.2 cm (approximately) on most measurement sites by manually adjusting the inlet valve from the reservoir. Steel pins, 0.3 cm in diameter and 25 cm long, were vertically inserted into the soil prior to application of water, with only the top 2 cm extending above the leveled soil surface. Such pins in both the inner- and outer-ring areas provided a reference for maintenance of a constant head of water. Only on site W3 was water ponded to a depth of 7 cm, with the inflow being controlled by float valves. The experimental setup at site W3 was essentially that described by Ahuja, El-Swaify, and Rahman (1976), with 30 cm diameter tanks supplying water to the rings. At the other sites, 15.2 cm diameter reservoirs supplied water to the inner ring, providing improved sensitivity in the measurement of water intake by soil in the inner ring. A glass sight tube attached to the side of the reservoir and connected to the inside of the reservoir at the bottom provided a means of measuring the level of the water surface in the reservoir at different times. Water was supplied to the outer rings from 0.21-m^3 (55-gal) drums; the large diameter of the drums was satisfactory in that accurate measurements of infiltration were not required in the outer buffer ring. Water level readings in the supply reservoir were taken every one to two minutes for the first 10 min if the water intake was sufficiently rapid to warrant such frequent readings. When infiltration approached a steady rate the time interval between readings was about 30 min. During the early period of infiltration, measurements required one person to read water levels on both reservoirs and another person to read the elapsed time on an electronic stopwatch and to record the data. The total period of infiltration measurement was usually two to four hours, depending on the time required for approximate steady infiltration to be achieved.

Infiltration was measured for both dry and wet antecedent conditions, the dry condition being the soil water content profile existing in the field when the infiltration rings were first installed, and the wet condition being the water content profile about three days following the dry run.

A computer program was developed to calculate cumulative infiltration, I, at each measurement time, t, for both inner and outer rings to provide measured I(t) curves. Another program accomplished least-squares analysis on each set of measured data to determine the best-fit equation for each set. The steady infiltration rate was graphically determined from the slope of the linear portion of the measured I(t) curve.

RESULTS. Cumulative infiltration data for the inner ring were fit with the five equations shown at the bottom of Table 3. The equation having the best fit (lowest residual sum of squares) for each set of data was used to represent the measured data; the selected equation number and the appropriate coefficients are given in Table 3. The cubic polynomial and power function equations gave the best results. The total time of infiltration, time to approximate steady infiltration, and cumulative infiltration at one hour elapsed time (wet run only) are also shown in Table 3. About one to three hours were required to achieve steady infiltration on all three soils. The cumulative infiltration in one hour was highly variable for the Lahaina soil. It is of interest to note that the L3-1 and L3-2 sites, which had the lowest cumulative infiltration for the Lahaina locations, were located in an area mapped Lahaina in the soil survey, but classified Molokai in this study (see App. A, L3 site). Thus, the lower infiltration rates for the L3 sites are consistent with the actual classification of this soil location as Molokai, since the Molokai $I_{1\ hr}$ values were generally lower than those for the L1 and L2 locations of the Lahaina soil.

Steady infiltration infiltration rates for the dry and wet antecedent conditions at each site are given in Table 4. The ratios of steady rates for the dry and wet runs range from 0.9 to 9.2, with the mean ratio for the Lahaina, Molokai and Wahiawa soils being respectively 2.1, 2.0, and 3.5.

TABLE 3. COEFFICIENTS OF BEST-FIT EQUATIONS FOR MEASURED CUMULATIVE-INFILTRATION VS. TIME, AND INFILTRATION DATA

SITE	DRY OR WET RUN	EQ. OF BEST FIT*	COEFFICIENTS† B(1)	B(2)	B(3)	B(4)	TOTAL INFIL-TRATION TIME (hr)	TIME TO APPROX. STEADY INFIL-TRATION	$I_{1\ hr}$† (cm)
L1-1	D	3	0.731	31.23	-3.553	0.610	2.67	1.12	-----
	W	3	-0.013	13.44	-1.038	0.125	4.33	1.58	12.54
L1-2	D	3	0.849	53.52	-8.112	1.106	3.00	1.73	-----
	W	3	1.339	23.76	-2.126	0.288	3.03	1.42	23.26
L2-1	D	4	17.62	0.743	-----	-----	4.25	3.51	----
	W	3	0.372	10.83	-2.274	0.368	3.17	1.53	9.30
L2-2	D	3	0.525	15.22	-3.617	0.477	3.83	2.06	----
	W	3	0.443	8.213	-2.021	0.275	3.75	2.00	6.91
L3-1	D	3	0.965	5.549	-0.767	0.081	4.17	2.37	----
	W	3	-0.255	2.358	-0.176	0.015	6.25	2.64	2.45
L3-2	D	4	5.803	0.485	-----	-----	3.50	3.19	----
	W	3	-0.113	1.419	-0.178	0.017	4.75	2.54	1.37
M1-1	D	4	12.08	0.518	-----	-----	4.75	4.28	----
	W	3	0.652	6.246	-1.052	0.101	5.50	2.83	5.95
M1-2	D	4	7.187	0.419	-----	-----	2.33	2.15	----
	W	3	-0.155	2.382	-0.711	0.121	2.33	1.60	1.64
M2-1	D	4	11.23	0.496	-----	-----	4.00	3.63	----
	W	4	4.458	0.386	-----	-----	3.75	3.45	4.84
M2-2	D	3	1.164	10.16	-1.454	0.225	3.83	1.43	----
	W	3	0.997	3.887	-0.582	0.071	4.58	1.99	4.37
M3-1	D	3	0.517	14.35	-2.264	0.245	4.25	2.36	----
	W	3	0.218	7.504	-1.252	0.128	5.08	2.60	6.60
M3-2	D	3	0.551	19.85	-4.325	0.440	4.58	2.81	----
	W	3	0.231	10.52	-2.746	0.471	1.83	1.51	8.48
M4-1	D	4	10.26	0.685	-----	-----	4.52	3.52	----
	W	3	1.387	6.386	-1.641	0.208	4.80	0.87	6.34
M4-2	D	4	5.069	0.550	-----	-----	3.98	3.04	----
	W	3	1.050	3.182	-0.756	0.085	5.20	1.18	3.56
M4-3	D	3	0.254	3.312	-1.110	0.180	3.42	1.09	----
	W	3	1.143	6.878	-2.937	0.388	4.40	0.92	5.47
W1-1	D	3	1.857	2.676	-4.939	0.546	3.95	2.41	----
	W	3	1.056	6.403	-0.728	0.060	5.72	3.03	6.79
W1-2	D	3	1.752	26.94	-4.876	0.824	2.75	1.38	----
	W	4	4.681	0.604	-----	-----	3.33	2.95	5.28
W2-1	D	4	35.53	0.530	-----	-----	0.50	0.45	-----
	W	3	3.166	16.91	-6.431	1.426	3.00	1.21	15.07
W2-2	D	3	1.574	122.1	-199.4	153.0	0.68	0.36	-----
	W	4	16.27	0.27	-----	-----	1.92	1.74	16.72
W3-1	D	3	4.621	3.776	-0.362	0.027	8.42	3.37	----
	W	3	1.423	4.110	-0.398	0.029	8.08	3.47	5.16
W3-2	D	3	3.843	15.05	-4.290	0.714	3.50	1.61	----
	W	3	4.281	3.914	-0.293	0.024	7.50	2.64	7.93
	W	3	3.394	5.044	-0.573	0.036	10.00	4.41	7.90

TABLE 3.—*Continued*

SITE	DRY OR WET RUN	EQ. OF BEST FIT*	COEFFICIENTS† B(1)	B(2)	B(3)	B(4)	TOTAL INFIL-TRATION TIME (hr)	TIME TO APPROX. STEADY INFIL-TRATION	$I_{1\,hr}$‡ (cm)
W3-3	D	3	1.229	19.59	-3.682	0.590	2.92	1.47	----
	W	3	3.504	5.687	-1.470	0.331	2.92	1.06	8.05
	W	4	8.310	0.516	-----	-----	2.67	2.41	8.83
W3-4	D	4	10.03	0.300	-----	-----	4.00	3.74	----
	W	4	10.01	0.274	-----	-----	3.50	3.28	10.28

*Eq. 1: $I = B(1) + [B(2)]t$

Eq. 2: $I = B(1) + [B(2)]t + [B(3)]t^2$

Eq. 3: $I = B(1) + [B(2)]t + [B(3)]t^2 + [B(4)]t^3$

Eq. 4: $I = [B(1)]t^{[B(2)]}$

Eq. 5: $I = [B(1)]e^{[B(2)]t}$

†For I expressed in cm and t in hr.

‡Cumulative infiltration in 1 hr (wet run), where I = cumulative infiltration, cm
t = time, hr.

TABLE 4. STEADY INFILTRATION RATES FOR DRY AND WET ANTECEDENT CONDITIONS

SOIL SERIES	SITE	STEADY INFILTRATION RATE (cm/hr) Dry	Wet	DRY:WET RATIO
Lahaina	L1-1	30.8	10.9	2.8
	L1-2	33.9	18.6	1.8
	L2-1	10.0	6.3	1.6
	L2-2	6.7	3.5	1.9
	L3-1	3.5	1.6	2.2
	L3-2	1.8	0.8	2.2
Molokai	M1-1	3.6	2.8	1.3
	M1-2	2.7	1.1	2.4
	M2-1	3.9	1.5	2.6
	M2-2	6.8	2.4	2.8
	M3-1	7.0	3.5	2.0
	M3-2	6.2	5.4	1.1
	M4-1	5.3	2.6	2.0
	M4-2	2.1	1.2	1.8
	M4-3	1.2	0.6	2.0
Wahiawa	W1-1	12.5	3.5	3.6
	W1-2	17.5	1.9	9.2
	W2-1	30.0	8.3	3.6
	W2-2	38.5	8.5	4.5
	W3-1	2.3	2.5	0.9
	W3-2	7.3	2.8	2.6
	W3-3	12.2	4.0	3.0
	W3-4	2.0	2.2	0.9

It is likely that the consistently lower steady rate for the wet antecedent condition is due to soil settling following the initial infiltration and subsequent drainage of the tilled soil.

The results of statistical analyses of infiltration data are presented on pages 58 to 66.

Hydraulic Conductivity of Unsaturated Soil

This section describes the method and results of determining the in situ unsaturated hydraulic conductivity, $K(\theta)$ or $K(h)$, of the field sites by the rigorous detailed analysis of $h(z, t)$ data taken during the post-infiltration drainage process. These results were used to evaluate the simplified methods described in Part I.

MATERIALS AND METHODS. The basis for determining the $K(\theta)$ or $K(h)$ was the integrated form of the Richards equation of unsaturated flow, similar to equations (3) or (4):

$$\frac{\partial}{\partial t}\int_0^{z_1} \theta \, dz = -K\left(-\frac{\partial h}{\partial z} + 1\right)_{z = z_1} .$$

The soil water pressure gradient, $\partial h/\partial z$, at any given time, t, and position, z_1, was computed from the measured tensiometric data with depth and time. A least-squares cubic spline was fitted to the suction-depth data for a given time to interpolate between the measured depths and to obtain slopes. The number and position of knots in the cubic spline were adjusted to obtain a smooth curve and to avoid getting the hydraulic gradients, $-\partial h/\partial z + 1$, that were negative at some points because of local fluctuations in the shape of the curve. In some cases, the random scatter in the experimental data was such that it was difficult to get a good fit to the data and also avoid all the local fluctuations.

The soil-water contents, $\theta(z, t)$, required for computing the left-hand-side term in the above equation were obtained from the fitted $h(z, t)$ data by using the soil water retention functions $\theta(h, z)$ measured on undisturbed soil cores in the laboratory. The $\theta(z)$ at any given time was calculated at a z interval of 5 cm, and the integral $\int_0^{z_1} \theta \, dz$ was determined by the trapezoidal rule. For determining the slope $\frac{\partial}{\partial t}\int_0^{z_1} \theta \, dz$, a cubic spline fit to the data of $\int_0^{z_1} \theta \, dz$ vs. t was employed.

RESULTS. Calculated hydraulic conductivities over the range of suctions measured during the drainage period, subsequent to steady infiltration, are given for each site in Appendix C. The data listed include, for each depth of measurement, the elapsed time, suction, water content, flux, gradient, and hydraulic conductivity.

Hydraulic Conductivity at Saturation

MATERIALS AND METHODS. When steady infiltration had been established in the wet run, soil water pressures were measured at various depths in the soil profile. The total head difference between two depths divided by the distance between the two depths gives the hydraulic gradient, in cm head per cm distance. The steady infiltration rate (water flux at field saturation), as given in Table 4, divided by the gradient gives the hydraulic conductivity at saturation by the Darcy equation.

RESULTS. Saturated hydraulic conductivity values for the 0- to 30-cm and 30- to 60-cm depths are given in Table 5 for all sites in which steady infiltration was achieved. Conductivities are generally highest in the 0 to 30 cm depth interval, probably because this layer is within the tilled Ap horizon while the 30 to 60 cm depth interval extends into the untilled B2

TABLE 5. FIELD-MEASURED HYDRAULIC CONDUCTIVITY AT SATURATION

Site	K_S at Depth Intervals, 0-30 cm (cm/hr)	K_S at Depth Intervals, 30-60 cm (cm/hr)	Site	K_S at Depth Intervals, 0-30 cm (cm/hr)	K_S at Depth Intervals, 30-60 cm (cm/hr)
L1-1	16.0	10.7	M3-1	6.9	3.6
L1-2	22.4	----	M3-2	6.0	6.2
L2-1	9.0	7.7	W1-1	6.9	6.4
L2-2	5.1	3.0	W1-2	3.3	1.7
L3-1	2.0	2.3	W3-1	3.1	2.9
L3-2	0.8	0.8	W3-2	2.6	4.0
M1-1	6.8	1.6	W3-3	4.2	3.6
M1-2	2.6	0.8	W3-4	2.2	2.5
M2-1	1.8	1.2			
M2-2	2.7	2.5			

NOTE: K_S = Hydraulic conductivity at saturation.

horizon. The relatively high hydraulic conductivities at both depths are consistent with the observed rapid drainage of these soils. There is no apparent trend of one soil series having a consistently higher conductivity than another series as the values vary widely within a given series. Statistical analyses are presented in a later section.

Sorptivity

MATERIALS AND METHODS. Field measurements of sorptivity by the method of Talsma (1969) were made at most of the sites listed in Table 1. Duplicate measurements (designated A and B) were taken near each replicate of the buffered-ring infiltration measurement. The procedures are given in Part I, pp. 37 and 38. Measurements were made in the tilled soil at the initial water content of the soil and again about two days later in the same ring on wet soil which had been covered in the interim by plastic. Antecedent gravimetric water contents for each sorptivity measurement were converted to the volumetric water contents by use of bulk density values measured on soil cores from the nearby infiltration measurement sites.

RESULTS. Sorptivity values (S) and associated antecedent water contents are given in Table 6. Since sorptivity is a function of water content (Fig. 30), the variation in S between measurement sites reflects spatial variability and water content effects. Sorptivity decreases with increasing water content so that in most cases lower values were obtained in the second (wet) run than in the initial (dry) run.

LABORATORY-MEASURED PROPERTIES

Determination of soil-water contents, corresponding to field-measured soil-water suctions measured by tensiometers during postinfiltration drainage, required measurement of the water content-suction relationship (retentivity) on soil cores in the laboratory. Profile water contents at various times were required for calculation of hydraulic conductivity of unsaturated soil from field drainage data as described on p. 48. Core measurements also allowed characterization of bulk density, total porosity, macroporosity, and in some cases, saturated conductivity. Similar information on other Hawai'i soils was presented by Green and Guernsey (1981).

TABLE 6. FIELD-MEASURED SORPTIVITY ON TILLED Ap HORIZONS OF THREE OXISOLS FOR INITIAL (DRY) AND SUBSEQUENT (WET) CONDITIONS

SITE	DUPLICATE MEASUREMENTS	INITIAL (DRY) RUN Water Content (% by vol.)	INITIAL (DRY) RUN Sorptivity ($cm/min^{\frac{1}{2}}$)	SECOND (WET) RUN Water Content (% by vol.)	SECOND (WET) RUN Sorptivity ($cm/min^{\frac{1}{2}}$)
L1-1	A	20.2	3.6	31.0	4.0
	B	20.2	2.9	27.2	2.9
L1-2	A	19.0	4.5	31.0	3.2
	B	20.7	5.5	33.7	3.3
L2-1	A	18.2	2.4	30.0	1.2
	B	18.6	1.9	30.5	1.2
L2-2	A	13.2	1.0	28.8	0.41
	B	14.0	0.7	31.4	0.57
L3-1	A	7.3	1.2	32.1	0.52
	B	7.4	1.0	30.9	0.41
L3-2	A	7.3	1.3	28.0	0.43
	B	7.6	1.5	39.2	0.40
M2-1	A	11.7	2.3	28.6	1.0
M2-2	A	10.1	1.6	32.9	1.1
M3-1	A	20.5	1.4	30.3	1.4
	B	20.5	1.4	31.2	1.4
M3-2	A	10.3	1.3	28.8	1.4
	B	10.9	1.4	32.5	1.4
W1-1	A	6.5	2.2	29.7	1.3
	B	5.5	2.1	19.2	1.8
W1-2	A	3.4	2.6	27.5	1.0
	B	3.3	1.7	25.0	1.3
W2-1	A	15.3	7.0	----	---
	B	16.4	3.4	----	---

NOTE: See Table 1 for Oxisols and site designations; also, Fig. 1 for site locations.

Materials and Methods

Soil core samples were taken, with little disturbance of field structure, at each of the field sites of infiltration and drainage measurements. Duplicate or triplicate cores were obtained from three depths to represent the Ap1, Ap2, and B2 horizons. The Ap1 and Ap2 layers evidenced visibly distinct structural characteristics. The Ap1 cores were taken near the soil surface, usually from the 1- to 9-cm interval. Ap2 cores were taken from the approximate middle of the Ap2 layer. B-horizon cores were taken so that the top of the core was at least 5 cm below the boundary of the Ap2 and B horizons. Brass rings, 9.84 cm in diameter by 7.62 cm high (volume = 579.5 cm^3) with a wall thickness of 0.16 cm, were attached to a 1.5 cm-long ring which was sharpened on one edge to aid penetration of the core ring into the soil with a minimum compression. The hand-operated sampler developed and used in the course of this study is described elsewhere (Chong, Khan, and Green 1982). Samples were obtained within the area of the outer infiltration ring about two weeks following the final infiltration run, with the soil at field capacity. Core depths and other information about each sampling site are given in Appendix B.

Core samples were wrapped with paraffin film in the field to prevent drying of the soil. About 0.5 mℓ of 37% formaldehyde solution was injected through the film into each end of the core to reduce microbial activity during storage. The cores were then stored at 4°C until used.

Prior to hydraulic conductivity and water retention measurements, excess soil on each end of the soil core was carefully trimmed to provide surfaces which were level with the ends of the brass core ring. Cores were then inserted into one end of a lucite conductivity cell which was constructed to accommodate the brass rings. A rubber "O" ring snuggly held the ring in the unit and provided a water-tight seal between the brass ring and the lucite end-plate. The conductivity cell end units had a plastic disc, 10.4 cm in diameter and drilled with about 100 holes (1-mm diam), as a support for either a thin layer of glass wool or a sheet of porous polyvinylchloride (S-grade PORVIC) against which the soil core was fitted. The soil core was then saturated with 0.25% formaldehyde solution for at least 14 hr prior to fitting the core with another end unit and subsequently attaching the whole cell to a constant-head burette for conductivity measurement.

Hydraulic conductivity was measured with the core at or near saturation, depending on the permeability of the core. Measurements on the highly porous Ap-horizon samples were made with the core saturated with water and with the highly permeable, glass wool-drilled plate combination supporting the soil. Less permeable Ap2 and B2 horizon cores were supported by PORVIC to allow a slight suction to be applied to the column during the conductivity measurement; this was done to remove water in large cracks or at the soil-ring interface, which might give anomalous results and thus not reflect the true average conductivity of the core. Holes (1-mm diam) drilled in the brass ring allowed air to enter the soil core. The air-entry suction of subsoil cores was assumed to exceed the suction imposed at the top and bottom of the vertically oriented core, so that the core was essentially saturated. The inlet was positioned 5.0 cm below the top of the core and the outlet 5.0 cm below the lower surface of the core, giving a unit hydraulic gradient and a maximum suction of 5.0-cm water at the upper and lower core boundaries. Deionized water was passed through the soil for about one hour before actual measurements were started. Three successive measurements, requiring about 20 to 120 min each, were made on each core. The ambient room temperature was 21 ± 1°C.

Following the hydraulic conductivity measurement, each core was fitted into a different cell in which a 1-bar air-entry porous ceramic plate provided support for the core and hydraulic continuity with a hanging water column. The other end of the core was sealed with paraffin film; two pinholes in the film provided air entry to the soil. A hanging water column connected to the outlet of each porous-plate cell allowed equilibration of the soil core with water at suctions of 10-, 25-, 50-, and 100-cm water. Outflow from a soil core after each increase in suction was measured in a 250-mℓ burette which was adjusted up or down as required to establish the desired suction. When cessation of outflow indicated that the soil was in equilibrium with water at the established suction, the suction was increased in two or three steps to the new suction value. After the final equilibration at 100-cm suction, the soil core was removed from the cell and weighed. Subsequently, water retention measurements were made on a standard pressure plate apparatus at pressures of 150-, 250-, 500-, and 1000-cm water. Two 1-bar porous ceramic plates in each chamber accommodated a total of eight soil cores, so that measurements could be simultaneously made on 16 cores in two chambers. Cores were weighed after each equilibration to allow calculation of water loss between each suction value. The soil core was oven dried and weighed after the final pressure step. A computer program was developed to calculate the volumetric water content at each suction value from the combined data obtained with the pressure plate apparatus and the hanging-water-column apparatus.

Bulk density was calculated for each core from the dry soil mass and core volume (579.4 cm^3). A particle density of 2.93 g/cm^3 was assumed to apply to all soils, although particle density measurements were made only on the Molokai soil at location M4. Porosity (ε), in cm^3/cm^3, was calculated from the bulk density (ρ_b) and particle density (ρ_p) by the relation, $\varepsilon = 1 - \rho_b/\rho_p$. The macroporosity ($cm^3/cm^3$) was obtained as the difference between total porosity and the volumetric water content at 50 cm water suction.

Results

Detailed results for each property measured on soil cores are presented in Appendix Table D. Data are organized in groups designated by series, horizon, location, and replicate with two or more observations in each group. A summary of these data (Table 7) includes some statistical information: the number of samples, mean values, standard deviation, minimum and maximum values, and the coefficient of variation (C.V.).

Saturated conductivity (*KS*) data are not included in the summary because reliable data were not obtained on many of the cores. *KS* values which appear valid are included in Appendix Table D. The reliability of *KS* measurements on cores was judged by comparing results on cores with field-measured values given in Table 5 and maximum *K* values in Appendix Table C. The laboratory method failed with many cores for the following reasons: (1) flow units which retained the soil with only perforated plates covered with glass wool (used principally for Ap1 samples) gave values which were generally too high, probably due to boundary flow, and (2) flow units equipped with PORVIC membrane gave conductivities which appeared too low on some samples, probably a result of a contact impedance at the soil-membrane interface, even with a slight desaturation. These difficulties are inherent in the measurement of saturated conductivity on soil cores, demonstrating the need for reliable and simple field methods.

Some generalizations can be made from the summary data in Table 7. The mean values of the various physical properties for a given horizon of three soil series are very similar relative to the variability within a given series, as evidenced by the minimum and maximum values or the standard de-

TABLE 7. SUMMARY OF SOIL PHYSICAL PROPERTIES OF THREE SOIL SERIES ON SOIL CORES

Variable	No. Samples	Mean	Standard Deviation	Minimum Value	Maximum Value	C.V.*
			LAHAINA SERIES			
Ap1 HORIZON						
BULKDEN	12	1.134	0.083	0.990	1.250	7.3
POROSITY	12	0.613	0.028	0.573	0.662	4.6
MACROPOR	12	0.150	0.056	0.067	0.242	37.1
THETA 10†	12	0.531	0.024	0.483	0.572	4.5
THETA 25	12	0.503	0.033	0.445	0.544	6.6
THETA 50	12	0.463	0.044	0.386	0.512	9.6
THETA 100	12	0.410	0.032	0.355	0.448	7.7
THETA 150	12	0.381	0.024	0.342	0.418	6.3
THETA 250	12	0.355	0.022	0.328	0.389	6.2
THETA 500	12	0.330	0.020	0.305	0.362	6.2
THETA 1000	12	0.309	0.021	0.274	0.338	6.7
Ap2 HORIZON						
BULKDEN	12	1.253	0.070	1.110	1.340	5.6
POROSITY	12	0.572	0.024	0.543	0.621	4.2
MACROPOR	12	0.108	0.031	0.062	0.154	28.6
THETA 10	12	0.515	0.026	0.489	0.564	5.0
THETA 25	12	0.499	0.029	0.463	0.552	5.8
THETA 50	12	0.464	0.025	0.426	0.501	5.3
THETA 100	12	0.424	0.028	0.384	0.490	6.7
THETA 150	12	0.398	0.020	0.372	0.436	5.0
THETA 250	12	0.380	0.018	0.348	0.414	4.6
THETA 500	12	0.359	0.018	0.326	0.394	5.1
THETA 1000	12	0.345	0.017	0.314	0.374	4.9
B21 HORIZON						
BULKDEN	12	1.357	0.060	1.220	1.460	4.4
POROSITY	12	0.537	0.020	0.502	0.584	3.8
MACROPOR	12	0.072	0.019	0.042	0.109	26.0
THETA 10	10	0.500	0.020	0.474	0.542	3.9
THETA 25	10	0.486	0.013	0.470	0.513	2.8
THETA 50	12	0.465	0.009	0.452	0.480	1.9
THETA 100	10	0.439	0.009	0.425	0.453	2.0
THETA 150	12	0.419	0.014	0.398	0.439	3.4
THETA 250	10	0.405	0.019	0.375	0.440	4.6
THETA 500	10	0.379	0.015	0.352	0.396	3.9
THETA 1000	10	0.357	0.016	0.328	0.374	4.4
			MOLOKAI SERIES			
Ap1 HORIZON						
BULKDEN	18	1.097	0.055	1.010	1.190	5.0
POROSITY	18	0.627	0.019	0.594	0.655	3.0
MACROPOR	18	0.155	0.040	0.101	0.245	15.6
THETA 10	18	0.558	0.020	0.495	0.580	3.6

*Coefficient of variation.
†THETA 10 is the volumetric water content at a suction of 10-cm water.

TABLE 7—*Continued*

Variable	No. Samples	Mean	Standard Deviation	Minimum Value	Maximum Value	C.V.*
MOLOKAI SERIES—*Cont.*						
Ap1 HORIZON—*Cont.*						
THETA 25	18	0.524	0.029	0.470	0.569	5.6
THETA 50	18	0.472	0.032	0.409	0.519	6.7
THETA 100	18	0.402	0.020	0.361	0.443	5.0
THETA 150	18	0.371	0.016	0.342	0.402	4.4
THETA 250	18	0.342	0.014	0.317	0.369	4.2
THETA 500	18	0.315	0.012	0.300	0.335	3.8
THETA 1000	18	0.294	0.011	0.281	0.318	3.9
Ap2 HORIZON						
BULKDEN	18	1.249	0.081	1.120	1.350	6.5
POROSITY	18	0.575	0.027	0.542	0.618	4.7
MACROPOR	18	0.079	0.044	0.026	0.169	56.1
THETA 10	18	0.536	0.019	0.507	0.569	3.6
THETA 25	18	0.525	0.018	0.498	0.559	3.4
THETA 50	18	0.496	0.029	0.443	0.540	5.8
THETA 100	18	0.444	0.025	0.387	0.485	5.5
THETA 150	18	0.411	0.028	0.341	0.462	6.8
THETA 250	18	0.382	0.026	0.326	0.436	6.8
THETA 500	18	0.355	0.025	0.306	0.408	7.1
THETA 1000	18	0.334	0.024	0.295	0.386	7.2
B21 HORIZON						
BULKDEN	18	1.313	0.078	1.160	1.410	5.9
POROSITY	18	0.553	0.027	0.519	0.604	4.9
MACROPOR	18	0.078	0.026	0.031	0.128	33.3
THETA 10	15	0.518	0.031	0.495	0.615	6.0
THETA 25	15	0.497	0.030	0.470	0.597	6.0
THETA 50	18	0.475	0.027	0.449	0.573	5.6
THETA 100	15	0.444	0.029	0.422	0.543	6.6
THETA 150	18	0.422	0.028	0.383	0.524	6.7
THETA 250	15	0.400	0.029	0.377	0.498	7.3
THETA 500	13	0.375	0.031	0.352	0.471	8.3
THETA 1000	13	0.347	0.030	0.323	0.440	8.7
WAHIAWA SERIES						
Ap1 HORIZON						
BULKDEN	19	1.078	0.136	0.860	1.230	12.6
POROSITY	19	0.632	0.047	0.580	0.706	7.4
MACROPOR	19	0.163	0.107	0.047	0.344	65.6
THETA 10	19	0.565	0.019	0.524	0.602	3.4
THETA 25	19	0.519	0.052	0.419	0.575	10.0
THETA 50	19	0.469	0.063	0.362	0.550	13.3
THETA 100	19	0.408	0.049	0.324	0.486	12.0
THETA 150	19	0.385	0.048	0.310	0.490	12.6
THETA 250	19	0.352	0.031	0.299	0.393	8.9
THETA 500	19	0.325	0.018	0.289	0.348	5.6
THETA 1000	19	0.308	0.014	0.282	0.330	4.5

*Coefficient of variation.

TABLE 7—*Continued*

Variation	No. Samples	Mean	Standard Deviation	Minimum Value	Maximum Value	C.V.*
WAHIAWA SERIES—*Cont.*						
Ap2 HORIZON						
BULKDEN	22	1.197	0.096	1.040	1.380	8.0
POROSITY	22	0.591	0.033	0.529	0.645	5.6
MACROPOR	22	0.107	0.051	0.022	0.212	47.6
THETA 10	18	0.549	0.026	0.498	0.582	4.7
THETA 25	18	0.533	0.030	0.475	0.573	5.6
THETA 50	22	0.484	0.032	0.430	0.545	6.6
THETA 100	18	0.437	0.026	0.406	0.492	6.0
THETA 150	22	0.415	0.024	0.382	0.465	5.7
THETA 250	18	0.388	0.022	0.363	0.430	5.5
THETA 500	18	0.356	0.015	0.338	0.385	4.2
THETA 1000	18	0.334	0.014	0.303	0.360	4.2
B21 HORIZON						
BULKDEN	22	1.337	0.095	1.210	1.530	7.1
POROSITY	22	0.544	0.032	0.478	0.587	5.9
MACROPOR	22	0.086	0.026	0.033	0.158	29.9
THETA 10	18	0.500	0.023	0.462	0.544	4.6
THETA 25	18	0.481	0.022	0.450	0.528	4.6
THETA 50	22	0.458	0.023	0.415	0.508	4.9
THETA 100	18	0.425	0.018	0.398	0.460	4.2
THETA 150	22	0.413	0.021	0.380	0.448	5.0
THETA 250	18	0.384	0.022	0.352	0.422	5.6
THETA 500	18	0.358	0.026	0.330	0.403	7.2
THETA 1000	18	0.339	0.027	0.310	0.388	7.8
B22 HORIZON						
BULKDEN	10	1.443	0.054	1.350	1.520	3.8
POROSITY	10	0.507	0.019	0.481	0.539	3.7
MACROPOR	10	0.064	0.017	0.040	0.090	16.6
THETA 10	10	0.478	0.030	0.439	0.544	6.3
THETA 25	10	0.464	0.020	0.441	0.510	4.3
THETA 50	10	0.443	0.018	0.425	0.485	4.1
THETA 100	10	0.420	0.014	0.402	0.450	3.3
THETA 150	10	0.405	0.011	0.388	0.428	2.7
THETA 250	10	0.383	0.011	0.371	0.400	2.9
THETA 500	10	0.361	0.008	0.350	0.370	2.0
THETA 1000	10	0.341	0.007	0.330	0.350	2.1

*Coefficient of variation.

viation. Most properties are consistently different for the three horizons within a given series; bulk density increases with depth, while total porosity and macroporosity decrease with depth. The mean total porosity exceeds 0.5 cm^3/cm^3 (50% of soil volume) in all horizons of all series, a consequence of the high clay content and high degree of aggregation of these soils.

A more detailed statistical analysis is presented in the next section.

SOIL SERIES AND LOCATION CONTRIBUTIONS TO VARIABILITY IN SOIL-WATER PROPERTIES AND CORRELATION BETWEEN PROPERTIES

The results of statistical analysis of data presented in the two sections of Part II are summarized here. The objectives of these analyses were

1. Determine if soil series mapping units delineated by the U.S. Soil Conservation Service could provide a practical means of dividing upland O'ahu soils into relatively homogeneous units for purposes of watershed analysis or irrigation water management
2. Identify easily measured soil properties which would serve as predictors of important hydrologic properties for which spatial variability must be characterized over large areas.

Analysis of variance (ANOVA) was applied to field and laboratory data to assist in achieving objective 1 above. The ANOVA of data for three <u>series</u>, at three <u>locations</u> for each series, with two <u>sites</u> at each location, provided a means of determining (a) if the soil series were statistically different with respect to a given property and (b) the variance contribution of the soil series relative to the contribution of locations within series. The analysis appropriate for a nested model, as provided by the SAS (Statistical Analysis System) ANOVA procedure, was used for five field-measured variables and four laboratory-measured variables.

For the second objective, various soil properties which were measured in the laboratory and field were statistically correlated by the SAS correlation procedure.

Variation in Hydrologic Properties

Analysis of variance procedures include a test of significance (the F test) which requires that errors be normally distributed. The normality assumption is valid for many soil physical properties, but not for all. For example, while soil water content in a field is likely to be normally distributed, hydraulic conductivity is often log-normally distributed. In the present work, the number of samples was generally too small to test accurately the nature of the statistical distribution of each property. However, frequency distributions were examined to detect strong deviations from normality.

The only field properties for which the frequency histograms showed strong deviation from normality were "FLUXWET" and "FLUXDRY", the steady infiltration rates under wet and dry antecedent conditions. The frequency distributions for FLUXWET and the log-transformed variable LFLUXWET are shown in Figure 32. The log transformation of both FLUXWET and FLUXDRY gave distributions which approach normality, thus the analysis of variance was accomplished on the transformed variables. In Figure 32 the letters L, M, and W, denoting the Lahaina, Molokai, and Wahiawa series, are used in the bar graphs to indicate the number from each soil series in each frequency group. The Lahaina soil was represented in both extreme groups, while the Molokai is characterized by lower steady fluxes and the Wahiawa by higher fluxes. This result is consistent with field observations of profile characteristics. The soils classified Lahaina were quite variable between the three locations, but Molokai soils had consistently less distinct, structural development than the Wahiawa soil.

Physical properties of soil cores tended to be normally distributed, although skewness was evident in some cases, e.g., in the distributions for bulk density of the Ap1 horizon, shown in Figure 33.1. Logarithmic transformations did not improve these distributions, and since they do not deviate from normal in an extreme way, the analysis of variance was performed on the original data.

The ANOVA procedure of SAS with nested classes and balanced data yielded information such as that given in Table 8 for LFLUXWET and in Table 9 for BULKDEN (bulk density).

The analysis of field data (Table 8) was based on two replicates at each of the three locations for each of the three soil series. The effects of series and "locations within series" were evaluated by an F test, using the error-mean square obtained from "replicates within locations and series." A summary of the analyses of five field-measured variables is given in Table 10. In addition to LFLUXDRY and LFLUXWET, three other infiltration variables were evaluated: the times required (hr) for steady infiltration to be reached with both dry and wet antecedent conditions (TIMEDRY and TIMEWET) and the cumulative infiltration (cm) in one hour during the wet run (CIAT1HR). Sorptivity was not included in the analysis because there were too many missing values. If 0.10 is chosen as the probability level below which the F test denotes significance, then the values of F are con-

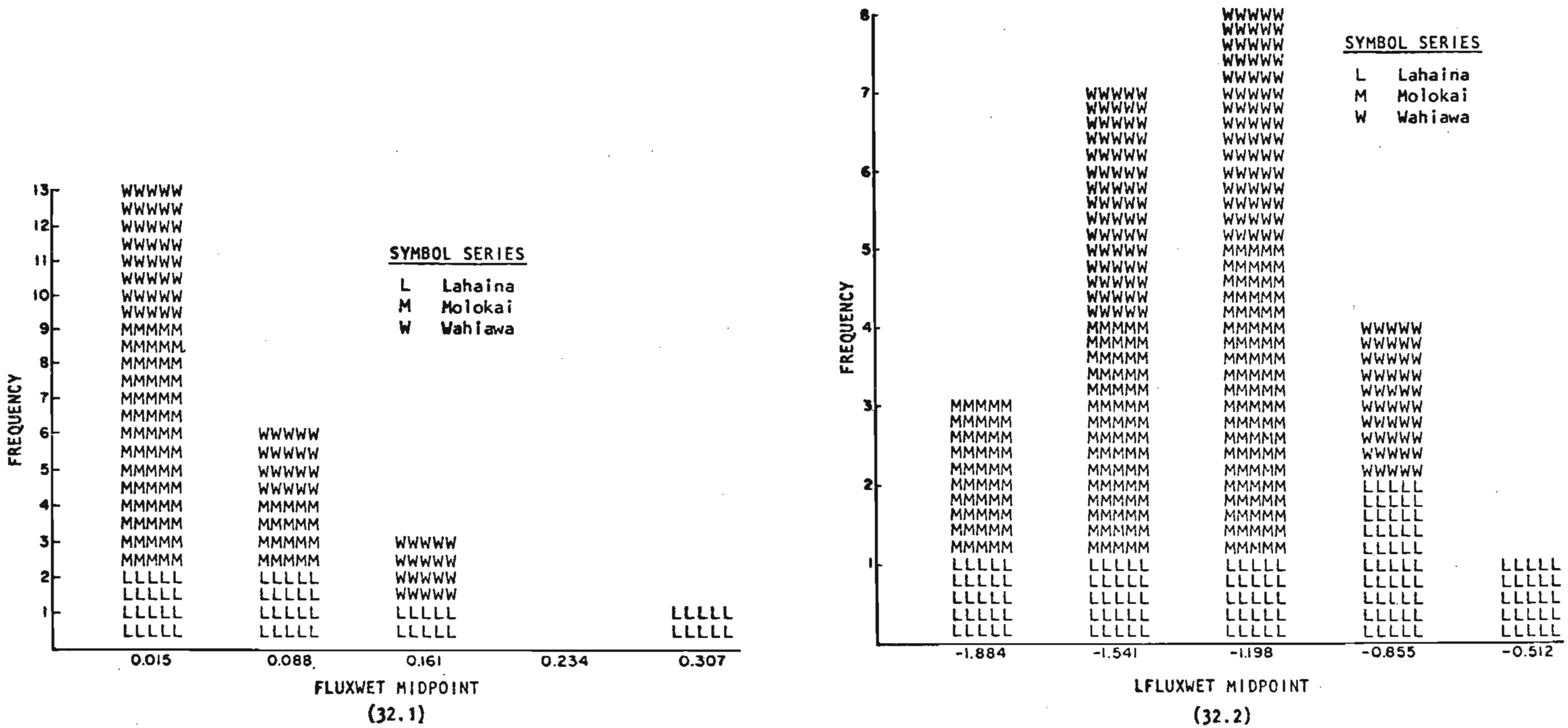
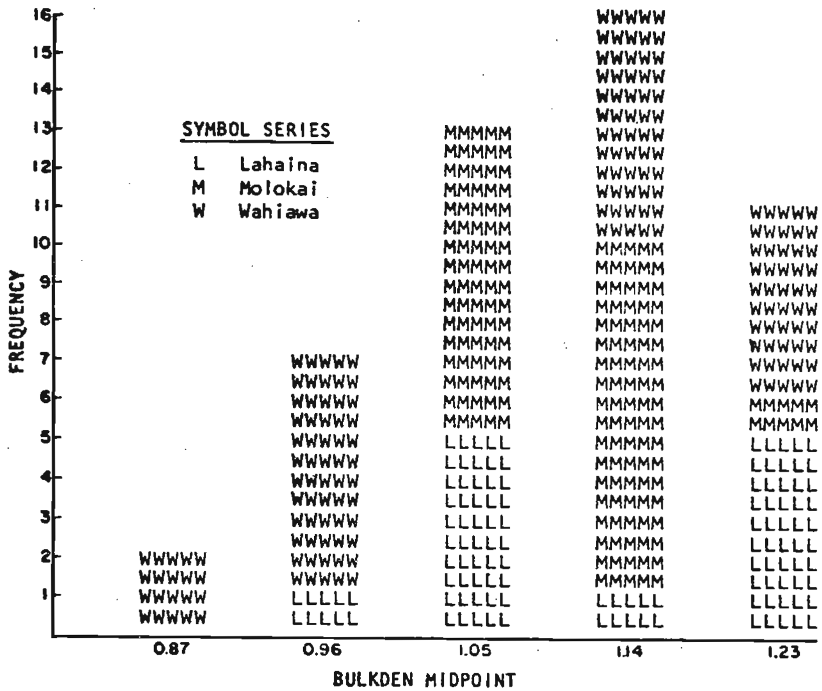
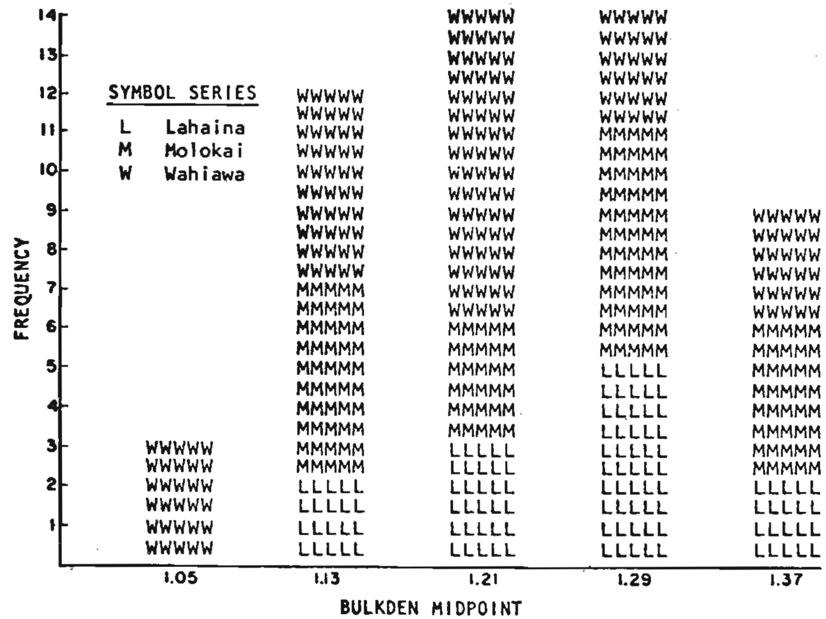


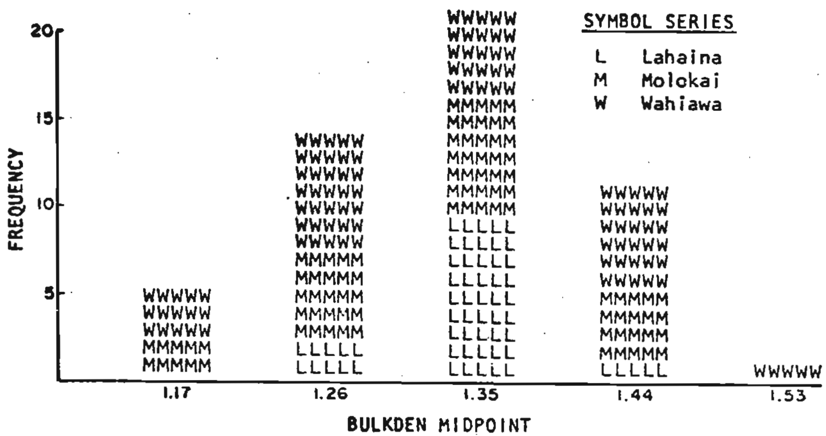
Figure 32. Frequency bar charts of FLUXWET and the logarithm of FLUXWET with series subgroup



(33.1)



(33.2)



(33.3)

Figure 33. Frequency bar charts of bulk density and the logarithm of bulk density with series subgroup

TABLE 8. EXAMPLE OF ANOVA OUTPUT FOR FIELD DATA; VARIABLE FLUXWET

	DF*	Sum of Squares	F Value	PR > F†	r^2	Standard Deviation	Mean	C.V.‡
Source						0.174	-1.251	13.9
Model	8	1.980	8.21	0.002	0.99			
Error	9	0.271	----	-----	----			
Series	2	0.189	3.13	0.093	----			
Location within series	6	1.791	9.91	0.002	----			

NOTE: SAS = statistical analysis system; ANOVA = analysis of variance; LFLUXWET = log-transformed steady infiltration rate, wet antecedent condition.

*Degrees of freedom.

†Probability that F values obtained by ANOVA were chance occurrences.

‡Coefficient of variation.

TABLE 9. EXAMPLE OF ANOVA OUTPUT FOR SOIL CORE DATA; VARIABLE BULKDEN

	DF	Sum of Squares	F Value	PR > F	r^2	Standard Deviation	Mean	C.V.
Source						0.032	1.084	2.9
Model	17	0.377	22.13	0.0001	0.95			
Error	18	0.018	-----	------	----			
Series	2	0.097	48.50	0.0001	----			
Location within series	6	0.262	43.50	0.0001	----			
Replicates within location	9	0.018	2.02	0.0977	----			

TABLE 10. SUMMARY OF VARIANCE ANALYSES (NESTED MODEL) OF FIELD-MEASURED HYDROLOGIC PROPERTIES

VARIABLE	MEAN	r^2	C.V.* (%)	PR > F†		
				Model	Series	Location
LFLUXDRY	-0.903	0.97	12.4	0.0001	0.0014‡	0.0001
LFLUXWET	-1.251	0.88	13.9	0.0024	0.0928‡	0.0015
TIMEDRY	2.35	0.68	37.4	0.1044	0.3138	0.0808
TIMEWET	2.30	0.72	23.8	0.0630	0.1669	0.0565
CIAT1HR	8.17	0.84	38.2	0.0077	0.0631‡	0.0065

*Coefficient variation.

†Denotes probability that F values obtained by ANOVA were chance occurrences; if 0.10 is chosen as probability level below which F test denotes significance, then values of F are considered significant when PR > F is less than 0.10.

‡Variables for which PR > F is ≤0.10 for series effect.

sidered significant when PR > F is less than 0.10. Thus, we can conclude that the soil series were different in their mean values of LFLUXDRY, LFLUXWET, and CIAT1HR. However, the effect of locations-within-series was also significant, so that the division of soil sites into series classes was no more effective in accounting for variability between field sites than was the location category.

This result suggests that separation of soil areas into different groups, each consisting of the same soil series, is not likely to be an effective means of getting relatively homogeneous soil units with respect to a given hydrologic property.

A similar analysis was conducted on laboratory core data for the properties listed in Table 11: bulk density, macroporosity, and volumetric water contents at 50-cm suction (THETA 50) and at 150-cm suction (THETA 150). These variables were thought to be those of greatest potential value for hydrologic characterization of soils. Macroporosity is a derived property based on bulk density and THETA 50: it should be positively related to hydraulic conductivity at saturation and perhaps also to sorptivity. THETA 150 is a reasonable estimate of the water content corresponding to the suction associated with field capacity of well-drained soils. In these analyses, each horizon was separately analyzed, and there were duplicate cores in each field replicate. The error mean square for core replicates within field replicates provided the estimate of variance used to test the variance

TABLE 11. SUMMARY OF VARIANCE ANALYSES (NESTED MODEL) OF SOIL CORE DATA

VARIABLE	HORIZON	MEAN	r^2	C.V.* (%)	PR > F†			
					Model	Series	Location	Rep.
BULKDENSITY (g/cm^3)	Ap1	1.08	0.95	2.9	0.0001	0.0001‡	0.0001	0.0977
	Ap2	1.20	0.91	3.1	0.0001	0.0001‡	0.0001	0.0029
	B21	1.32	0.69	4.1	0.399	0.0220‡	0.0510	0.1801
MACROPOROSITY (cm^3/cm^3)	Ap1	0.167	0.97	10.4	0.0001	0.0001‡	0.0001	0.0287
	Ap2	0.116	0.73	25.6	0.0152	0.0065‡	0.0269	0.1208
	B21	0.079	0.63	27.0	0.1071	0.0126‡	0.3929	0.2364
THETA 50 (cm^3/cm^3)	Ap1	0.463	0.96	2.7	0.0001	0.0001‡	0.0001	0.0102
	Ap2	0.474	0.68	4.6	0.0526	0.1056	0.0109	0.4914
	B21	0.468	0.40	5.5	0.7716	0.5040	0.6749	0.6961
THETA 150 (cm^3/cm^3)	Ap1	0.374	0.84	4.9	0.0003	0.0804‡	0.0001	0.2909
	Ap2	0.401	0.60	4.5	0.1736	0.4721	0.0678	0.3604
	B21	0.420	0.63	4.9	0.1188	0.9217	0.0548	0.1875

*Coefficient variation.
†Denotes probability that F values obtained by ANOVA were chance occurrences; if 0.10 is chosen as probability level below which F test denotes significance, then values of F are considered significant when PR F is less than 0.10.
‡Variables for which PR > F is ⩽0.10 for series effect.

contribution of series, locations, and field replicates (Table 9). The series effect was significant for bulk density and macroporosity at all three horizon depths; only in the Apl horizon was the series effect significant for THETA 50 and THETA 150. However, the value of PR > F was less for the series than for location in only three of the eight cases in which series effects were significant. Thus, the core data suggest, as did the field measured properties, that soil maps of the upland areas of central O'ahu would not be particularly useful in delineating soil areas of relative homogeneity with respect to hydrologic properties. Perhaps this result is not surprising in that soil-water properties, such as conductivity and retentivity, are not principal criteria used in separating soils into different series.

Correlation of Soil-Water Properties

If easily measured soil properties (property X_1) could be used to estimate a soil-water property of interest, such as hydraulic conductivity (X_2)—which is more difficult to measure, then perhaps the spatial variability of

X_2 could be evaluated by extensive measurements of X_1 in an area of interest. A high correlation between X_1 and X_2 would suggest the possibility of such a procedure. The steady flux is one of the most useful values for characterizing water conduction of the soil profile, but it is time-consuming to measure. Correlations of FLUXDRY, LFLUXDRY, FLUXWET, and LFLUXWET with field-measured sorptivity and laboratory measurements of bulk density and macroporosity gave the results in Table 12. The numbers of observations were too

TABLE 12. CORRELATION OF FIELD-MEASURED STEADY FLUX WITH OTHER MEASURED SOIL PROPERTIES FOR ALL SOILS AND SITES

	FLUXDRY	LFLUXDRY	FLUXWET	LFLUXWET
SORPDRY	0.78 0.0009 14	0.72 0.0033 14	0.68 0.0066 14	0.64* 0.0134† 14‡
SORPWET	0.88 0.0001 15	0.70 0.0033 15	0.78 0.0006 15	0.65 0.0077 15
LSORPDRY	0.83 0.0002 14	0.77 0.0010 14	0.70 0.0047 14	0.65 0.0113 14
LSORPWET	0.72 0.0024 15	0.61 0.0137 15	0.61 0.0139 15	0.56 0.0296 15
BDA1	-0.48 0.0188 23	-0.50 0.014 23	0.14 0.52 23	-0.27 0.20 23
BDA2	-0.47555 0.02 23	-0.55127 0.0064 23	-0.26214 0.22 23	-0.45386 0.029 23
BDB2	-0.06 0.77 23	0.14 0.51 23	0.02 0.90 23	0.07 0.73 23
MACA1	0.68 0.0003 23	0.57 0.00041 23	0.38 0.0716 23	0.37 0.0813 23
MACA2	0.69 0.0003 23	0.64 0.0010 23	0.54 0.0071 23	0.57 0.0040 23
MACB2	-0.03 0.89 23	-0.19 0.37 23	-0.19 0.36 23	-0.23 0.28 23

*Correlation coefficient, r.
†Probability of a value greater than r under the hypothesis $\rho = 0$.
‡Number of observations.

few to provide conclusive results, but the data suggest that none of the more easily measured properties would be particularly good predictors of the steady flux. Neither bulk density nor macroporosity when correlated with FLUXDRY and FLUXWET, or the log-transformations of these variables, gave r values greater than 0.7. Sorptivity variables gave higher correlations with flux variables than core data, but r values between 0.7 and 0.8 do not suggest that sorptivity would be a good predictor of steady flux. This result is not surprising in that the steady flux depends on water conduction through the soil profile at a hydraulic gradient near one, while sorptivity, as measured in this study, describes water conduction in the top few centimeters of the soil with hydraulic gradients often much higher than one.

Since hydraulic conductivity of field soils—especially in the unsaturated state—cannot be predicted from other soil properties with much accuracy, actual measurement of $K(h)$ or $K(\theta)$ in the field is necessary if the hydraulic conductivity function is required. The simplified methods described in pp. 5-34, Part I provide means of characterizing the conducvitity of field soils. However, these methods are still too time-consuming for an intensive analysis of spatial variability of a large land area which might require hundreds of measurements. The sorptivity measurement, on the other hand, may be very useful for such variability analyses, as the measurement is simple and takes very little time. Sorptivity data, however, are useful only in predictions of ponded infiltration such as are described in pp. 34-42, Part I; these measurements do not provide information about water conduction properties of the soil below the top few centimeters.

GLOSSARY

BDA1	Bulk density, A1 horizon (g/cm^3)
BULKDEN	Bulk density (g/cm^3)
CIAT1HR	Cumulative infiltration, 1 hr (cm)
D	Soil-water diffusivity (cm^2/min)
$D_L(\theta)$	Soil-water diffusivity, depth L (cm^3/min)
$\partial h/\partial z$	Soil-water pressure gradient (cm/cm)
ε	Porosity

FLUXDRY	Steady infiltration rate, dry antecedent condition (cm/min)
*K*50	Conductivity corresponding to 50-cm suction (cm/min)
$K_L(\theta)$	Hydraulic conductivity, depth L (cm/min)
$K(\tau)$, $K(h)$, $K(\theta)$	Unsaturated hydraulic conductivity, in situ (cm/min)
KS	Saturated hydraulic conductivity measured on cores (cm/hr)
LFLUXDRY	Log-transformed (FLUXDRY) variable
LSORPDRY	Log transformation of SORPDRY
MACROPOR	Macroporosity (cm^3/cm^3)
MACA1	Macroporosity of A1 horizon (cm^3/cm^3)
S	Sorptivity ($cm/min^{\frac{1}{2}}$)
SORPDRY	Sorptivity, dry antecedent condition ($cm/min^{\frac{1}{2}}$)
TIMEDRY	Time to steady infiltration with dry antecedent condition (hr)
TIMEWET	Time to steady infiltration with wet antecedent condition (hr)
THETA 50	Volumetric water content, 50cm suction (cm^3/cm^3)
$\theta(z, t)$	Soil water content as a function of depth and time (cm^3/cm^3)
$\theta(\tau)$	Soil-water content as a function of suction (cm^3/cm^3)
τ	Soil-water suction (cm water), the negative of h
h	Soil-water pressure head (cm water)

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APPENDIX CONTENTS

APPENDIX TABLES

APPENDIX TABLE A.1. DESCRIPTION OF SOILS AT EXPERIMENTAL SITES

Site:	W1
Soil:	Wahiawa silty clay, Tropeptic Eutrustox; clayey, kaolinitic, isohyperthermic family
Location:	O'ahu UH Poamoho Experimental Farm; Poamoho II site, about 15 m (50 ft) SW of Kaukonahua Rd. and 46 m (150 ft) NW of reservoir
Date:	5 July 1977
Description by:	S. Nakamura, Soil Conservation Service
Topography:	Gently sloping upland; 7% slope
Parent Material:	Residuum from basic igneous rock
Elevation:	213 m (700 ft)
Annual Rainfall:	1 016 mm (40 in.)
Drainage and Permeability:	Well drained; moderately rapid permeability (low end of moderately rapid)
Erosion:	None
Stoniness:	None
Vegetation:	Guineagrass, natal redtop, lantana, koa-haole
Remarks:	Representative of Wahiawa series

Profile Description: (Colors for moist soil unless otherwise noted; all textures "apparent field textures")

Ap 0-30 cm (0-12 in.)—Very dusky red (2.5 YR 2/2) silty clay; weak, very fine granular structure; friable, very sticky and plastic; many pores; many roots; many very fine manganese concretions; clear, smooth boundary

B21 30-96 cm (12-38 in.)—Dark reddish brown (2.5 YR 2/4) silty clay; gritty due to earthy lumps; strong, fine and very fine subangular blocky structure; few roots; common very fine pores; common manganese concretions and stains; nearly continuous pressure faces; compact in place; diffuse, smooth boundary

B22 96-112 cm (38-44 in.)—Dark reddish brown (2.5 YR 2/4) silty clay; moderate, fine and medium subangular blocky structure; friable, stocky and plastic; few roots, many very fine pores; common pressure faces; common manganese stains and concretions; firm in place

APPENDIX A—*Continued*

Site:	W2
Soil:	Wahiawa silty clay; Tropeptic Eutrustox; clayey, kaolinitic, isohyperthermic family
Location:	O'ahu PRI Waipio; site about 183 m (600 ft) NE of PRI buildings
Date:	5 July 1977
Description by:	S. Nakamura, Soil Conservation Service
Topography:	Gently sloping uplands; 4% slopes
Parent Material:	Residuum from basic igneous rock
Elevation:	216 m (710 ft)
Annual Rainfall:	1 016 mm (40 in.)
Drainage and Permeability:	Well drained; moderately rapid permeability (low end of moderately rapid)
Erosion:	None
Stoniness:	None
Vegetation:	Abandoned pineapple
Remarks:	Representative of Wahiawa series

Profile Description: (Colors for moist soil unless otherwise noted; all textures "apparent field textures")

Ap 0-41 cm (0-16 in.)—Dark reddish brown (2.5 YR 2/4) silty clay; weak, very fine granular with some clods; friable, sticky and plastic; many roots; many pores; few holes up to 7.62 cm (3 in.) in diameter due to decomposed pineapple stumps; clear smooth boundary

B2 41-117 cm (16-46 in.)—Dusky red (10 R 3/4) silty clay; gritty due to earthy lumps; moderate and strong fine and very fine subangular blocky structure; friable, sticky and plastic; few roots; many very fine pores; common pressure faces; common very fine manganese concretions; firm in place

APPENDIX A—*Continued*

Site:	W3
Soil:	Wahiawa silty clay; Tropeptic Eutrustox; clayey, kaolinitic, isohyperthermic family
Location:	O'ahu, about 5.6 km (3½ miles) S of Kunia in Oahu Sugar Field 157; Plot 1, about 3 m (10 ft) E of cane haul road
Date:	1 October 1976
Description by:	S. Nakamura, Soil Conservation Service
Topography:	Nearly level upland; about 1% slopes
Parent Material:	Residuum from basic igneous rock
Elevation:	186 m (610 ft)
Annual Rainfall:	762 mm (30 in.)
Drainage and Permeability:	Well drained; moderate permeability
Erosion:	None
Stoniness:	None
Vegetation:	Irrigated sugarcane
Remarks:	Transitional soil to Lahaina series a typical Wahiawa has moderate structure throughout the solum and manganese concretions in the A horizon; rainfall and elevation at this site in the lower range compared to a typical Wahiawa; profile descriptions of plots 3 and 4 similar

<u>Profile Description</u>: (Colors for moist soil unless otherwise noted; all textures "apparent field textures")

A1 0-43 cm (0-17 in.)—Dusky red (2.5 YR 3/2) silty clay; weak, very fine granular structure, few clods; friable, sticky and plastic; many roots; many pores; gradual wavy boundary

B21 43-69 cm (17-27 in.)—Dark red (2.5 YR 2/4) silty clay with patches of dusky red; weak, fine and medium subangular blocky structure; friable, sticky and plastic; common roots, many very fine pores; common very fine manganese concretions; clear wavy boundary

B23 69-140 cm (27-55 in.)—Dark red (2.5 YR 2/4) silty clay; moderate very fine and fine subangular blocky structure; friable sticky and plastic; few roots in upper part; many very fine and few fine and medium pores; many very fine manganese concretions; firm in place; common earthy lumps

APPENDIX A—*Continued*

Site:	L1
Soil:	Lahaina silty clay; Tropeptic Haplustox; clayey, kaolinitic, isohyperthermic family
Location:	O'ahu Mililani site in Oahu Sugar field (adjacent to waste water reuse project site)
Date:	30 August 1977
Description by:	S. Nakamura, Soil Conservation Service
Topography:	Gently sloping uplands, 4% slopes
Parent Material:	Residuum from basic igneous rock
Elevation:	160 m (525 ft)
Annual Rainfall:	711 mm (28 in.)
Drainage and Permeability:	Well drained; moderate permeability
Erosion:	None
Stoniness:	None
Vegetation:	Sugarcane
Remarks:	Representative of Lahaina series; however, surface layer cloddy due to tillage

<u>Profile Description</u>: Lahaina silty clay—Mililani site
(Colors for moist soil unless otherwise noted; all textures "apparent field textures")

Ap 0-30 cm (0-12 in.)—Dark reddish brown (2.5 YR 2/4) silty clay; cloddy due to tillage; clods are primarily gravel size; very hard, sticky and plastic; common roots; loose in places; clear, smooth boundary

B21 30-45 cm (12-18 in.)—Dusky red (10 R 3/4) silty clay; weak medium and coarse subangular blocky structure; very friable, sticky and plastic; common roots; many very fine pores; compact due to tillage; many very fine manganese concretions; gradual wavy boundary

B22 45-107 cm (18-42 in.)—Dusky red (10 R 3/4) silty clay; strong very fine subangular blocky structure; friable, sticky and plastic; few roots; many very fine pores; many very fine manganese concretions; many shiny pressure faces; compact in place

APPENDIX A—*Continued*

Site:	L2
Soil:	Lahaina silty clay; Tropeptic Haplustox; clayey, kaolinitic, isohyperthermic family
Location:	O'ahu, Oahu Sugar Field 221 (NW corner)
Date:	30 August 1977
Description by:	S. Nakamura, Soil Conservation Service
Topography:	Nearly level upland; 1% slopes
Parent Material:	Residuum from basic igneous rock
Elevation:	165 m (540 ft)
Annual Rainfall:	711 mm (28 in.)
Drainage and Permeability:	Well drained; moderate permeability
Erosion:	None
Stoniness:	None
Vegetation:	Sugarcane, swollen fingergrass
Remarks:	Representative of Lahaina series

Profile Description: Lahaina silty clay, Field 221
(Colors for moist soil unless otherwise noted; all textures "apparent field textures")

Ap 0-41 cm (0-16 in.)—Dark reddish brown (2.5 YR 3/4) silty clay; weak, very fine granular structure with few clods; friable, sticky and plastic; many roots; many pores; compacted by tillage in places; clear, smooth boundary

B2 41-92 cm (16-36 in.)—Dusky red (10 R 3/4) silty clay; moderately fine and very fine subangular blocky structure; few roots; common very fine pores; friable, sticky and plastic; many very fine manganese concretions; common shiny pressure faces

APPENDIX A—*Continued*

Site:	L3
Soil:	Molokai silty clay loam; Typic Torrox; clayey, kaolinitic, isohyperthermic family
Location:	O'ahu, Oahu Sugar Field 146 (north)
Date:	30 August 1977
Description by:	S. Nakamura, Soil Conservation Service
Topography:	Gently sloping uplands; 3% slopes
Parent Material:	Residuum from basic igneous rock
Elevation:	162 m (530 ft)
Annual Rainfall:	686 mm (27 in.)
Drainage and Permeability:	Well drained; moderate permeability
Erosion:	None
Stoniness:	None
Vegetation:	Sugarcane
Remarks:	Borderline between Molokai and Lahaina soils (more like Molokai, but mapped as Lahaina); silty clay loam textures and weak structure in the B2 horizon, typical of Molokai, unlike Lahaina soils, lacks moderate or strong structure in upper B2 horizon

Profile Description: Molokai silty clay loam, Field 146 (north) (Colors for moist soil unless otherwise noted; all textures "apparent field textures")

Ap 0-48 cm (0-19 in.)—Dark reddish brown (2.5 YR 2/4) heavy silty clay loam; weak, fine and medium subangular blocky structure; friable, sticky and plastic; many roots; many pores

B2 48-89 cm (19-35 in.)—Dusky red (10 R 3/4) silty clay loam; weak, fine and medium subangular blocky structure; friable, sticky and plastic; many roots; many very fine pores

APPENDIX A—*Continued*

Site:	M1
Soil:	Molokai silty clay loam; Typic Torrox; clayey, kaolinitic, isohyperthermic family
Location:	O'ahu, Oahu Sugar Field 146 (south)
Date:	30 August 1977
Description by:	S. Nakamura, Soil Conservation Service
Topography:	Gently sloping upland, 3% slopes
Parent Material:	Residuum from basic igneous rock
Elevation:	128 m (420 ft)
Annual Rainfall:	635 mm (25 in.)
Drainage and Permeability:	Well drained; moderate permeability
Erosion:	None
Stoniness:	None
Vegetation:	Swollen fingergrass, guineagrass, sugarcane
Remarks:	Representative of Molokai series (Clean fine gravel and glass found in bottom of pit—may have been site of old irrigation ditch)

<u>Profile Description</u>: Molokai silty clay loam, Field 146 (south) (Colors for moist soil unless otherwise noted; all textures "apparent field textures")

Ap 0-38 cm (0-15 in.)—Dark reddish brown (2.5 YR 3/4) silty clay loam; weak, very fine granular structure; very friable, sticky and plastic; many roots; many very fine pores

B2 38-81 cm (15-32 in.)—Dark reddish brown (2.5 YR 3/4) silty clay laom; weak, fine and medium subangular blocky structure; very friable, sticky and plastic; many roots; many very fine pores

APPENDIX A—*Continued*

Site:	M2
Soil:	Molokai silty clay loam; Typic Torrox; clayey, kaolinitic, isohyperthermic family
Location:	O'ahu, HSPA Kunia Substation, block C; site about 46 m (150 ft) south of NE corner of block
Date:	30 August 1977
Description by:	S. Nakamura, Soil Conservation Service
Topography:	Gently sloping upland; 3% slopes
Parent Material:	Residuum from basic igneous rock
Elevation:	70 m (230 ft)
Annual Rainfall:	635 mm (25 in.)
Drainage and Permeability:	Well drained; moderate permeability
Erosion:	None
Stoniness:	Boulder in lower profile
Vegetation:	Sugarcane
Remarks:	Representative of Molokai series

Profile Description: Molokai silty clay loam, HSPA
(Colors for moist soil unless otherwise noted; all textures "apparent field textures")

Ap 0-28 cm (0-11 in.)—Dark reddish brown (2.5 YR 2/4) silty clay loam; weak, very fine granular structure with few clods; friable, sticky and plastic, but clods are firm; many roots; clear smooth boundary

B21 28-68 cm (11-27 in.)—Dark red (2.5 YR 3/6) silty clay loam; weak, fine and medium subangular blocky structure; very friable, slightly plastic; few roots; many very fine pores; compact in place; gradual wavy boundary

B22 68-102 cm (27-40 in.)—Dark red (2.5 YR 3/6) silty clay loam; moderate fine and very fine subangular blocky structure; friable, sticky and plastic; no roots; many very fine pores; compact in place

APPENDIX A—*Continued*

Site:	M3
Soil:	Molokai silty clay loam; Typic Torrox; clayey, kaolinitic, isohyperthermic family
Location:	O'ahu, W of Crestview; site in Oahu Sugar Field 410, approximately 183 m (600 ft) SW of reservoir
Date:	30 August 1977
Description by:	S. Nakamura, Soil Conservation Service
Topography:	Gently sloping uplands; 4% slopes
Parent Material:	Residuum from basic igneous rock
Elevation:	76 m (250 ft)
Annual Rainfall:	635 mm (25 in.)
Drainage and Permeability:	Well drained; moderate permeability
Erosion:	None
Stoniness:	None
Vegetation:	Sugarcane
Remarks:	Representative of Molokai series

Profile Description: Molokai silty clay loam, Field 410
(Colors for moist soil unless otherwise noted; all textures "apparent field textures")

Ap 0-36 cm (0-14 in.)—Dark reddish brown (2.5 YR 2/4) silty clay loam; weak, very fine granular structure; with few clods; friable, sticky and plastic; many roots; many pores; gradual wavy boundary

B21 36-56 cm (14-22 in.)—Dusky red (10 R 3/4) silty clay loam; weak very fine granular structure; very friable, sticky and plastic; many very fine pores; many roots; gradual smooth boundary

B22 56-89 cm (22-35 in.)—Dusky red (10 R 3/4) silty clay loam; weak, fine and medium subangular blocky structure; very friable, sticky and plastic; many very fine pores; many roots; clear smooth boundary

B23 89-114 cm (35-45 in.)—Dark reddish brown (2.5 YR 2/4) clay loam; gritty due to hard earthy lumps; strong very fine subangular blocky structure; common very fine pores; few roots; firm, slightly sticky and slightly plastic; difficult to break down when rubbed; nearly continuous pressure faces, reddish brown sugary coatings in pores

APPENDIX TABLE B.1. OBSERVATIONS OF FIELD SITE CONDITION AND CORE-SAMPLE DEPTHS, O'AHU, HAWAI'I

LOCATION	SITE CONDITION	SITES AND SOIL-CORE DEPTHS	
		Site No.	Cores (cm)
W1	Shallower Ap than usual for Wahiawa soils. Site rototilled recently so that Ap1 was very fluffy; Ap2 was not recently disturbed. The Rototiller may have developed a slight "pan" which restricted downward water movement; horizontal water movement into the pit beside the ring at W1-1 did occur. The site had grass and weed cover prior to tillage; thus, the tilled area contained quite a lot of organic material.	W1-1	3-11 18-26 39-47
		W1-2	3-11 18-26 43-51
W2	Site covered by an old stand of pineapple; plants were removed and the soil tilled by hand and leveled before installation of rings. In a nearby pit, the Ap was seen to contain large voids, perhaps 5 cm in diameter and 20-30 cm long, presumably from decomposed pineapple plant stumps which were disked into the soil after the last crop. Roots proliferated throughout the Ap. The placement of rings (center) appeared to be in the large interrow space, but was not established with certainty. Water movement into the Ap was extremely fast, and horizontal water movement at the Ap-B interface appeared rapid.	W2-1	2-10 37-45 55-63
		NOTE: Mixed red and brown soil in 37-45 cm and much denser than above. Some dense clods <3 cm diameter in 2-10 cm depth and many roots; quite loose.	
		W2-2	2-10 36-44 57-65
		NOTE: •Sample "A" of 2-10 cm has ~8-mm compaction; and clods and roots in surface samples. •Ap2 samples contain chunks of B material. Core "B" at 57-65 cm has insect tunnel at bottom.	
W3	Site is close to border having Kunia soil (KyA). The subsoil was fairly typical of Wahiawa, sufficiently dense to limit root penetration, and with well-defined structure. The field was drip irrigated. Measurements were made in 1.8 m interrow space of a 1 yr old cane crop.	W3-1, 4	4-12 19-27 42-50 74-78 105-109

APPENDIX TABLE B.1—*Continued*

LOCATION	SITE CONDITION	SITES AND SOIL-CORE DEPTHS: Site No.	Cores (cm)
L1	Site is north of a cane experiment using sewage effluent in a furrowed border area. The soil was dry and free of weeds. Ridges were leveled and rings installed with centers located on the old ridge. This soil was very cloddy and strongly aggregated. Large clods disintegrated rapidly in water, but small aggregates seemed very water-stable. After the infiltration runs, the stable aggregates were apparent on the soil surface in contrast to the Molokai sites. When soil pits were dug, the subsoil structure appeared intermediate to the Molokai and Wahiawa soils. In the L1-1 measurement area, dark soil bands in the red soil matrix were apparent, even down to 70+ cm; these bands were not apparently due to deep tillage. The Ap1-B boundary was clear in the easy plot. Subsoil aggregates were firm and felt almost cindery.	L1-1	1-9 "A" 0-8 "B" 25-33 "A" 30-39 "B" 76-85
		NOTE: •1-9 "A": Rock along side; cane piece along wall of core came out. •0-8 "B": Big hard clod at bottom of ring. •30-39 "B": Got too deep by mistake, but soil is not much different than at 25-33; all very cloddy. These cores may not do a good job of describing the horizon because of the small core size relative clod size. •76-85: Subsoil generally reddish in color but has bands of brown soil, apparently not due to tillage. Undisturbed B horizon appears to start at 50 cm; we went deep for the cores in an attempt to get below the mixed red and brown material	
		L1-2	1-9 "A" 0-8 "B" 24-32 56-64 "A" 53-61 "B"

APPENDIX TABLE B.1—*Continued*

LOCATION	SITE CONDITION	SITES AND SOIL-CORE DEPTHS: Site No.	Cores (cm)
L1	(*Continued*)	NOTE: •1-9 "A": ½-cm compaction. •0-8 "B": Slight compaction from base of jack support. •Surface cores have many clods in matrix of loose unstable soil. •24-32: Very cloddy but more compact than Ap	
L2	Site is in a large area of the Lahaina series, but within 50 m of Molokai series in a drainage area in an adjacent field. This field was in cane being dried out prior to harvest. Two ridges were found near the field border that were extra-wide; the area was leveled by pulling soil from both side ridges and the center ridge into the furrows. Sorptivity measurements were made on the same ridge, only farther into the field.	L2-1, 2	1-9 25-33 55-63
		NOTE: •Ap1 very friable, has few roots and is easy to sample. •Ap2 more massive than above; some very dense B-clods are mixed in the A matrix and thus were avoided in the cores taken. •Core rings went into the B horizon only with much pressure. Water poured on top of the core does not perceptibly enter the soil which must have a very low conductivity.	
L3	Soil at this site is mapped Lahaina series but (according to S. Nakamura) is more like the Molokai series. Measurements were made between drip lines in the recently replanted field. Water had been applied for a couple of days to irrigate the newly planted seed pieces and then no water was applied until after our infiltration measurements and a few days of redistribution. A subsequent irrigation interfered with the last few days of redistribution.	L3-1	1-9 25-33 53-61
		L3-2	1-9 25-33 60-68
		NOTE: •Ease with which infiltration rings were installed correlated	

APPENDIX TABLE B.1—*Continued*

LOCATION	SITE CONDITION	SITES AND SOIL-CORE DEPTHS: Site No.	SITES AND SOIL-CORE DEPTHS: Cores (cm)
L3	(*Continued*)	well with the measured depth of the Ap1 horizon; rings went in easily in L3-2, but with some difficulty in L3-1.	
M1	Site had just been harvested (cane)—it had been drip irrigated. The rings were placed in the 1.8 m interrow space in locations where surface compaction by the recent harvest was minimal. The surface was tilled about 10 cm deep before infiltration measurements. A nearby pit revealed that the plow layer consisted of a reasonably friable surface 20 cm underlain by 30 cm of cloddy compacted soil; the compaction may have resulted from field preparation when the soil was too wet. The surface may have been retilled to improve tilth for rooting and drip tube insertion. There were many roots in the cloddy zone, mainly between the clods, and root proliferation was excellent in the B horizon. It is likely that infiltration rates would be limited by the dense Ap layer. Dispersion of soil at the surface was severe and infiltration rates were very slow relative to other sites measured thus far. The plantation ripped most areas of this field before replanting for the ratoon crop and insertion of drip tubing. The L3 Lahaina site is at the N end of this same field.	M1-1, 2 NOTE: •Tilled surface was slightly compacted; contained small clods of red material in matrix of loose material. •Ap2 was compacted, probably by tillage when the previous crop was planted; very chunky with many dense chunks and many roots in the spaces between chunks. •The 27-35 cm "A" sample (M1-1) had many roots. A piece of concrete at the bottom was removed, leaving a 3/4 cm deep by 9 cm square space—filled with soil and pressed firm. •59-67 cm (M1-2) "A" sample has small depression on top to be filled and edges on the bottom.	1-9 27-35 59-67
M2	Site is just 20 to 30 m south of the location of previous soil-water studies by Rao, Green, Kanehiro and Balasubramanian. Subsoil core data from the previous study will be used for the present study, but Ap cores were taken at the present sites. The soil was furrowed deeply for cane but no cane was planted in this area. Nut grass cover was	M2-1 NOTE: Many roots in upper end of sample at 23-31 cm and B material in lower; sample "A" contains a small rock.	1-9 23-31

APPENDIX TABLE B.1—*Continued*

LOCATION	SITE CONDITION	SITES AND SOIL-CORE DEPTHS: Site No.	SITES AND SOIL-CORE DEPTHS: Cores (cm)
M2	(*Continued*) fairly heavy. In leveling the site for infiltration, one ridge was leveled to fill the furrows on both sides; this gave an apparent Ap horizon that was shallower than would have been obtained by filling each furrow with half of the ridge on each side (as was done for subsequent sites). The inner ring was centered on the former ridge. In M2-2 pit the B horizon was darker than in M2-1 pit, probably due to decomposing rock just W of the inner ring. There were many root channels and some roots in the B horizon. Fairly sharp boundary between the Ap and B.	M2-2 NOTE: •Many small nutgrass plants on this site. •18-26 cm, sample "B": some subsoil material mixed with A horizon; sample "A" has no red material.	1-9 18-26
M3	This field had been in furrow-irrigated cane and was harvested only a few days when we prepared the site. We selected ridges that had not been altered much during harvesting and prepared the site in the usual manner.	M3-1	1-9 19-27 49-57
		M3-2	1-9 20-28 48-56
M4	This location was added to the study one year after other measurements to provide more detailed data of sorptivity, infiltration, and redistribution needed for S.K. Chong's Ph.D. dissertation work. The field was tilled and uncropped at the time of our measurements; it had been previously planted to sugarcane.	M4-1	1-9 24-32 46-54
		M4-2	0-8 21-29 42-50
		M4-3	1-9 18-27 43-51

APPENDIX TABLE C.1. HYDRAULIC CONDUCTIVITY AND ASSOCIATED SUCTION, WATER CONTENT, FLUX, AND HYDRAULIC GRADIENT DURING POST-INFILTRATION DRAINAGE, SITE L1-1, O'AHU, HAWAI'I

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydrailic Conductivity (cm/min)
30	40	2	0.520	6.38E-03	1.02	6.25E-03
	60	5	0.515	7.30E-03	1.04	7.05E-03
	100	8	0.509	8.80E-03	0.76	1.16E-02
	120	7	0.510	8.24E-03	0.86	9.56E-03
	158	9	0.506	6.97E-03	0.91	7.64E-03
	218	13	0.499	5.43E-03	0.93	5.83E-03
	240	14	0.496	5.22E-03	0.94	5.58E-03
	1490	49	0.435	6.12E-04	1.38	4.44E-04
	2815	67	0.423	3.59E-04	1.65	2.17E-04
	4190	80	0.415	1.29E-04	1.70	7.56E-04
	5960	96	0.405	2.71E-05	1.89	1.43E-05
	8460	112	0.400	4.77E-04	1.85	2.58E-04
60	40	-10	0.549	7.82E-03	0.33	2.35E-02
	60	-5	0.549	9.46E-03	0.43	2.18E-02
	100	-1	0.549	1.24E-02	0.94	1.32E-02
	120	2	0.546	1.12E-02	0.89	1.26E-02
	158	4	0.542	9.92E-03	0.86	1.16E-02
	218	8	0.536	9.26E-03	0.81	1.14E-02
	240	9	0.535	9.06E-03	0.81	1.12E-02
	1490	53	0.476	9.85E-04	0.84	1.17E-03
	2815	74	0.461	5.93E-04	0.80	7.39E-04
	4190	89	0.451	3.00E-04	0.84	3.57E-04
	5960	103	0.443	1.50E-04	0.72	2.09E-04
	8460	120	0.437	4.56E-04	0.60	7.57E-04
90	40	-17	0.549	5.99E-03	1.61	3.71E-03
	60	-13	0.549	9.25E-03	1.40	6.60E-03
	100	0	0.549	1.41E-02	0.95	1.49E-02
	120	-1	0.549	1.24E-02	0.90	1.38E-02
	158	1	0.549	1.16E-02	0.91	1.28E-02
	218	4	0.547	1.26E-02	1.01	1.24E-02
	240	6	0.539	1.24E-02	1.06	1.17E-02
	1490	45	0.484	1.38E-03	0.78	1.79E-03
	2815	63	0.469	8.62E-04	0.64	1.34E-03
	4190	77	0.459	4.82E-04	0.55	8.77E-04
	5960	90	0.451	2.63E-04	0.54	4.87E-04
	8460	102	0.443	5.06E-04	0.55	9.18E-04

APPENDIX TABLE C.2. HYDRAULIC CONDUCTIVITY AND ASSOCIATED SUCTION, WATER CONTENT, FLUX, AND HYDRAULIC GRADIENT DURING POST-INFILTRATION DRAINAGE, SITE L1-2, O'AHU, HAWAI'I

Measure-ment Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
20	29	3	0.517	3.04E-02	0.45	6.72E-02
	39	5	0.513	2.17E-02	0.74	2.94E-02
	49	7	0.509	1.46E-02	0.51	2.84E-02
	59	8	0.506	8.98E-03	0.78	1.15E-02
	89	11	0.500	1.78E-03	0.75	2.36E-03
	119	13	0.496	1.71E-03	0.75	2.29E-03
	1404	46	0.427	1.86E-04	-0.43	-4.27E-03
	2769	61	0.411	2.17E-04	-0.33	-6.51E-03
	4079	73	0.402	1.78E-04	-0.80	-2.21E-03
	5864	82	0.395	9.76E-05	0.69	1.42E-04
	8384	99	0.381	5.11E-05	0.48	1.06E-04
	11129	105	0.379	4.51E-05	1.20	3.76E-05
	12749	105	0.379	4.36E-05	2.39	1.82E-05
30	29	-1	0.532	4.12E-02	0.71	5.76E-02
	39	2	0.526	2.95E-02	0.56	5.24E-02
	49	3	0.523	1.99E-02	0.62	3.20E-02
	59	5	0.518	1.24E-02	0.49	2.56E-02
	89	8	0.511	2.76E-03	0.50	5.49E-03
	119	10	0.506	2.66E-03	0.50	5.30E-03
	1404	40	0.448	3.77E-04	0.99	3.80E-04
	2769	58	0.428	2.99E-04	1.57	1.90E-04
	4079	71	0.419	2.29E-04	1.78	1.28E-04
	5864	87	0.409	1.49E-04	2.13	7.01E-05
	8384	103	0.400	7.78E-05	2.22	3.51E-05
	11129	118	0.396	5.11E-05	2.92	1.75E-05
	12749	128	0.393	5.90E-05	3.23	1.83E-05
50	29	-10	0.490	4.72E-02	0.11	4.15E-01
	39	-7	0.490	3.40E-02	0.76	4.46E-02
	40	-6	0.490	2.32E-02	0.42	5.51E-02
	59	-5	0.490	1.48E-02	0.89	1.67E-02
	89	-3	0.490	3.84E-03	0.70	5.48E-03
	119	-1	0.490	3.72E-03	0.70	5.29E-03
	1404	51	0.469	6.44E-04	1.59	4.04E-04
	2769	76	0.458	4.55E-04	1.17	3.90E-04
	4079	90	0.452	3.30E-04	0.78	4.23E-04
	5864	107	0.446	2.17E-04	0.93	2.34E-04
	8384	127	0.440	1.18E-04	1.02	1.16E-04
	11129	144	0.436	8.22E-05	0.51	1.59E-04
	12749	153	0.434	9.22E-05	1.03	8.97E-05

APPENDIX TABLE C.3. HYDRAULIC CONDUCTIVITY AND ASSOCIATED SUCTION, WATER CONTENT, FLUX, AND HYDRAULIC GRADIENT DURING POSTINFILTRATION DRAINAGE FOR SITE L2-1 (SET 1), O'AHU, HAWAI'I

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
20	25	3	0.544	1.46E-02	0.39	3.74E-02
	30	4	0.543	1.09E-02	0.33	3.29E-02
	40	8	0.539	8.24E-03	0.21	3.92E-02
	50	12	0.534	8.37E-03	0.21	4.05E-02
	80	17	0.529	6.22E-03	0.14	4.54E-02
	111	21	0.525	3.11E-03	0.06	5.19E-02
	140	24	0.521	2.15E-03	0.06	3.85E-02
	170	27	0.517	2.13E-03	0.13	1.59E-02
	206	31	0.511	2.06E-03	0.06	3.56E-02
	235	33	0.508	1.97E-03	0.06	3.35E-02
	1015	66	0.463	5.50E-04	0.17	3.26E-03
	1465	78	0.449	4.63E-04	0.27	1.74E-03
	2575	97	0.426	3.04E-04	0.18	1.70E-03
	4060	118	0.408	1.78E-04	0.25	7.01E-04
	5650	135	0.394	1.14E-04	0.40	2.83E-04
	6940	144	0.387	9.08E-05	0.37	2.46E-04
	8590	158	0.379	5.66E-05	0.56	1.02E-04
	9970	166	0.375	4.05E-05	0.63	6.43E-05
	12670	184	0.367	9.30E-05	0.69	1.35E-04
30	25	-1	0.573	2.95E-02	0.84	3.50E-02
	30	0	0.573	1.79E-02	0.79	2.27E-02
	40	3	0.570	8.96E-03	0.69	1.30E-02
	50	6	0.566	9.19E-03	0.62	1.49E-02
	80	10	0.562	7.40E-03	0.49	1.50E-02
	111	14	0.559	4.61E-03	0.47	9.81E-03
	140	17	0.556	3.77E-03	0.48	7.87E-03
	170	21	0.551	3.76E-03	0.50	7.44E-03
	206	24	0.548	3.66E-03	0.47	7.71E-03
	235	26	0.545	3.51E-03	0.47	7.44E-03
	1015	60	0.469	9.81E-04	0.59	1.67E-03
	1465	72	0.452	7.83E-04	0.57	1.38E-03
	2575	91	0.425	4.72E-04	0.65	7.30E-04
	4060	112	0.404	2.77E-04	0.67	4.12E-04
	5650	131	0.391	1.80E-04	0.70	2.57E-04
	6940	141	0.384	1.45E-04	0.83	1.74E-04
	8590	155	0.376	9.08E-05	0.95	9.51E-05
	9970	165	0.732	6.26E-05	1.06	5.89E-05
	12670	184	0.365	1.35E-04	1.17	1.16E-04
60	25	-3	0.491	5.66E-02	0.64	8.90E-02
	30	-3	0.491	2.93E-02	0.64	4.60E-02
	40	-2	0.491	7.60E-03	0.64	1.18E-02
	50	-1	0.491	7.93E-03	0.62	1.28E-02
	80	1	0.491	8.14E-03	0.62	1.31E-02
	111	4	0.488	7.88E-03	0.64	1.23E-02
	140	7	0.485	7.88E-03	0.64	1.24E-02
	170	11	0.482	7.92E-03	0.62	1.27E-02
	206	14	0.480	7.75E-03	0.64	1.21E-02

APPENDIX TABLE C.3—*Continued*

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
60—*Cont.*	235	16	0.478	7.44E-03	0.64	1.16E-02
	1015	53	0.457	1.90E-03	0.66	2.89E-03
	1465	63	0.453	1.50E-03	0.66	2.26E-03
	2575	86	0.444	8.85E-04	0.65	1.37E-03
	4060	107	0.437	5.14E-04	0.67	7.69E-04
	5650	126	0.431	3.45E-04	0.74	4.69E-04
	6940	140	0.426	2.91E-04	0.78	3.73E-04
	8590	157	0.421	1.87E-04	0.85	2.19E-04
	9970	169	0.419	1.23E-04	0.85	1.45E-04
	12670	192	0.414	2.35E-04	0.97	2.44E-04
90	25	-25	0.491	6.70E-02	0.18	3.69E-01
	30	-25	0.491	3.30E-02	0.22	1.51E-01
	40	-22	0.491	6.15E-03	0.28	2.23E-02
	50	-19	0.491	6.35E-03	0.36	1.78E-02
	80	-15	0.491	7.70E-03	0.51	1.50E-02
	111	-11	0.491	9.21E-03	0.49	1.87E-02
	140	-9	0.491	9.76E-03	0.46	2.12E-02
	170	-5	0.491	9.81E-03	0.47	2.09E-02
	206	-1	0.491	9.60E-03	0.-6	2.07E-02
	235	1	0.491	9.22E-03	0.46	1.99E-02
	1015	36	0.466	2.29E-03	0.44	5.23E-03
	1465	50	0.458	1.79E-03	0.56	3.21E-03
	2575	67	0.452	1.06E-03	0.29	3.65E-03
	4060	89	0.443	6.58E-04	0.34	1.94E-03
	5650	113	0.435	4.66E-04	0.53	8.76E-04
	6940	123	0.431	3.95E-04	0.30	1.30E-03
	8590	143	0.425	2.62E-04	0.38	6.83E-04
	9970	152	0.422	1.78E-04	0.25	7.20E-04
	12670	177	0.417	2.82E-04	0.28	1.02E-03
120	25	-33	0.491	8.32E-02	1.57	5.30E-02
	30	-32	0.491	3.86E-02	1.55	2.49E-02
	40	-29	0.491	2.95E-03	1.50	1.97E-03
	50	-26	0.491	3.28E-03	1.41	2.33E-03
	80	-19	0.491	6.20E-03	1.33	4.65E-03
	111	-17	0.491	9.60E-03	1.30	7.41E-03
	140	-15	0.491	1.07E-02	1.29	8.34E-03
	170	-11	0.491	1.08E-02	1.26	8.57E-03
	206	-8	0.491	1.06E-02	1.23	8.60E-03
	235	-7	0.491	1.02E-02	1.20	8.48E-03
	1015	31	0.468	2.92E-03	1.43	2.04E-03
	1465	45	0.461	2.17E-03	1.29	1.67E-03
	2575	57	0.455	1.19E-03	1.32	8.98E-04
	4060	80	0.447	8.30E-04	1.24	6.70E-04
	5650	106	0.437	6.05E-04	1.14	5.31E-04
	6940	112	0.435	4.88E-04	1.14	4.27E-04
	8590	133	0.428	3.36E-04	1.13	2.97E-04
	9970	139	0.426	2.51E-04	1.13	2.22E-04
	12670	163	0.420	3.28E-04	1.08	3.04E-04

APPENDIX TABLE C.4. HYDRAULIC CONDUCTIVITY AND ASSOCIATED SUCTION, WATER CONTENT, FLUX, AND HYDRAULIC GRADIENT DURING POSTINFILTRATION DRAINAGE FOR SITE L2-2 (SET 1), O'AHU, HAWAI'I

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
20	28	2	0.577	2.15E-02	0.77	2.78E-02
	38	7	0.567	1.41E-02	0.66	2.15E-02
	48	10	0.561	9.84E-03	0.66	1.49E-02
	58	14	0.553	8.60E-03	0.56	1.53E-02
	68	17	0.547	8.70E-03	0.59	1.48E-02
	78	19	0.543	8.43E-03	0.59	1.44E-02
	98	23	0.535	6.82E-03	0.57	1.20E-02
	118	27	0.527	4.79E-03	0.55	8.78E-03
	148	30	0.522	2.83E-03	0.51	5.51E-03
	178	32	0.518	2.19E-03	0.56	3.93E-03
	238	37	0.510	2.15E-03	0.47	4.56E-03
	308	42	0.501	1.97E-03	0.44	4.46E-03
	1083	72	0.460	5.40E-04	0.41	1.33E-03
	1548	83	0.446	5.02E-04	0.47	1.06E-03
	2668	105	0.421	3.86E-04	0.45	8.49E-04
	4128	127	0.400	2.46E-04	0.45	5.51E-04
	5718	144	0.383	1.74E-04	0.58	3.02E-04
	7008	155	0.374	1.46E-04	0.76	1.92E-04
	8658	169	0.363	9.76E-05	0.96	1.02E-04
	10038	177	0.357	7.72E-05	1.10	7.04E-05
	13008	201	0.340	2.05E-04	1.26	1.63E-04
30	28	2	0.522	2.45E-02	1.16	2.11E-02
	38	6	0.521	1.66E-02	1.00	1.67E-02
	48	8	0.520	1.20E-02	0.94	1.28E-02
	58	11	0.519	1.07E-02	0.76	1.40E-02
	68	14	0.519	1.08E-02	0.70	1.54E-02
	78	16	0.518	1.05E-02	0.70	1.49E-02
	98	19	0.517	8.52E-03	0.58	1.48E-02
	118	23	0.516	6.06E-03	0.52	1.16E-02
	148	25	0.516	3.70E-03	0.47	7.95E-03
	178	28	0.513	2.91E-03	0.53	5.51E-03
	238	31	0.509	2.86E-03	0.40	7.11E-03
	308	36	0.505	2.64E-03	0.35	7.63E-03
	1083	65	0.474	8.42E-04	0.29	2.94E-03
	1548	77	0.462	7.49E-04	0.40	1.8 E-03
	2668	99	0.439	5.39E-04	0.39	1.37E-03
	4128	122	0.424	3.34E-04	0.51	6.58E-04
	5718	141	0.413	2.39E-04	0.78	3.06E-04
	7008	154	0.405	2.07E-04	1.04	1.99E-04
	8658	172	0.396	1.40E-04	1.43	9.81E-05
	10038	181	0.391	1.08E-04	1.59	6.82E-05
	13008	209	0.377	2.89E-04	2.12	1.36E-04

APPENDIX TABLE C.4—*Continued*

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
60	28	-7	0.508	2.52E-02	0.36	6.98E-02
	38	-6	0.508	1.82E-02	0.36	5.06E-02
	48	-5	0.508	1.41E-02	0.34	4.09E-02
	58	-4	0.508	1.30E-02	0.41	3.17E-02
	68	-3	0.508	1.31E-02	0.40	3.29E-02
	78	-1	0.508	1.27E-02	0.38	3.32E-02
	98	1	0.507	1.06E-02	0.42	2.50E-02
	118	3	0.505	7.92E-03	0.41	2.95E-02
	148	5	0.504	5.32E-03	0.44	1.22E-02
	178	7	0.502	4.46E-03	0.37	1.20E-02
	238	12	0.497	4.38E-03	0.50	8.71E-03
	308	16	0.494	4.08E-03	0.55	7.44E-03
	1083	46	0.469	1.58E-03	0.70	2.26E-03
	1548	59	0.460	1.37E-03	0.67	2.05E-03
	2668	83	0.444	9.39E-04	0.76	1.23E-03
	4128	110	0.429	5.73E-04	0.90	6.37E-04
	5718	136	0.418	4.24E-04	1.02	4.13E-04
	7008	147	0.413	3.88E-04	0.89	4.34E-04
	8658	172	0.402	2.82E-04	1.00	2.81E-04
	10038	185	0.396	2.30E-04	1.14	2.02E-04
	13008	232	0.375	5.72E-04	1.53	3.74E-04

APPENDIX TABLE C.5. HYDRAULIC CONDUCTIVITY AND ASSOCIATED SUCTION, WATER CONTENT, FLUX, AND HYDRAULIC GRADIENT DURING POSTINFILTRATION DRAINAGE FOR SITE L3-1 (SET 1), O'AHU, HAWAI'I

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
20	10	2	0.496	5.86E-02	1.04	5.66E-02
	15	0	0.497	3.53E-02	0.88	4.01E-02
	25	4	0.496	4.01E-03	0.74	5.42E-03
	35	6	0.495	-6.66E-03	0.59	-1.14E-02
	50	11	0.494	-6.45E-03	0.70	-9.22E-03
	80	18	0.492	-9.89E-04	0.71	-1.39E-03
	110	22	0.491	5.44E-03	0.75	7.25E-03
	140	25	0.490	7.07E-03	0.77	9.19E-03
	155	26	0.489	6.69E-03	0.76	8.80E-03
	875	67	0.463	-1.45E-03	1.14	-1.27E-03
	2885	78	0.455	8.56E-04	1.34	6.40E-04
	3920	124	0.429	4.32E-04	1.44	2.99E-04
	5610	133	0.425	-8.63E-05	1.81	-4.76E-05
	6879	145	0.420	4.57E-04	1.57	2.91E-04
30	10	1	0.496	7.35E-02	0.75	9.74E-02
	15	-1	0.497	4.39E-02	0.85	5.16E-02
	25	3	0.496	4.32E-03	1.04	4.16E-03
	35	5	0.495	-9.20E-03	1.23	-7.47E-03
	50	9	0.494	-8.92E-03	0.92	-9.68E-03
	80	15	0.492	-1.48E-03	0.79	-1.88E-03
	110	20	0.491	7.28E-03	0.82	8.92E-03
	140	23	0.490	9.51E-03	0.88	1.08E-02
	155	24	0.490	9.00E-03	0.89	1.01E-02
	875	69	0.461	-1.92E-03	1.20	-1.60E-03
	2885	82	0.452	1.14E-03	1.48	7.74E-04
	3920	128	0.427	5.90E-04	1.47	4.01E-04
	5610	142	0.421	-1.07E-04	1.97	-5.43E-05
	6879	152	0.417	5.90E-04	1.73	3.41E-04
60	10	-6	0.504	1.19E-01	0.99	1.21E-01
	15	-4	0.504	7.22E-02	1.01	7.12E-02
	25	4	0.502	9.11E-03	0.84	1.09E-02
	35	11	0.496	-1.24E-02	0.72	-1.73E-02
	50	7	0.499	-1.20E-02	0.80	-1.50E-02
	80	11	0.496	-4.90E-04	0.88	-5.55E-04
	110	16	0.492	1.31E-02	0.91	1.44E-02
	140	21	0.489	1.65E-02	0.91	1.80E-02
	155	23	0.487	1.56E-02	0.97	1.60E-02
	875	70	0.451	-2.82E-03	0.79	-3.57E-03
	2885	88	0.440	1.84E-03	0.72	2.54E-03
	3920	132	0.419	1.02E-03	0.69	1.48E-03
	5610	154	0.412	-1.40E-04	0.53	-2.67E-04
	6875	158	0.411	7.72E-04	0.40	1.91E-03

APPENDIX TABLE C.5—*Continued*

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
90	10	-2	0.504	1.42E-01	1.18	1.20E-01
	15	-2	0.504	8.64E-02	1.12	7.74E-02
	25	0	0.504	1.21E-02	1.09	1.11E-02
	35	1	0.504	-1.34E-02	1.01	-1.32E-02
	50	4	0.501	-1.29E-02	1.16	-1.11E-02
	80	10	0.497	1.83E-03	1.10	1.67E-03
	110	16	0.492	1.92E-02	1.16	1.66E-02
	140	22	0.488	2.34E-02	1.25	1.88E-02
	155	25	0.485	2.22E-02	1.25	1.78E-02
	875	65	0.454	-3.76E-03	1.13	-3.32E-03
	2885	80	0.445	2.55E-03	1.14	2.23E-03
	3920	123	0.423	1.45E-03	1.00	1.45E-03
	5610	137	0.417	-1.88E-04	0.95	-1.98E-04
	6875	139	0.417	9.37E-04	0.89	1.05E-03

APPENDIX TABLE C.6. HYDRAULIC CONDUCTIVITY AND ASSOCIATED SUCTION, WATER CONTENT, FLUX, AND HYDRAULIC GRADIENT DURING POSTINFILTRATION DRAINAGE FOR SITE L3-2 (SET 1), O'AHU, HAWAI'I

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
20	7	-1	0.541	3.16E-03	1.17	2.71E-03
	12	4	0.539	6.30E-03	0.97	6.48E-03
	22	6	0.538	9.07E-03	0.88	1.03E-02
	32	12	0.535	8.84E-03	0.69	1.27E-02
	44	18	0.532	6.82E-03	0.55	1.24E-02
	54	20	0.530	4.66E-03	0.50	9.31E-03
	64	22	0.529	3.11E-03	0.51	6.15E-03
	84	26	0.527	1.88E-03	0.54	3.49E-03
	119	29	0.524	1.87E-03	0.57	3.27E-03
	149	32	0.521	1.82E-03	0.62	2.93E-03
	179	36	0.518	1.74E-03	0.61	2.85E-03
	197	37	0.517	1.69E-03	0.60	2.81E-03
	917	67	0.485	6.06E-04	0.89	6.82E-04
	1467	82	0.467	5.27E-04	1.04	5.04E-04
	2892	104	0.442	1.71E-04	1.31	1.30E-04
	3967	117	0.434	1.30E-04	1.38	9.44E-05
	5652	129	0.427	6.08E-06	1.50	4.05E-06
30	7	1	0.506	5.04E-03	1.24	4.06E-03
	12	4	0.505	8.03E-03	1.08	7.47E-03
	22	6	0.505	1.07E-02	1.09	9.81E-03
	32	11	0.503	1.05E-02	1.01	1.04E-02
	44	15	0.501	8.23E-03	0.90	9.15E-03
	54	17	0.500	5.84E-03	0.84	6.94E-03
	64	19	0.500	4.14E-03	0.91	4.56E-03
	84	23	0.498	2.79E-03	0.89	3.13E-03
	119	27	0.495	2.78E-03	1.01	2.76E-03
	149	31	0.491	2.72E-03	1.07	2.55E-03
	179	34	0.488	2.59E-03	1.06	2.45E-03
	197	35	0.487	2.50E-03	1.05	2.38E-03
	917	69	0.459	8.36E-04	1.40	5.97E-04
	1467	85	0.446	7.57E-04	1.52	4.99E-04
	2892	111	0.431	2.38E-04	1.98	1.20E-04
	3967	125	0.425	1.80E-04	2.10	8.56E-05
	5652	138	0.420	2.34E-05	2.12	1.11E-05
50	7	2	0.509	7.39E-03	0.64	1.15E-02
	12	4	0.507	1.07E-02	0.83	1.28E-02
	22	6	0.505	1.36E-02	0.76	1.79E-02
	32	9	0.502	1.33E-02	0.59	2.27E-02
	44	13	0.497	1.09E-02	0.70	1.55E-02
	54	15	0.495	8.26E-03	0.78	1.07E-02
	64	17	0.493	6.40E-03	0.66	9.64E-03
	84	22	0.488	4.95E-03	0.85	5.84E-03
	119	28	0.482	4.97E-03	0.83	5.98E-03
	149	32	0.478	4.85E-03	0.76	6.42E-03
	179	36	0.475	4.60E-03	0.90	5.10E-03
	197	38	0.473	4.42E-03	1.05	4.21E-03
	917	73	0.445	1.22E-03	0.62	1.96E-03
	1467	89	0.433	1.20E-03	0.36	3.31E-03
	2892	119	0.414	3.61E-04	0.03	1.30E-02
	3967	134	0.406	2.87E-04	-0.06	-5.17E-03
	5652	142	0.402	1.37E-05	-0.55	-2.49E-05

APPENDIX TABLE C.7. HYDRAULIC CONDUCTIVITY AND ASSOCIATED SUCTION, WATER CONTENT, FLUX, AND HYDRAULIC GRADIENT DURING POSTINFILTRATION DRAINAGE FOR SITE M1-1, O'AHU, HAWAI'I

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
30	30	2	0.518	3.52E-02	0.83	4.24E-02
	110	6	0.515	5.48E-03	0.77	7.10E-03
	140	11	0.512	5.40E-03	0.82	6.56E-03
	170	16	0.510	5.17E-03	0.75	6.86E-03
	919	65	0.465	1.06E-03	0.71	1.50E-03
	2734	107	0.435	3.36E-04	0.77	4.37E-04
	3934	126	0.426	2.22E-04	0.64	3.47E-04
	5839	147	0.416	1.43E-04	0.86	1.66E-04
	7219	164	0.409	1.25E-04	0.97	1.29E-04
	8279	176	0.405	1.03E-04	0.97	1.07E-04
	10016	190	0.400	7.87E-05	1.18	6.67E-05
	11419	203	0.395	8.37E-05	1.29	6.50E-05
	12559	211	0.394	1.04E-04	1.29	8.03E-05
60	80	-2	0.505	3.37E-02	1.01	3.33E-02
	110	2	0.503	8.86E-03	1.02	8.67E-03
	140	6	0.499	8.70E-03	0.93	9.35E-03
	170	9	0.496	8.34E-03	0.91	9.15E-03
	919	61	0.453	2.00E-03	0.88	2.26E-03
	2734	105	0.427	5.93E-04	0.86	6.89E-04
	3934	127	0.417	4.24E-04	0.93	4.54E-04
	5839	152	0.406	2.91E-04	0.97	3.01E-04
	7219	171	0.401	2.50E-04	1.02	2.45E-04
	8279	182	0.397	2.14E-04	1.05	2.04E-04
	10016	200	0.392	1.67E-04	1.06	1.57E-04
	11419	214	0.389	1.50E-04	1.05	1.43E-04
	12559	225	0.387	1.51E-04	1.08	1.40E-04
90	80	1	0.504	3.01E-02	1.02	2.96E-02
	110	5	0.501	1.26E-02	0.97	1.30E-02
	140	6	0.499	1.24E-02	0.96	1.28E-02
	170	9	0.497	1.18E-02	0.92	1.29E-02
	919	54	0.457	2.68E-03	0.60	4.44E-03
	2734	94	0.433	8.63E-04	0.47	1.84E-03
	3934	114	0.423	6.38E-04	0.43	1.49E-03
	5839	140	0.411	4.39E-04	0.52	8.49E-04
	7219	160	0.404	3.67E-04	0.43	8.63E-04
	8279	172	0.400	3.13E-04	0.43	7.26E-04
	10016	188	0.396	2.42E-04	0.42	5.76E-04
	11419	203	0.392	2.09E-04	0.47	4.46E-04
	12559	212	0.390	1.98E-04	0.46	4.34E-04

APPENDIX TABLE C.8. HYDRAULIC CONDUCTIVITY AND ASSOCIATED SUCTION, WATER CONTENT, FLUX, AND HYDRAULIC GRADIENT DURING POST-INFILTRATION DRAINAGE FOR SITE M1-2, O'AHU, HAWAI'I

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
30	30	1	0.532	9.14E-02	0.64	1.42E-01
	50	6	0.529	2.51E-02	0.49	5.09E-02
	70	11	0.525	3.50E-03	0.35	1.00E-02
	90	14	0.523	3.33E-03	0.41	8.20E-03
	120	18	0.520	3.14E-03	0.35	8.90E-03
	150	22	0.518	3.01E-03	0.45	6.76E-03
	180	24	0.516	2.88E-03	0.47	6.12E-03
	970	69	0.453	9.87E-04	0.87	1.13E-03
	2745	109	0.422	4.22E-04	1.12	3.76E-04
	3945	127	0.413	3.36E-04	1.21	2.76E-04
	5730	151	0.402	1.93E-04	1.34	1.45E-04
	7230	167	0.396	8.85E-05	1.48	6.00E-05
	8290	173	0.394	4.17E-05	0.88	4.71E-05
50	30	5	0.511	8.88E-02	0.92	9.67E-02
	50	10	0.511	2.71E-02	1.02	2.56E-02
	70	16	0.505	7.04E-03	1.70	4.14E-03
	90	11	0.510	6.86E-03	0.51	1.34E-02
	120	23	0.497	6.61E-03	1.72	3.85E-03
	150	20	0.499	6.38E-03	0.73	8.79E-03
	180	28	0.491	6.14E-03	1.39	4.42E-03
	970	62	0.466	2.26E-03	-0.82	-2.75E-03
	2745	96	0.446	5.83E-04	-1.94	-3.01E-04
	3945	108	0.439	5.75E-04	-2.92	-1.97E-04
	5730	140	0.426	3.31E-04	-2.18	-1.52E-04
	7230	160	0.418	2.82E-04	-1.86	-1.51E-04
	8290	355	0.384	5.75E-04	17.69	3.25E-05

APPENDIX TABLE C.9. HYDRAULIC CONDUCTIVITY AND ASSOCIATED SUCTION, WATER CONTENT, FLUX, AND HYDRAULIC GRADIENT DURING POST-INFILTRATION DRAINAGE FOR SITE M3-1, O'AHU, HAWAI'I

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
20	15	3	0.570	-1.76E-02	0.47	-3.77E-02
	25	8	0.567	1.98E-02	0.49	4.06E-02
	35	13	0.565	1.90E-02	0.40	4.79E-02
	45	16	0.563	1.42E-02	0.32	4.49E-02
	55	19	0.561	8.42E-03	0.29	2.87E-02
	75	24	0.559	3.55E-03	0.21	2.71E-02
	105	27	0.556	3.24E-03	0.27	1.20E-02
	135	31	0.553	3.14E-03	0.22	1.41E-02
	165	33	0.550	3.14E-03	0.27	1.17E-02
	225	38	0.545	3.03E-03	0.29	1.04E-02
	290	42	0.541	2.73E-03	0.34	8.08E-03
	1035	73	0.495	5.32E-04	0.55	9.65E-04
	1485	82	0.478	5.41E-04	0.64	8.50E-04
	2675	106	0.443	4.06E-04	0.70	5.76E-04
	4155	126	0.424	1.75E-04	0.90	1.94E-04
	5495	141	0.411	1.09E-04	0.98	1.12E-04
	7230	156	0.401	9.18E-05	1.19	7.72E-04
	8430	168	0.396	5.89E-05	1.24	4.73E-05
	9675	179	0.392	6.38E-06	1.47	4.34E-06
30	15	-2	0.571	-1.63E-02	0.48	-3.35E-02
	25	2	0.570	2.24E-02	0.36	6.16E-02
	35	7	0.568	2.14E-02	0.32	6.72E-02
	45	9	0.566	1.62E-02	0.31	5.21E-02
	55	12	0.565	9.63E-03	0.25	3.66E-02
	75	15	0.564	4.10E-03	0.16	2.50E-02
	105	20	0.561	3.75E-03	0.28	1.36E-02
	135	23	0.560	3.77E-03	0.26	1.43E-02
	165	26	0.558	3.95E-03	0.27	1.44E-02
	225	31	0.552	4.04E-03	0.32	1.26E-02
	290	36	0.547	3.75E-03	0.42	9.02E-03
	1035	69	0.501	9.23E-04	0.74	1.24E-03
	1485	80	0.482	8.98E-04	0.84	1.07E-03
	2675	105	0.444	6.40E-04	0.98	6.54E-04
	4155	127	0.424	2.77E-04	1.17	2.37E-04
	5495	144	0.408	1.74E-04	1.46	1.20E-04
	7230	161	0.399	1.50E-04	1.74	8.61E-05
	8430	174	0.394	9.81E-05	1.79	5.50E-05
	9675	186	0.389	1.39E-05	1.94	7.16E-06

APPENDIX TABLE C.9—*Continued*

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
60	15	-9	0.514	-2.71E-02	1.15	-2.37E-02
	25	-8	0.514	2.67E-02	1.08	2.48E-02
	35	-5	0.514	2.58E-02	1.01	2.57E-02
	45	-2	0.514	2.04E-02	1.01	2.02E-02
	55	0	0.514	1.33E-02	1.01	1.32E-02
	75	2	0.512	7.28E-03	1.01	7.18E-03
	105	7	0.506	6.83E-03	0.90	7.60E-03
	135	10	0.502	6.97E-03	0.94	7.41E-03
	165	13	0.499	7.35E-03	0.90	8.14E-03
	225	19	0.492	7.57E-03	0.90	8.40E-03
	290	25	0.484	7.01E-03	0.90	7.82E-03
	1035	61	0.452	1.47E-03	0.63	2.33E-03
	1485	73	0.444	1.50E-03	0.63	2.38E-03
	2675	101	0.426	1.17E-03	0.63	1.86E-03
	4155	127	0.410	5.75E-04	0.70	8.26E-04
	5495	149	0.396	3.40E-04	0.61	5.59E-04
	7230	171	0.392	2.27E-04	0.63	3.60E-04
	8430	186	0.390	1.58E-04	0.67	2.34E-04
	9675	200	0.388	9.21E-05	0.67	1.37E-04
90	15	-2	0.514	-3.08E-02	1.09	-2.82E-02
	25	-2	0.514	2.82E-02	1.15	2.45E-02
	35	0	0.514	2.75E-02	1.14	2.42E-02
	45	2	0.511	2.29E-02	1.11	2.06E-02
	55	4	0.509	1.66E-02	1.11	1.49E-02
	75	7	0.506	1.10E-02	1.12	9.82E-03
	105	8	0.504	1.05E-02	1.09	9.66E-03
	135	12	0.500	1.06E-02	1.01	1.05E-02
	165	14	0.498	1.09E-02	1.03	1.06E-02
	225	20	0.491	1.09E-02	1.02	9.82E-02
	290	25	0.484	9.95E-03	1.01	2.11E-03
	1035	52	0.458	1.82E-03	0.86	2.34E-03
	1485	63	0.451	1.94E-03	0.83	2.24E-03
	2675	89	0.434	1.62E-03	0.72	1.25E-03
	4155	116	0.416	8.66E-04	0.69	8.29E-03
	5495	133	0.406	5.27E-04	0.64	8.29E-04
	7230	154	0.395	3.23E-04	0.61	5.29E-04
	8430	169	0.392	2.11E-04	0.53	3.99E-04
	9675	182	0.391	1.20E-04	0.46	2.60E-04

APPENDIX TABLE C.10. HYDRAULIC CONDUCTIVITY AND ASSOCIATED SUCTION, WATER CONTENT, FLUX, AND HYDRAULIC GRADIENT DURING POST-INFILTRATION DRAINAGE FOR SITE M3-2, O'AHU, HAWAI'I

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
20	18	5	0.586	2.98E-02	0.60	4.98E-02
	22	7	0.582	2.31E-02	0.56	4.17E-02
	32	13	0.570	1.66E-02	0.49	3.42E-02
	42	17	0.562	1.60E-02	0.43	3.74E-02
	52	19	0.558	1.31E-02	0.44	2.99E-02
	62	21	0.553	9.44E-03	0.39	2.43E-02
	72	23	0.549	6.88E-03	0.37	1.88E-02
	87	26	0.543	5.03E-03	0.43	1.19E-02
	117	30	0.535	4.08E-03	0.29	1.39E-02
	147	33	0.528	3.83E-03	0.35	1.10E-02
	207	37	0.520	3.67E-03	0.32	1.15E-02
	267	42	0.509	2.80E-03	0.35	8.08E-03
	315	44	0.504	2.01E-03	0.36	5.54E-03
	390	48	0.496	1.48E-03	0.35	4.21E-03
	1120	73	0.450	8.51E-04	0.62	1.36E-03
	1570	74	0.449	6.43E-04	0.70	9.25E-04
	2745	96	0.409	3.07E-04	0.98	3.14E-04
	4240	104	0.399	1.31E-04	1.04	1.26E-04
	5580	120	0.387	7.79E-05	1.31	5.93E-05
	7315	137	0.374	1.58E-04	1.50	1.05E-04
30	18	2	0.558	4.68E-04	0.79	5.92E-02
	22	3	0.556	3.42E-02	0.73	4.70E-02
	32	8	0.550	2.13E-02	0.61	3.50E-02
	42	11	0.546	2.05E-02	0.50	4.13E-02
	52	13	0.543	1.70E-02	0.50	3.39E-02
	62	15	0.541	1.28E-02	0.51	2.50E-02
	72	17	0.539	9.64E-03	0.46	2.10E-02
	87	20	0.534	7.14E-03	0.45	1.58E-02
	117	3	0.530	5.50E-03	0.41	1.33E-02
	147	26	0.526	5.37E-03	0.33	1.62E-02
	207	30	0.517	5.75E-03	0.39	1.46E-02
	267	35	0.507	4.43E-03	0.33	1.34E-02
	315	38	0.501	3.03E-03	0.46	6.63E-03
	390	42	0.492	2.11E-03	0.45	4.68E-03
	1120	70	0.451	1.22E-03	0.73	1.67E-03
	1570	75	0.445	9.22E-04	1.31	7.06E-04
	2745	99	0.414	4.42E-04	1.51	2.92E-04
	4240	113	0.406	1.91E-04	2.40	7.98E-05
	5580	129	0.396	1.26E-04	2.29	5.50E-05
	7315	147	0.386	2.66E-04	2.37	1.12E-04

APPENDIX TABLE C.10—*Continued*

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
60	18	-7	0.523	5.50E-02	0.64	8.57E-02
	22	-5	0.523	4.26E-02	0.71	6.02E-02
	32	-1	0.523	2.97E-02	0.71	4.18E-02
	42	0	0.523	2.85E-02	0.70	4.09E-02
	52	1	0.522	2.41E-02	0.65	3.71E-02
	62	3	0.520	1.87E-02	0.64	2.92E-02
	72	3	0.520	1.46E-02	0.62	2.35E-02
	87	5	0.518	1.10E-02	0.57	1.93E-02
	117	8	0.514	8.05E-03	0.58	1.38E-02
	147	11	0.511	8.38E-03	0.66	1.26E-02
	207	17	0.504	1.03E-02	0.65	1.59E-02
	267	20	0.501	8.30E-03	0.65	1.28E-02
	315	24	0.496	5.73E-03	0.60	9.64E-03
	390	29	0.492	4.05E-03	0.63	6.44E-03
	1120	58	0.469	2.28E-03	0.48	4.72E-03
	1570	66	0.464	1.71E-03	0.19	9.24E-03
	2745	92	0.447	8.13E-04	0.14	5.83E-03
	4240	115	0.436	3.69E-04	-0.12	-3.19E-03
	5580	129	0.430	2.42E-04	-0.08	-3.28E-03
	7315	151	0.421	4.92E-04	0.06	8.63E-03

APPENDIX TABLE C.11. HYDRAULIC CONDUCTIVITY AND ASSOCIATED SUCTION, WATER CONTENT, FLUX, AND HYDRAULIC GRADIENT DURING POST-INFILTRATION DRAINAGE FOR SITE W1-1, O'AHU, HAWAI'I

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
20	29	5	0.581	1.02E-02	0.91	1.13E-02
	37	7	0.572	1.09E-02	0.55	1.99E-02
	48	9	0.565	1.11E-02	0.42	2.61E-02
	78	11	0.558	9.70E-03	0.34	2.86E-02
	108	13	0.552	7.57E-03	0.22	3.45E-02
	138	16	0.541	5.57E-03	0.21	2.69E-02
	169	18	0.534	4.56E-03	0.24	1.87E-02
	198	19	0.531	4.15E-03	0.24	1.70E-02
	228	20	0.528	3.76E-03	0.21	1.82E-02
	258	22	0.521	3.46E-03	0.19	1.80E-02
	288	23	0.517	3.17E-03	0.28	1.12E-02
	348	23	0.517	2.65E-03	0.20	1.34E-02
	908	37	0.475	5.37E-04	0.33	1.62E-03
	1563	46	0.448	5.52E-04	0.40	1.38E-03
	2598	59	0.426	1.90E-04	0.47	4.06E-04
	2848	61	0.424	1.99E-04	0.46	4.34E-04
	4001	71	0.412	2.37E-04	0.38	6.18E-04
	5448	82	0.400	1.70E-05	0.49	3.48E-05
	8448	100	0.379	6.30E-04	0.58	1.08E-03
30	29	3	0.568	1.28E-02	0.72	1.78E-02
	37	2	0.569	1.27E-02	0.56	2.27E-02
	48	3	0.568	1.25E-02	0.52	2.42E-02
	78	4	0.567	1.13E-02	0.45	2.49E-02
	108	6	0.566	8.76E-03	0.48	1.84E-02
	138	9	0.563	6.25E-03	0.42	1.47E-02
	169	11	0.561	5.08E-03	0.43	1.18E-02
	198	12	0.560	4.68E-03	0.43	1.09E-02
	228	13	0.559	4.32E-03	0.44	9.86E-03
	258	15	0.558	4.01E-03	0.37	1.08E-02
	288	17	0.556	3.73E-03	0.45	8.30E-03
	348	17	0.536	3.20E-03	0.51	6.24E-03
	908	31	0.532	1.01E-03	0.51	2.00E-03
	1563	41	0.506	8.70E-04	0.62	1.41E-03
	2598	56	0.476	3.56E-04	0.76	4.71E-04
	2848	57	0.475	3.39E-04	0.66	5.10E-04
	4001	67	0.462	3.15E-04	0.69	4.53E-04
	5448	79	0.447	1.65E-04	0.75	2.21E-04
	8448	98	0.423	4.06E-04	0.80	5.07E-04

APPENDIX TABLE C.11—*Continued*

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
60	29	-12	0.508	6.19E-03	0.71	8.73E-03
	37	-3	0.508	1.20E-02	0.90	1.34E-04
	48	-1	0.508	1.42E-02	1.00	1.41E-02
	78	1	0.507	1.31E-02	1.02	1.29E-02
	108	3	0.505	1.04E-02	0.98	1.06E-02
	138	4	0.504	7.59E-03	0.98	7.72E-03
	169	5	0.503	6.31E-03	0.98	6.42E-03
	198	6	0.502	5.88E-03	0.98	5.99E-03
	228	7	0.501	5.49E-03	0.98	5.59E-03
	258	8	0.500	5.14E-03	0.99	5.21E-03
	288	8	0.500	4.83E-03	0.98	4.91E-03
	348	11	0.496	4.24E-03	1.01	4.20E-03
	908	23	0.484	1.69E-03	0.97	1.74E-03
	1563	35	0.474	1.41E-03	0.97	1.45E-03
	2598	48	0.465	6.58E-04	0.85	7.72E-04
	2848	51	0.463	5.83E-04	0.89	6.58E-04
	5448	71	0.454	4.51E-04	0.81	5.58E-04
	8448	89	0.446	-1.99E-04	0.72	-2.76E-04
90	29	-5	0.508	1.20E-03	1.59	7.53E-04
	37	-4	0.508	1.15E-02	1.28	8.98E-03
	48	0	0.508	1.54E-02	1.09	1.41E-02
	78	0	0.508	1.42E-02	1.04	1.37E-02
	108	1	0.507	1.16E-02	1.12	1.03E-02
	138	3	0.505	9.03E-03	1.09	8.31E-03
	169	6	0.502	7.76E-03	1.10	7.08E-03
	198	7	0.501	7.27E-03	1.10	6.63E-03
	228	8	0.500	6.81E-03	1.10	6.21E-03
	258	9	0.499	6.40E-03	1.10	5.84E-03
	288	11	0.496	6.02E-03	1.07	5.64E-03
	348	13	0.495	5.33E-03	1.06	5.05E-03
	908	27	0.480	2.18E-03	1.12	1.95E-03
	1563	37	0.473	1.72E-03	1.01	1.70E-03
	2598	47	0.466	8.41E-04	0.92	9.18E-04
	2848	48	0.465	7.38E-04	0.90	8.19E-04
	4001	56	0.461	4.98E-04	0.76	6.52E-04
	5448	66	0.456	5.84E-04	0.76	7.67E-04
	8448	81	0.450	-3.82E-04	0.71	-5.41E-04

APPENDIX TABLE C.12. HYDRAULIC CONDUCTIVITY AND ASSOCIATED SUCTION, WATER CONTENT, FLUX, AND HYDRAULIC GRADIENT DURING POST-INFILTRATION DRAINAGE FOR SITE W1-2, O'AHU, HAWAI'I

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
20	70	10	0.569	2.49E-02	0.22	1.15E-01
	85	11	0.564	1.52E-02	0.12	1.30E-01
	98	13	0.557	9.29E-03	0.07	1.39E-01
	127	15	0.548	4.16E-03	0.07	6.25E-02
	157	16	0.544	4.42E-03	0.02	1.99E-01
	188	18	0.533	4.26E-03	0.04	1.10E-01
	215	19	0.529	3.77E-03	-0.02	-1.70E-01
	248	20	0.527	3.04E-03	0.02	1.37E-01
	278	22	0.516	2.50E-03	0.04	6.42E-02
	308	22	0.518	2.07E-03	-0.02	-9.33E-02
	338	23	0.513	1.77E-03	0.06	3.18E-02
	400	25	0.506	1.52E-03	0.02	6.84E-02
	966	37	0.465	1.15E-03	0.00	1.38E-03
	1621	50	0.422	4.90E-04	0.06	8.02E-03
	2651	62	0.408	1.75E-04	0.18	9.84E-04
	2856	64	0.406	1.80E-04	0.12	1.47E-03
	4054	74	0.394	1.84E-04	0.28	6.49E-04
	5496	84	0.383	1.51E-04	0.32	4.73E-04
	8526	100	0.365	-6.75E-07	0.42	-1.60E-06
30	70	1	0.567	2.56E-02	0.09	2.79E-01
	85	2	0.566	1.60E-02	0.10	1.60E-01
	98	3	0.565	1.02E-02	0.04	2.45E-01
	127	5	0.563	5.49E-03	0.04	1.32E-01
	157	6	0.562	6.06E-03	0.05	1.21E-01
	188	8	0.560	5.85E-03	-0.01	-7.02E-01
	215	8	0.559	5.01E-03	0.08	-6.68E-02
	248	10	0.558	3.76E-03	0.05	7.52E-02
	278	12	0.555	2.85E-03	-0.01	-3.42E-01
	308	12	0.556	2.16E-03	0.06	3.71E-02
	338	14	0.554	1.70E-03	0.05	3.40E-02
	400	15	0.553	1.44E-03	0.05	2.88E-02
	966	27	0.538	1.83E-03	0.03	5.50E-02
	1621	40	0.506	8.30E-04	0.08	9.97E-03
	2651	54	0.478	3.24E-04	0.26	1.25E-03
	2856	55	0.476	3.18E-04	0.12	2.54E-03
	4054	67	0.460	2.86E-04	0.32	9.03E-04
	5496	77	0.445	2.38E-04	0.41	5.78E-04
	8526	94	4.421	5.99E-05	0.49	1.22E-04

APPENDIX TABLE C.12—*Continued*

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
50	70	-11	0.494	2.39E-02	0.89	2.68E-02
	85	-9	0.494	1.54E-02	0.97	1.59E-02
	98	-8	0.494	1.02E-02	1.04	9.80E-03
	127	-6	0.494	6.13E-03	1.04	5.89E-03
	157	-5	0.494	6.76E-03	1.01	6.72E-03
	188	-5	0.494	6.54E-03	0.95	6.91E-03
	215	-4	0.494	5.63E-03	1.17	4.81E-03
	248	-1	0.494	4.24E-03	1.01	4.22E-03
	278	-1	0.494	3.25E-03	0.95	3.43E-03
	308	1	0.493	2.50E-03	0.97	2.48E-03
	338	2	0.492	2.00E-03	0.94	2.12E-03
	400	4	0.490	1.74E-03	1.01	1.73E-03
	966	18	0.478	2.31E-03	1.30	1.78E-03
	1621	32	0.467	1.15E-03	1.33	8.69E-04
	2651	47	0.456	4.89E-04	1.17	4.18E-04
	2856	48	0.455	4.59E-04	1.48	3.10E-04
	4054	59	0.451	3.63E-04	0.98	3.69E-04
	5496	69	0.447	3.12E-04	0.82	3.79E-04
	8526	87	0.440	9.31E-05	0.78	1.19E-04

APPENDIX TABLE C.13. HYDRAULIC CONDUCTIVITY AND ASSOCIATED SUCTION, WATER CONTENT, FLUX, AND HYDRAULIC GRADIENT DURING POSTINFILTRATION DRAINAGE FOR SITE W3-2 (SET 1), O'AHU, HAWAI'I

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
20	620	6	0.570	-2.34E-02	0.44	5.30E-02
	623	7	0.568	1.93E-02	0.40	4.82E-02
	625	9	0.567	2.74E-02	0.39	7.09E-02
	627	10	0.565	2.67E-02	0.36	7.47E-02
	630	13	0.563	2.33E-02	0.32	7.25E-02
	635	15	0.560	1.63E-02	0.30	5.42E-02
	650	21	0.554	7.29E-03	0.24	2.99E-02
	665	25	0.550	7.07E-03	0.19	3.63E-02
	690	30	0.540	5.99E-03	0.22	2.77E-02
	735	38	0.527	3.72E-03	0.30	1.26E-02
	795	42	0.520	2.18E-03	0.27	7.97E-03
	870	46	0.512	1.46E-03	0.28	5.25E-03
	990	52	0.502	9.69E-04	0.29	3.34E-03
	1170	59	0.494	8.35E-04	0.35	2.41E-03
	1460	69	0.484	6.73E-04	0.38	1.79E-03
	1760	78	0.472	5.47E-04	0.40	1.36E-03
	2165	86	0.464	3.96E-04	0.45	8.88E-04
	2980	99	0.449	1.85E-04	0.49	3.77E-04
	3625	106	0.444	1.22E-04	0.51	2.39E-04
	4395	116	0.438	1.66E-04	0.57	2.93E-04
30	620	1	0.574	-1.50E-02	0.64	-2.35E-02
	623	2	0.573	2.49E-02	0.63	3.93E-02
	625	4	0.572	3.25E-02	0.59	5.49E-02
	627	5	0.571	3.18E-02	0.57	5.63E-02
	630	7	0.569	2.81E-02	0.49	5.79E-02
	635	9	0.566	2.05E-02	0.45	4.53E-02
	650	14	0.561	1.07E-02	0.40	2.66E-02
	665	18	0.558	1.04E-02	0.35	2.97E-02
	690	23	0.552	8.88E-03	0.32	2.77E-02
	735	30	0.540	5.64E-03	0.20	2.82E-02
	795	34	0.533	3.44E-03	0.30	1.14E-02
	870	39	0.524	2.44E-03	0.36	6.81E-03
	990	46	0.513	1.65E-03	0.40	4.13E-03
	1170	53	0.501	1.30E-03	0.46	2.84E-03
	1460	63	0.490	9.98E-04	0.48	2.09E-03
	1760	73	0.479	8.53E-04	0.52	1.64E-03
	2165	80	0.470	6.41E-04	0.52	1.23E-03
	2980	94	0.454	3.07E-04	0.59	5.17E-04
	3625	101	0.446	2.03E-04	0.63	3.22E-04
	4395	112	0.440	2.64E-04	0.61	4.31E-04

APPENDIX TABLE C.13—*Continued*

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
60	620	-4	0.492	-2.73E-02	0.90	-3.03E-02
	623	-3	0.492	3.08E-02	0.90	3.40E-02
	625	-3	0.492	4.15E-02	0.88	4.74E-02
	627	-3	0.492	4.08E-02	0.86	4.76E-02
	630	-3	0.492	3.56E-02	0.82	4.33E-02
	635	-2	0.492	2.60E-02	0.78	3.32E-02
	650	2	0.491	2.32E-02	0.75	1.76E-02
	665	4	0.488	1.28E-02	0.70	1.82E-02
	690	8	0.483	1.15E-02	0.66	1.74E-02
	735	9	0.482	8.88E-03	0.54	1.66E-02
	795	18	0.472	6.72E-03	0.64	1.05E-02
	870	25	0.464	5.60E-03	0.70	7.38E-03
	990	33	0.457	3.66E-03	0.77	4.77E-03
	1170	42	0.450	2.56E-03	0.76	3.37E-03
	1460	52	0.442	1.82E-03	0.77	2.34E-03
	1760	62	0.436	1.66E-03	0.75	2.20E-03
	2165	69	0.432	1.30E-03	0.75	1.73E-03
	2980	85	0.423	6.31E-04	0.76	8.26E-04
	3625	94	0.418	4.39E-04	0.80	5.48E-04
	4395	102	0.413	6.00E-04	0.78	7.69E-04
90	620	-5	0.492	-2.73E-02	1.10	-2.49E-02
	623	-5	0.492	3.22E-02	1.06	3.03E-02
	625	-5	0.492	4.30E-02	1.08	3.97E-02
	627	-5	0.492	4.25E-02	1.07	3.96E-02
	630	-4	0.492	3.70E-02	1.13	3.27E-02
	635	-4	0.492	2.76E-02	1.10	2.50E-02
	650	-1	0.492	1.43E-02	1.07	1.34E-02
	665	0	0.492	1.34E-02	1.03	1.30E-02
	690	3	0.489	1.31E-02	1.02	1.28E-02
	735	5	0.486	1.33E-02	1.15	1.16E-02
	795	14	0.477	1.14E-02	1.06	1.08E-02
	870	21	0.468	7.99E-03	1.03	7.74E-03
	990	31	0.459	5.09E-03	1.04	4.89E-03
	1170	38	0.453	3.46E-03	0.96	3.60E-03
	1460	48	0.444	2.39E-03	0.96	2.50E-03
	1760	57	0.439	2.22E-03	0.87	2.56E-03
	2165	64	0.435	1.73E-03	0.89	1.95E-03
	2980	79	0.426	8.37E-04	0.81	1.03E-03
	3625	88	0.421	6.25E-04	0.81	7.72E-04
	4395	99	0.415	9.48E-04	0.87	1.09E-03

APPENDIX TABLE C.14. HYDRAULIC CONDUCTIVITY AND ASSOCIATED SUCTION, WATER CONTENT, FLUX, AND HYDRAULIC GRADIENT DURING POST-INFILTRATION DRAINAGE FOR SITE W3-3, O'AHU, HAWAI'I

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
20	540	3	0.579	-3.40E-02	0.71	-4.80E-02
	545	7	0.576	8.20E-03	0.55	1.50E-02
	550	10	0.573	1.64E-02	0.43	3.84E-02
	555	13	0.571	2.06E-02	0.38	5.40E-02
	560	15	0.568	1.84E-02	0.29	6.43E-02
	570	18	0.566	8.82E-03	0.18	4.88E-02
	590	23	0.562	1.58E-03	0.17	9.34E-03
	630	38	0.557	2.24E-03	0.08	2.66E-02
	675	33	0.553	2.29E-03	0.09	2.50E-02
	825	42	0.544	1.51E-03	0.15	1.00E-02
	1095	53	0.533	8.31E-04	0.19	4.28E-03
	1385	64	0.516	6.34E-04	0.26	2.47E-03
	2465	73	0.501	3.04E-04	0.35	8.58E-04
	2825	80	0.491	2.98E-04	0.34	8.69E-04
	3590	91	0.473	2.72E-04	0.37	7.35E-04
	4325	99	0.460	2.31E-04	0.43	5.41E-04
	5600	110	0.451	1.55E-04	0.54	2.90E-04
	6495	119	0.444	1.16E-04	0.57	2.05E-04
	7925	130	0.436	7.70E-05	0.71	1.09E-04
	11470	151	0.421	6.55E-05	0.95	6.88E-05
	13645	162	0.414	1.07E-04	0.99	1.07E-04
30	540	0	0.582	-6.44E-02	0.73	-8.81E-02
	545	3	0.580	8.27E-03	0.63	1.32E-02
	550	5	0.578	2.32E-02	0.53	4.37E-02
	555	7	0.576	2.98E-02	0.47	6.37E-02
	560	9	0.574	2.68E-02	0.40	6.66E-02
	570	11	0.573	1.26E-02	0.35	3.56E-02
	590	16	0.568	2.00E-03	0.31	6.40E-03
	630	20	0.564	3.03E-03	0.30	1.00E-02
	675	25	0.560	3.17E-03	0.30	1.06E-02
	825	35	0.551	2.13E-03	0.34	6.22E-03
	1095	46	0.541	1.22E-03	0.41	2.96E-03
	1385	57	0.526	9.38E-04	0.46	2.05E-03
	2465	67	0.510	4.84E-04	0.52	9.26E-04
	2825	74	0.499	4.84E-04	0.54	8.98E-04
	3590	85	0.481	4.53E-04	0.56	8.03E-04
	4325	94	0.468	3.86E-04	0.61	6.32E-04
	5600	106	0.454	2.56E-04	0.72	3.55E-04
	6495	116	0.447	1.90E-04	0.74	2.56E-04
	7925	128	0.438	1.25E-04	0.80	1.55E-04
	11470	151	0.421	1.02E-04	1.06	9.60E-05
	13645	163	0.414	1.61E-04	1.14	1.41E-04

APPENDIX TABLE C.14—*Continued*

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
60	540	-5	0.518	-1.37E-01	0.94	-1.46E-01
	545	-5	0.518	7.31E-04	0.91	8.02E-04
	550	-4	0.518	3.01E-02	0.88	3.44E-02
	555	-4	0.518	4.19E-02	0.83	5.07E-02
	560	-3	0.518	3.86E-02	0.80	4.81E-02
	570	-2	0.581	1.85E-02	0.81	2.30E-02
	590	1	0.516	3.60E-03	0.74	4.87E-03
	630	7	0.508	5.40E-03	0.74	7.24E-03
	675	11	0.502	5.75E-03	0.72	7.96E-03
	825	22	0.486	4.40E-03	0.75	5.86E-03
	1095	35	0.469	2.88E-03	0.80	3.58E-03
	1385	47	0.454	1.98E-03	0.81	2.46E-03
	2465	58	0.445	6.85E-04	0.80	8.61E-04
	2825	66	0.439	7.70E-04	0.82	9.41E-04
	3950	78	0.431	8.32E-04	0.83	1.00E-03
	5600	102	0.415	4.78E-04	0.91	5.26E-04
	6495	112	0.412	3.49E-04	0.92	3.77E-04
	7925	124	0.408	2.30E-04	0.91	2.52E-04
	11470	153	0.399	1.80E-04	1.00	1.80E-04
	13645	168	0.396	2.58E-04	1.05	2.46E-04
90	540	-4	0.518	-1.76E-01	1.07	-1.64E-01
	545	-4	0.518	-6.88E-03	1.07	-6.44E-03
	550	-4	0.518	2.67E-02	1.07	2.50E-02
	555	-4	0.518	4.35E-02	1.08	4.05E-02
	560	-4	0.518	4.20E-02	1.07	3.94E-02
	570	-3	0.518	2.16E-02	1.06	2.05E-02
	590	-2	0.518	6.94E-03	1.02	6.83E-03
	630	3	0.514	9.40E-03	0.95	9.94E-03
	675	6	0.509	9.75E-03	0.93	1.05E-02
	825	18	0.492	7.25E-03	0.94	7.68E-03
	1095	31	0.474	4.52E-03	0.92	4.90E-03
	1385	43	0.459	2.99E-03	0.89	3.36E-03
	2465	53	0.448	8.28E-04	0.84	9.83E-04
	2825	60	0.443	1.00E-03	0.82	1.22E-03
	3590	72	0.435	1.15E-03	0.81	1.42E-03
	4325	82	0.428	1.03E-03	0.82	1.27E-03
	5600	98	0.417	6.60E-04	0.82	8.06E-04
	6495	109	0.413	4.74E-04	0.84	5.62E-04
	7925	121	0.409	3.07E-04	0.86	3.57E-04
	11470	149	0.400	2.40E-04	0.77	3.11E-04
	13645	164	0.396	3.46E-04	0.75	4.62E-04

APPENDIX TABLE C.15. HYDRAULIC CONDUCTIVITY AND ASSOCIATED SUCTION, WATER CONTENT, FLUX, AND HYDRAULIC GRADIENT DURING POSTINFILTRATION DRAINAGE FOR SITE W3-4, (SET 1), O'AHU, HAWAI'I

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
30	19	1	0.575	9.44E-02	0.76	1.24E-01
	27	3	0.570	7.37E-02	0.64	1.16E-01
	37	6	0.562	5.15E-92	0.56	9.26E-02
	57	11	0.551	1.93E-02	0.44	4.37E-02
	87	17	0.537	1.52E-03	0.42	3.65E-03
	147	24	0.522	2.34E-03	0.35	6.74E-03
	267	32	0.509	2.23E-03	0.35	6.45E-03
	417	38	0.499	9.96E-04	0.39	2.52E-03
	597	45	0.490	4.72E-04	0.50	9.50E-04
	867	53	0.480	4.64E-04	0.48	9.56E-04
	1407	66	0.466	4.06E-04	0.67	6.04E-04
	2382	83	0.450	2.73E-04	0.70	3.87E-04
	4467	103	0.430	1.36E-04	0.94	1.45E-04
	6702	123	0.418	1.03E-04	1.08	9.46E-05
	9717	142	0.408	7.33E-95	1.25	5.85E-05
	14012	166	0.399	4.83E-05	1.44	3.34E-05
	19782	191	0.393	2.78E-05	1.73	1.61E-05
	24057	210	0.389	1.96E-05	1.94	1.01E-05
	29822	230	0.386	1.24E-05	2.20	5.65E-06
	40137	258	0.382	1.12E-05	1.88	5.94E-06
60	19	-6	0.558	1.08E-01	0.77	1.39E-01
	27	-5	0.558	8.50E-02	0.82	1.04E-01
	37	-4	0.558	6.08E-02	0.74	8.19E-02
	57	-3	0.558	2.58E-02	0.67	3.85E-02
	87	1	0.556	6.64E-03	0.58	1.15E-02
	147	7	0.545	7.65E-03	0.60	1.26E-02
	267	15	0.530	6.28E-03	0.61	1.04E-02
	417	25	0.513	2.77E-03	0.71	3.88E-03
	597	34	0.502	1.29E-03	0.73	1.76E-03
	867	42	0.491	1.27E-03	0.76	1.68E-03
	1407	56	0.474	1.10E-03	0.68	1.62E-03
	2382	74	0.459	7.07E-04	0.73	9.72E-04
	4467	98	0.439	3.13E-04	0.71	4.38E-04
	6702	121	0.426	2.34E-04	0.77	3.05E-04
	9717	141	0.415	1.65E-04	0.76	2.17E-04
	14012	166	0.404	1.11E-04	0.70	1.59E-04
	19782	193	0.394	6.99E-05	0.58	1.20E-04
	14057	211	0.388	5.47E-05	0.45	1.21E-04
	29822	230	0.382	3.76E-05	0.25	1.53E-04
	40137	254	0.376	1.70E-05	0.18	9.50E-05

APPENDIX TABLE C.15—*Continued*

Measurement Depth (cm)	Time (min)	Suction (cm water)	Water Content (cm^3/cm^3)	Flux (cm/min)	Gradient (cm/cm)	Hydraulic Conductivity (cm/min)
90	19	-10	0.524	8.86E-02	1.00	8.68E-02
	27	-8	0.524	7.12E-02	0.97	7.35E-02
	37	-8	0.524	5.26E-02	1.03	5.10E-02
	57	-7	0.524	2.57E-02	1.07	2.39E-02
	87	-4	0.524	1.10E-02	1.12	9.86E-03
	147	2	0.522	1.20E-02	1.03	1.16E-92
	267	9	0.513	9.42E-03	1.01	9.29E-03
	417	21	0.499	4.16E-03	0.98	4.23E-03
	597	29	0.491	1.94E-03	0.93	2.08E-03
	867	37	0.484	1.91E-03	0.87	2.20E-03
	1407	49	0.473	1.65E-03	0.82	2.02E-03
	2382	65	0.462	1.06E-03	0.65	1.64E-03
	4467	89	0.447	4.69E-04	0.73	6.40E-04
	6702	112	0.435	3.46E-04	0.70	4.96E-04
	9717	132	0.426	2.43E-04	0.71	3.41E-04
	14012	156	0.417	1.62E-04	0.78	2.07E-04
	19782	179	0.410	1.04E-04	0.74	1.39E-04
	24057	195	0.405	8.33E-05	0.73	1.14E-04
	29822	209	0.401	6.02E-05	0.73	8.27E-05
	40137	232	0.395	3.08E-05	0.80	3.86E-05
120	19	-12	0.487	7.37E-02	0.71	1.04E-01
	27	-11	0.487	6.04E-02	0.68	8.93E-02
	37	-8	0.487	4.62E-02	0.79	5.82E-02
	57	-3	0.487	2.56E-02	0.97	2.65E-02
	87	2	0.484	1.46E-02	1.05	1.39E-02
	147	6	0.481	1.54E-02	1.07	1.44E-02
	267	13	0.473	1.20E-02	1.10	1.08E-02
	417	22	0.463	5.25E-03	1.06	4.97E-03
	597	28	0.457	2.41E-03	1.02	2.35E-03
	867	34	0.453	2.38E-03	0.95	2.49E-03
	1407	44	0.444	2.06E-03	0.85	2.44E-03
	2382	55	0.437	1.32E-03	0.80	1.65E-04
	4467	82	0.425	5.93E-04	0.78	7.59E-04
	6702	104	0.415	4.55E-04	0.75	6.05E-04
	9717	125	0.407	3.19E-04	0.80	4.01E-04
	14012	152	0.398	1.96E-04	0.74	2.64E-04
	19782	175	0.394	1.18E-04	0.67	1.77E-04
	24057	190	0.392	9.90E-05	0.55	1.81E-04
	29822	206	0.390	7.67E-05	0.47	1.64E-04
	40137	226	0.385	.470E-05	-0.08	-6.16E-04

APPENDIX TABLE D.1. WATER RETENTION AND PHYSICAL PROPERTIES OF INDIVIDUAL SOIL CORES FROM ALL EXPERIMENTAL SITES

OBSERVATION	DEPTH	WATER CONTENT (cm^3/cm^3) Suction (cm of water)								BULK DENSITY	POROSITY	MACRO-POROSITY	*KS**
	(cm)	10	25	50	100	150	250	500	1000	(g/cm^3)	--- (cm^3/cm^3) ---		(cm/hr)
						Lahaina Series, Ap1 Horizon, L-1, Rep. 1							
1	1-9	0.522	0.460	0.386	0.355	0.342	0.328	0.318	0.305	1.09	0.628	0.242	----
2	1-9	0.536	0.454	0.404	0.368	0.358	0.328	0.314	0.305	1.09	0.628	0.224	----
						Lahaina Series, Ap1 Horizon, L-1, Rep. 2							
3	1-9	0.523	0.497	0.426	0.375	0.352	0.336	0.319	0.309	1.14	0.611	0.185	----
4	1-9	0.483	0.445	0.413	0.387	0.374	0.363	0.347	0.337	1.24	0.577	0.164	----
						Lahaina Series, Ap1 Horizon, L-2, Rep. 1							
5	1-9	0.559	0.539	0.495	0.432	0.390	0.355	0.317	0.291	1.07	0.635	0.140	----
6	1-9	0.514	0.502	0.467	0.408	0.374	0.342	0.311	0.290	1.09	0.628	0.161	----
						Lahaina Series, Ap1 Horizon, L-2, Rep. 2							
7	1-9	0.550	0.518	0.466	0.420	0.373	0.337	0.305	0.274	0.99	0.662	0.196	----
8	1-9	0.572	0.544	0.506	0.432	0.381	0.344	0.313	0.289	1.05	0.642	0.136	----
						Lahaina Series, Ap1 Horizon, L-3, Rep. 1							
9	1-9	0.533	0.518	0.493	0.423	0.395	0.370	0.344	0.319	1.19	0.594	0.101	----
10	1-9	0.508	0.506	0.482	0.436	0.408	0.382	0.353	0.326	1.22	0.584	0.102	----
						Lahaina Series, Ap1 Horizon, L-3, Rep. 2							
11	1-9	0.544	0.528	0.512	0.442	0.410	0.381	0.354	0.328	1.19	0.594	0.082	----
12	1-9	0.528	0.521	0.506	0.448	0.418	0.389	0.362	0.338	1.25	0.573	0.067	----
						Lahaina Series, Ap2 Horizon, L-1, Rep. 1							
13	25-33	0.504	0.470	0.430	0.400	0.386	0.377	0.362	0.352	1.28	0.563	0.133	----
14	30-39	0.504	0.478	0.437	0.406	0.396	0.388	0.374	0.365	1.30	0.556	0.119	----

*Saturated conductivity.

APPENDIX TABLE D.1—*Continued*

OBSERVATION	DEPTH (cm)	WATER CONTENT (cm^3/cm^3) Suction (cm of water) 10	25	50	100	150	250	500	1000	BULK DENSITY (g/cm^3)	POROSITY ---(cm^3/cm^3)---	MACROPOROSITY	*KS** (cm/hr)
						Lahaina Series, Ap2 Horizon, L-1, Rep. 2							
15	24-32	0.517	0.478	0.441	0.406	0.389	0.377	0.361	0.348	1.24	0.577	0.136	19.368
16	24-32	0.498	0.463	0.426	0.384	0.372	0.373	0.356	0.346	1.23	0.580	0.154	10.548
						Lahaina Series, Ap2 Horizon, L-2, Rep. 1							
17	25-33	0.564	0.552	0.483	0.410	0.373	0.348	0.326	0.314	1.11	0.621	0.138	2.112
18	25-33	0.561	0.541	0.482	0.416	0.383	0.358	0.332	0.319	1.15	0.608	0.126	0.654
						Lahaina Series, Ap2 Horizon, L-2, Rep. 2							
19	25-33	0.504	0.500	0.478	0.490	0.416	0.391	0.364	0.348	1.30	0.556	0.078	0.84
20	25-33	0.535	0.533	0.501	0.434	0.398	0.373	0.347	0.333	1.21	0.587	0.086	1.14
						Lahaina Series, Ap2 Horizon, L-3, Rep. 3							
21	25-33	0.491	0.487	0.467	0.440	0.424	0.398	0.374	0.35	1.30	0.556	0.089	----
22	25-33	0.497	0.493	0.480	0.433	0.411	0.387	0.367	0.35	1.33	0.546	0.066	----
						Lahaina Series, Ap2 Horizon, L-3, Rep. 2							
23	25-33	0.517	0.507	0.465	0.417	0.394	0.374	0.355	0.339	1.25	0.573	0.108	----
24	25-33	0.489	0.487	0.481	0.453	0.436	0.414	0.394	0.374	1.34	0.543	0.062	----
						Lahaina Series, B21 Horizon, L-1, Rep. 1							
25	76-84	0.523	0.503	0.480	0.453	0.435	0.416	0.392	0.372	1.29	0.560	0.080	0.276
26	76-84	0.542	0.513	0.475	0.439	0.439	0.440	0.375	0.356	1.22	0.584	0.109	0.372
						Lahaina Series, B21 Horizon, L-1, Rep. 2							
27	56-64	0.480	0.473	0.463	0.446	0.433	0.416	0.396	0.372	1.37	0.532	0.069	0.096
28	53-61	0.493	0.488	0.476	0.450	0.435	0.416	0.393	0.374	1.39	0.526	0.050	0.570

*Saturated conductivity.

APPENDIX TABLE D.1—*Continued*

OBSER-VATION	DEPTH (cm)	WATER CONTENT (cm^3/cm^3) Suction (cm of water) 10	25	50	100	150	250	500	1000	BULK DENSITY (g/cm^3)	POROS-ITY (cm^3/cm^3)	MACRO-POROSITY (cm^3/cm^3)	*KS** (cm/hr)
				Lahaina Series, B21 Horizon, L-2, Rep. 1									
29	55-63	0.474	0.470	0.460	0.437	0.421	0.407	0.388	0.367	1.46	0.502	0.042	0.0582
30	55-63	0.493	0.473	0.456	0.442	0.424	0.407	0.386	0.360	1.39	0.526	0.070	0.1680
				Lahaina Series, B21 Horizon, L-2, Rep. 2									
31	52-60	0.496	0.488	0.471	0.435	0.417	0.396	0.374	0.351	1.39	0.526	0.055	0.12
32	55-63	0.502	0.483	0.461	0.431	0.406	0.384	0.360	0.337	1.36	0.536	0.075	0.24
				Lahaina Series, B21 Horizon, L-3, Rep. 1									
33	53-60	0.497	0.486	0.464	0.432	0.413	0.394	0.373	0.35	1.38	0.529	0.065	----
34	53-60	-----	-----	0.456	-----	0.409	-----	-----	----	1.37	0.532	0.076	----
				Lahaina Series, B21 Horizon, L-3, Rep. 2									
35	60-68	0.5	0.485	0.463	0.425	0.398	0.375	0.352	0.328	1.34	0.543	0.080	----
36	60-68	---	-----	0.452	-----	0.400	-----	-----	-----	1.32	0.549	0.097	----
				Molokai Series, Ap1 Horizon, L-1, Rep. 1									
37	1-9	0.547	0.509	0.449	0.399	0.371	0.345	0.319	0.298	1.13	0.614	0.165	----
38	1-9	0.549	0.493	0.454	0.423	0.393	0.356	0.332	0.309	1.19	0.594	0.140	----
				Molokai Series, Ap1 Horizon, L-1, Rep. 2									
39	1-9	0.561	0.546	0.502	0.443	0.402	0.369	0.335	0.31	1.16	0.604	0.102	----
40	1-9	0.495	0.489	0.470	0.417	0.393	0.367	0.335	0.31	1.14	0.611	0.141	----
				Molokai Series, Ap1 Horizon, L-2, Rep. 1									
41	1-9	0.579	0.556	0.506	0.416	0.389	0.358	0.329	0.300	1.15	0.61	0.104	----
42	1-9	0.580	0.569	0.519	0.419	0.380	0.348	0.317	0.292	1.12	0.62	0.101	----

*Saturated conductivity.

APPENDIX TABLE D.1—*Continued*

OBSER-VATION	DEPTH (cm)	WATER CONTENT (cm^3/cm^3) Suction (cm of water) 10	25	50	100	150	250	500	1000	BULK DENSITY (g/cm^3)	POROS-ITY	MACRO-POROSITY ---(cm^3/cm^3)---	*KS** (cm/hr)
		Molokai Series, Ap1 Horizon, L-2, Rep. 2											
43	1-9	0.548	0.524	0.490	0.401	0.366	0.336	0.305	0.282	1.10	0.627	0.137	----
44	1-9	0.560	0.545	0.493	0.393	0.361	0.331	0.305	0.282	1.12	0.620	0.127	----
		Molokai Series, Ap1 Horizon, L-3, Rep. 1											
45	1-9	0.547	0.531	0.486	0.411	0.365	0.334	0.303	0.281	1.04	0.645	0.159	----
46	1-9	0.566	0.538	0.494	0.413	0.371	0.338	0.309	0.287	1.04	0.645	0.151	----
		Molokai Series, Ap1 Horizon, L-3, Rep. 2											
47	1-9	0.573	0.537	0.491	0.408	0.368	0.339	0.309	0.287	1.07	0.635	0.144	----
48	1-9	0.577	0.553	0.491	0.395	0.361	0.332	0.309	0.287	1.01	0.655	0.164	----
		Molokai Series, Ap1 Horizon, L-4, Rep. 1											
49	1-9	0.575	0.540	0.472	0.392	0.350	0.326	0.30	0.281	1.06	0.641	0.169	----
50	2-10	0.568	0.552	0.489	0.414	0.374	0.348	0.32	0.298	1.12	0.620	0.131	----
		Molokai Series, Ap1 Horizon, L-4, Rep. 2											
51	0-8	0.552	0.504	0.430	0.374	0.357	0.332	0.312	0.295	1.08	0.634	0.204	----
52	0.8	0.548	0.486	0.432	0.389	0.375	0.352	0.330	0.318	1.16	0.607	0.175	----
		Molokai Series, Ap1 Horizon, L-4, Rep. 3											
53	1-9	0.568	0.493	0.427	0.372	0.353	0.326	0.306	0.291	1.03	0.651	0.224	----
54	1-9	0.545	0.470	0.409	0.361	0.342	0.317	0.301	0.286	1.02	0.654	0.245	----
		Molokai Series, Ap2 Horizon, L-1, Rep. 1											
55	28-36	0.519	0.506	0.482	0.440	0.414	0.382	0.353	0.332	1.33	0.546	0.064	2.346
56	27-35	0.507	0.501	0.479	0.441	0.416	0.389	0.361	0.337	1.34	0.543	0.064	0.330

*Saturated conductivity.

APPENDIX TABLE D.1—*Continued*

OBSERVATION	DEPTH (cm)	WATER CONTENT (cm³/cm³) Suction (cm of water) 10	25	50	100	150	250	500	1000	BULK DENSITY (g/cm³)	POROSITY --- (cm³/cm³)	MACROPOROSITY (cm³/cm³) ---	*KS** (cm/hr)
					Molokai Series, Ap2 Horizon, L-1, Rep. 2								
57	27-35	0.513	0.498	0.443	0.436	0.400	0.366	0.337	0.314	1.17	0.601	0.158	3.588
58	27-35	0.540	0.534	0.496	0.435	0.404	0.375	0.345	0.322	1.22	0.584	0.088	1.710
					Molokai Series, Ap2 Horizon, L-2, Rep. 1								
59	23-31	0.512	0.503	0.478	0.440	0.414	0.387	0.361	0.338	1.31	0.556	0.078	0.426
60	23-31	0.515	0.508	0.483	0.445	0.421	0.396	0.371	0.349	1.33	0.549	0.066	0.228
					Molokai Series, Ap2 Horizon, L-2, Rep. 2								
61	19-27	0.566	0.526	0.448	0.387	0.341	0.326	0.306	0.295	1.13	0.617	0.169	0.132
62	19-27	0.530	0.521	0.488	0.434	0.404	0.379	0.352	0.335	1.28	0.566	0.078	0.822
					Molokai Series, Ap2 Horizon, L-3, Rep. 1								
63	19-27	0.564	0.559	0.540	0.447	0.403	0.365	0.334	0.311	1.16	0.604	0.064	1.98
64	19-28	0.569	0.558	0.526	0.450	0.402	0.369	0.339	0.315	1.16	0.604	0.078	8.52
					Molokai Series, Ap2 Horizon, L-3, Rep. 2								
65	21-29	0.557	0.541	0.49	0.420	0.393	0.364	0.341	0.329	1.16	0.604	0.114	8.34
66	21-29	0.538	0.515	0.46	0.406	0.376	0.348	0.321	0.300	1.12	0.618	0.158	12.12
					Molokai Series, Ap2 Horizon, L-4, Rep. 1								
67	24-32	0.546	0.536	0.516	0.447	0.405	0.377	0.350	0.330	1.22	0.586	0.070	----
68	24-32	0.540	0.536	0.528	0.458	0.414	0.382	0.352	0.329	1.28	0.567	0.039	----
					Molokai Series, Ap2 Horizon, L-4, Rep. 2								
69	21-29	0.532	0.528	0.516	0.469	0.440	0.408	0.379	0.360	1.30	0.559	0.043	----
70	21-29	0.537	0.533	0.525	0.478	0.449	0.415	0.385	0.365	1.31	0.556	0.031	----

*Saturated conductivity.

APPENDIX TABLE D.1—*Continued*

OBSERVATION	DEPTH (cm)	WATER CONTENT (cm^3/cm^3) Suction (cm of water) 10	25	50	100	150	250	500	1000	BULK DENSITY (g/cm^3)	POROSITY --- (cm^3/cm^3)---	MACROPOROSITY	*KS** (cm/hr)
						Wahiawa Series, B21 Horizon, L-3, Rep. 3							
148	58-62	0.501	0.468	0.438	0.408	0.392	0.370	0.341	0.326	1.35	0.539	0.101	------
149	58-62	0.521	0.488	0.460	0.431	0.412	0.387	0.356	0.340	1.26	0.570	0.110	------
150	58-61	0.503	0.488	0.464	0.409	0.412	0.382	0.345	0.318	1.41	0.519	0.055	------
151	58-62	0.489	0.465	0.444	0.414	0.401	0.378	0.349	0.333	1.42	0.515	0.071	------
						Wahiawa Series, B21 Horizon, L-3, Rep. 4							
152	42-50	0.511	0.495	0.415	0.42	0.395	0.366	0.332	0.31	1.25	0.573	0.158	11.682
153	42-50	0.538	0.528	0.508	0.46	0.422	0.390	0.352	0.32	1.24	0.577	0.069	7.854
						Wahiawa Series, B22 Horizon, L-3, Rep. 1							
154	74-77	0.476	0.460	0.435	0.416	0.400	0.382	0.362	0.341	1.42	0.515	0.080	-----
155	74-77	0.469	0.460	0.432	0.411	0.398	0.376	0.353	0.332	1.44	0.509	0.077	-----
156	74-77	0.470	0.460	0.432	0.409	0.395	0.372	0.351	0.330	1.40	0.522	0.090	-----
157	105-109	0.439	0.452	0.438	0.420	0.408	0.391	0.369	0.348	1.50	0.488	0.050	-----
158	105-109	0.488	0.465	0.445	0.422	0.408	0.400	0.365	0.346	1.39	0.526	0.081	-----
159	105-109	0.451	0.445	0.430	0.412	0.400	0.382	0.360	0.342	1.52	0.481	0.051	-----
						Wahiawa Series, B22 Horizon, L-3, Rep. 4							
160	72-80	0.544	0.510	0.485	0.450	0.428	0.400	0.370	0.350	1.35	0.539	0.054	-----
161	72-80	0.481	0.470	0.455	0.429	0.410	0.390	0.365	0.344	1.48	0.495	0.040	0.744
162	103-110	0.454	0.441	0.425	0.402	0.388	0.371	0.350	0.332	1.49	0.491	0.066	-----
163	103-110	0.507	0.482	0.458	0.431	0.412	0.371	0.368	0.341	1.44	0.509	0.051	-----

*Saturated conductivity.

APPENDIX TABLE D.1—*Continued*

OBSER-VATION	DEPTH (cm)	WATER CONTENT (cm^3/cm^3) Suction (cm of water) 10	25	50	100	150	250	500	1000	BULK DENSITY (g/cm^3)	POROS-ITY --- (cm^3/cm^3)	MACRO-POROSITY (cm^3/cm^3) ---	*KS** (cm/hr)
					Wahiawa Series, B21 Horizon, L-1, Rep. 1								
132	39-46	0.498	0.482	0.466	0.445	0.433	0.422	0.403	0.384	1.30	0.556	0.090	0.294
133	39-46	0.497	0.480	0.461	0.441	0.426	0.418	0.400	0.381	1.28	0.563	0.102	1.614
					Wahiawa Series, B21 Horizon, L-1, Rep. 2								
134	43-50	0.493	0.476	0.459	0.439	0.424	0.416	0.403	0.388	1.35	0.539	0.080	0.0450
135	43-50	0.476	0.466	0.449	0.432	0.422	0.414	0.400	0.386	1.40	0.522	0.073	0.2154
					Wahiawa Series, B21 Horizon, L-2, Rep. 1								
136	55-63	-----	-----	0.465	-----	0.439	-----	-----	-----	1.32	0.549	0.084	-----
137	55-63	-----	-----	0.473	-----	0.439	-----	-----	-----	1.21	0.587	0.114	-----
					Wahiawa Series, B21 Horizon, L-2, Rep. 2								
138	57-65	-----	-----	0.479	-----	0.445	-----	-----	-----	1.26	0.57	0.091	-----
139	57-65	-----	-----	0.481	-----	0.448	-----	-----	-----	1.29	0.56	0.079	-----
					Wahiawa Series, B21 Horizon, L-3, Rep. 1								
140	42-50	0.530	0.508	0.475	0.428	0.398	0.368	0.338	0.318	1.21	0.587	0.112	-----
141	42-50	0.492	0.468	0.432	0.400	0.380	0.352	0.330	0.313	1.36	0.536	0.104	-----
142	42-50	0.544	0.528	0.495	0.449	0.422	0.390	0.362	0.340	1.21	0.587	0.092	0.252
					Wahiawa Series, B21 Horizon, L-3, Rep. 2								
143	58-62	0.462	0.450	0.430	0.406	0.390	0.368	0.342	0.324	1.48	0.495	0.065	-----
144	58-62	0.513	0.485	0.458	0.429	0.412	0.390	0.365	0.345	1.38	0.529	0.071	-----
145	58-62	0.478	0.462	0.430	0.398	0.380	0.358	0.332	0.326	1.48	0.495	0.065	-----
146	58-62	0.469	0.458	0.445	0.427	0.412	0.390	0.355	0.335	1.53	0.478	0.033	-----
147	58-62	0.483	0.468	0.440	0.411	0.388	0.362	0.338	0.324	1.42	0.515	0.075	-----

*Saturated conductivity.

APPENDIX TABLE D.1—*Continued*

OBSERVATION	DEPTH (cm)	WATER CONTENT (cm^3/cm^3) Suction (cm of water) 10	25	50	100	150	250	500	1000	BULK DENSITY (g/cm^3)	POROSITY ---	MACRO-POROSITY (cm^3/cm^3)	*KS** (cm/hr)
		Wahiawa Series, Ap2 Horizon, L-2, Rep. 1											
114	36-44	-----	-----	0.451	-----	0.425	-----	-----	-----	1.12	0.618	0.167	----
115	36-44	-----	-----	0.449	-----	0.417	-----	-----	-----	1.12	0.618	0.169	----
		Wahiawa Series, Ap2 Horizon, L-2, Rep. 2											
116	37-45	-----	-----	0.430	-----	0.401	-----	-----	-----	1.05	0.642	0.212	----
117	37-45	-----	-----	0.473	-----	0.439	-----	-----	-----	1.04	0.645	0.172	----
		Wahiawa Series, Ap2 Horizon, L-3, Rep. 1											
118	19-27	0.516	0.510	0.486	0.445	0.425	0.413	0.368	0.344	1.23	0.580	0.094	4.74
119	19-27	0.546	0.538	0.500	0.423	0.398	0.368	0.345	0.324	1.20	0.590	0.090	6.84
120	19-27	0.535	0.533	0.508	0.431	0.405	0.378	0.350	0.331	1.25	0.573	0.065	2.88
		Wahiawa Series, Ap2 Horizon, L-3, Rep. 2											
121	38-42	0.573	0.573	0.525	0.471	0.442	0.412	0.370	0.335	1.24	0.577	0.052	----
122	38-42	0.574	0.560	0.512	0.424	0.400	0.375	0.342	0.303	1.17	0.601	0.089	----
123	38-42	0.508	0.492	0.460	0.428	0.410	0.385	0.340	0.318	1.38	0.529	0.069	----
124	38-42	0.509	0.508	0.492	0.470	0.452	0.422	0.378	0.351	1.35	0.539	0.047	----
		Wahiawa Series, Ap2 Horizon, L-3, Rep. 3											
125	38-42	0.559	0.555	0.495	0.456	0.432	0.400	0.362	0.340	1.26	0.570	0.075	----
126	38-42	0.576	0.466	0.545	0.492	0.465	0.430	0.385	0.360	1.27	0.567	0.022	----
127	38-42	0.564	0.564	0.530	0.467	0.438	0.402	0.352	0.318	1.24	0.577	0.047	----
128	38-42	0.498	0.478	0.442	0.414	0.400	0.372	0.338	0.323	1.37	0.532	0.090	----
		Wahiawa Series, Ap2 Horizon, L-3, Rep. 4											
129	19-27	0.582	0.475	0.430	0.406	0.386	0.368	0.340	0.327	1.18	0.597	0.167	-----
130	19-27	0.568	0.550	0.512	0.464	0.435	0.405	0.380	0.356	1.19	0.594	0.082	1.932
131	19-27	0.540	0.515	0.470	0.422	0.402	0.378	0.352	0.335	1.23	0.580	0.110	6.120

*Saturated conductivity.

APPENDIX TABLE D.1—*Continued*

OBSERVATION	DEPTH (cm)	WATER CONTENT (cm³/cm³) Suction (cm of water) 10	25	50	100	150	250	500	1000	BULK DENSITY (g/cm³)	POROSITY --- (cm³/cm³) ---	MACROPOROSITY --- (cm³/cm³) ---	K_S* (cm/hr)
					Wahiawa Series, Ap1 Horizon, L-3, Rep. 1								
99	4-12	0.542	0.518	0.486	0.426	0.49	0.358	0.328	0.304	1.20	0.590	0.104	7.74
100	4-12	0.532	0.518	0.490	0.440	0.40	0.368	0.338	0.316	1.22	0.584	0.094	3.36
					Wahiawa Series, Ap1 Horizon, L-3, Rep. 2								
101	13-17	0.566	0.538	0.500	0.447	0.420	0.385	0.343	0.323	1.21	0.587	0.087	----
102	13-17	0.568	0.555	0.512	0.450	0.425	0.390	0.348	0.330	1.23	0.580	0.068	----
103	13-17	0.562	0.545	0.500	0.445	0.418	0.385	0.328	0.305	1.20	0.590	0.090	----
					Wahiawa Series, Ap1 Horizon, L-3, Rep. 3								
104	13-17	0.570	0.575	0.532	0.443	0.412	0.378	0.340	0.323	1.18	0.597	0.065	----
105	13-17	0.568	0.565	0.550	0.486	0.435	0.393	0.348	0.328	1.18	0.597	0.047	----
106	13-17	0.584	0.575	0.530	0.448	0.418	0.383	0.343	0.318	1.16	0.604	0.074	----
107	13-17	0.571	0.568	0.532	0.466	0.426	0.375	0.335	0.313	1.17	0.601	0.069	----
					Wahiawa Series, Ap1 Horizon, L-3, Rep. 4								
108	4-12	0.570	0.565	0.540	0.433	0.395	0.360	0.335	0.317	1.17	0.601	0.061	4.14
109	4-12	0.581	0.570	0.518	0.422	0.390	0.358	0.328	0.310	1.14	0.611	0.093	7.38
					Wahiawa Series, Ap2 Horizon, L-1, Rep. 1								
110	17-25	0.566	0.554	0.509	0.424	0.397	0.375	0.357	0.339	1.13	0.614	0.105	5.94
111	17-25	0.558	0.541	0.470	0.407	0.386	0.363	0.344	0.330	1.08	0.631	0.161	4.62
					Wahiawa Series, Ap2 Horizon, L-1, Rep. 2								
112	17-25	0.557	0.542	0.491	0.419	0.388	0.372	0.357	0.339	1.14	0.611	0.120	20.58
113	17-25	0.558	0.543	0.476	0.406	0.382	0.363	0.347	0.331	1.10	0.625	0.149	8.16

*Saturated conductivity.

APPENDIX TABLE D.1—*Continued*

OBSERVATION	DEPTH (cm)	WATER CONTENT (cm^3/cm^3) Suction (cm of water) 10	25	50	100	150	250	500	1000	BULK DENSITY (g/cm^3)	POROSITY --- (cm^3/cm^3)---	MACROPOROSITY	*KS** (cm/hr)
Molokai Series, B21 Horizon, L-4, Rep. 1													
85	46-54	0.512	0.496	0.476	0.45	0.432	0.412	0.386	0.358	1.36	0.539	0.063	----
86	46-54	-----	-----	0.466	----	0.416	-----	-----	-----	1.34	0.546	0.080	----
Molokai Series, B21 Horizon, L-4, Rep. 2													
87	42-50	0.533	0.512	0.487	0.456	0.433	0.413	0.387	0.356	1.25	0.576	0.089	----
88	42-50	-----	-----	0.469	-----	0.420	-----	-----	-----	1.24	0.580	0.111	----
Molokai Series, B21 Horizon, L-4, Rep. 3													
89	43-51	0.533	0.51	0.484	0.452	0.426	0.401	0.369	0.338	1.21	0.590	0.106	----
90	43-51	-----	----	0.472	-----	0.416	-----	-----	-----	1.22	0.586	0.114	----
Wahiawa Series, Ap1 Horizon, L-1, Rep. 1													
91	3-10	0.571	0.526	0.442	0.379	0.343	0.335	0.315	0.297	0.97	0.669	0.227	----
92	3-10	0.554	0.496	0.430	0.379	0.360	0.344	0.326	0.308	0.97	0.669	0.239	----
Wahiawa Series, Ap1 Horizon, L-1, Rep. 2													
93	3-10	0.552	0.505	0.431	0.371	0.362	0.330	0.315	0.301	0.96	0.672	0.241	----
94	3-10	0.586	0.506	0.414	0.358	0.330	0.316	0.301	0.282	0.93	0.683	0.269	----
Wahiawa Series, Ap1 Horizon, L-2, Rep. 1													
95	2-10	0.602	0.431	0.381	0.344	0.328	0.307	0.300	0.296	0.92	0.687	0.306	----
96	2-10	0.577	0.469	0.397	0.351	0.331	0.310	0.299	0.292	0.88	0.700	0.303	----
Wahiawa Series, Ap1 Horizon, L-2, Rep. 2													
97	2-10	0.524	0.419	0.373	0.345	0.329	0.321	0.310	0.300	0.93	0.684	0.311	----
98	2-10	0.552	0.423	0.362	0.324	0.310	0.299	0.289	0.285	0.86	0.706	0.344	----

*Saturated conductivity.

APPENDIX TABLE D.1—*Continued*

OBSERVATION	DEPTH (cm)	WATER CONTENT (cm^3/cm^3) Suction (cm in water) 10	25	50	100	150	250	500	1000	BULK DENSITY (g/cm^3)	POROSITY --- (cm^3/cm^3)	MACROPOROSITY (cm^3/cm^3) ---	KS^* (cm/hr)
					Molokai Series, Ap2 Horizon, L-4, Rep. 3								
71	17-26	0.537	0.533	0.527	0.476	0.448	0.414	0.389	0.368	1.32	0.553	0.026	-----
72	19-28	0.520	0.518	0.512	0.485	0.462	0.436	0.408	0.386	1.35	0.542	0.030	-----
					Molokai Series, B21 Horizon, L-1, Rep. 1								
73	59-67	0.495	0.484	0.463	0.431	0.408	0.385	0.360	0.330	1.4	0.522	0.059	0.330
74	59-69	0.496	0.479	0.456	0.428	0.405	0.381	0.354	0.323	1.4	0.522	0.066	0.702
					Molokai Series, B21 Horizon, L-1, Rep. 2								
75	59-67	0.500	0.488	0.473	0.445	0.422	0.40	0.374	0.344	1.41	0.519	0.046	0.516
76	59-67	0.499	0.478	0.460	0.432	0.413	0.39	0.361	0.329	1.37	0.532	0.072	0.432
					Molokai Series, B21 Horizon, L-2, Rep. 1								
77	42-46	0.535	0.492	0.477	0.436	0.415	0.393	0.352	0.335	1.32	0.549	0.072	-----
78	42-46	0.528	0.492	0.478	0.432	0.430	0.405	0.377	0.352	1.40	0.522	0.044	-----
					Molokai Series, B21 Horizon, L-2, Rep. 2								
79	38-42	0.522	0.508	0.485	0.452	0.428	0.393	-----	-----	1.27	0.567	0.082	-----
80	38-42	0.495	0.470	0.449	0.423	0.403	0.380	-----	-----	1.24	0.577	0.128	-----
					Molokai Series, B21 Horizon, L-3, Rep. 1								
81	49-58	0.503	0.486	0.458	0.422	0.383	0.377	0.352	0.327	1.33	0.546	0.088	0.3498
82	49-58	0.501	0.484	0.461	0.431	0.408	0.384	0.360	0.329	1.33	0.546	0.085	0.3006
					Molokai Series, B21 Horizon, L-3, Rep. 2								
83	48-57	0.615	0.597	0.573	0.543	0.524	0.498	0.471	0.440	1.16	0.604	0.031	0.4920
84	48-57	0.502	0.485	0.467	0.433	0.412	0.392	0.369	0.344	1.38	0.529	0.062	0.3036

*Saturated conductivity.