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Legowo, Eko, Ph.D.

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ESTIMATION OF WATER EXTRACTABILITY AND HYDRAULIC CONDUCTIVITY IN TROPICAL MOLLISOLS, ULTISOLS, AND ANDISOLS

A DISSERTATION SUBMITTED TO THE GRADUATE DIVISION OF THE
UNIVERSITY OF HAWAII IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN AGRONOMY AND SOIL SCIENCE

MAY 1987

By

Eko Legowo

Dissertation Committee:

Goro Uehara, Chairman
Paul C. Ekern
Richard E. Green
Haruyoshi Ikawa
I-pai Wu

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Finally, I dedicate my dissertation to my mother, the late Mrs. Soedarjati Hardjodipurwo, who worked very hard to raise her son to be a man only to miss seeing her son's success.

ABSTRACT

Simple methods to estimate water extractability and hydraulic conductivity were tested in nine Mollisols, Ultisols and Andisols. A neutron hydroprobe was used to monitor soil water content over depth and time. A method to estimate soil water extractability developed by Ritchie was adapted. The applicability of the calibrated method was tested with independent soil data using the CERES model, a crop simulation model developed by a multidisciplinary team of scientists from the Grassland, Soil, and Water Research Laboratory in Temple, Texas. Using the estimated values of plant extractable water as inputs, the CERES model simulated 72% of the soil water content data points ranged from 0.08 to 0.50 m^3/m^3 with deviations of less than 0.03 m^3/m^3 from the observed values. The method requires inputs of bulk density, organic matter content, and 1.5 MPa water content for Andisols, and bulk density, organic matter content, and sand and silt content for other soils.

Simple methods to estimate hydraulic conductivity developed by Libardi et al. (1980), Chong et al. (1981), and Sisson et al. (1980) were compared. The methods require only soil water content measurements. Besides having one assumption associated with each method, all methods operate on the assumption of unit hydraulic gradient during redistribution and an exponential relationship between hydraulic conductivity and water content. The results showed that the method which assumes a power function between water content and time consistently gave higher estimates of saturated hydraulic conductivity than methods

which assume a logarithmic or exponential functions. Using means and variances of the estimated saturated hydraulic conductivity for estimating spatial variability of soil water flux showed that the choice of method only affected the estimation of spatial variability of soil water flux at early time after cessation of ponding. At longer times, the differences among the estimated saturated hydraulic conductivity by each method did not greatly influence the estimated spatial variability of the soil water flux.

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CHAPTER I

INTRODUCTION

One of the most important factors to determine land quality is the availability of water (FAO, 1983). When other environmental conditions are favorable for crop growth, the availability of water determines whether or not a crop will perform well in a particular area. When soil moisture is limited, total mineral nutrient uptake will likely be limited and crop growth retarded (Jenne et al., 1958). In turn, the crop yield will be affected. Indeed, the major cause of year-to-year variation in yield is variations in soil water deficits (Ritchie, 1980). Under rainfed agriculture, water availability to the growing crop becomes the most significant single factor limiting yields (Arar, 1980).

The soil water availability and variability are expressed as soil moisture regime classes in Soil Taxonomy (SCS, 1975). However, there are still many difficulties in determining the soil moisture regime criteria. Particularly for the tropics, the soil moisture regimes remain a controversial issue (Cline, 1980). The problems of establishing the soil moisture regimes are the lack of data and deficiencies in the computational methods (ICOMMORT, 1980).

In order to evaluate the condition of water in soil completely, one must know the amount and energy of water in the soil and the way they change over space and time (Taylor et al., 1961). Soils of the tropical region have been known to behave differently from soils of the temperate region (Uehara and Gillman, 1981). The behavior of soils is mostly influenced by two soil properties: mineralogy and texture. Soils of the temperate region are dominated by permanent charge minerals and high activity clays. On the other hand, soils of the tropical region are dominated by variable charge minerals and low activity clays. The properties of variable surface charge and low activity clays affect soil structure and pore size distribution of tropical soils. Because of them, tropical soils are generally better aggregated and have larger inter-aggregate pores than soils of the temperate region.

In the tropics, as well as elsewhere in the world, land is characterized by large spatial and temporal variations in water availability. Two types of field heterogeneity are distinguished, i.e., deterministic heterogeneity and stochastic heterogeneity (Philip, 1980). In the case of deterministic heterogeneity, various soil properties vary spatially and temporally in a known way. It often demands an extension of established methods of analysis and may involve important phenomena not present in the analogous homogeneous problem. In the stochastic heterogeneity, the variation of soil properties is irregular, may involve many scales, and is imperfectly known. Models that consider the dynamics of the soil water balance as related to soil, weather, and plant parameters are needed to assist in minimizing risks. The United States Department of Agriculture, Crop Systems Evaluation Unit, at Temple, Texas, has developed crop models called Crop-Environment Resource Synthesis (CERES) (Jones et al., 1983). It is designed to incorporate minimum sets of climate, soil, plant, and management data to predict crop performance. The main components of the models are soil water balance, nitrogen dynamics, phenological development, and crop growth. Early tests of CERES models by Jones (1982), Chinene (1983), French and Hodges (1985), Godwin and Viek (1985), Otter and Ritchie (1985), and Singh (1985) demonstrate that the CERES models can be a powerful tool for the tropics. Their efforts, however, have brought attention to the fact that the water balance component needs to be further studied and calibrated.

Water content in any layer of a soil can be increased by precipitation, irrigation, or flow from an adjacent layer, and can decrease due to soil evaporation, root absorption, or flow to an adjacent layer. The limits to which water can increase or decrease are inputs to the water balance model. In situations where water input supply is marginal, accuracy of the water limit inputs is quite important (Ritchie, 1985). The laboratory method for the determination of soil water limits--wilting point and field capacity--has been known to be unsatisfactory (van Bavel et al., 1968; Ritchie, 1981), but in situ measurements are laborious and time consuming. Attempts have been made to estimate field measured soil water limits from other soil characteristics (Ratliff et al., 1983; Cassel et al., 1983), but the models do not work for volcanic ash soils and remain largely untested for the tropical region.

Besides the water retention limits, water movement is another important component contributing to availability of water in a soil. Therefore, characterization of soil hydraulic properties over large areas is often necessary. Unfortunately, the conventional procedures are unwieldy and time consuming. Libardi et al. (1980), Chong et al.

(1981), and Sisson et al. (1980) have simplified the method to provide fast, inexpensive characterization of hydraulic conductivity over large areas. The applicability of their methods for a Calcic Haploxeroll in Utah has been validated by Jones and Wagenet (1984). If the simplified methods are also applicable to soils in the tropics, the methods will be most useful.

This study characterizes water retention and water transmission of some tropical soils and tests the applicability of models developed under conditions different from these soils. The Benchmark Soils Project of the University of Hawaii and Puerto Rico (1979) has verified the hypothesis that soils belonging to the same family classified according to Soil Taxonomy (SCS, 1975) have a homogeneous set of characteristics that can be used to predict crop response and performance under adequate soil moisture. As an extension of this hypothesis, it can be assumed that results of this study will be beneficial to any other tropical region as well. The objectives of this study are as follows:

1. To evaluate water availability limits and drainage patterns of some tropical Mollisols, Ultisols, and Andisols,

2. To test and calibrate the Ritchie soil water extractability model (presented at the IBSNAT Conference 1984),

3. To assess the applicability of the calibrated Ritchie soil water extractability model in the CERES soil water balance model, and

4. To compare and test the applicability of simplified methods of estimating hydraulic conductivity.

CHAPTER II

LITERATURE REVIEW

Soil Water Assessment by a Neutron Method

Determination of soil water content can be brought to pass by direct and indirect methods (Gardner, 1965). Direct methods are those methods which directly determine the amount of water removed from a sample by evaporation, drainage, or chemical reaction. Indirect methods involve measurement of a property of some objects placed in the soil or measurement of some properties of the soil which are affected by soil water content. The neutron scattering method is such an indirect method.

The neutron moisture meter was designed to measure in situ volumetric soil water content and its change in time and space. The volumetric soil water content is related to the count rate of slow neutrons and obtained from a calibration curve. There are three processes involved in the application of the neutron probe to estimate soil water contents (Goodspeed, 1981);

1. emission of fast neutrons from a radioactive source,
2. moderation of the neutrons to thermal velocities by collisions with soil constituents and back-scattering towards the instrument, and
3. selective detection and counting of thermal neutrons at a point close to the source.

Radioactive sources commonly used for this purpose are radium-226 and americium-241. Both radium and americium emit alpha particles and gamma rays. Other possible sources are polonium-210, actinium-227, and plutonium-239. The only suitable element available to act as the target for alpha particles is beryllium-9. When bombarded by alpha particles, beryllium produces neutrons in the ratio of about 30 neutrons per million alpha particles (Hammond, 1977).

Slowing and scattering of neutrons involve two major factors: the transfer of energy at each collision and the statistical probability of collision (Gardner, 1965). The average energy transfer at collision of a neutron with other nuclei depends largely upon the mass number of the nuclei encountered. The statistical probability of collision is related to the scattering cross section of the target element. The cross section is somewhat higher in the thermal energy range. Hydrogen, having a nucleus of about the same size and mass as the neutron, has a much greater thermalizing effect on fast neutrons than any other element. Most of the hydrogen in soil is associated with water. In addition, oxygen has an appreciable scattering cross section. Thus, the effect of water on slowing or thermalizing fast neutrons is so dominant that the neutron scattering technique can be used to measure the soil water content. However, other elements found in soil such as beryllium, carbon, nitrogen, and fluorine also have appreciable scattering cross sections. But their effect are in part compensated by other elements such as iron, potassium, cadmium, boron, lithium, and chlorine which capture thermal neutrons.

In order to accurately measure the slow neutron flux, the detector of a neutron moisture meter must be able to ignore fast neutrons while responding as efficiently as possible to the thermal neutrons. The most commonly used detector is a boron trifluoride proportional counter. Other detectors are helium-3 filled proportional counter and lithium-6 glass scintillators.

The resolution of water content measurements is restricted by the nature of the neutron-scattering and thermalization process. The volume of soil involved in the measurement will largely depend upon the water content and the energies of the emitted fast neutrons. Van Bavel (1958) reported that at best the practical resolution was about 15 cm, i.e. the soil volume most greatly affecting the slow-neutron count rate was a 15 cm diameter sphere (Gardner, 1965). Based on the findings with silica and Catano sand, Shirazi and Isobe (1976) also concluded that the sphere of importance was within a radius of 15 to 18 cm. Similarly, Greacen et al. (1981) reported that for many soils more than 75% of the count rate could be shown to arise from the volume of soil within 10 cm of the outside of the access tube. The diameter of the sphere increases with decreasing water content. Because of this low resolution, the neutron moisture meter cannot detect sharp differences in water content between soil horizons (McHenry, 1963). Measurements close to the soil surface are also unreliable because of the soil-air discontinuity. However, the neutron scattering technique is likely to be of sufficient accuracy for many practical uses in terms of overall water content (Gardner, 1965).

Soil Water Availability Concepts

Soil water availability is the adequacy of soil water to meet evapotranspiration and to maximize water use efficiency (Jamison, 1956).

The term soil water availability has been used interchangeably with available water capacity, water retention difference, potential extractable water, and plant extractable water. The upper limit of the soil water availability is the water content at field capacity and the lower limit is the water content at permanent wilting point. The conventional method of evaluating the limits is to measure water contents of soil samples at potentials of -33 kPa or -10 kPa for the field capacity and -1.5 MPa for the wilting point by means of a pressure membrane or plate apparatus. The water content at 10 kPa tension is widely used in the United Kingdom, Australia, and Canada to estimate the field capacity (El-Swaify, 1980). Although there is increasing acceptance of the 10 kPa tension to estimate field capacity, occurrence of air entrapment under field situations enables the water content at 33 kPa tension to be used to estimate the water content at field capacity (Uehara and Gillman, 1981). The United States Department of Agriculture usually estimates the field capacity of clayey and loamy soils with the 33 kPa value and sandy soils with the 10 kPa value (SCS, 1971). The following formula is commonly used to estimate soil water availability:

$$AWC = (FC - WP)\ 100 \times BD \times (1 - CF)\ 100 \qquad (2.1)$$

where AWC = available water capacity (m/m)

FC = gravimetric water content of soil fragment of less than 2 mm diameter in soil sample at 33 kPa or 10 kPa tension (kg/kg)

WP = gravimetric water content of soil fragment of less than 2 mm diameter at 1.5 MPa tension (kg/kg)

BD = bulk density of soil sample at 33 kPa (Mg/m^3)

CF = volumetric fraction of soil fragment or more than 2 mm diameter (m^3/m^3).

However, the static laboratory determination of soil water availability has been criticized because the laboratory estimation of available water depends on soil characteristics and does not consider the role of the plant (Miller, 1967). Wilcox (1962) pointed out that plants can extract water at soil water contents greater than field capacity, and some of the so-called available water is positionally unavailable due to continued deep drainage. To avoid the use of the field capacity concept, Miller (1967) proposed another concept of available water as follows:

Available water = Initial water + Added water
- Deep drainage - Water held at wilting (2.2)

The initial water may be estimated by soil sampling and the amount of water applied may be measured by soil sampling or by metering irrigation water. The water held by the soil at permanent wilting may be estimated from the 1.5 MPa value. Miller (1967) could not find any reliable method to evaluate integrated drainage. He also stated that the wilting point was not a precise value, but the error involved was small. However, as a result of an experiment conducted on Maui, Hawaii, as will be discussed later in Chapter V, it is now known that this error is not small. The difference between permanent wilting of pasture grasses measured in the field and the 1.5 MPa water content measured in the laboratory could be as high as 30% by volume for Inceptisols (Andepts), 15% for Ultisols, and 5% for Mollisols of Maui.

Ritchie (1981) showed a rather large decrease in water content near the soil surface due to evaporation on the one hand and incomplete depletion in the lower profile due to low root density on the other hand. Because of this he recommended that the upper and lower limit of available water be measured in the field. He defined in situ soil water availability as follows:

Soil water extractability = Field measured drained upper limit - Field measured lower limit (2.3)

where soil water extractability is the available water measured in the field, drained upper limit of soil water extractability is the water content measured when the drainage rate is about 0.1 cm/day, and the lower limit of soil water extractability is the lowest measured water content corresponding to the dryest period when the vegetation is permanently wilted.

Soil Water Movement Processes

Flow rate of a liquid through a porous medium is governed by a driving force acting on the liquid and the property of the conducting medium. This statement is known as Darcy's law. In a one-dimensional system, this statement can be written as

$$q = - K \, dH/dx \tag{2.4}$$

where q is flux density (or simply called flux), i.e. volume of water flowing through a unit cross-sectional area per unit of time. The total pressure head drop per unit of distance in the direction of flow, dH/dx, is the hydraulic gradient. It is the driving force. Defining a force as a gradient of a scalar potential, soil water potential P_t (Joules/kg) for isothermal conditions may be defined as

$$P_t = P_p + P_s + P_e + P_z \quad (2.5)$$

where P_p is pressure potential, P_s is solute potential, P_e is electrical potential, and P_z is gravitational potential. For most field studies, it is generally assumed that P_s and P_e are spatially and temporally invariant (Nielsen et al., 1986). Corey and Klute (1985), however, showed that the pressure and gravitational components appearing in the thermodynamic potential of the water component and the potential of the solution referred to different kinds of element and should not be added. The potentials are expressed in terms of energy per unit mass. Potentials can also be expressed on a unit weight basis that is usually referred to as head (m), as has been used in equation 2.4, by dividing the mass potentials with acceleration of gravity. In addition, potentials can also be expressed on a unit volume basis (Joules/m^3), which is dimensionally the same as pressure (Newton/m^2) or Pascal (Pa), by multiplying the mass potentials with the density of water.

The proportionality factor, K, which relates water flux to hydraulic gradient is designated as hydraulic conductivity. In a saturated soil of stable structure and rigid porous medium, the hydraulic conductivity is characteristically constant (Hillel, 1980, p. 178). Therefore, Darcy's equation can be used to predict ratio of water flow due to different gradients imposed on a medium. Thus, hydraulic conductivity can be considered as a characteristic water transmission coefficient for a medium. Hydraulic conductivity K is affected by soil and fluid characteristics. The soil characteristics which affect hydraulic conductivity are total porosity, distribution of pore sizes, and tortuosity. The fluid characteristics which affect hydraulic conductivity are fluid density and viscosity. Theoretically, hydraulic conductivity can be divided into two factors: intrinsic permeability (m) of the soil and fluidity (f) of the liquid. Since fluidity is inversely proportional to viscosity as

$$f = n\ g\ /\ v \tag{2.6}$$

where v is viscosity in poise units (10^{-5} Newton sec/cm^2), n is fluid density (g/cm^3), and g is gravitational acceleration (cm/sec^2), the intrinsic permeability can be formulated as

$$m = K\ v\ /\ (n\ g) \tag{2.7}$$

where m is expressed in terms of cm^2 and K is expressed in cm/sec.

Darcy's law is sufficient only to describe flow processes when potential and gradient at each point along the conducting system remain constant with time. The condition is called steady or stationary state. In unsteady or transient flow processes, in which the magnitude and direction of the flux and potential gradient vary with time t, Darcy's law needs to be supported with the law of mass conservation. The mass conservation law states that if a rate of inflow into a volume element is greater than a rate of outflow, the volume element must store the excess and increase its water content. Conversely, if outflow exceeds inflow, the storage must decrease. It can be expressed as an equation of continuity:

$$d\theta/dt = -\ dq/dx \tag{2.8}$$

If Darcy's law and the mass conservation law are combined, a general flow equation results which in a one-dimensional system can be expressed as

$$\frac{d\theta}{dt} = \frac{d}{dx} \left(K \frac{dH}{dx}\right) \tag{2.9}$$

In unsaturated soils, however, water movement proceeds differently. The moving force is not the gradient of a positive pressure potential but a gradient of negative pressure potential. Water tends to flow from places where matric suction is lower to places where matric suction is higher. The hydraulic conductivity in an unsaturated soil is not a constant number, but it decreases correspondingly as the soil dries. The hydraulic conductivity near saturation is the most sensitive measure of temporal changes of hydraulic properties (Mapa et al., 1986). Parkes and Waters (1980) found that actually only a minor proportion of the soil pore space was contributing to flow through the whole profile. Upon drying, water is moving in preferential paths (Rice et al., 1986), and in a structured sandy loam the preferential flow continues to occur to at least 1.2 m depth (Richter and Jury, 1986). Large macropores of highly structured soils provide preferential paths for the soil solution to follow, especially under saturated conditions (Kanchanasut et al., 1978). Under unsaturated conditions, however, larger "micropores" could result in preferential flow. Therefore, as matric suction develops, the largest pores which are the most conductive will be emptied first, leaving the smaller pores which are less conductive to transport water. As a result, hydraulic conductivity usually drops drastically by several orders of magnitude during transition from saturation to conditions of unsaturation. While it is true that a sandy soil conducts water more rapidly than a clayey soil in a saturated condition, the opposite happens when the soils are unsaturated.

With the provision that hydraulic conductivity is not a constant, but a function of matric suction of water content, Darcy's law can be extended to unsaturated flow,

$$q = - K(P_p)\ dH/dx \tag{2.10}$$

or

$$q = - K(\theta)\ dH/dx \tag{2.11}$$

In combination with the equation of continuity, it leads to the following form of Richard's equation (Nielsen et al., 1986):

$$C(P_p)\frac{dP_p}{dt} = \frac{d}{dz}\left(K(P_p)\left(\frac{dP_p}{dz} + \frac{dP_z}{dz}\right)\right) + E_i \tag{2.12}$$

where $C(P_p) = d\theta/dP_p$ is the differential water capacity or the slope of the soil water retention curve, and E_i represents various sources and sinks in the system notably those resulting from plant water extraction in the soil root zone.

CHAPTER III

MATERIALS AND METHODS

Location of the Study Area

In order to achieve the research objectives, the field work was conducted on the west slope of Mount Haleakala on the Island of Maui, Hawaii. Nine benchmark experimental sites in an area of about 25 km x 25 km located between the north and south-western rift of the mountain have been selected for careful study. It is approximately located at 21^{o}N and 157^{o}W. The high variability in soil and climatic characteristics over relatively short distance was a significant factor in the selection of the project location. The location has demonstrated its suitability as a natural laboratory for studying effects of environment on plant growth and reproduction (Britten, 1962). A description of the sites is presented in Table 3.1. The location map is presented in Figure 3.1.

Mean annual rainfall ranges from approximately 380 mm in the rain-shadow of the mountain to 1910 mm on the windward side of the mountain. However, in some places, particularly in the northern part of the area, rainfall is relatively constant from sea level to more than 1800 m, as can be seen from Figure 3.1. Elevations range from near sea level to over 1640 m. Mean annual air temperatures range from 13.5^{o}C in the highest elevation to 24.3^{o}C in the lowest site, with corresponding mean annual soil temperatures at 50 cm depth ranging from 15.6^{o}C to 29.4^{o}C (Ikawa and Kourouma, 1985).

Table 3.1

Soils and environmental characteristics of the experimental sites

Site	Soil Series	Elevation (m)	Mean Annual Rainfall (mm)	Soil Classification
H.POKO	Paia	99	1100	MOLLISOLS (Oxic Haplustolls, very fine, kaolinitic, isohyperthermic)
WAIAKOA	Keahua	375	380	MOLLISOLS (Torroxic Haplustolls, fine, kaolinitic, isohyperthemic)
OMAOPIO	Keahua	530	440	MOLLISOLS (Torroxic Haplustolls, fine, kaolinitic, isohyperthermic)
PAUWELA	Haiku	153	1250	ULTISOLS (Humoxic Tropohumults, clayey, ferritic, isohyperthermic)
KUIAHA	Haiku	283	1910	ULTISOLS (Homoxic Tropohumults, clayey, ferritic, isohyperthermic)
MAKAWAO	Makawao	640	1830	ULTISOLS (Humoxic Tropohumults, clayey, oxidic, isothermic)
HAPAPA	Kula	1160	760	ANDISOLS (Typic Eutrandepts, medial, isothermic)
OLINDA	Olinda	1150	1270	ANDISOLS (Entic Dystrandepts, medial, isomesic)
PUUPAHU	Kaipoioi	1640	1070	ANDISOLS (Typic Dystrandepts, medial, isomesic)

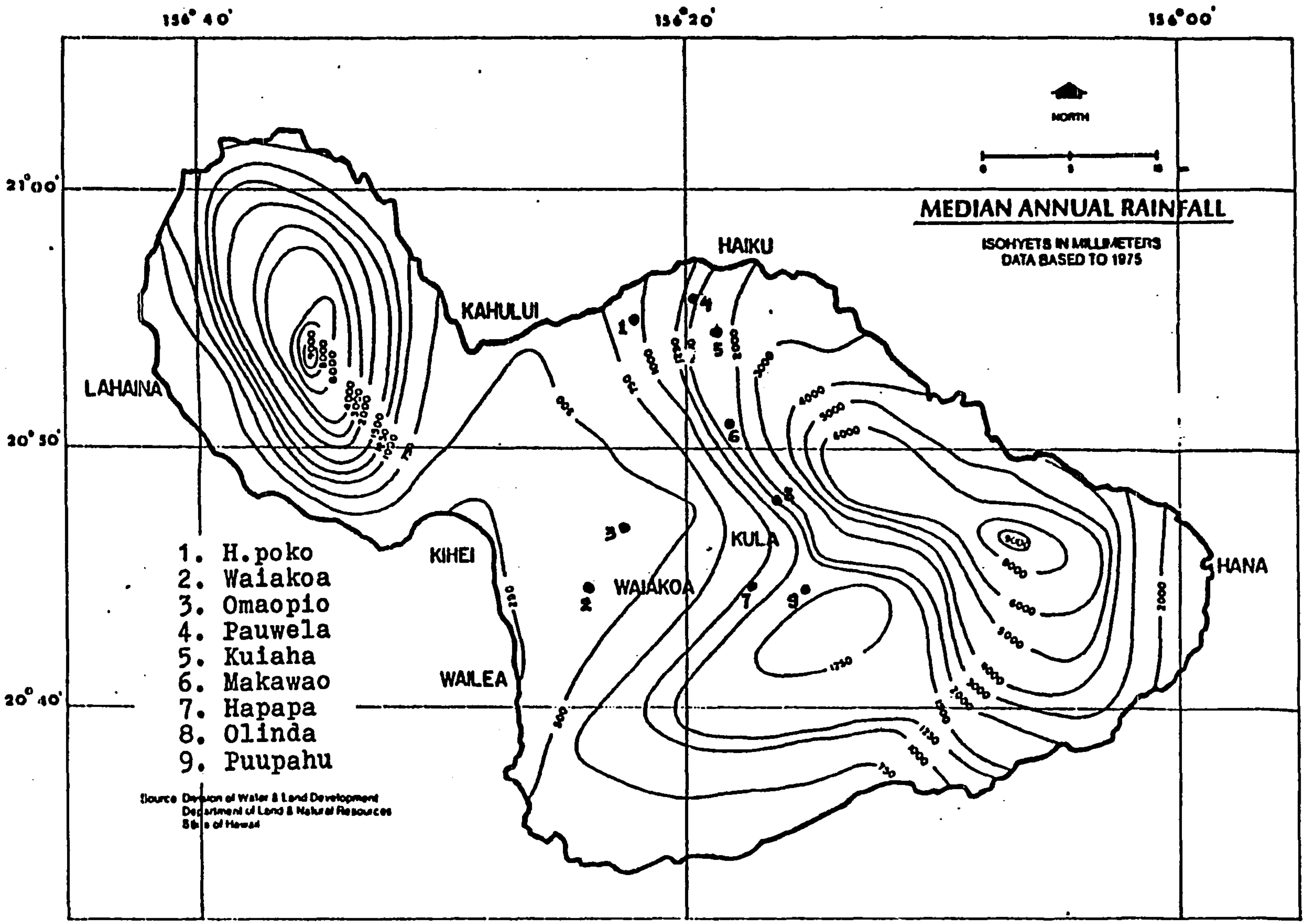


Figure 3.1. Location of the study sites

Soils of the benchmark sites consist of three Mollisols, three Ultisols, and three Inceptisols. All Inceptisols belong to the sub order Andepts. The Andepts will be reclassified under a new order Andisol (Leamy, 1981). Hereafter these three Inceptisol sites will be referred to as Andisol sites.

Soil moisture regime of the study area ranges from torric to udic, while soil temperature regime ranges from isohyperthermic to isomesic. Particle-size classes consist of fine, clayey, and medial and the mineralogy classes are kaolinitic, oxidic, and ferritic, and amorphous. The soils of the study area are as follows:

(1) Paia Series, a very-fine kaolinitic isohyperthermic family of Oxic Haplustolls, i.e. Hamakuapoko site,

(2) Keahua Series, a fine kaolinitic isohyperthermic family of Torroxic Haplustolls, i.e. Waiakoa and Omaopio site,

(3) Haiku Series, a clayey ferritic isohyperthermic family of Humoxic Tropohumults, i.e. Pauwela and Kuiaha site,

(4) Makawao Series, a clayey oxidic isothermic family of Humoxic Tropohumults, i.e. Makawao site,

(5) Kula Series, a medial isothermic family of Typic Eutrandepts, i.e. Hapapa site,

(6) Olinda Series, a medial isomesic family of Entic Dystrandepts, i.e. Olinda site, and

(7) Kaipoioi Series, a medial isomesic family of Typic Dystrandepts, i.e. Puupahu site.

Hosaka and Ripperton (1955) reported the occurrence of primarily shrub with or without some trees at the drier lower elevations and an open or closed forest with or without shrub at the wetter higher elevations. Now, economic crops dominate the study area, e.g.: sugarcane from sea level to about 200 m, pineapple from about 200 to 600 m above sea level (a.s.l.), vegetables and flowers from about 600 to 1000 m a.s.l., pine trees from about 1000 to 1300 m a.s.l., and lastly pasture dominates those areas where lack of water constrains intensive farming.

Sugar, pineapple and diversified agriculture productions of Maui are of great importance to the State of Hawaii. In 1985, Maui produced 263,000 Mg of raw sugar. Pineapple on Maui county accounts for about 70% of the state's production with $36.4 million value. In terms of crop sales, diversified agriculture accounts for approximately 13% of the state's total crop value. As of 1984, vegetables and melons are ranked first with a crop value of $9 million, followed by cattle with $6.9 million, flowers and nursery products with $4.5 million, forage and grain products with $3.7 million, hogs with $1.9 million, fruits (other than pineapple) with $343,000, and other livestock products with $125,000 value (First Hawaiian Bank Research Department, 1986).

Field Method

Collection of Weather Data

The Soil Climate Project of the University of Hawaii has had weather stations monitoring the study area since July, 1983. The data have been recorded automatically with CR-21 Microloggers as manufactured by the Campbell Scientific Company. The daily data of rainfall, air temperature (maximum and minimum), soil temperature (at 10 cm and 50 cm depth), and solar radiation have been available since the weather stations were first installed (Ikawa, unpublished data).

The model RG-2501 Sierra Tipping Bucket Raingages were used to record rainfall. The RG-2501 was designed for the National Weather Service by the manufacturer as a low cost tipping bucket raingage. The unit has a 203 mm orifice and is constructed of aluminum and stainless steel. The Model 201 Relative Humidity Sensors were used to measure relative humidity and air temperature. The 201 unit contains a Phys-Chemical Research Model PCRC-11 relative humidity sensor and a Fenwal UUT-51J1 thermistor. Model 101 Temperature Probes were used to measure soil temperature. The 101 unit incorporates a Fenwal Electronics UUT-51J1 thermistor in a water-proof probe. Model LI-200S Silicon Pyranometers were used to record energy flux density. A calibration constant, as determined by LI-COR, is provided by the factory.

Collection of Soil Samples

Field examination, description, and sampling of pedons took place in September, 1983, to March, 1984. The soil on each site was excavated for careful study. The activity was organized by the Soil Climate Project, University of Hawaii, in cooperation with the Soil Conservation Service. The standard procedures, as described in the Soil Survey Manual (1951), were used to describe and sample the pedons.

Measurement of Soil Water Content

Neutron access tubes with an inside diameter of 51 mm were installed to a depth of 160 cm on each site. The area surrounding the tubes was covered with a dense growth of native grasses. A model 503DR neutron hydroprobe, manufactured by the Campbell Scientific Company, was used to monitor soil water content over depth and time. The unit has a 1.85 GBq Americium-241/Beryllium-9 probe. The first measurement was made at approximately a month after the access tubes were installed to allow soil settlement and stability. Water content measurements were taken both under natural conditions governed by weather fluctuation and under controlled conditions following ponding.

Calibration of the Neutron Hydroprobe

The neutron hydroprobe was calibrated by collecting soil samples with a soil auger adjacent to the access tube and matching their water contents to the corresponding neutron count reading. The calibration curve produced in this manner was used to estimate water content as a function of time and depth at that site.

Laboratory Methods

The soil samples collected from Waiakoa, Omaopio, Makawao, Olinda, Hapapa, and Puupahu were analyzed by the National Soil Survey Laboratory in Lincoln, Nebraska, whereas the samples from Hamakuapoko, Pauwela, and Kuiaha were analyzed by the IBSNAT and Soil Climate Projects, University of Hawaii. The revised Soil Survey Report Number 1 (SCS, 1972), "Soil Survey Laboratory Methods and Procedures for Collecting Soil Samples," was followed for analyzing the samples.

The soil moisture samples collected for hydroprobe calibration purpose were analyzed in Soil Physics Laboratory of the Department of Agronomy and Soil Science, University of Hawaii, following standard procedure of gravimetric method.

Computer Simulation Methods

Data collected from nine sites were used to validate Ritchie soil water extractability model. The model was modified by adjusting its coefficients and algorithms to match the drained upper limit, lower limit, and water extractability of the Mollisols, Ultisols, and Andisols of the study area.

The aim of this exercise was to see if the upper and lower limits obtained in this manner might be used in a water balance model to predict soil water content over space and time. The water balance model of CERES (Crop-Environment Resource Synthesis) simulates soil water changes. The model was used to test the applicability of the calibrated Ritchie soil water extractability model. The test was conducted by using the estimated values of soil water extractability as inputs in running CERES's soil water balance model and comparing the outputs with measured values.

CHAPTER IV

CALIBRATION OF THE NEUTRON HYDROPROBE

Introduction

Practical limitations of the using of neutron hydroprobe make proper calibration essential. It has been found that factory calibration curves are usually not satisfactory (Rawls and Asmussen, 1973). Questions have been raised as to whether neutron moisture meter equipment should be calibrated in the laboratory or in field, and whether a calibration curve is required for each site or each soil. Precision, accuracy, and ease are usually used as criteria for the choice of method (Greacen et al., 1981). The range of water content sampled for the calibration is an important factor in determining precision. If the range of water content occurring in the field is restricted, laboratory calibration may be the only way to obtain the required range and the required precision. Where the high precision is not required, the choice of method is determined largely by ease and accuracy. It is not easy to create laboratory conditions that resemble field conditions. In addition, at very low water content the laboratory method is inconvenient due to the requirement of a large volume of soil. Therefore, for soils where water can be added easily and very low water contents, field calibration is usually preferred.

Rawls and Asmussen (1973) and Babalola (1978), found that one calibration curve was sufficient for soils of the Georgia Coastal Plain and Nigeria. Their calibration curves were independent of soils and depths. However, since neutron probe measurements are affected by soil texture (Cannell and Asbell, 1974; Gornat and Goldberg, 1972; Lal, 1974), bulk density (Holmes, 1966; Lal, 1974; Luebs et al., 1968; Olgaard and Haahr, 1967), neutron absorbing elements, and hydrogen sources other than water, many workers (Cannell and Asbell, 1974; Greacen, 1981; Holmes, 1966; Lal, 1974; and Luebs et al., 1968, among others) suggest that neutron probe calibration should be specific to a particular situation. Greacen et al. (1981) suggested that a calibration curve be established for a particular neutron meter and type of installation and for general classes of soils. They suggested that calibration curves be established for such soil classes as sands, normal mineral soils, cracking clays, organic soils, and soils dominated by a particular mineral such as calcium carbonate, ironstone, or gravel.

In this study, soil conditions varied not only from site to site but also from horizon to horizon. The apparent soil texture varied from silt loam to clay, bulk density ranged from 0.29 to 1.70 Mg/m^3, and dithionite-citrate extractable iron, a neutron absorbing element, ranged from 3.9 to 20.04%. For these reasons, calibration curves for each soil, textural class, site, and soil horizon were developed.

Materials and Methods

Soil Moisture Sampling

The neutron hydroprobe used in this experiment was the model 503DR manufactured by the Campbell Scientific Company. The hydroprobe was calibrated with soil moisture samples collected at the depths and times corresponding to several neutronprobe readings. The first samples were taken one month after the access tubes were installed. Two auger samplings, 60-90 cm from the access tube were collected for each site. The soil was collected from the 30, 50, 70, 90, 110, 130, and 150 cm depths. The sampling was repeated 3 to 6 times over a one year period under natural conditions and 2 to 3 times following artificial ponding. Soil moisture was determined in the laboratory by oven drying to 105^{o}C for 48 hours.

Development of Calibration Curves

Neutron hydroprobe calibration is designed to predict water content from observed neutron count rate, and commercial neutron moisture meters produce linear calibration curves over the range of water content of interest to agronomic practices (Nicolls et al., 1981). Rawls and Asmussen (1973) showed that the relationship between the ratio of probe counts and standard count and soil water was linear in the range between 4 and 40% of soil water by volume. However, where the liner or probe components contain large amounts of hydrogenous material, the calibration curve becomes slightly concave towards the water content axis, and in the case of a swelling clay, a logarithmic relationship is preferred (Greacen et al., 1981).

In this study, the relationship between the neutron count ratio and volumetric water content was assumed to be linear and the least-squares method was used to describe the dependence of neutron counts to soil water content. Neutron count data were recorded as the ratio of observed count rate to the count rate in a standard medium. The standard medium provided by the manufacturer (CPN Corp., 1984) consisting of a neutron shield was used. The water content data were expressed as volumetric water content. This was achieved by multiplying the gravimetric moisture content with the corresponding 33 kPa bulk density and correcting for coarse rock fragments. The neutron count ratios (NCR) were plotted against volumetric water contents (VWC) for each horizon.

Results and Discussion

Regression Model

The relationship between neutron hydroprobe counts and soil water content can be expressed by an equation of the form Y = a + b X, where Y and X are the volumetric water content (VWC) and the ratio of the count rate in the soil to the count rate in the standard medium (NCR), respectively, or vice versa, a is the intercept, and b is the slope of the line. The slope of the line is described by the relationship

$$b = \frac{(X_i - \bar{X})\ (Y_i - \bar{Y})}{(X_i - \bar{X})^2} \qquad (4.1)$$

where $\bar{Y}$ and $\bar{X}$ are the mean of VWC and NCR respectively, or vice versa. If VWC is regressed on NCR, the bias in the coefficient will depend on the variance of NCR. On the other hand, if NCR is regressed on VWC, a similar but opposite effect will result.

In field calibration, the values of VWC are obtained by sampling. The sampling variance can be calculated by taking replicate samples. In the case of NCR, however, the variance is also due to the heterogenous distribution of free water, constitutional water, bulk density, and neutron absorbers, and it is not possible to estimate it (Greacen et al., 1981). Thus, the regression of NCR on VWC would give a better calibration curve than a curve based on regressing VWC on NCR.

The calibration curve was obtained by expressing NCR = a + b VWC explicitly in terms of VWC using the equation VWC = A + B NCR, where A = a/b and B = 1/b. The difference between the inverted calibration coefficient of NCR on VWC and calibration coefficient of VWC on NCR was inversely proportional to the correlation coefficient (r) of the calibration curve, as shown in Tables 4.1 to 4.3. The choice of the regression model becomes less important as the deviations from the regression line diminishes. For data sets with low correlation coefficients, a wrong decision can lead to serious bias in the calibration equation.

Calibration Curve

When the data for all soils and depths were combined as shown in Table 4.1 and Figure 4.1, only about 61% of the variance could be explained by VWC (r = 0.7820). This is most likely a consequence of the high variability in bulk density, texture, and iron content. The coefficients of variation (CV) were 44%, 104%, and 35% for bulk density, clay content, and iron content respectively, as shown in Table 4.4.

When the data were grouped according to soil order, only the Mollisols behaved alike, r = 0.9418. The Ultisols and Andisols had correlation coefficients of 0.4484 and 0.8326, respectively. As discussed later in Chapter V, the lower limits of soil water extractability for the Mollisols were very low, ranging from 0.14 to 0.32 m^3/m^3. The lower water content for a given count ratio in the Mollisols

Table 4.1

Intercept (a,A) and slope (b,B) of neutron hydroprobe calibration curves grouped by soil orders

SOIL	VWC on NCR		NCR on VWC INVERTED		r	(B-b)/b x 100
	a	b	A	B		
Mollisols	-10.0830	38.7697	-15.7051	54.9898	0.9418**	13
Ultisols	10.2912	36.8463	-135.6432	183.2274	0.4484**	397
Andisols	-31.7024	75.1124	-68.9935	108.3612	0.8326**	44
All soils	-18.7302	63.1110	-60.1282	103.2066	0.7820**	64

Table 4.2

Intercept (a,A) and slope (b,B) of neutron hydroprobe calibration curves grouped by apparent soil texture

TEXTURE	VWC on NCR		NCR on VWC INVERTED		r	(B-b)/b x 100
	a	b	A	B		
Si.loam	-30.7332	75.1638	-79.5904	118.1042	0.7977**	57
Si.c.loam	-27.9380	65.5984	-32.0900	73.9060	0.9421**	13
Si.clay	-0.1435	43.7898	-102.6863	148.0056	0.5440**	238
Clay	20.6140	31.0787	-98.4349	155.1133	0.4477^{ns}	399

Table 4.3

Intercept (a,A) and slope (b,B) of neutron hydroprobe calibration curves grouped by soil horizons

SITE /HOR.	VWC on NCR		NCR on VWC INVERTED		r	(B-b)/b x 100
	a	b	A	B		
H.POKO:						
Ap/Bw	-28.7616	70.4087	-44.8056	87.3744	0.8977**	24
WAIAKOA:						
Bw	-12.5598	51.0268	-14.5837	53.5378	0.9763**	5
OMAOPIO:						
Bw	-2.4635	39.8136	-5.6823	43.1455	0.9696**	8
PAUWELA:						
AB	-52.0909	97.3221	-63.8130	109.6443	0.9421*	13
Bw	9.6094	37.7376	6.5703	40.8602	0.9610**	8
Bt1	14.4418	28.0686	9.4302	33.1231	0.9205**	18
Bt2	-20.7717	59.8076	-27.2135	66.5203	0.9565**	11
KUIAHA:						
Ap	-9.5424	71.5412	-10.9276	72.9964	0.9900**	2
Bw	-66.4679	117.1362	-71.4207	121.8368	0.9805**	4
Bt	-121.3928	162.7323	-141.1680	180.7991	0.9484*	11
BC	-138.5467	163.9591	-146.6920	170.8701	0.9795**	4
CB	-95.9802	118.0366	-98.6247	120.2154	0.9909**	2
MAKAWAO:						
Bt	-32.2582	93.0289	-52.6120	116.0133	0.8955**	25
CB	-56.9072	77.7216	-78.4760	97.7651	0.8916**	26
HAPAPA:						
Bw1	-10.6935	61.8518	-14.7748	66.5832	0.9716**	6
Bw2	-6.7461	62.5992	-9.1402	64.7325	0.9834**	3
Bw3/1	-0.3903	54.1740	-6.2125	59.1667	0.9569**	9
Bw4/2	-98.4221	127.8816	-101.9323	130.9175	0.9883**	2
OLINDA:						
Bw	-23.0191	63.6733	-29.9852	70.3878	0.9511**	11
BC	-21.8597	58.6535	-27.6734	64.1330	0.9563**	9
PUUPAHU:						
Bw	-36.2065	76.2355	-44.9223	84.0612	0.9523**	10
2C	18.3141	33.4883	17.0595	34.5685	0.9843**	3
3Bw1	-10.3537	65.3190	-13.4031	67.8983	0.9808**	4
3Bw2	-109.7281	138.0821	-141.1896	163.7170	0.9184**	9
4CR	-135.0250	153.8807	-138.2581	156.5068	0.9916**	2

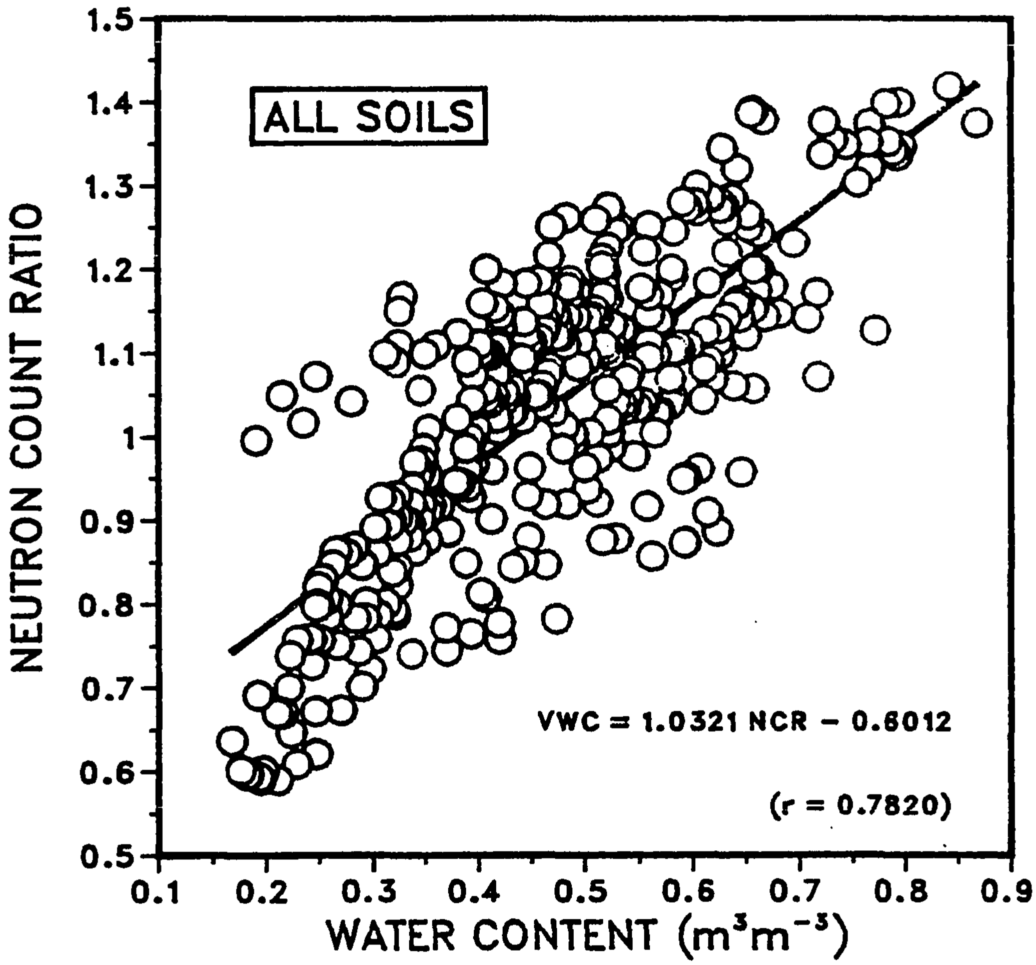


Figure 4.1. Neutron hydroprobe calibration curve for all soils.

Table 4.4

Mean and coefficient of variation of bulk density, clay content, iron content

GROUPING	B.D.(Mg/m^3)		CLAY (%)		IRON (%)[a]	
	MEAN	C.V. (%)	MEAN	C.V. (%)	MEAN	C.V. (%)
All soils	1.01	44	29.5	104	10.3	35
Nonvolcanic ash	1.36	11	51.3	48	10.5	40
Mollisols	1.33	10	50.3	42	8.3	5
Ultisols	1.37	12	51.5	51	11.2	41
Andisols	0.55	35	1.9	45	10.1	28

[a]Dithionite-citrate extractable iron.

suggests that bound water was lower in this group of soils. The calibration curve for Mollisols is presented in Figure 4.2.

The low correlation coefficient for the Ultisols is possibly caused by the high variability of their iron content, i.e. from 3.9% to 20.0% (CV = 41%). Iron absorbs thermal neutrons, but it is likely that absorbed thermal neutrons are compensated by others generated by non-water protons in organic matter and inorganic clay. In case of Andisols, the main source of variance is very likely associated with bulk density (CV = 35%). The bulk density of the Andisols varied from 0.29 to 0.84 Mg/m3. However, the effect of bulk density on neutron readings is usually small compared to the effect of soil moisture and its distribution in the soil profile (Cannell and Asbell, 1974). As

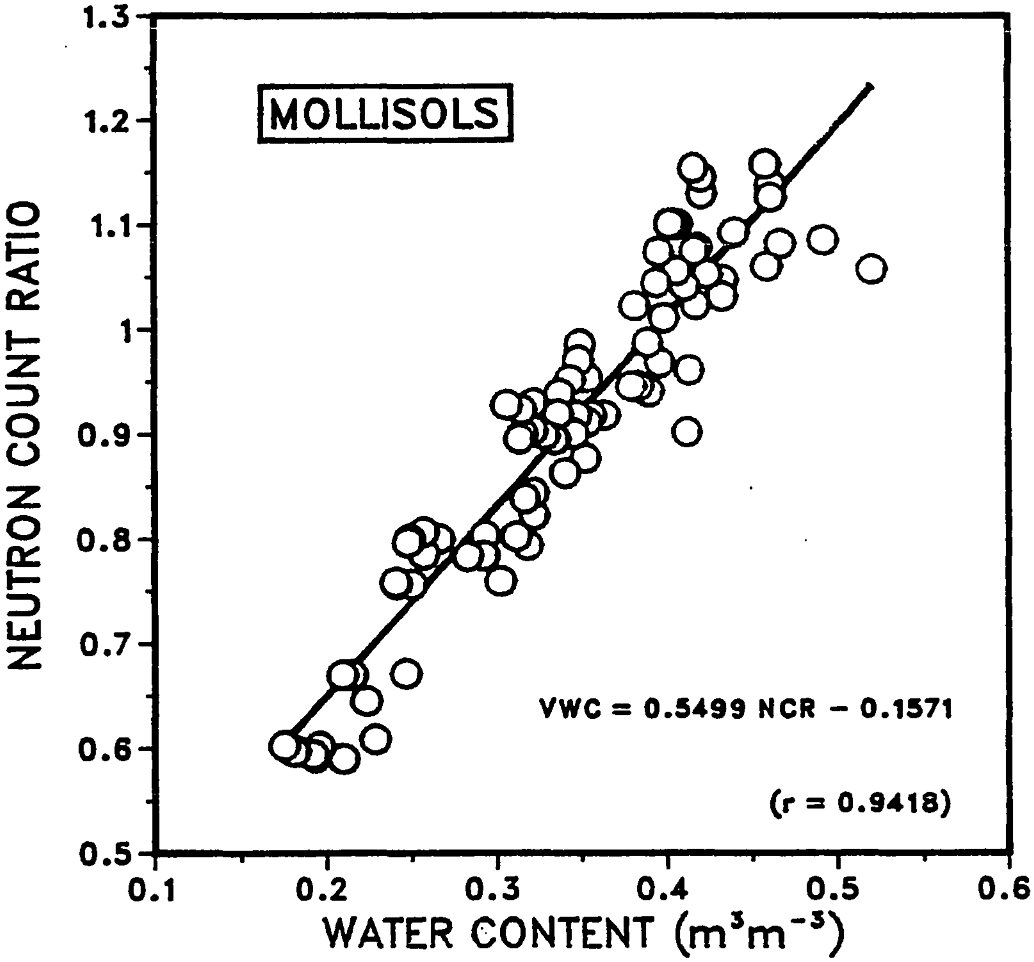


Figure 4.2. Neutron hydroprobe calibration curve for Mollisols.

expected, the correlation coefficients for the Andisols were not as low as those for the Ultisols.

When the data were grouped according to soil textural classes, as shown in Table 4.2, the result as expected showed higher correlation between NCR and VWC for loams than clay soils. However, only the silty clay loam resulted in a high coefficient (r = 0.9421). Surprisingly the silt loams had a lower coefficient than the silty clay loams, i.e. r = 0.7977. It should be noted, however, that the silt loams were mainly from the Andisols. As discussed previously, the main source of variation of the Andisols is in their bulk density and not their clay contents. The calibration curve for the silty clay loam is presented in Figure 4.3.

When the data were plotted for all horizons within each site, only the Mollisols (Hamakuapoko, Waiakoa, and Omaopio sites) showed good correlation between NCR and VWC, with correlation coefficients of 0.8977, 0.9763, and 0.9606 respectively. For this reason soil water content was estimated from calibration curves developed for each horizon as illustrated in Appendix A, Appendix Figures A.1-A.9 and given in Table 4.3.

Conclusions

Widespread use of neutron hydroprobe in spatially variable soils is limited by the need to calibrate the device for each soil, and in many cases for every horizon. Variability in bulk density, clay content, and iron oxide content made it necessary to calibrate the probe for every horizon. This study shows that neutron scattering

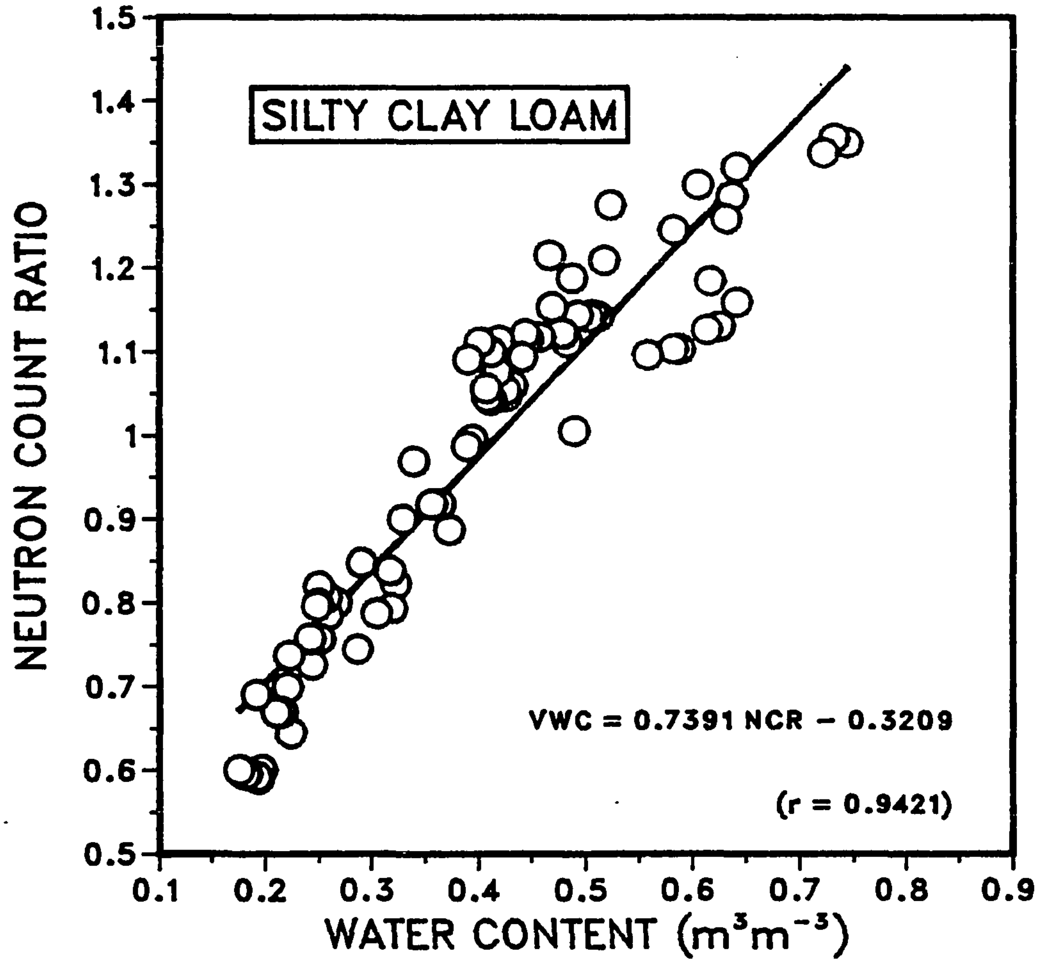


Figure 4.3. Neutron hydroprobe calibration curve for silty clay loam soils.

techniques for measuring water content can be justified only when a site is used for intensive, long term monitoring of water. If not, the cost of calibration would make the measurement cost prohibitively high.

CHAPTER V

ESTIMATION OF PLANT EXTRACTABLE WATER

Introduction

For any given soil there is an upper and a lower limit to the amount of water that is available for plant use. In contrast to the conventional laboratory method, the limits of soil water extractability are measured in the field. These important soil properties are not now collected in routine soil characterization studies and most likely will not be included in soil survey reports in the near future owing to the high cost and labor requirement of measuring these limits. In such situations, a model that estimates field measured soil water availability from readily available data is needed.

Ritchie (1984, personal communication) has developed such a model based on data collected in the continental United States. The model utilizes sand, silt and organic matter content and bulk density to estimate the lower limit and plant extractable water. The plant extractable water and its upper and lower limits are required inputs to run the CERES crop growth model. Since its adoption by the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) Project, the Ritchie water extractability model has been used by IBSNAT's collaborators to assess extractable soil water to operate the CERES model. However, the model has not been tested for volcanic ash soils and highly aggregated soils. If the Ritchie model can be adapted for these conditions, the model will be most useful for the IBSNAT's collaborators and the tropics in general.

Materials and Methods

Measurement of Plant Extractable Water

Measurement of Lower Limit

Water in soil profiles were monitored in the field under natural conditions from August, 1984 to June, 1985. Due to erratic in rainfall, the interval of soil water measurements was irregular but was conducted as frequently as possible ranging in time intervals of one week to one month. The water contents of the surface horizons were measured gravimetrically and the deeper layers with a neutron hydroprobe. The lowest measured water content corresponding to the driest period when the vegetation was permanently wilted was defined as lower limit of soil water extractability (LOL). The lower limits generally occurred in November 1984, when soil water content attained minimum values and remained constant.

Measurement of Drained Upper Limit

In June 1985, the sites were ponded with water for about 24 hours. The changes in profile water content were checked frequently to assure that steady state water flow condition had been attained. Ponding was then discontinued and the plots were covered with plastic sheeting to prevent evaporation. The measurement time intervals after cessation of ponding were 5-10 minutes for the first two hours, 30-60 minutes for the first day following the first two hours, once a day for the first week, and 2-4 days thereafter for 3-4 weeks. Soil water content measured at the time when water flow was at steady state condition was defined as saturation water content (SAT). Soil water content measured at the time when drainage rate was about 0.1 cm/d was defined as the drained upper limit of extractable soil water (DUL). The difference between the drained upper limit (DUL) and lower limit (LOL) of soil water extractability was calculated and defined as plant extractable water (PEXW).

Calibration of Soil Water Extractability Model

Testing of the Ritchie Model

Data generated from nine sites (Hamakuapoko, Waiakoa, Omaopio, Pauwela, Kuiaha, Makawao, Hapapa, Olinda, and Puupahu) were used to test and calibrate Ritchie's model of soil water extractability. Ritchie's equations are as follows:

$$LOL = W1\ (1-0.01\ OM)\ (1+BD-D) + 0.0023\ OM \qquad (5.1)$$

$$PEXW = W2\ (1-0.01\ OM) + (D-BD)\ 0.2 + 0.0055\ OM \qquad (5.2)$$

$$DUL = LOL + PEXW \qquad (5.3)$$

where

LOL = lower limit (m^3/m^3)

PEXW = plant extractable soil water (m^3/m^3)

DUL = drained upper limit (m^3/m^3)

BD = bulk density (Mg/m^3)

OM = organic matter (%)

$$D = 1.5 - (0.01923\ SAND) + (0.0008324\ SAND^2) - (1.083 \times 10^{-5}\ SAND^3) + (4.662 \times 10^{-8}\ SAND^4) \qquad (5.4)$$

W1 = interim variable to estimate LOL (m^3/m^3)

and W2 = interim variable to estimate PEXW (m^3/m^3).

If sand content > 75%,

$$W1 = 0.19 - 0.0017\ SAND \quad (5.5)$$

$$W2 = 0.429 - 0.00388\ SAND \quad (5.6)$$

If sand content < 75% and silt content > 70%,

$$W1 = 0.16 \quad (5.7)$$

$$W2 = 0.429 - 0.00388\ SAND \quad (5.8)$$

If sand content < 75% and silt content < 70%,

$$W1 = 0.0542 + 0.00409\ CLAY \quad (5.9)$$

$$W2 = 0.1079 + 5.004001 \times 10^{-4}\ SILT \quad (5.10)$$

where

SAND = sand content (%)

SILT = silt content (%)

CLAY = clay content (%).

To adapt the Ritchie model, the interim variables (W1, W2 and D) were modified so that the model estimated extractable water and its limits satisfactorily. W1 was adjusted to fit the measured lower limit, W2 to fit extractable water and D to fit bulk density data. Since the data clustered into three groups, the lower limit and plant extractable water data were grouped into three groups corresponding to the soil orders Mollisols, Ultisols and Andisols. The bulk density data were grouped into volcanic and nonvolcanic ash as these two groups have different ranges in bulk density.

Testing the CERES Soil Water Balance Model

The soil water balance subroutine of the CERES model was used to test the reliability of the modified Ritchie's model of soil water extractability. The CERES's soil water balance model has been adapted for the tropics by Chinene (1983) and Singh (1985). They used the Wahiawa silty clay, a clayey kaolinitic isohyperthermic family of Tropeptic Eutrustox in their study.

The water balance component of the CERES has two principal functions: (1) to calculate redistribution and drainage of water during and after precipitation or irrigation, and (2) to calculate soil evaporation and plant transpiration. Singh (1985) presented the complete computer program for the model. The model evaluates soil water balance using the following equations,

$$SW = RAIN + AIRR - EP - ES - RUNOFF - DRAIN \qquad (5.11)$$

Equation 5.11 equates the quantity of soil water (SW) to precipitation (RAIN), irrigation (AIRR), transpiration from plants (EP), evaporation from soil (ES), runoff (RUNOFF), and drainage from the profile (DRAIN). Water content in any soil layer can increase from inflow from adjacent layers and can decrease from soil evaporation, root absorption, or outflow to an adjacent layer. The extent to which water can increase or decrease is controlled by the lower limit (LOL) and drained upper limit (DUL) of soil water extractability and saturation water content (SAT). The output of the water balance model is very sensitive to these inputs.

Infiltration of water into a soil is calculated as the difference between precipitation and/or irrigation and runoff. Daily precipitation and the amounts and dates of irrigation are inputs to the model. Runoff is calculated by a curve number technique described by the USDA-Soil Conservation Service (SCS, 1972). This technique has been modified for use in CERES by Williams et al. (1983) for layered soils.

Runoff is calculated according to the formula:

$$RUNOFF = PB \times PB / (PRECIP + 0.8\ R2) \quad (5.12)$$

where PB = temporary variable used to determine whether runoff occurs (mm),

$$PB = PRECIP - 0.2\ R2 \quad (5.13)$$

PRECIP = temporary variable used for summation of irrigation (AIRR) and precipitation (RAIN), and

R2 = SCS curve number retention parameter (mm).

The SCS curve number retention parameter (R2) is calculated from SUM, a weighted sum of soil water in the profile (unitless, 0-1), and SMX, the maximum value of R2 (mm), with equation as follows:

$$R2 = SMX\ (1-SUM) \quad (5.14)$$

SMX is calculated from:

$$SMX = 254\ (100/CN1 - 1) \quad (5.15)$$

and

$$CNI = -16.91 + 1.348\ CN2 - 0.01379\ CN2^2 + 0.0001172\ CN2^3 \quad (5.16)$$

where CN2 = curve number used to calculate runoff.

The runoff curve number varies from 0 for no runoff, to 100 when all water is runoff. The curve number depends on the hydraulic soil group and soil cover and can be obtained from tables. Cooley and Lane (1982) modified runoff curve numbers for sugarcane and pineapple fields in Hawaii. Their modified curve numbers were lower than the Soil Conservation Service handbook values. The greatest differences were associated with porous soils and complete cover conditions.

Drainage and soil water redistribution are calculated in a loop which moves water down from the top soil to lower layers. Drainage takes place whenever the water content (SW) exceeds the drained upper limit (DUL). The drainage formulation is

$$DRAIN = (SW - DUL) \times SWCON \times DLAYR \quad (5.17)$$

where SWCON is soil specific conductance parameter and DLAYR is soil layer thickness. The value of SWCON may vary greatly among soils, but is assumed to be constant for a given soil because the most limiting layer is assumed to dominate drainage from all parts of the soil profile. The value of SWCON can vary from 0 for no drainage, to 1 for instantaneous drainage.

Potential evapotranspiration (EO) is computed using an equilibrium evaporation concept as modified by Priestley and Taylor (1972). If maximum air temperature (TEMPMX) is less than 5.0^{o}C,

$$EO = EEQ \times 0.01 \times EXP\ (0.18\ (TEMPMX + 20)) \quad (5.18)$$

if TEMPMX is between 5.0^{o}C and 35.0^{o}C,

$$EO = EEQ \times 1.1 \quad (5.19)$$

and if TEMPMX is greater than 35.0^{o}C,

$$EO = EEQ \times ((TEMPMX - 35) \times 0.05 + 1.1) \quad (5.20)$$

where EEQ is equilibrium evaporation.

The potential evapotranspiration is calculated by multiplying equilibrium evaporation by 1.1 to account for the effect of unsaturated air. When maximum air temperature exceeds 35^{o}C, the constant is increased to account for advection, and when maximum air temperature is less than $5^{o}C$, the constant is reduced to account for stomatal closure. A constant of 1.26 was determined by Priestley and Taylor (1972) for saturated surfaces. Although the constant is also a function of wind speed, surface roughness and the entrainment of dry air at the top of the atmospheric boundary layer, it depends primarily on the surface resistance (de Bruin, 1983). The constant equals to 1.3, 1.0, and 0.6 when the surface resistance equals to 0, 60, and 250 s/m respectively.

The equilibrium evaporation (EEQ) is influenced by solar radiation (SOLRAD), soil albedo (ALBEDO), and mean daytime temperature (TD), as,

$$EEQ = SOLRAD\ (2.04 \times 10^{-4} - 1.83 \times 10^{-4} \times ALBEDO) \times (TD + 29) \quad (5.21)$$

where ALBEDO is estimated from bare soil albedo (SALB) and leaf area index (LAI),

$$ALBEDO = 0.23 - (0.23 - SALB) \times EXP(-0.75\ LAI) \quad (5.22)$$

and TD is estimated from maximum air temperature (TEMPMX) and minimum air temperature (TEMPMN),

$$TD = 0.60\ TEMPMX + 0.40\ TEMPMN \quad (5.23)$$

Potential rate of soil evaporation (EOS) is calculated according to the following rules

$$EOS = ED\ (1 - 0.43\ LAI) \quad (5.24)$$

if $LAI < 1$, and

$$EOS = EO / 1.1\ EXP\ (-0.4\ LAI) \quad (5.25)$$

if $LAI < 1$.

Actual evapotranspiration (ET) is calculated with a model developed by Ritchie (1972). The procedure separates soil evaporation (ES) from plant transpiration (EP). The evaporation from a soil surface ES is calculated in two stages. The first consist of the constant rate stage in which ES is limited only by a supply of energy to the surface, and the second involves the falling rate stage in which water movement to evaporating sites near the surface is controlled by soil hydraulic properties. The first stage continues until a soil-dependent upper limit of stage-1 evaporation (U) is reached. Soil evaporation then enters stage-2. If the value of cumulative soil evaporation in stage-1 (SUMES1) is less than or equal to U,

$$ES = EOS \qquad (5.26)$$

However, if the value of SUMESI exceeds U,

$$ES = EOS - 0.4\ (SUMESI - U) \qquad (5.27)$$

When this occurs, the value of cumulative soil evaporation in stage-2 (SUMES2) is calculated as follows:

$$SUMES2 = 0.6\ (SUMESI - U) \qquad (5.28)$$

and the time after stage-2 evaporation begins (T) is calculated as

$$T = SUMES2\ /\ 3.5)^2 \qquad (5.29)$$

As the soil continues to dry during stage-2 evaporation, T increases by 1.0 each day and ES is calculated as

$$ES = 3.5\ T^{0.5} - SUMES2 \qquad (5.30)$$

Transpiration by the plants (EP) is calculated using equations as follows:

$$EP = EO (1 - EXP (-LAI) \quad (5.31)$$

if LAI < 3.0, and

$$EP = EO \quad (5.32)$$

if LAI > 3.0.

However, if (EP + ES) is greater than EO, then

$$EP = EO - ES \quad (5.33)$$

To validate the accuracy of the CERES soil water balance model, the model was tested with soils used in this study. The model was evaluated by comparing measured and simulated soil water contents at depth of 30, 50, 70 and 90 cm for nine random dates after the lower limit of soil extractability had been reached (August to November, 1984). Three sites in the ustic moisture regime represented by low, medium, and high elevation sites were chosen. The availability of daily weather data (precipitation, solar radiation, and maximum and minimum air temperature), the wide range of soil water contents, the wide range of soil temperature regimes, and the wide range of soil mineralogical classes were the bases for choosing these sites. They were the Waiakoa (Keahua Series, a fine kaolinitic isohyperthermic family of Torroxic Haplustolls), Hapapa (Kula Series, a medial isothermic family of Typic Eutrandepts), and Puupahu (Kaipoioi Series, a medial isomesic family of Typic Dystrandepts) sites.

Validation of the Modified Ritchie Model

The modified Ritchie model for estimating soil water extractability could not be tested since other data of measured lower and upper limit of soil water extractability were not available for comparison. As an alternative test, the modified model was tested for its capacity to predict soil water content over depth and time with the CERES model. To run the CERES model, field measured extractable water (PEXW) and its limits (DUL and LOL) are required. These variables are usually not available but can be estimated from the modified soil water extractability model. The aim is to test the reliability of the modified soil water extractability model by subjecting the estimated parameters to a water balance test. Since the Ritchie water extractability model was developed for this purpose, this should be the appropriate way to test the modified Ritchie model.

A Mollisol, an Ultisol, and an Andisol were used to test the applicability of the modified water extractability model. The sites and their corresponding soils were: (1) Holopuni (Keahua Series, a fine kaolinitic isohyperthemic family of Torroxic Haplustolls), (2) Haliimaile (Hamakuapoko Series, a clayey oxidic isohyperthermic family of Orthoxic Tropohumults), and (3) Kekoa (Pane Series, a medial isothermic family of Oxic Dystrandepts). These sites had not been used to calibrate the Ritchie water extractability model or test the CERES water balance model. They lack field measured soil water extractability data but have soil characterization data (sand, silt, clay, organic matter and 1.5 MPa water content and bulk density) that can be used to estimate the lower limit, upper limit and extractable water. Each site has a weather station that records daily solar radiation, precipitation, and maximum and minimum air temperature. These minimum data sets enable the CERES water balance model to be used in these locations. Neutron access tubes installed at these sites provided the soil water data needed for comparison with the simulated results.

The model was tested by comparing measured soil water content with simulated soil water content at depth of 30, 50, 70 and 90 cm for 8-14 randomly selected times between August 1985 to June 1986.

Results and Discussion

Evaluation of Soil Water Extractability

Lower Limit of Soil Water Extractability

Results in Table 5.1 show that the lower limit of available soil water can be very different from the permanent wilting point. It is interesting to note that relative to the 1.5 MPa value the lower limit of plant extractable water is overestimated in Mollisols and underestimated in Ultisols except at the Pauwela site, and in Andisols except at the Olinda site. There are several reasons why the two methods yield different results. The greater natural subsoil fertility of Mollisols enables plants to exploit submoisture more effectively than in Ultisols and Andisols. The effect of subsoil fertility on the extractable water has been reported by Brown (1971) who observed that in the 30 to 150 cm depth increment, only about half as much water was extracted by winter wheat from unfertilized soils relative to the fertilized treatment. Similarly, Chinene (1983) reported that when a Wahiawa silty clay soil was fertilized with 198 kg/ha P and 186 kg/ha N, the amount of water extracted by maize was about twice the amount extracted from the control plots. There are indications that improved crop models can now simulate responses to fertilizer application and their consequence on water extraction.

Table 5.1

Total water content (cm) and volumetric water content (m^3/m^3) at the lower limit of extractable soil water in the 0-100 cm and 0-160 cm depths

SITE	FIELD				LABORATORY			
	100 cm		160 cm		100 cm		160 cm	
	cm	m^3/m^3	cm	m^3m^3	cm	m^3/m^3	cm	m^3/m^3
MOLLISOLS:								
H.poko	30	0.30	51	0.32	35	0.35	57	0.36
Waiakoa	19	0.19	35	0.22	25	0.25	NA	NA
Omaopio	23	0.23	41	0.26	29	0.29	48	0.30
MEAN	24	0.24	42	0.26	30	0.30	53	0.33
ULTISOLS:								
Pauwela	32	0.32	51	0.32	34	0.34	52	0.33
Kuiaha	45	0.45	70	0.44	30	0.30	49	0.31
Makawao	35	0.35	56	0.35	29	0.29	NA	NA
MEAN	37	0.37	59	0.37	31	0.31	51	0.32
ANDISOLS:								
Hapapa	48	0.48	77	0.48	19	0.19	29	0.18
Olinda	24	0.24	42	0.26	24	0.24	NA	NA
Puupahu	48	0.48	73	0.45	18	0.18	29	0.18
MEAN	40	0.40	64	0.40	20	0.20	29	0.18
MEAN ALL SOILS	34	0.34	55	0.34	27	0.27	44	0.28

In the laboratory methods, the water retained at a given negative pressure is mostly influenced by soil texture and mineralogy. For soils whose clay fraction consists mainly of crystalline minerals, the 1.5 MPa water content is closely related to clay and organic matter content. But for soils dominated by short range order minerals, as in Andisols, the 1.5 MPa water content is only remotely related to clay content. In Andisols, water is held mostly in small voids rather than on clay surfaces (Maeda and Warkentin, 1975; Rousseaux and Warkentin, 1976). The volume of small voids is directly related to content of allophane (Warkentin and Maeda, 1980), therefore the wilting percentage is more related to allophane content than to clay content. Before analysis, many laboratories air dried their samples. The irreversible change in physical and mechanical properties of allophanic soils due to drying is well known. These phenomena cause laboratory estimated lower limit to underestimate the true lower limit in Andisols.

Among the sites with soils from the Ultisol order, the Pauwela is unique in that its base saturation is more than 35% in the top 87 cm, whereas the Makawao and Kuiaha has base saturation of less than 11%. The Kuiaha pedon is a typical Haiku Series, whereas the Pauwela pedon, although a member of the Haiku Series it is yellower in some parts of the A and B horisons (S. Nakamura, 1984, personal communication). The Pauwela site is located in an experimental station of the NifTAL (Nitrogen Fixation in Tropical Agricultural Legumes) Project. It is possible that this soil has been limed in the past and the resultant fertility enables the vegetation to extract water effectively. As a consequence, this soil has a lower field measured wilting percentage than the other Ultisols and is overestimated by the laboratory method.

Among the sites with Andisols, analyses of the clay fraction by X-ray diffraction methods indicate that the soil from the Olinda site contains large quantities of mica and kaolin including chlorite-vermiculite intergrades, goethite and quartz. In addition, analysis by electron microscopy showed high content of goethite-ferrihydrite intergrades, a small amount of halloysite and allophane, and trace amount of imogolite (Wada et al., 1986). This clearly proves that the soil at the Olinda site is not an Andisol and should be expected to have a lower water holding capacity in the field. In contrast to this, the laboratory results show that the Olinda soil has high water holding characteristic. This discrepancy is caused by the fact that in typical Hydric Dystrandepts, laboratory air drying of samples markedly lowers their water holding properties. This did not occur in the Olinda soil because it did not contain large quantities of short range order minerals. Consequently, the field measured wilting point was overestimated by the laboratory method.

The lower limit of extractable water can also vary considerably among soil layers within a profile as can be seen in Figures 5.1-5.3. Noticeably lower water contents are associated with the surface layers. This is caused by soil evaporation. On medium and fine textured soils, evaporation from the surface dries the soil to a much lower water potential than is possible by plant roots (Ritchie, 1981). In Figure 5.1, the lower limit is found to be relatively low to a depth of 30 cm and rises to a constant level down to 130 cm. This appears to be

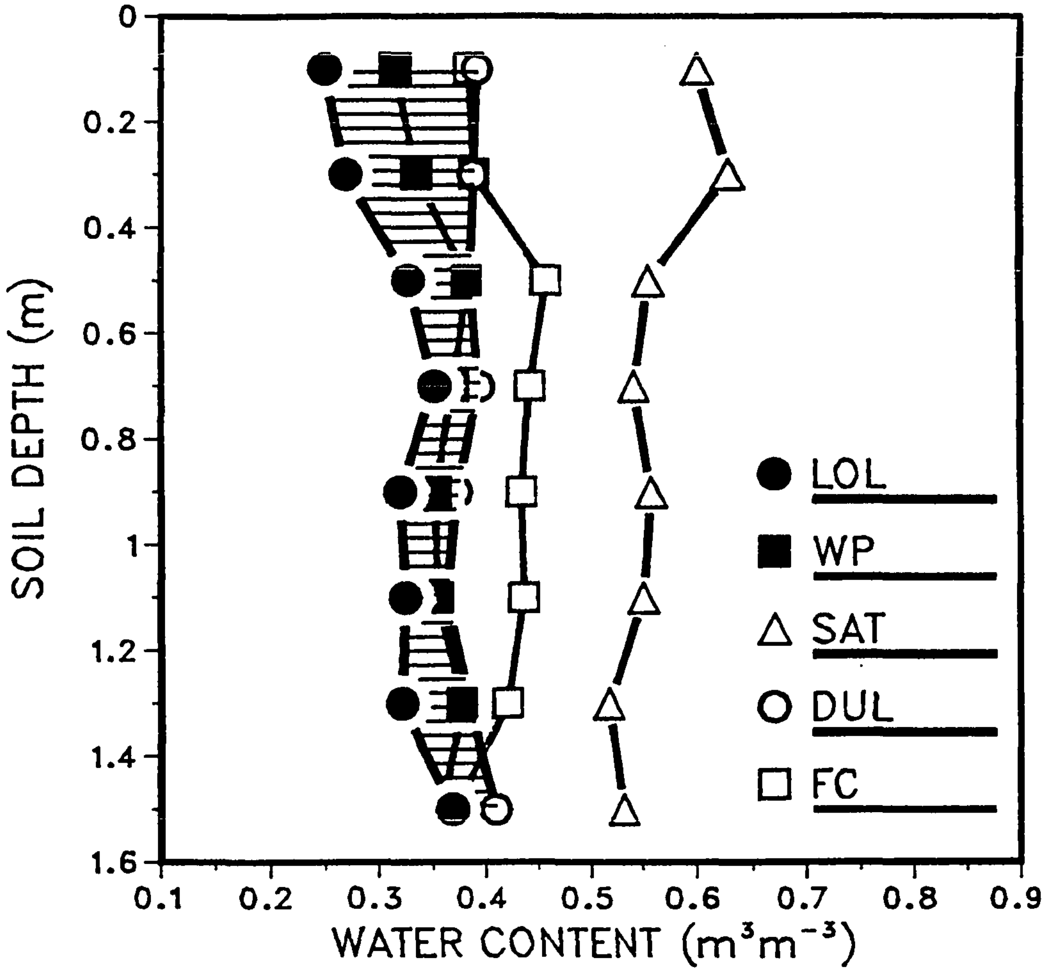


Figure 5.1. Comparison of laboratory measured permanent wilting point (WP) and field capacity (FC) with field measured lower limit (LOL), drained upper limit (DUL), and saturation (SAT) in Hamakuapoko site (Oxic Haplustolls).

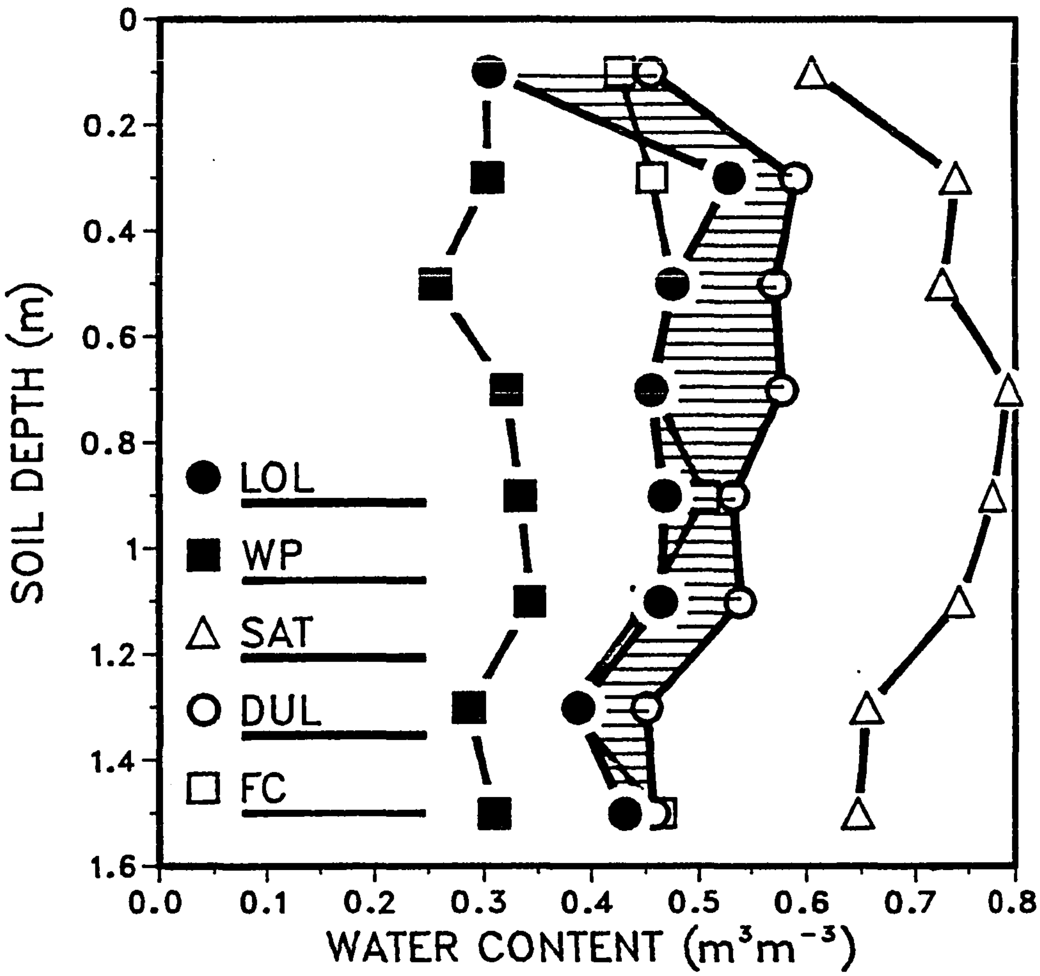


Figure 5.2. Comparison of laboratory measured permanent wilting point (WP) and field capacity (FC) with field measured lower limit (LOL), drained upper limit (DUL), and saturation (SAT) in Kuiaha site (Humoxic Tropohumults).

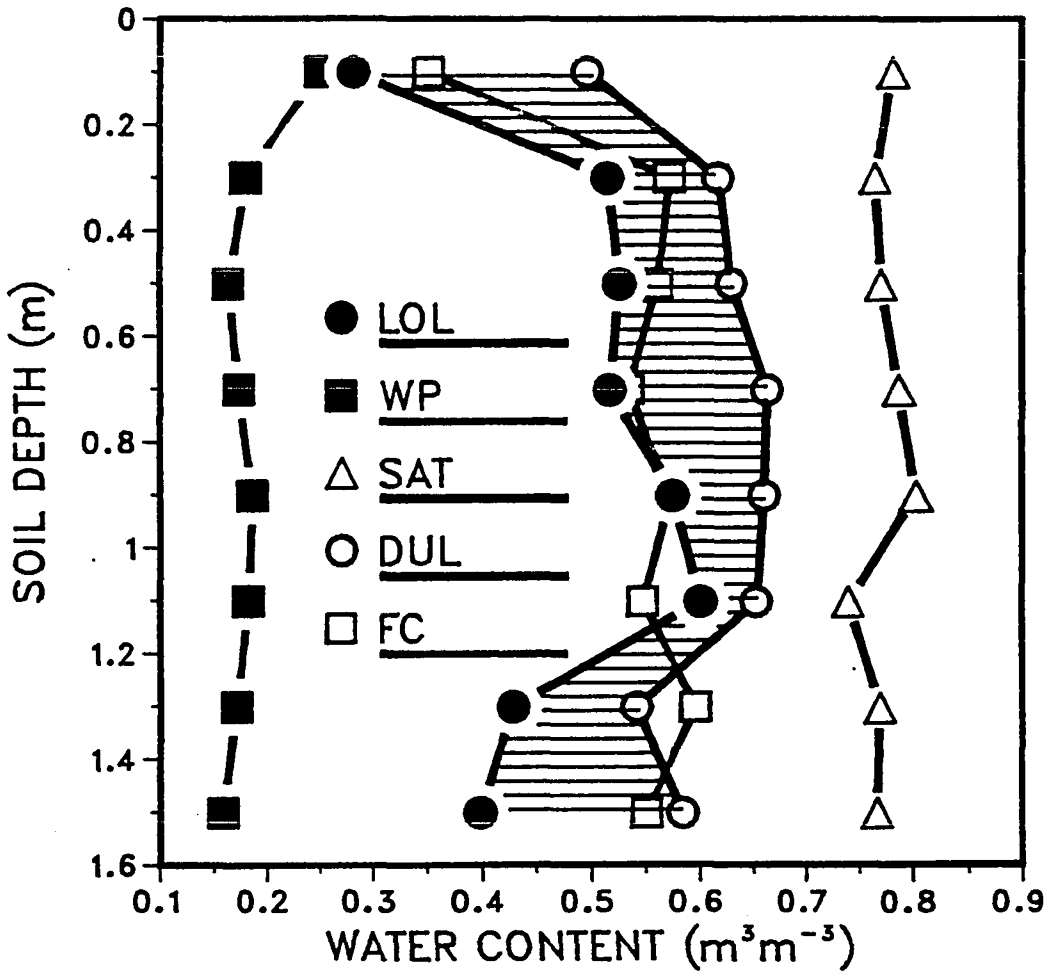


Figure 5.3. Comparison of laboratory measured permanent wilting point (WP) and field capacity (FC) with field measured lower limit (LOL), drained upper limit (DUL), and saturation (SAT) in Hapapa site (Typic Eutrandepts).

the case with homogeneous soils such as the one at Hamakuapoko and other Mollisols. Grasses growing on these soils extract water to at least 130 cm.

However, in layered soils such as in the Ultisols and Andisols, the lower limit varied markedly among soil layers. The high variability in physical and chemical properties among layers causes plant roots to behave differently in each soil layer. Thus, the lower limit in these soils is difficult to estimate. For example, the results in Figure 5.2 and Figure 5.3 show that the lower limit at 30 cm depth of the Kuiaha site and 110 cm depth of the Hapapa site are considerably higher than their adjacent horizons. The layers at 30 cm depth (Ap2 horizon) in the Kuiaha site and 110 cm depth (Bw3 horizon) in the Hapapa site have the highest bulk density, the lowest CEC, the lowest extractable bases, the lowest base saturation, and the lowest pH in their respective profiles. This clearly illustrates the fact that the lower limit of extractable water is not a physical property but a biophysical characteristic of the soil.

Upper Limit of Soil Water Extractability

The upper limit of extractable soil water is attained when drainage out of a thoroughly wetted profile has become negligibly small. The time after cessation of ponding when drainage becomes negligibly small varies among soils. It is usually assumed to be two days. Results in Table 5.2, however, show that the time needed to attain a drainage rate of 0.1 cm/d could vary from 2 to 26 days dependent on the soil and depth chosen. The deviations between the

Table 5.2

Time (hours) after cessation of ponding to attain the drained upper limit of extractable soil water

SITE	SOIL DEPTH (cm)								
	010	030	050	070	090	110	130	150	MEAN
MOLLISOLS:									
H.poko	305	305	305	305	305	305	305	305	305
Waiakoa	261	261	261	289	458	458	458	458	363
Omaopio	234	234	266	266	266	266	266	266	258
MEAN	267	267	277	287	343	343	343	343	309
ULTISOLS:									
Pauwela	306	306	306	306	306	306	306	306	306
Kuiaha	50	309	309	478	478	478	478	478	382
Makawao	190	527	527	527	527	527	527	631	498
MEAN	182	381	381	437	437	437	437	472	395
ANDISOLS:									
Hapapa	165	165	213	213	213	213	213	213	201
Olinda	263	285	361	437	437	437	437	437	387
Puupahu	117	264	264	264	264	264	382	382	275
MEAN	182	238	279	305	305	305	344	344	288
MEAN ALL SOILS	210	295	312	343	362	362	375	386	331

two methods could be up to 7% of the bulk soil volume, as shown in Table 5.3.

Results in Table 5.4 show that field capacity is overestimated in Mollisols and underestimated in Ultisols and Andisols. In the laboratory, saturation of the sample can be achieved prior to determination of the water release curve. In the field, however, fully saturated condition rarely exists due to persistence of encapsulated air within and between soil aggregates. Encapsulated air is defined as the volume of soil air that is completely isolated by water from external atmosphere (Bond and Collis-George, 1981). Air encapsulation of 7.3 to 15.5% (Green, Rao and Balasubramanian, unpublished data) and 1.1 to 6.3% (Fayer and Hillel, 1986) of the bulk soil volume have been reported. Under ponded conditions, it took up to 28 days to eliminate encapsulated air from a Typic Dystrochrept profile (Fayer and Hillel, 1986). Elimination of entrapped air in the laboratory but their unavoidable occurrence in the field results in an overestimation of the water content at field capacity in heavy textured soils such as the Mollisols investigated in this study.

Ultisols, however, with low surface charge density and low activity clays, behave differently from Mollisols. Many highly weathered, clayey soils of the tropics are heavy textured, they have moisture release curve similar to light soils (Sharma and Uehara, 1968). In light soils, such slight shrinkage as may occur can only be due to rearrangement of the particles to a form of somewhat closer packing (Childs, 1969, p. 115). Hence as the initially saturated soil losses water, the lost water in the pore space must be replaced by air. In the field, only the surface horizon has pores that contact directly

Table 5.3

Comparison of the soil water contents attained when drainage rate was about 0.1 cm/d (A) with the soil water contents attained 2 days after cessation of ponding (B)

SITE/METHOD		WATER CONTENT (m^3/m^3) AT SOIL DEPTH (cm) OF								
		010	030	050	070	090	110	130	150	MEAN
H.poko	A	.39	.39	.39	.39	.38	.38	.38	.38	.385
	B	.42	.43	.43	.43	.43	.43	.43	.44	.430
	B-A	.03	.04	.04	.04	.05	.05	.05	.06	.045
Waiakoa	A	.33	.31	.29	.29	.30	.31	.32	.34	.311
	B	.40	.36	.35	.35	.36	.37	.38	.39	.370
	B-A	.07	.05	.06	.06	.06	.06	.06	.05	.059
Omaopio	A	.41	.39	.39	.39	.39	.39	.39	.39	.393
	B	.42	.40	.40	.40	.40	.40	.40	.40	.403
	B-A	.01	.01	.01	.01	.01	.01	.01	.01	.010
Pauwela	A	.43	.43	.45	.46	.46	.46	.47	.47	.454
	B	.47	.46	.47	.47	.48	.48	.49	.49	.476
	B-A	.04	.03	.02	.01	.02	.02	.02	.02	.022
Kuiaha	A	.45	.51	.53	.54	.54	.54	.53	.52	.520
	B	.45	.54	.56	.58	.59	.59	.57	.57	.556
	B-A	.00	.03	.03	.04	.05	.05	.04	.05	.036
Makawao	A	.43	.43	.44	.47	.48	.45	.45	.44	.449
	B	.45	.46	.47	.49	.50	.47	.47	.47	.473
	B-A	.02	.03	.03	.02	.02	.02	.02	.03	.024
Hapapa	A	.50	.56	.58	.60	.61	.62	.61	.60	.585
	B	.54	.59	.61	.63	.64	.64	.63	.63	.614
	B-A	.04	.03	.03	.03	.03	.02	.02	.03	.029
Olinda	A	.68	.57	.52	.48	.44	.43	.43	.44	.499
	B	.70	.60	.55	.51	.48	.46	.46	.47	.529
	B-A	.02	.03	.03	.03	.04	.03	.03	.03	.030
Puupahu	A	.59	.54	.53	.55	.58	.60	.63	.62	.580
	B	.61	.57	.56	.57	.60	.63	.65	.64	.604
	B-A	.02	.03	.03	.02	.02	.03	.02	.02	.024

Table 5.4

Total water content (cm) and volumetric water content (m^3/m^3) at the drained upper limit of extractable soil water in the 0-100 cm and 0-160 cm depths

SITE	FIELD				LABORATORY			
	100 cm		160 cm		100 cm		160 cm	
	cm	m^3/m^3	cm	m^3/m^3	cm	m^3/m^3	cm	m^3/m^3
MOLLISOLS:								
H.poko	38	0.38	62	0.39	42	0.42	67	0.42
Waiakoa	31	0.31	54	0.34	36	0.36	NA	NA
Omaopio	39	0.39	63	0.39	36	0.36	60	0.37
MEAN	36	0.36	59	0.37	38	0.38	63	0.39
ULTISOLS:								
Pauwela	46	0.46	75	0.47	45	0.45	69	0.43
Kuiaha	55	0.55	83	0.52	46	0.46	72	0.45
Makawao	48	0.48	72	0.45	45	0.45	NA	NA
MEAN	50	0.50	77	0.48	46	0.46	71	0.44
ANDISOLS:								
Hapapa	61	0.61	97	0.61	52	0.52	86	0.54
Olinda	44	0.44	71	0.44	54	0.54	NA	NA
Puupahu	59	0.59	99	0.62	55	0.55	92	0.57
MEAN	55	0.55	89	0.56	54	0.54	89	0.55
MEAN ALL SOILS	47	0.47	75	0.47	46	0.46	74	0.46

with open air. The displacement of water by air becomes increasingly difficult as pore size decreases and pore tortuosity and distance from the soil surface increases. In the laboratory, exposure of all pores to open air is more readily achieved than in the field because of the small size of the samples. The displacement of water by air is easier and the pressure needed to reach hydrostatic equilibrium becomes lower than in the field. As a result, the upper limit of soil water extractability in strongly aggregated soils, such as Ultisols, is underestimated by laboratory method of 33 kPa water content.

In soils dominated by amorphous materials, such as Andisols, soil particles are cemented by amorphous materials. The amorphous materials coat crystalline particles and the coated particles coalesce to form stable aggregates (Jones and Uehara, 1973). If the soil is routinely dried, as part of the laboratory procedure, hydrated non-crystalline materials dehydrate irreversibly into aggregates of silt, sand, and gravel size (SCS, 1975, p. 235). Upon drying the soil becomes extremely porous and the field capacity decreases markedly, more so than the wilting percentage (Warkentin and Maeda, 1980). Hence the 33 kPa water content determined in laboratory underestimates the field condition.

Tensions of 0.5 to 60 kPa have been reported for field capacity (Baver et al., 1972). The results in this study indicate that field capacity of Mollisols needs to be estimated with water tension more than 33 kPa and Ultisols and Andisols with less than 33 kPa. In general, however, 33 kPa water content can be considered as an average field capacity. The difference between means of field capacity measured in the field and 33 kPa water content measured in the laboratory was found to be not significant at the 5% level based on a Newman-Keuls range test (Table 5.4). Therefore, many workers still prefer to use 33 kPa water content to estimate field capacity. This parameter is readily available in standard soil survey reports and generally well understood by field soil scientists. Zobeck (1980), for example, proposed the use of 33 kPa as the equilibrium moisture tension of the entire soil moisture control section after infiltration.

Plant Extractable Water

Plant extractable water is underestimated in Mollisols and Andisols by laboratory results (Table 5.5). Grasses growing on the Mollisols' sites of Hamakuapoko, Waiakoa, and Omaopio extract water to levels as low as 0.26 m^3/m^3. These soils have low organic matter content averaging about 1.35 to 1.82% which lowers the drained upper limit to low values as well. On the other extreme the Andisols' sites of Hapapa, Olinda, and Puupahu have high drained upper limits of as high as 0.55 m^3/m^3, but also have characteristically high permanent wilting points (Warkentin and Maeda, 1980). At the Ultisols' sites of Pauwela, Kuiaha, and Makawao, the soils have intermediate values of lower limit and drained upper limit. In the final analysis, although the upper and lower limits of extractable water fluctuate greatly among soil orders and soils in general, the difference between these two limits is less variable.

Table 5.5

Total water content (cm) and volumetric water content (m^3/m^3) of extractable soil water in the 0-100 cm and 0-160 cm depths

SITE	FIELD				LABORATORY			
	100 cm		160 cm		100 cm		160 cm	
	cm	m^3/m^3	cm	m^3/m^3	cm	m^3/m^3	cm	m^3/m^3
MOLLISOLS:								
H. poko	8	0.09	11	0.07	7	0.07	10	0.06
Waiakoa	12	0.12	19	0.12	11	0.11	NA	NA
Omaopio	16	0.16	21	0.13	7	0.07	11	0.07
MEAN	12	0.12	17	0.11	8	0.08	11	0.07
ULTISOLS:								
Pauwela	13	0.13	24	0.15	12	0.12	17	0.11
Kuiaha	10	0.10	13	0.08	16	0.16	23	0.15
Makawao	13	0.13	15	0.10	16	0.16	NA	NA
MEAN	12	0.12	18	0.11	15	0.15	20	0.13
ANDISOLS:								
Hapapa	13	0.13	20	0.13	33	0.33	56	0.35
Olinda	20	0.20	29	0.18	30	0.30	NA	NA
Puupaha	11	0.11	27	0.17	37	0.37	63	0.39
MEAN	15	0.15	25	0.16	33	0.33	59	0.37
MEAN ALL SOILS	13	0.13	20	0.13	19	0.19	30	0.19

Testing of the Soil Water Extractability Model

The nine experimental sites located in Hamakuapoko, Waiakoa, Omaopio, Pauwela, Kuiaha, Makawao, Hapapa, Olinda and Puupahu provided independent data to test the Ritchie soil water extractability model. The testing was conducted by comparing model predictions with measured values of lower limit, upper limit and extractable water.

Results in Figure 5.4 show that the model underestimates lower limit values in Ultisols and Andisols and produces nearly acceptable results for the Mollisols. This is not surprising since the model was originally developed for soils of the continental United States where Mollisols are abundant. In nonvolcanic ash soils, the lower limit is principally governed by clay and sand content. In Mollisols, all of the values above the 1:1 line have more than 50% clay and less than 10% sand, while most of the values below the line have less than 30% clay and more than 15% sand. In Ultisols, better results were obtained when clay content was high (> 55%) and sand content was low (< 5%). Under these situations the differences between measured and predicted values were less than 0.02 m^3/m^3. However, the deviations became very large when the clay content decreased and sand content increased. With clay is less than 50% and sand is more than 10%, the underestimation exceeds 0.17 m^3/m^3. In Andisols, the model fails completely. The model underestimates the lower limit by a large amount and is insensitive to input values. In this study, "sand" content of the Andisols varies from 42 to 81%, "silt" from 18 to 51%, "clay" from 1 to 8%, organic matter from 10 to 19%, and bulk density from 0.38 to 0.79 Mg/m^3. The problem does not reside in the model but in

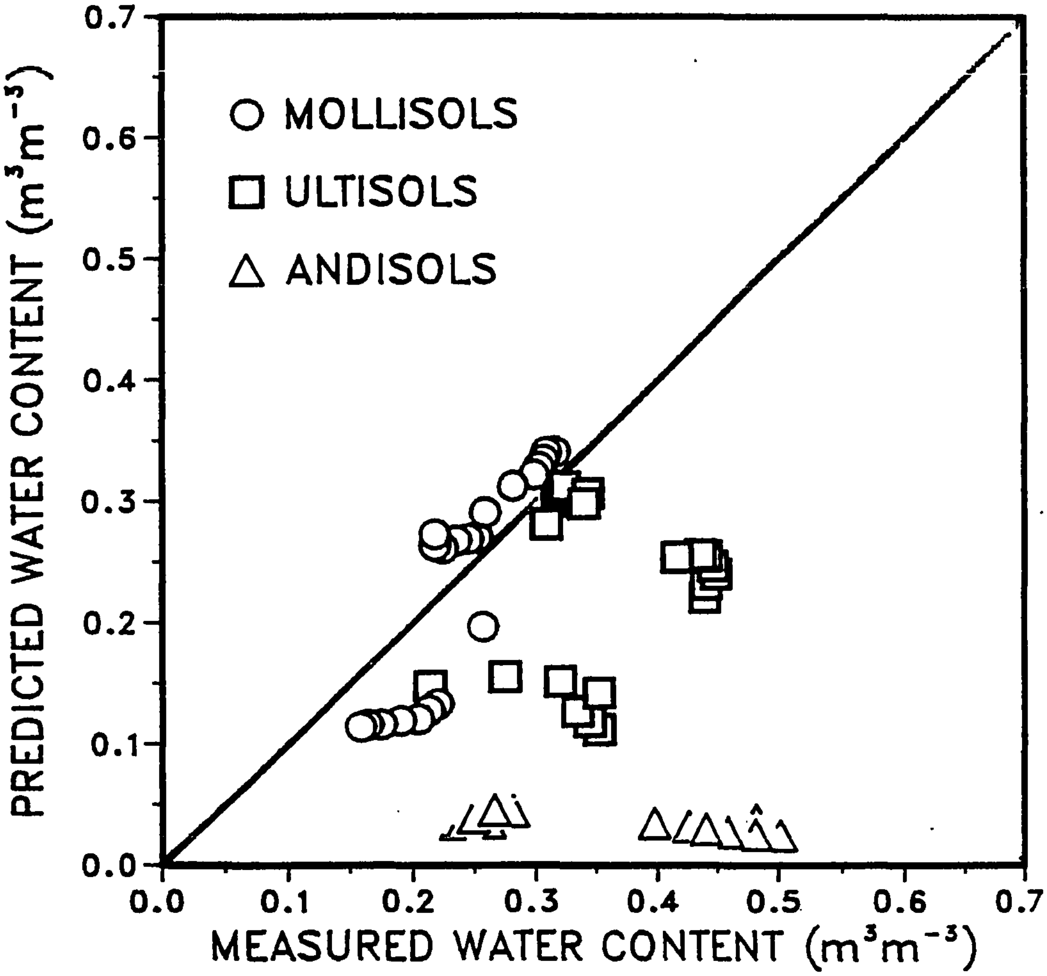


Figure 5.4. Comparison of measured and predicted LOL where the predicted value was obtained with the Ritchie model.

the quality of the laboratory data that are used to estimate the lower limit. As indicated earlier, air drying of the samples prior to mechanical analysis irreversibly alters the samples so that a fine textured material becomes coarse textured.

Ritchie's model does not compute the upper limit (DUL) directly, but derives it from the addition of the plant extractable water (PEXW) to the lower limit (LOL). Results in Figure 5.5 show that the model predicts extractable water in Mollisols and Ultisols adequately well, but fails to do so in Andisols. The difference between measured and predicted values is less than 0.08 m^3/m^3 for Mollisols and less than 0.07 m^3/m^3 for Ultisols. The prediction of extractable water is strongly influenced by silt content. When sand is < 75% and silt is > 70%, the model estimates extractable water from silt content and corrects the results with bulk density, organic matter, and sand content. In Andisols, the "silt" and "sand" values are laboratory artifacts, and are grossly overestimated resulting in an overestimated extractable water content. There is a general tendency, however, for the predicted value to be closer to the 1:1 line when the "silt" content is high. Best agreement between measured and predicted values occur when the "silt" content is about 50%.

Since the upper limit is obtained by adding extractable water to the lower limit, it is dependent on these two parameters. The calculated upper limit in nonvolcanic ash soils relies heavily on the estimated lower limit, whereas in Andisols, it is dependent on both the lower limit and extractable water. Results in Figure 5.6 show that for Mollisols the model makes good prediction for the upper limit with differences between measured and predicted values of less than

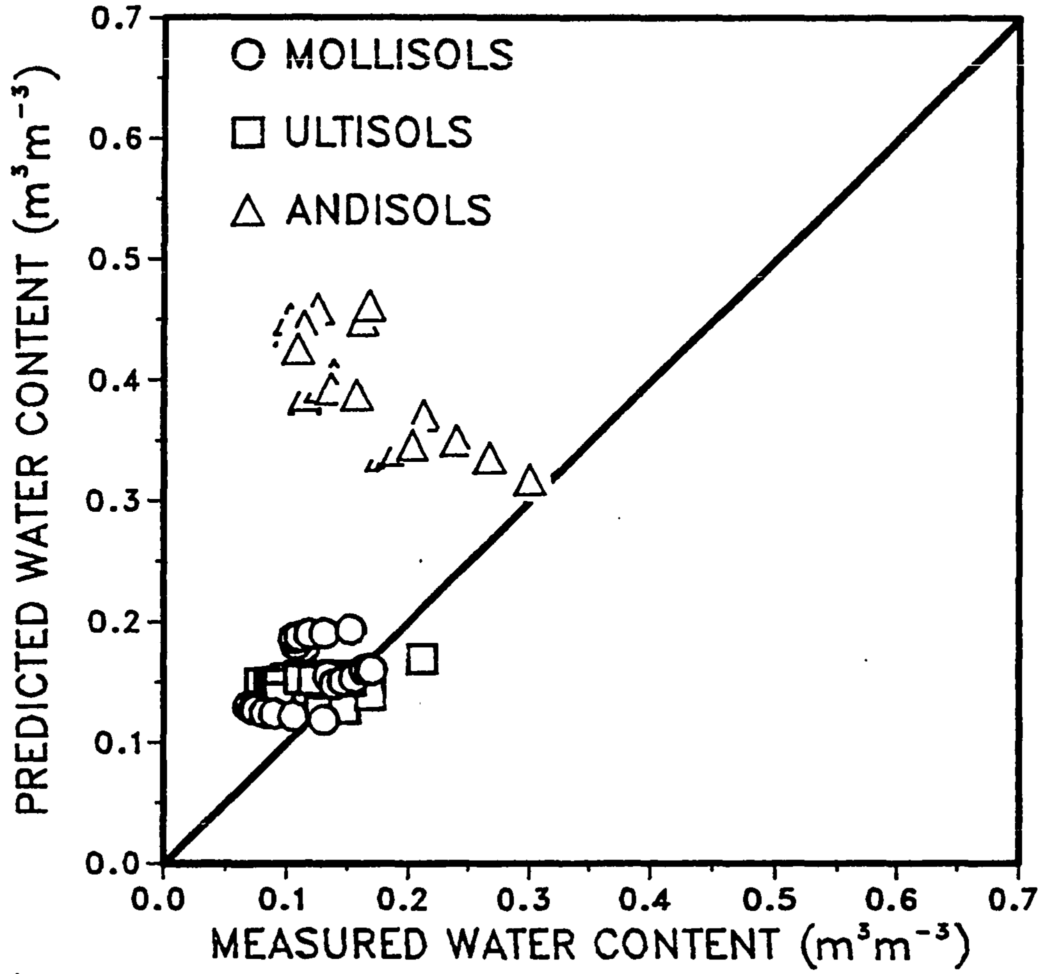


Figure 5.5. Comparison of measured and predicted PEXW where the predicted value was obtained with the Ritchie model.

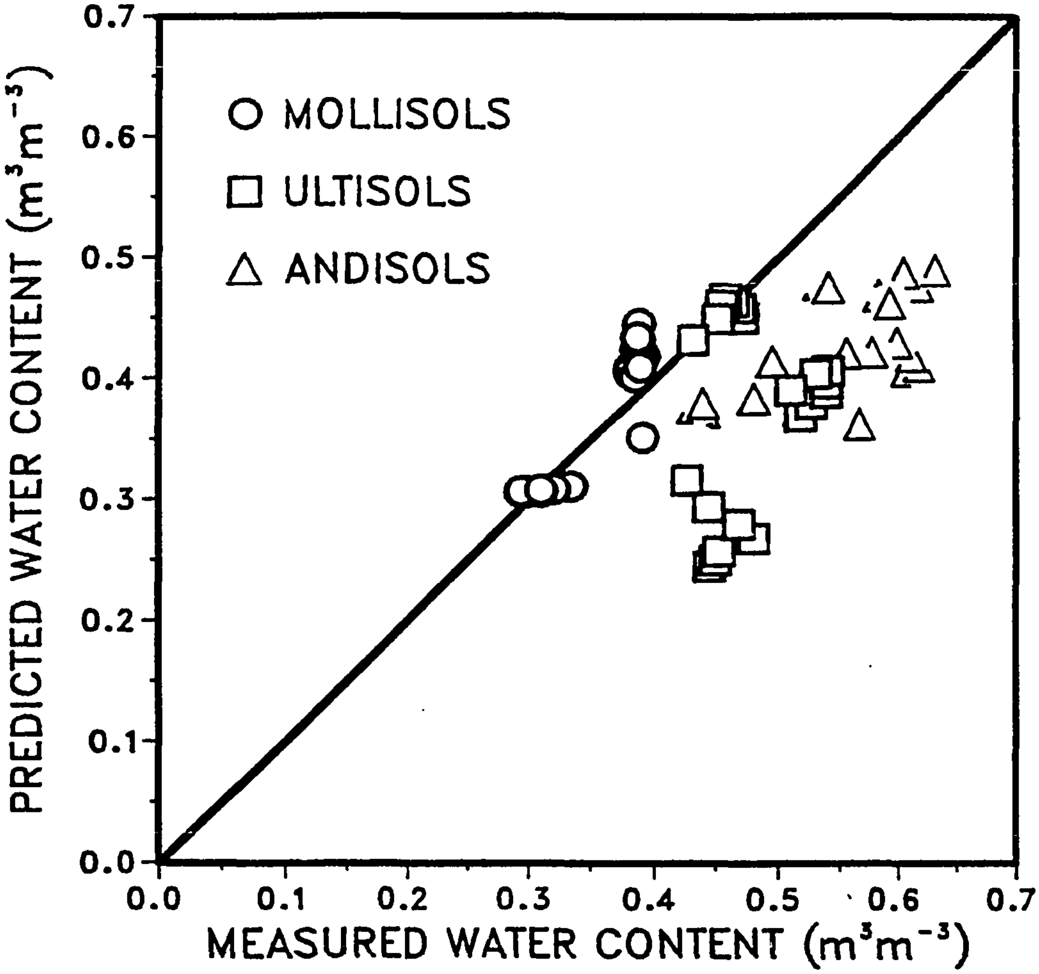


Figure 5.6. Comparison of measured and predicted DUL where the predicted value was obtained with the Ritchie model.

0.06 m^3/m^3. The prediction of the drained upper limit for Ultisols is not good. The lower limit is underestimated and consequently, the drained upper limit is also underestimated. In Andisols, the model also underestimates the drained upper limit for reasons described earlier.

Adapting the Soil Water Extractability Model

Ritchie's model of soil water extractability utilizes sand, silt, clay, and organic matter content, and bulk density to predict the lower limit and extractable water. The model groups soils into three classes: (1) soils with sand < 75% and silt < 70%, (2) soils with sand < 75% and silt > 70%, and (3) soils with sand > 75%. These categories, however, do not meet the needs of soils dominated by non-crystalline materials. As has been discussed previously, the textural classes of soils dominated by amorphous materials, even if they are properly analyzed, require special interpretation for purpose of prediction. To circumvent this problem the soils under study were also grouped on the basis of soil order. If a tetrahedron, whose apexes represent soils dominated by organic matter, oxides, non-crystalline materials, and smectite, corresponding to the soil orders Histosols, Oxisols, Andisols, and Vertisols respectively, the Mollisols fall near the Vertisols, and the Ultisols near the Oxisols (Uehara and Gillman, 1981). In this way the soils under study can be placed on the corners of an isoceles triangle with the Andisols (Hapapa, Olinda, and Puupahu) at the head, Mollisols (Hamakuapoko, Waiakoa, and Omaopio) at one foot, and Ultisols (Pauwela, Kuiaha, and Makawao) at the other foot. By grouping soils in this way, it is possible to stratify and group soils that correspond to a particular form of the Ritchie model. The implication is that more than one form of the Ritchie model is needed to accommodate all soils.

In adjusting the model, care was taken to preserve the structure and form of the Ritchie model. It was necessary, however, to modify W1 in all soils, and W2 and D in Andisols. Clay content was chosen as an explanatory variable to estimate W1 in Mollisols and Ultisols, bulk density to estimate W1 and W2 in Andisols, and 1.5 MPa water content to estimate D in Andisols. These variables are highly correlated with other soil properties collected for soil characterization and can be assumed to be correlated with other properties such as the lower limit and extractable water.

The measured lower limits in Mollisols had highly significant linear correlation with clay content ($r = 0.8130^{**}$). In the modified model, therefore, the W1 in Mollisols was explained as a simple linear function of clay content. In Ultisols, however, the linear correlation between the measured lower limits and clay content was not significant. In this case, the polynomial relationship was then taken into consideration. A quartic function of clay content was found to be highly significant ($r = 0.7340^{**}$) and chosen to define W1. In Andisols, the measured lower limits and plant extractable water correlated significantly at the 1% level with bulk density ($r = 0.8277^{**}$ and $r = 0.7601^{**}$) and bulk density correlated significantly at the 1% level with 1.5 MPa water content ($r = 0.8641^{**}$). For these reasons, the modified model in Andisols defined W1 and W2 as a simple linear function of bulk density and D as a simple linear function of 1.5 MPa water content.

A flow diagram of the calibrated model is presented in Figure 5.7. A simple computer program written in Basic for running the calibrated model is presented in Appendix B (exhibit B.1). The calibrated model can be explained as follows:

$$LOL = W1\ (1 - 0.01\ OM)\ (1 + BD - D) + 0.0023\ OM \qquad (5.34)$$

$$PEXW = W2\ (1 - 0.01\ OM) + (D - BD) \times 0.2 + 0.0055\ OM \qquad (5.35)$$

$$DUL = LOL + PEXW \qquad (5.36)$$

where:

LOL = lower limit of soil water extractability (m^3/m^3)

PEXW = plant extractable water (m^3/m^3)

DUL = drained upper limit (m^3/m^3)

W1 = interim variable to estimate lower limit (m^3/m^3)

W2 = interim variable to estimate plant extractable water (m^3/m^3)

D = interim variable to estimate bulk density (Mg/m^3)

BD = bulk density (Mg/m^3)

OM = organic matter content (%).

If the soil is an Andisol, then

$$W1 = 0.728128 - 0.572037\ BD \qquad (5.37)$$

$$W2 = -\ 0.046181 + 0.359909\ BD \qquad (5.38)$$

$$D = 1.67 - 0.0300342\ W15 \qquad (5.39)$$

where:

W15 = gravimetric water content at 1.5 MPa tension (%).

For other soils, change D into:

$$D = 1.5 - 0.01923\ SAND + 0.0008324\ SAND^2 - 1.083 \times 10^{-5}\ SAND^3 + 4.662 \times 10^{-8}\ SAND^4 \qquad (5.40)$$

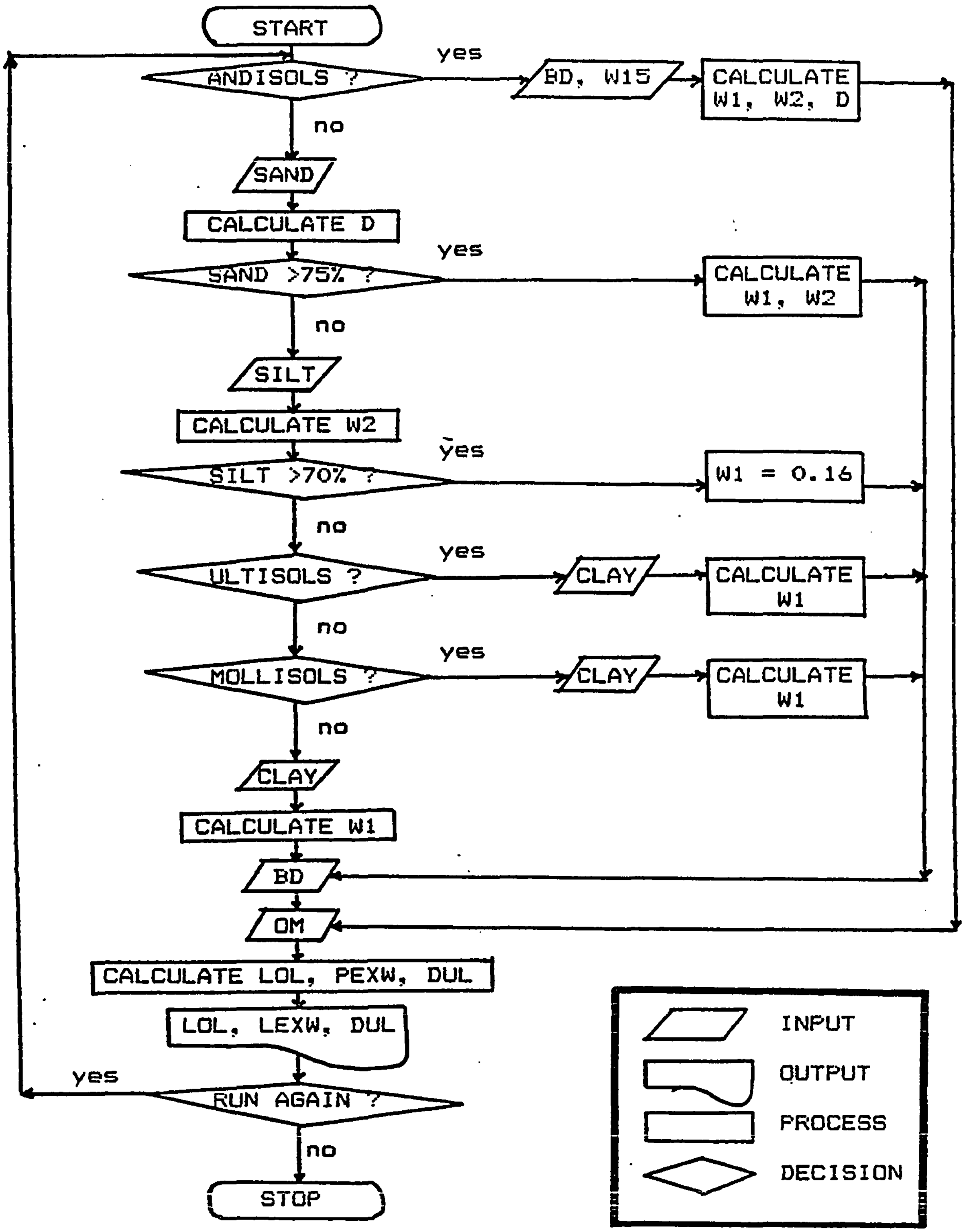


Figure 5.7. Flow diagram of soil water extractability model.

where:

SAND = sand content (%).

If the soil is not an Andisol and has sand content > 75%, change W1 and W2 into:

$$W1 = 0.19 - 0.0017\ SAND \qquad (5.41)$$

$$W2 = 0.429 - 0.00388\ SAND \qquad (5.42)$$

For other than above soils, change W2 into:

$$W2 = 0.1079 + 5.004001 \times 10^{-4}\ SILT \qquad (5.43)$$

where:

SILT = silt content (%).

If the soil is not an Andisol, has sand content < 75%, and has silt content > 70%, change W1 into:

$$W1 = 0.16 \qquad (5.44)$$

If the soil is an Ultisol that has sand content < 75% and silt content < 70% change W1 into:

$$W1 = 1.278654 - 0.12333\ CLAY + 0.005091\ CLAY^2 - 0.82393 \times 10^{-4}\ CLAY^3 + 0.458 \times 10^{-6}\ CLAY^4 \qquad (5.45)$$

where:

CLAY = clay content (%).

If the soil is a Mollisol that has sand content < 75% and silt content < 70%, change W1 into:

$$W1 = 0.127929 + 0.002194\ CLAY \qquad (5.46)$$

If the soil is not an Andisol, Ultisol, or Mollisol, but has sand content < 75% and silt content < 70%, change W1 into:

$$W1 = 0.0542 + 0.00409\ CLAY \qquad (5.47)$$

Verification of the Modified Soil Water Extractability Model

In Figures 5.8-5.10, the measured results are compared with the results obtained from the calibrated Ritchie model for soils used to calibrate the model. In Mollisols, the calibration reduces the maximum deviation from the 1:1 line from 0.09 m^3/m^3 in the Ritchie model to 0.07 m^3/m^3 in the modified model for the lower limit and from 0.06 m^3/m^3 to 0.03 m^3/m^3 for the upper limit. There was no attempt to modify the algorithm for extractable water, and therefore the maximum deviation of the predicted value of extractable water after calibration remained the same as before, i.e. 0.08 m^3/m^3. There was only little change in the results for the Mollisols because Ritchie's original model was already adequate for Mollisols.

In Ultisols, however, the calibration greatly improved the predicted lower and upper limit. The maximum deviation was reduced from 0.24 m^3/m^3 to 0.05 m^3 for the lower limit and from 0.20 m^3/m^3 to 0.08 m^3/m^3 for the upper limit resulting in a maximum deviation in the calculated value of extractable water of 0.07 m^3/m^3.

In Andisols, the calibration overcomes the trend to underestimate the lower and upper limits and to overestimate extractable water. The maximum deviation from 1:1 line is reduced from 0.48 m^3/m^3 with the original model to 0.16 m^3/m^3 with the calibrated model for the lower limit. The deviations are still large, but are mostly less than 0.08 m^3/m^3. The highest deviations occurred in the Bw3 horizon of Hapapa site at a depth of 90-130 cm. This horizon had the highest content of iron oxides of the entire profile and was more compact than the underlying and overlying horizons. In the prediction of extractable

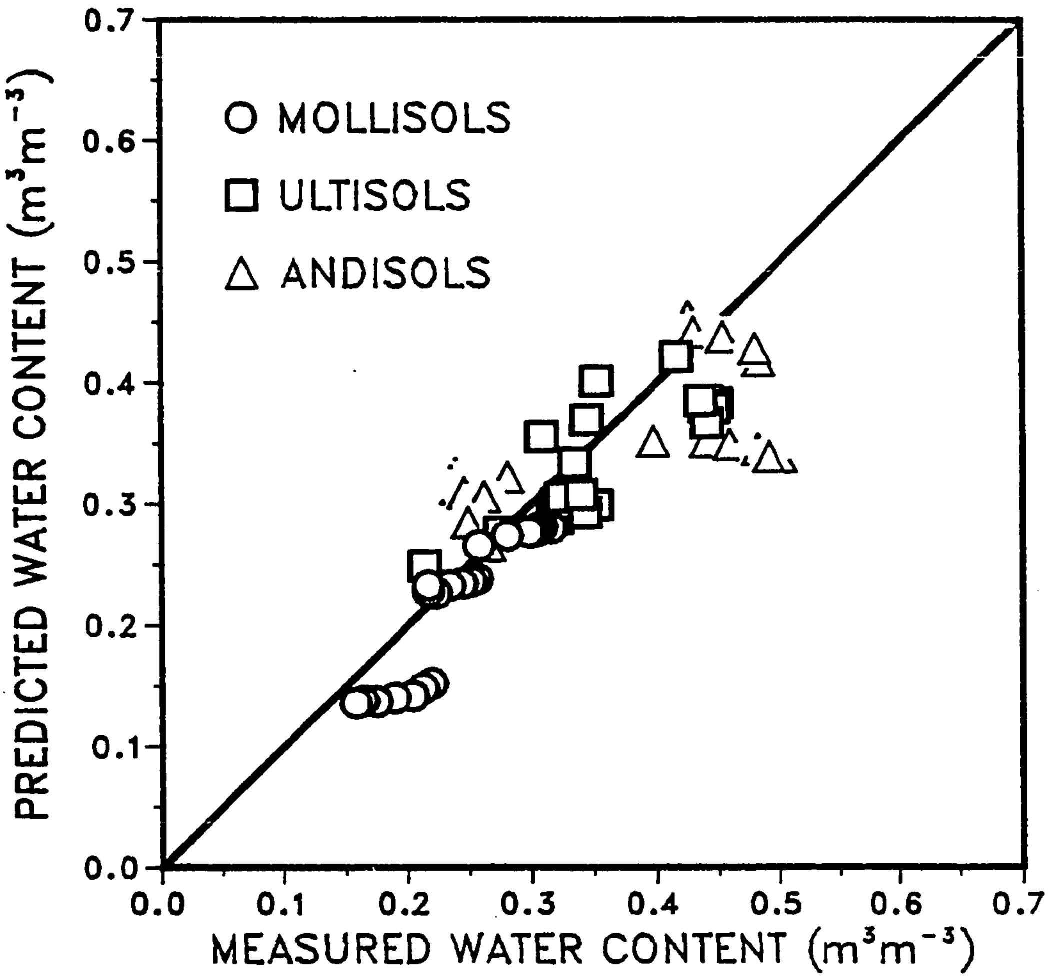


Figure 5.8. Comparison of measured and predicted LOL where the predicted value was obtained with the modified Ritchie model.

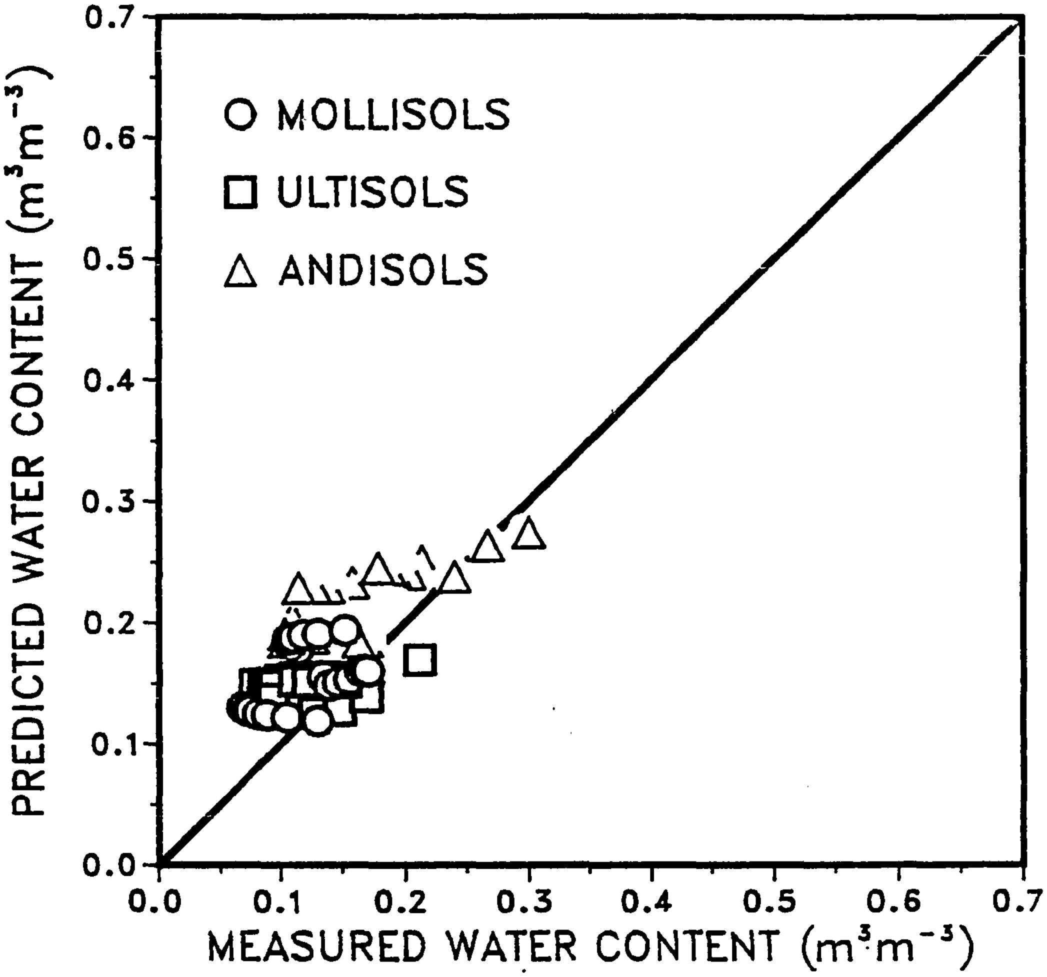


Figure 5.9. Comparison of measured and predicted PEXW where the predicted value was obtained with the modified Ritchie model.

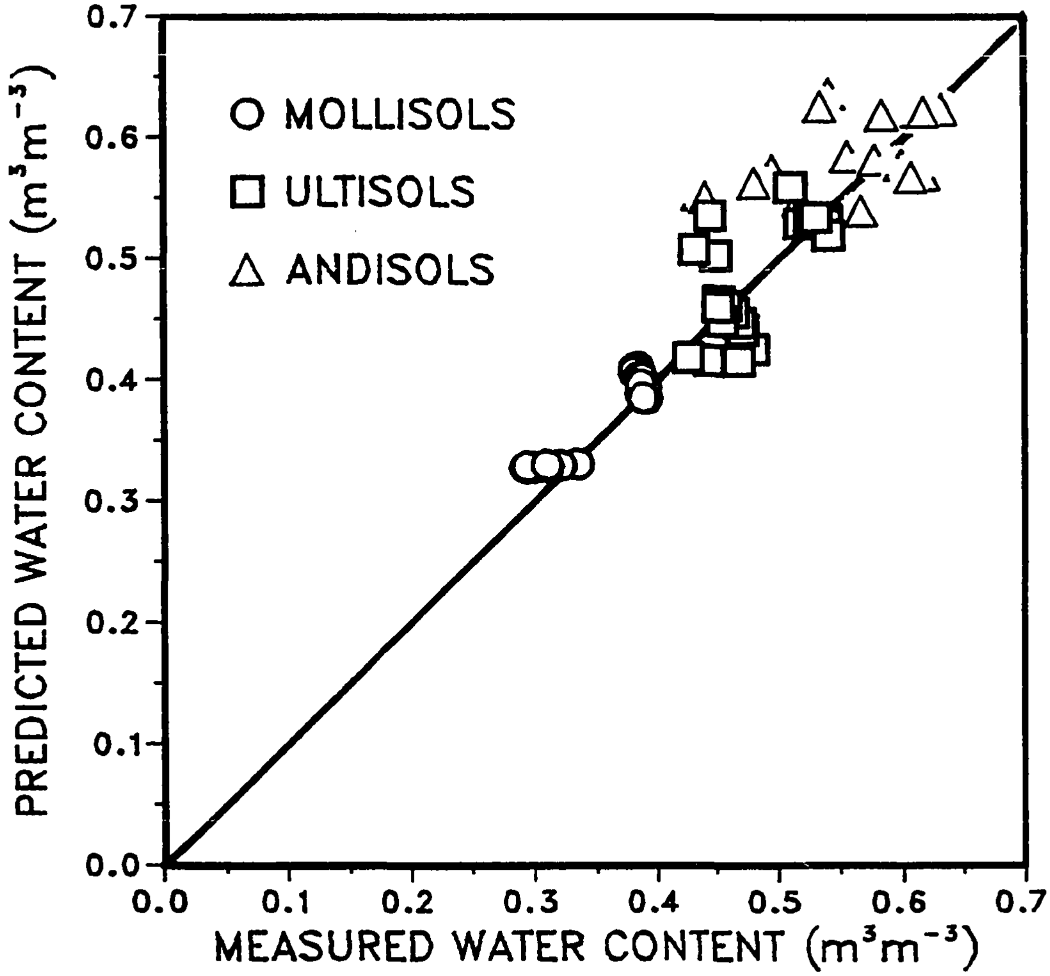


Figure 5.10. Comparison of measured and predicted DUL where the predicted value was obtained with the modified Ritchie model.

water, the maximum deviation was reduced from 0.35 m^3/m^3 to 0.09 m^3/m^3, whereas, in the prediction of the upper limit, the maximum deviation was reduced from 0.21 m^3/m^3 to 0.12 m^3/m^3. It is quite possible that the results for the Andisols are controlled by the quality of the laboratory data and not by the model or the field measured upper and lower limits of extractable water.

Validation of CERES's Soil Water Balance Model

The CERES's soil water balance model used in this work has been previously calibrated for Oxisols by Chinene (1983) and Singh (1985). It was not possible to test this model in Ultisols because the required climatic data were not available. However, as has been mentioned previously, Ultisols are close relatives of Oxisols and one may therefore assume that if the model works well for Oxisols, Mollisols, and Andisols, it will very likely perform well for Ultisols.

The validation work was conducted in a ustic moisture regime along a transect covering three temperature regimes including the isohyperthermic, isothermic, and isomesic soil temperature regime. Results in Figure 5.11 show that the model simulates a wide range of soil water content over time and soil depth very well. Comparison using Newman-Keuls range test (Hicks, 1973) indicated that the mean of measured and simulated values was not significantly different at the 5% level. Among 108 soil water measurements made between August 1984 to June 1985 at depths ranging from 30 to 90 cm, and water content ranging from 0.17 m^3/m^3 to 0.68 m^3/m^3, 90% of the simulated values deviated less than 0.05 m^3/m^3 from the 1:1 line. This included 70% with

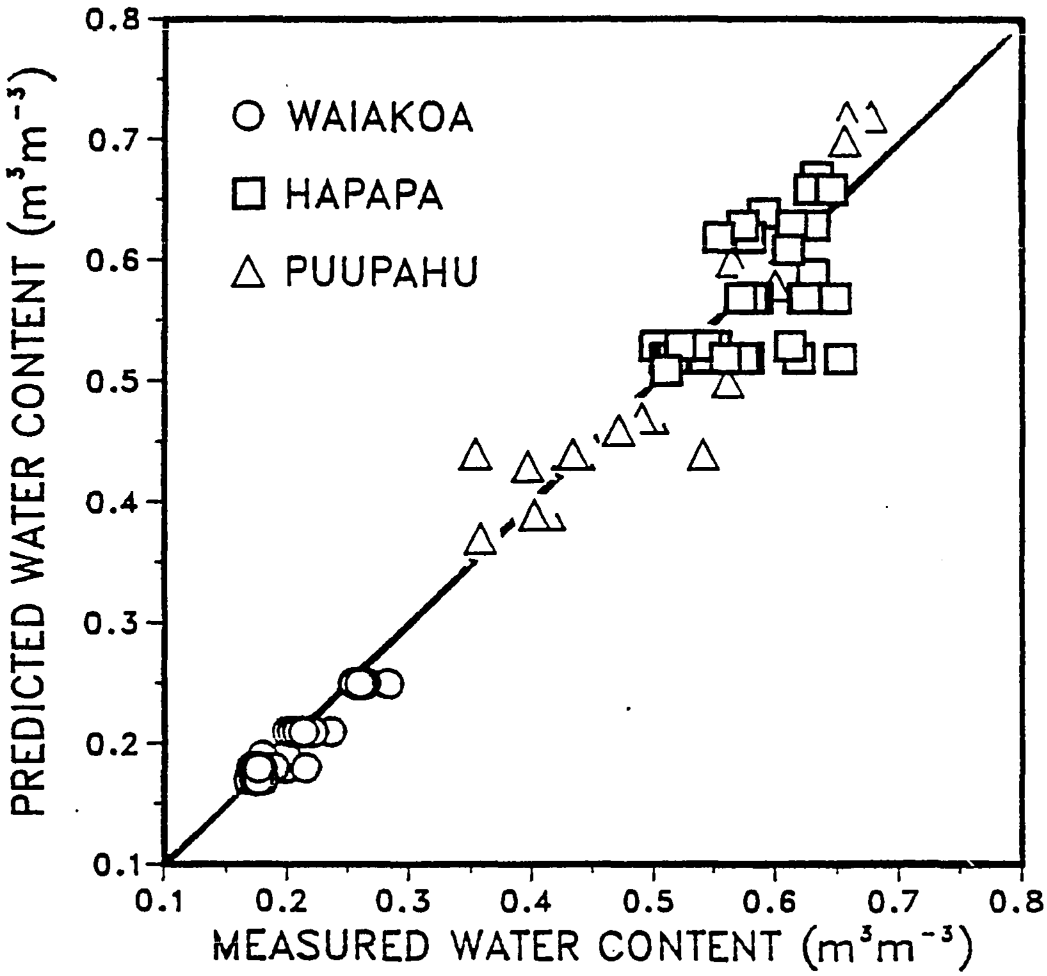


Figure 5.11. Comparison of measured and predicted soil water content where the predicted values were obtained with the CERES model.

deviations less than 0.02 m^3/m^3 and 19% simulated perfectly. There is a high correlation ($r = 0.9830$) between measured and predicted values and there is no indication that one layer is better simulated than another. The correlation coefficient between measured and predicted values ranges from 0.9771 to 0.9898 for individual soil layers.

In the Waiakoa soil, the model simulates soil water content quite accurately. Although the range of measured water content is narrow, i.e. 0.17 to 0.28 m^3/m^3, the correlation between measured and predicted values is high ($r = 0.9577$). The mean of simulated values is not significantly different at 1% level with the mean of measured values. There is no simulated value that deviates more than 0.04 m^3/m^3 from the measured value, and 90% of the data points are within 0.01 m^3/m^3 of the 1:1 line.

At Hapapa site, the range of measured soil water content is also narrow but the amount is much higher than at Waiakoa. Mean annual soil temperature in Hapapa is 18.6^{o}C at the 10 cm depth and 18.1^{o}C at the 50 cm depth (Ikawa and Kourouma, 1985). About 80% of the simulated values are within 0.05 m^3/m^3 of the 1:1 line. However, there are 2 points that fall outside this scatter band. Consequently, the correlation coefficient between measured and simulated values is low ($r = 0.5829$). These two points, which have deviations of 0.10 m^3/m^3 and 0.13 m^3/m^3, were measured in January 1985 when there was uncertainty about the performance of the weather station because of a lightning strike. It is suspected that the inconsistent results were caused by erroneous climatic data inputs. Even so the means of the simulated and measured water contents are not significantly different at the 5% level.

The Puupahu site has one of the widest measured water contents among the three sites, ranging from 0.35 to 0.68 m^3/m^3. Correlation between measured and simulated values is high (r = 0.9300). Ninety-four percent (94%) of the data points are within 0.6 m^3/m^3 of the 1:1 line and 50% deviate less than 0.01 m^3/m^3 from the line. Comparing their means, the simulated mean value is not significantly different with the measured mean value at the 5% level. Puupahu is a Dystrandept that occurs in a humid location with a pronounced dry season (SCS, 1975, p. 232). Therefore, a wide range of field soil moisture content can be expected in this soil. However, Table 5.6 shows that the wide fluctuations in water content occurred only in the top layers, i.e. 30 to 50 cm depth. In the deeper layers, the water content remains constantly high. Possibly, the low soil temperature and/or low subsoil fertility limits root growth and water extraction in the deeper layers.

Table 5.6

Range of natural water content from November 1984 to June 1985 of Puupahu site

SOIL DEPTH (cm)	WATER CONTENT (m^3/m^3)		
	LOWEST	HIGHEST	RANGE
030	0.36	0.56	0.20
050	0.35	0.54	0.19
070	0.53	0.58	0.05
090	0.59	0.68	0.09

The Puupahu site has a temperature regime with mean annual soil temperature of 15.9^{o}C at the 10 cm depth and 15.6^{o}C at 50 cm (Ikawa and Kourouma, 1985).

Validation of the Modified Soil Water Extractability Model

The CERES's soil water balance model was used to test the modified Ritchie model on an independent group of soils. The CERES model was used to simulate soil water content from August 1984 to June 1985 in the 30-90 cm depth, at the Holopuni, Haliimaile, and Kekoa sites. The model required daily weather data and soil water extractability data estimated by the calibrated Ritchie model.

Results in Figure 5.12 show that there is a good agreement between measured and simulated values of soil water content over time and soil depth. Mean separation using Newman-Keuls range test (Hicks, 1973) points out that the predicted value mean is not significantly different from the measured value mean at the 1% level. Of the 132 data points, 72% were within 0.03 m^3/m^3 of the 1:1 line. The correlation between measured and simulated values at each depth is high. The correlation coefficient does not vary greatly with depth being 0.9473, 0.9447, 0.9734 and 0.9918 for the 30, 50, 70 and 90 cm depth respectively. The model can also simulate water content over a wide range. The measured water content ranged from 0.08 to 0.50 m^3/m^3. Correlation between measured and simulated values in this range was high (r = 0.9670).

However, correlation between measured and simulated water content for each soil was not as high as when all soils were considered because the range for a soil is narrow and the deviation remains approximately

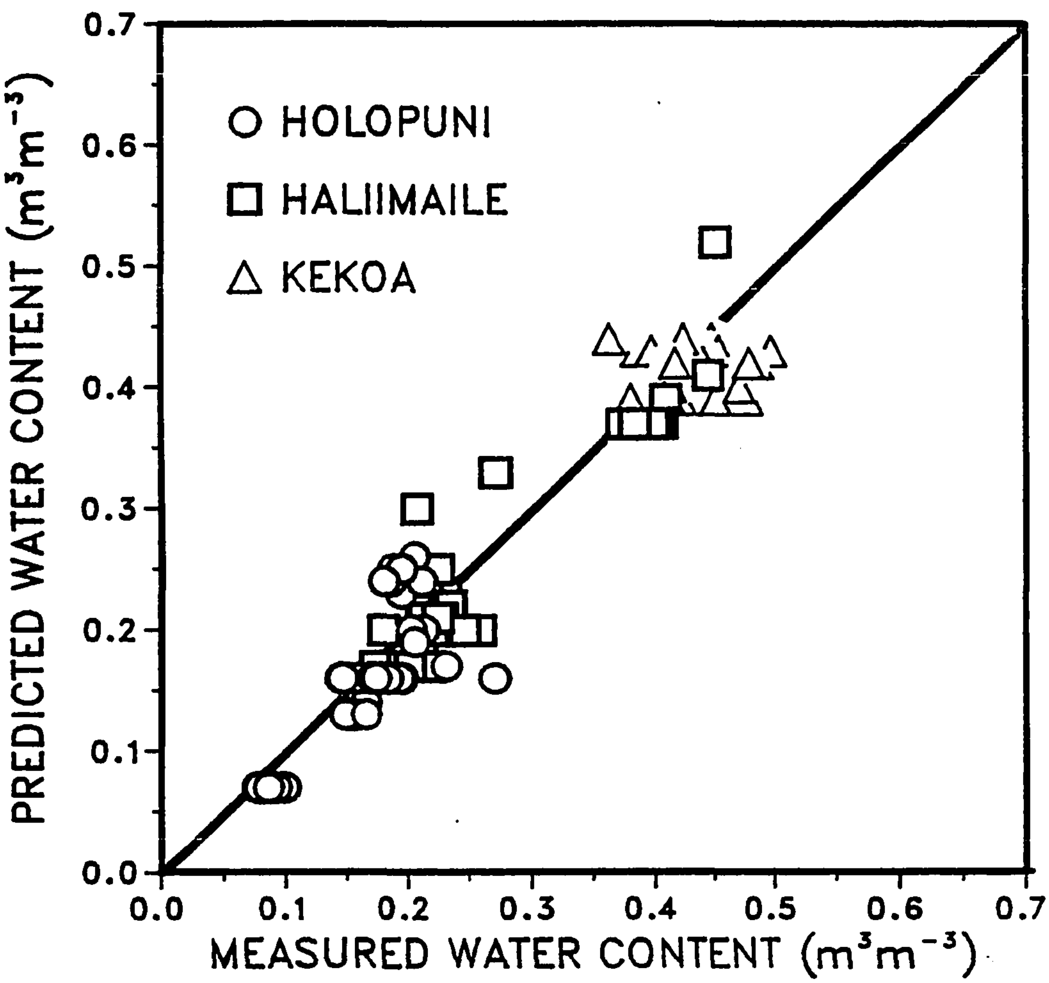


Figure 5.12. Comparison of measured and predicted soil water content where the predicted values were obtained with the CERES model that utilized LOL, DUL, and PEXW estimated by the modified Ritchie model.

the same. In Holopuni, the measured water content ranges from 0.08 to 0.21 m^3/m^3. This soil is a member of the same soil series as the Waiakoa, but shallower and more gravelly. This soil is a Mollisol with a torridic-ustic moisture regime and isohyperthermic temperature regime. Low rainfall and high evapotranspiration cause this soil to always be dry. In Holopuni, the model simulates soil water content very well. Eighty-one percent (81%) of the data points are within 0.03 m^3/m^3 of the 1:1 line and no value deviates more than 0.06 m^3/m^3 from the 1:1 line. Posteriori range test using the Newman-Keuls procedure indicates that the mean of simulated water contents is not significantly different from the mean of measured values at the 5% level. However, since the field water content is highly attenuated, the correlation between measured and predicted values is only moderate ($r = 0.8297$).

Haliimaile is one of the sites with the widest range of measured water content. Haliimaile is an Ultisol with a udic moisture regime and an isohyperthermic temperature regime. The well distributed, high rainfall enables this soil to have high water content in most months of the year. However, this soil also has a dry spell lasting no more than 90 cumulative days in most years, so that the soil experiences low water content during a short period in most years. The CERES model simulates water content in Haliimaile satisfactorily. The means of the simulated and measured water contents are not significantly different at the 5% level. About 81% of the measured water contents are within 0.03 m^3/m^3 of the 1:1 line. The wide water content range and the small deviations result in a high correlation between measured and simulated values (r = 0.9319).

At the Kekoa site, correlation between measured and simulated water content is low (r = 0.1453). Comparison using Newman-Keuls procedure also shows a highly significant difference between measured and predicted values. However, the fault may not lie with the CERES model but with the fact that the water content range is highly attenuated, ranging from 0.36 to 0.50 m^3/m^3. Kekoa is an Oxic Dystrandept with a udic moisture regime and an isothermic temperature regime. A well-distributed rainfall and cool temperature keep the soil moist through much of the year. The simulated results deviate variably from 0 to 0.9 m^3/m^3. In comparison with the soils at the Holopuni and Haliimaile sites, the Kekoa site has the highest percentage of perfect simulation. Perfect simulation make up 5, 13, and 23% of the Holopuni, Haliimaile and Kekoa sites respectively. About 90% of the simulated values from Kekoa deviate less than 0.6 m^3/m^3 from the measured values, including 64% that deviate less than 0.3 m^3/m^3.

Conclusions

Soil water extractability and the lower and upper limit of extractability are required inputs to run crop models such as CERES. However, field measured data are usually not available. Laboratory methods for estimating them have been shown to be unreliable.

Prediction of soil water extractability using the Ritchie model is satisfactory for Mollisols but unsatisfactory for Ultisols and Andisols. The model underestimates the lower and upper limits by as much as 24% and 20% respectively in Ultisols and up to 48% and 21% in Andisols. The Ritchie model predicts the amount of extractable water accurately in Mollisols and Ultisols, but not in Andisols. The model overestimates extractable water by as much as 35% in Andisols. However, the model can be calibrated to adequately predict the lower limit (LOL), upper limit (DUL) and extractable water (PEXW). For non-volcanic ash soils, the calibrated model requires inputs of sand (SAND), silt (SILT), clay (CLAY), organic matter (OM), and bulk density (BD). For volcanic ash soils, the calibrated model requires 1.5 MPa water (W15), organic matter (OM) content, and bulk density (BD). The equations for the modified model are as follows:

(1) Mollisols (with sand < 75% and silt < 70%),

$$\text{LOL} = (0.127929 + 0.002194\ \text{CLAY})(1 - 0.01\ \text{OM})(1 + \text{BD} - \text{D}) + 0.0023\ \text{OM} \tag{5.48}$$

$$\text{PEXW} = (0.1079 + 5.004001 \times 10^{-4}\ \text{SILT})(1 - 0.01\ \text{OM}) + 0.2\ (\text{D} - \text{BM}) + 0.0055\ \text{OM} \tag{5.49}$$

$$\text{DUL} = \text{LOL} + \text{PEXW} \tag{5.50}$$

where

$$\text{D} = 1.5 - 0.01923\ \text{SAND} + 0.0008324\ \text{SAND}^2 - 1.083 \times 10^{-5}\ \text{SAND}^3 + 4.662 \times 10^{-8}\ \text{SAND}^4 \tag{5.51}$$

(2) Ultisols (with sand < 75% and silt < 70%),

$$\text{LOL} = \text{W1}\ (1 - 0.01\ \text{OM})(1 + \text{BD} - \text{D}) + 0.0023\ \text{OM} \tag{5.52}$$

$$\text{PEXW} = (0.1079 + 5.004001 \times 10^{-4}\ \text{SILT})(1 - 0.01\ \text{OM}) + 0.2\ (\text{D} - \text{BD}) + 0.0055\ \text{OM} \tag{5.53}$$

$$\text{DUL} = \text{LOL} + \text{PEXW} \tag{5.54}$$

where

$$D = 1.5 - 0.01923\ SAND + 0.0008324\ SAND^2 - 1.083 \times 10^{-5}\ SAND^3 + 4.662 \times 10^{-8}\ SAND^4 \qquad (5.55)$$

$$W1 = 1.278654 - 0.12333\ CLAY + 0.005091\ CLAY^2 - 0.82393 \times 10^{-4}\ CLAY^3 + 0.458 \times 10^{-6}\ CLAY^4 \qquad (5.56)$$

(3) Andisols,

$$LOL = (0.728128 - 0.572037\ BD)\ (1 - 0.01\ OM)\ (BD + 0.0300342\ W15 - 0.67) + 0.0023\ OM \qquad (5.57)$$

$$PEXW = (-0.046181 + 0.359909\ BD)\ (1 - 0.01\ OM) + 0.2\ (1.67 - 0.0300342\ W15 - BD) + 0.0055\ OM \qquad (5.58)$$

$$DUL = LOL + PEXW \qquad (5.59)$$

The modified soil water extractability model reduced the maximum deviation to 0.07 m^3/m^3 from 0.09 m^3/m^3 for the lower limit and to 0.03 m^3/m^3 from 0.06 m^3/m^3 for the upper limit in Mollisols. In Ultisols, the model removed a tendency of the original model to underestimate the measured value and reduced the maximum deviation to 0.05 m^3/m^3 from 0.24 m^3/m^3 for the lower limit and to 0.08 m^3/m^3 from 0.20 m^3/m^3 for the upper limit of soil water extractability. The prediction of extractable water in Mollisols and Ultisols remains unchanged from the original model, with maximum deviation of 0.08 m^3/m^3 and 0.07 m^3/m^3 respectively for the two orders. In Andisols, the calibrated model removes the trend for underestimating the lower and upper limit and a trend to overestimate extractable water. The model has reduced the maximum deviation of lower limit, upper limit and extractable water in Andisols to 0.16 m^3/m^3 from 0.48 m^3/m^3, 0.05 m^3/m^3 from 0.21 m^3/m^3, and 0.9 m^3/m^3 from 0.35 m^3/m^3 respectively.

The practical importance of the soil water extractability model is its ability to supply appropriate data inputs required to operate crop growth models without undertaking costly and time consuming field measurements. When used in conjunction with the modified soil water extractability model, the CERES model was able to simulate soil water over time and soil depth satisfactorily. About 72%, 81% and 64% of the simulated water contents deviate less than 0.03 m^3/m^3 from field measured data points in a Mollisol, Ultisol and Andisol, respectively. Validation of the CERES soil water balance model in Oxisols (Chinene, 1983; Singh, 1985), Mollisols and Andisols shows that the model can be used successfully in the tropics.

CHAPTER VI

ESTIMATION OF HYDRAULIC CONDUCTIVITY

Introduction

Water moving into and out of soil profiles is an important natural process. One of the essential parameters for describing this process is the soil hydraulic conductivity. Numerous field and laboratory procedures have been developed to measure soil hydraulic conductivity (Boersma, 1965a, 1965b; Klute, 1965a, 1965b; Bouwer and Jackson, 1974). However, application of these procedures is constrained by the need for accuracy and economy, since the parameter is subject to spatial variations in the field. In situ field measurement is considered of the most accurate and reliable, but many of the methods require heavy investment in equipment, labor, and time. Field methods generally require tensiometers for measurement of hydraulic gradients and neutron or gamma ray devices to measure water content so that water flux may be calculated. Large quantities of water and long periods are required to saturate the soil and establish equilibrium conditions. When measurements in a large number of field locations are required, the conventional procedures become impractical.

The need for economical methods has led researchers to simplify the procedures. The solution of the drainage equation is markedly simplified by assuming unity hydraulic gradient during soil water redistribution. With this assumption the rate of change of soil water content in the profile can be used to calculate the hydraulic conductivity, as shown by Nielsen et al. (1973):

$$K_z(\theta) = - z \frac{d\theta}{dt} \tag{6.1}$$

where K_z = hydraulic conductivity at depth z, cm/hour

θ = average soil water content in the soil profile to depth z, m^3/m^3

t = time, hour.

Additional simplifying assumptions about water flow during redistribution have produced several quick and easy methods for estimating in situ relationship between hydraulic conductivity and water content. These methods, although somewhat approximate, provide the means to characterize hydraulic relationships over large areas at low cost.

Simplified methods to estimate hydraulic conductivity have been developed by Libardi et al. (1980), Chong et al. (1981), and Sisson et al. (1980). These methods which only require soil water content measurements estimate drainage from uniform field soils quite adequately. However, they have not been adequately tested for layered soils. Jones and Wagenet (1984) tested the simplified methods in a nonsaline Kidman sandy loam (Calcic Haploxeroll, coarse loamy, mixed, mesic) soil. They concluded that the simplified methods would be most useful in developing fast estimates of soil water properties over large areas as long as high precision of saturated hydraulic conductivity at a particular location was not required.

Materials and Methods

Field Experiment

Nine sites were used in this study. They were located at (1) Hamakuapoko, (2) Waiakoa, (3) Omaopio, (4) Pauwela, (5) Kuiaha, (6) Makawao, (7) Hapapa, (8) Olinda, and (9) Puupahu. Neutron access tubes were installed to a depth of 160 cm at each site. A plastic cylinder of 33 cm in diameter and 30 cm height was placed around each access tube and inserted to a soil depth of 10 cm so that water could be ponded around the tube. An earth mound was formed 50 cm from the tube to pond water and minimize lateral flow from the inner cylinder during infiltration.

Water was ponded until steady state flow was achieved. Most sites needed about 24 hours of ponding to establish steady flow. At steady state, ponding was discontinued and the area surrounding the access tube was covered with a 3 m x 3 m plastic sheet to prevent evaporation. Water content was measured at 20 cm intervals to a depth of 160 cm. The first measurement was taken when water had just disappeared from the soil surface. The measurements were continued at time intervals of 5-10 minutes for the first two hours, 30-60 minutes for the first day following the first two hours, once a day for the first week, and 2-4 days thereafter for 4 weeks following cessation of ponding.

Theory

Hydraulic Conductivity

For estimating hydraulic conductivity, five simplified methods referred to as (1) Libardi-θ Method (Libardi et al., 1980), (2) Libardi-Flux Method (Libardi et al., 1980), (3) Chong-θ Method (Chong et al., 1981), (4) Sisson-θ Method (Sisson et al., 1980), and (5) Sisson-W Method (Sisson et al., 1980), were used. All five methods begin with the Richards' equation, which describes one-dimensional water flow as

$$\frac{d\theta}{dt} = \frac{d}{dz} \{ K(\theta) \frac{dH}{dz} \} \tag{6.2}$$

Libardi-θ, Libardi-Flux, Sisson-θ and Sisson-W methods operate on the following four assumptions:

1. Water flux at t = 0 is constant throughout the soil profile,
2. For t > 0, the water flux at the soil surface is negligible,
3. The relationship between hydraulic conductivity and water content is of the form

   $$K(\theta) = K_o \exp \{ k (\theta - \theta_o) \} \tag{6.3}$$

   where $K(\theta)$ is hydraulic conductivity, K_o and θ_o are the values of K and θ measured during steady state infiltration, and k is a constant.

4. Unit hydraulic gradient

   $$\frac{dH}{dz} = -1 \tag{6.4}$$

   is maintained

The Chong-θ method operates on the same assumptions except for assumption number 3.

Libardi et al. (1980) also assumed that the relationship between the average soil water content above a particular depth and water content at that depth is linear, and has the form:

$$\theta^* = a\,\theta + b \qquad (6.5)$$

where θ* is the average soil water content to a depth z, θ is the soil water content at depth z, and "a" and "b" are constants.

Integration of the Richards' equation using these assumptions gives:

$$- a\, z\, \frac{d\theta}{dt} = K_o \exp\ \{ k\, (\theta - \theta_o) \} \qquad (6.6)$$

If Equation 6.6 is then integrated over time, rearranged, and assumed to apply only for t greater than 2 hours, the following results:

$$\theta_o - \theta = \frac{1}{k} \ln(t) + \frac{1}{k} \ln \left(\frac{k\, K_o}{a\, z} \right) \qquad (6.7)$$

The parameters for Equation 6.7 can be obtained by plotting $(\theta_o - \theta)$ versus ln(t) for each depth and a knowledge of "a" from Equation 6.5.

Taking the logarithm of Equation 6.6, gives:

$$\ln \left[a\, z\, \frac{d\theta}{dt} \right] = - k\, (\theta_o - \theta) + \ln(K_o) \qquad (6.8)$$

Using $\frac{d\theta^*}{dt}$ instead of $\frac{d\theta}{dt}$, gives:

$$\ln \left[z\, \frac{d\theta^*}{dt} \right] = - k\, (\theta_o - \theta) + \ln(K_o) \qquad (6.9)$$

A semi-log plot of the absolute value of [z (dθ*/dt)] versus $(\theta_o - \theta)$ gives k and $\ln(K_o)$ from the slope and intercept, respectively. The advantage of this method is that θ* is more stable than θ, particularly at greater depths.

Chong et al. (1981) did not assume Equation 6.5 and instead assumed the power function

$$\theta^* = A\, t^B \qquad (6.10)$$

where A and B are constants. By combining Equation 6.10 and Equation 6.2, the relationship

$$K(\theta^*) = z\ A^{1/B} B\ \theta^{*(B-1)/B} \tag{6.11}$$

is obtained. The hydraulic conductivity at depth z of a soil profile can be calculated with (6.11) for a wide range of soil water contents if the constants A and B can be determined.

Sisson et al. (1980) applied the unit gradient to the Richards' equation to obtain

$$\frac{d\theta}{dt} = \frac{dK(\theta)}{d\theta} \quad \frac{d\theta}{dz} \tag{6.12}$$

Solution of Equation 6.12 using the Lax (1972) method, gives:

$$\theta_o - \theta = \frac{1}{k} \ln(t) + \frac{1}{k} \ln\left(\frac{k\ K_o}{z}\right) \tag{6.13}$$

A plot at each depth z of the $(\theta_o - \theta)$ versus ln(t) produces a linear relationship which gives k and K_o. The advantage of this method is that it is claimed to be valid for all times including the early drainage phase.

If we now consider

$$W = W(z,t) = \int_0^z \theta\ dz, \tag{6.14}$$

it can be shown using Equation 6.3 that

$$W(z,t) = \theta_o\ z + \frac{z}{k} \left\{ \ln\left(\frac{z}{K_o\ k\ t}\right) - 1 \right\} \tag{6.15}$$

Dividing Equation 6.15 by z and rearranging gives:

$$\frac{W(z,t)}{z} = \theta_o - \frac{1}{k} \{ 1 - \ln(\frac{z}{K_o k}) \} - \frac{1}{k} \ln(t) \qquad (6.16)$$

A plot of W(z,t)/z versus ln(t) gives k from the slope, and K_o from:

$$K_o = \frac{z}{k} \exp \{ k (\theta_o - c) - 1 \} \qquad (6.17)$$

where c is the intercept of Equation 6.16

Soil Water Flux

Simplified methods for estimating K_o and k can be justified if they are useful in generating reliable relationships between K and θ so that soil water flux can be calculated. In Equation 6.3 K(θ) was assumed to be exponentially related to $(\theta_o - \theta)$. A simplified drainage equation (Warrick et al., 1977) was used to describe steady state water flux in a soil profile,

$$J_L = K_o (1 + k K_o \frac{t}{L})^{-1} \qquad (6.18)$$

where J_L was the Darcy flux (cm/day) at depth L (cm) and time t (day). Assuming K_o and k to be independent variables, equations proposed by Rao et al. (1977) may be used to estimate the mean water flux $MEAN(J_L)$ and variance $VAR(J_L)$,

$$MEAN(J_L) = \frac{MEAN(K_o)}{\{ 1 + (t/L) \, MEAN(K_o) \, MEAN(k) \}} \qquad (6.19)$$

$$VAR(J_L) = \frac{VAR(K_o) + (t/L)^2 \, MEAN(K_o)^4 \, VAR(k)}{\{ 1 + (t/L) \, MEAN(K_o) \, MEAN(k) \}^4} \qquad (6.20)$$

where MEAN(K_o), MEAN(k), VAR(K_o), and VAR(k) are the means and variances of K_o and k, respectively, calculated for each simplified method.

Results and Discussion

Evaluation of Drainage Patterns

Relationship of Average Soil Water Content and Soil Water Content

The results in Table 6.1 show that there is a linear relationship between average soil water content (θ^*) above a particular depth and soil water content (θ) at that depth,

$$\theta^* = a\,\theta + b \tag{6.21}$$

The correlation between θ^* and θ is high, with the correlation coefficient exceeding 0.84 in all layers and the standard deviation of residual θ^* is within the errors one would expect from neutron probe measurements. The value of "a" indicates the rate of water content change in a particular layer relative to the average water content change in the soil layers above it. A value less than one indicates that the soil layer at a depth z is losing water faster than the overlying soil layers. Similarly a value greater than one indicates that θ at depth z is changing more slowly than θ^*. The intercept "b" indicates the relative magnitude of θ to θ^*. A negative value indicates that θ is higher than θ^*.

In this connection it was discovered that there are six types of soil profiles. They are:

Table 6.1

Linear relationship between average soil water content to a particular depth (θ^*) and soil water content at the particular depth (θ), $\theta^* = a\,\theta + b$

SITE	DEPTH (cm)	a	b	r[a]	s[b]
H.poko	040	0.9840	0.0015	0.9813	0.0113
	100	0.8631	0.0824	0.9460	0.0149
	160	0.9289	-0.0051	0.8468	0.0228
Waiakoa	040	1.0261	0.0173	0.9807	0.0142
	100	0.9626	-0.0003	0.9667	0.0189
	160	1.7229	-0.4217	0.9863	0.0088
Omaopio	040	1.0693	-0.0039	0.9807	0.0054
	100	1.2649	-0.1081	0.9717	0.0053
	160	1.3044	-0.1128	0.9849	0.0036
Pauwela	040	0.8097	0.1099	0.9645	0.0132
	100	1.1230	-0.0781	0.9165	0.0127
	160	0.9281	0.0134	0.9209	0.0113
Kuiaha	040	1.0592	-0.1177	0.9796	0.0069
	100	0.6991	0.1673	0.9831	0.0077
	160	0.5984	0.2521	0.8963	0.0219
Makawao	040	0.8573	0.0604	0.9749	0.0181
	100	0.7386	0.0879	0.9503	0.0267
	160	1.5909	-0.2487	0.9250	0.0272
Hapapa	040	1.5706	-0.4091	0.9873	0.0110
	100	1.1717	-0.1611	0.9787	0.0109
	160	0.8484	0.1156	0.9914	0.0074
Olinda	040	0.8088	0.1987	0.9924	0.0049
	100	0.7335	0.2456	0.9804	0.0105
	160	1.5113	-0.2967	0.8512	0.0257
Puupahu	040	1.0677	0.0037	0.9906	0.0071
	100	1.5832	-0.5538	0.9737	0.0080
	160	0.9171	0.1466	0.8983	0.0133

[a]Correlation coefficient θ^* and θ

[b]Standard deviation of the residual θ^*.

(1) Profiles where changes in θ are always slower than that of θ, e.g. Omaopio;

(2) Profiles where changes in θ are always faster than that of θ^*, e.g. Hamakuapoko;

(3) Profiles where changes in θ are slower in the upper horizons, but faster in the deeper horizon than that of θ^*, e.g. Kuiaha, Hapapa, and Puupahu;

(4) Profiles where changes in θ are faster in the upper horizon, but slower in the lower horizon than that of θ^*, e.g. Makawao and Olinda;

(5) Profiles where changes in θ relative to changes in θ^* alternate from slow to fast in relatively short distance with the top layer being the slower one, e.g. Waiakoa; and

(6) Profiles where changes in θ relative to changes in θ^* alternate from fast to slow in a relatively short distance with the top layer being the faster one, e.g. Pauwela.

This demonstrates that profile types 1 and 2 have contrasting water conducting characteristics, whereas profile types 3 to 6 are combinations of types 1 and 2. Type 1 profile is characterized by smooth drainage throughout the profile. This is indicated by the relatively smooth exponential decrease in water content with time (Figure 6.1). The correlation between θ^* and θ is very high ($r > 0.97$) and the standard deviation of the residual θ^* is very small ($s < 0.006$), as shown in Table 6.1. In this profile, the upper layer drains faster than the lower layer.

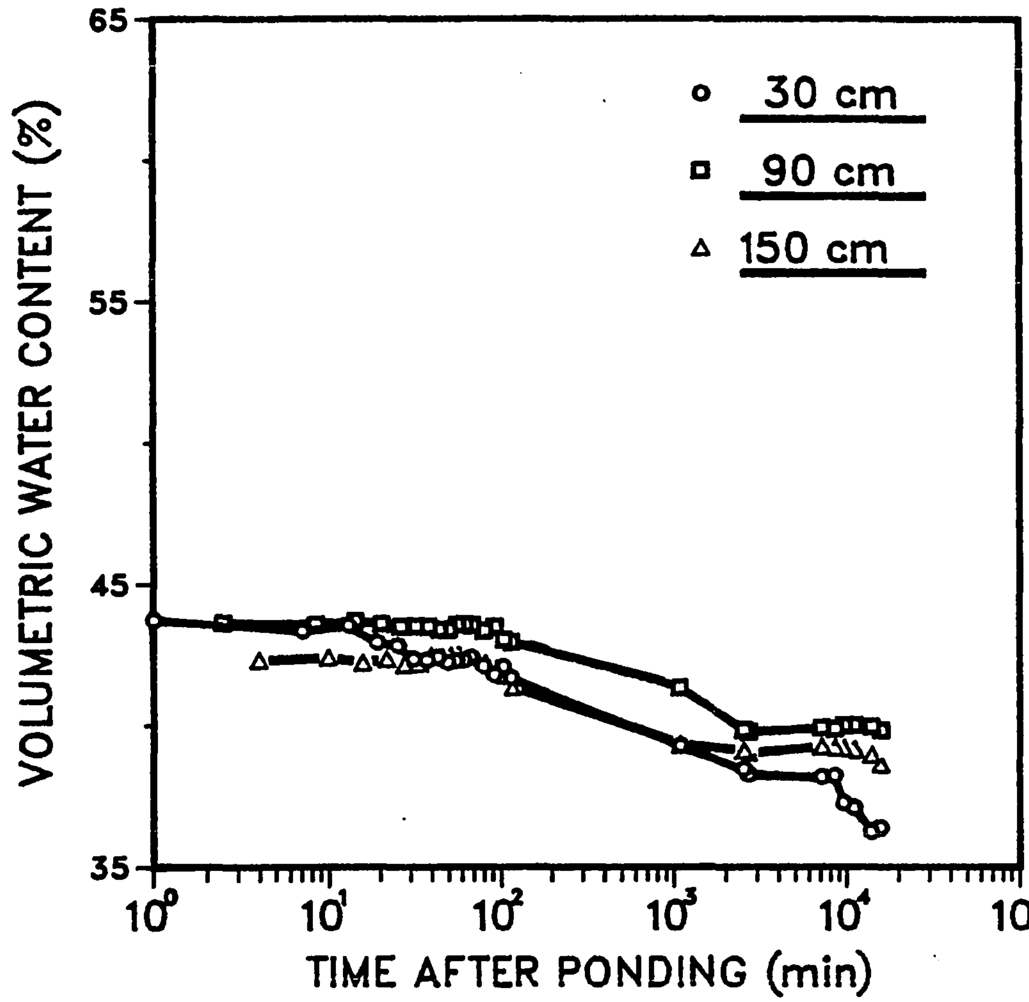


Figure 6.1. Drainage curves of Omaopio site (Type 1 profile).

On the other hand, the type 2 profile has an uneven drainage pattern, as can be seen in Figure 6.2. The lower the soil layer in a profile, the greater the unevenness as indicated by the lower correlation coefficient and the higher standard deviation in the relationship between θ^* and θ. As exemplified by the Hamakuapoko profile, the correlation coefficients between θ^* and θ are 0.98, 0.95, and 0.85 at the soil depth of 40, 100, and 160 cm respectively, and the corresponding standard deviations are 0.011, 0.015, and 0.023 (Table 6.1). The Hamakuapoko soil has large interaggregate pores. The soil particles are highly aggregated, especially at the 84-157 cm depth, and this feature can be determined by the gritty nature of the field textures. When this kind of soil is water saturated, its conductivity is very high. However, once the macropores drain, the conductivity drops drastically and drainage proceeds very slowly.

Average Soil Water Content Redistribution

After cessation of ponding, average water content of a soil profile decreases with time. This average water content in a profile can be described satisfactorily by a power function or a logarithmic function of time.

$$\theta^* = A\, t^{B} \tag{6.22}$$

and $$\theta^* = A' + B' \ln(t) \tag{6.23}$$

In equations 6.22 and 6.23 θ^* is the average soil water content (m^3/m^3) to a specified depth, t is time (hour), and A, B, A' and B' are constants.

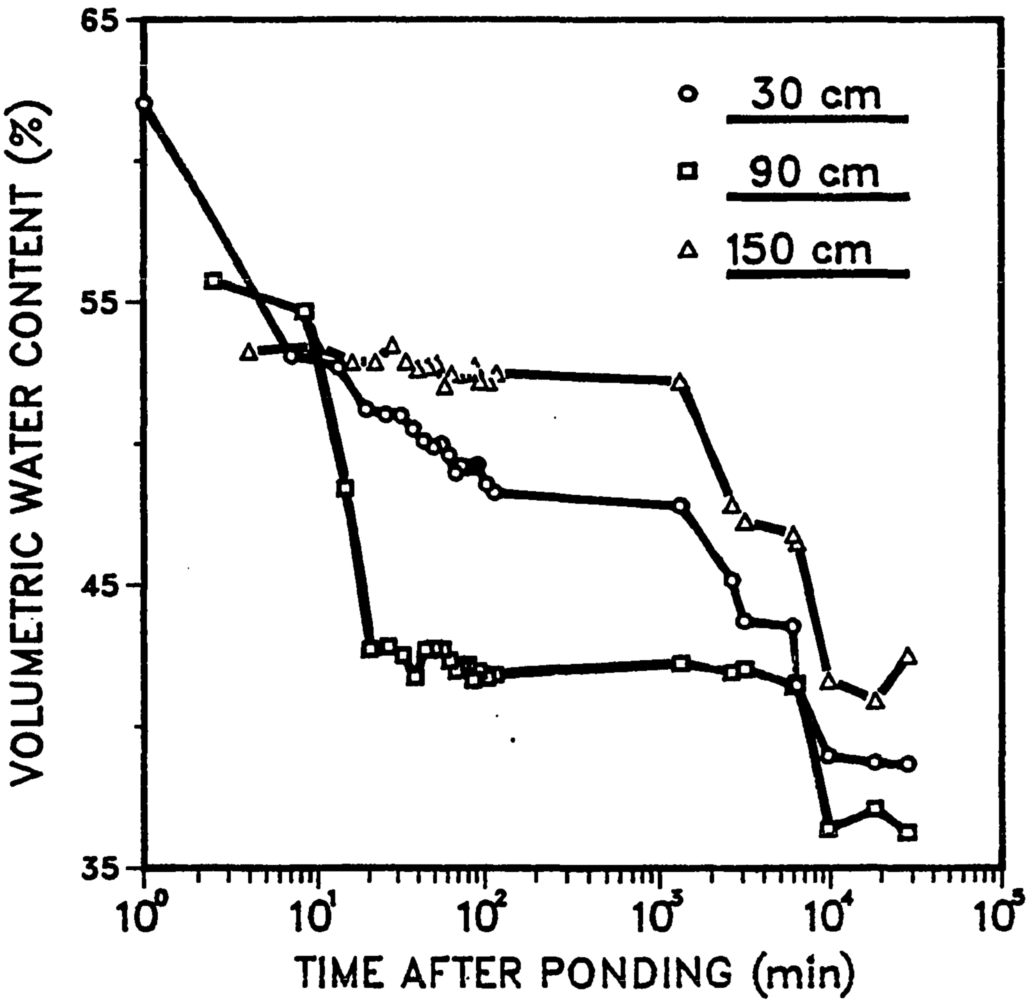


Figure 6.2. Drainage curves of Hamakuapoko site (Type 2 profile).

Use of the power function generates correlation coefficients of better than 0.92 and standard deviations of no more than 0.046 in all soils and layers (Table 6.2). The change in average soil water content at depth 0 to z is smoother than the change in soil water content at depth z as indicated by the higher correlation coefficient and lower standard deviation of the former (see Table 6.3 for comparison). Using the power function to describe changes in water content at a specified depth,

$$\theta = A' t^{B'} \tag{6.24}$$

results in correlation coefficients as low as 0.74 and standard deviations as high as 0.071. It turns out that the correlation between $\ln(\theta^*)$ and $\ln(t)$ of the power function model is generally slightly poorer in soils where θ in top layers change faster than that of θ^* (Profile type 2, 4, and 6). In these soils the standard deviation of the residual θ^* generally tends to be higher.

Constant A of Equation 6.22 is always positive and B is always negative. Constant A corresponds to the near saturation value of θ^*. It is always positive because it is a maximum value in the model. Constant B on the other hand is an indicator of saturation percentage. It is always negative because the logarithm of a number less than unity is negative. The disadvantage of the power function model is that θ^* cannot be defined when $t = 0$ because B is also undefinable.

Equation 6.23 is also an excellent model for describing average soil water content during redistribution in a profile. Correlation coefficient between θ^* and $\ln(t)$ of more than 0.91 were found for all soils and layers (Table 6.4). Regression of θ^* on $\ln(t)$ resulted in

Table 6.2

A and B of the equation $\theta^* = A\ t^B$ and the correlation coefficient between $\ln(\theta^*)$ and $\ln(t)$ for average soil water content above a specified depth

SITE	DEPTH (cm)	A	B	r^a	s^b
H.poko	040	0.4936	-0.0399	0.9716	0.0263
	100	0.4653	-0.0306	0.9239	0.0331
	160	0.4780	-0.0317	0.9412	0.0292
Waiakoa	040	0.4321	-0.0568	0.9932	0.0188
	100	0.4381	-0.0592	0.9961	0.0143
	160	0.4543	-0.0458	0.9968	0.0098
Omaopio	040	0.4429	-0.0215	0.9891	0.0091
	100	0.4364	-0.0188	0.9890	0.0077
	160	0.4337	-0.0183	0.9848	0.0086
Pauwela	040	0.5180	-0.0293	0.9472	0.0254
	100	0.5181	-0.0204	0.9465	0.0171
	160	0.5377	-0.0204	0.9667	0.0130
Kuiaha	040	0.5675	-0.0160	0.9827	0.0083
	100	0.6187	-0.0200	0.9460	0.0183
	160	0.6203	-0.0285	0.9805	0.0149
Makawao	040	0.5438	-0.0423	0.9465	0.0441
	100	0.6140	-0.0448	0.9455	0.0458
	160	0.5706	-0.0430	0.9674	0.0328
Hapapa	040	0.6942	-0.0414	0.9820	0.0198
	100	0.7207	-0.0314	0.9895	0.0109
	160	0.7209	-0.0344	0.9845	0.0143
Olinda	040	0.6379	-0.0186	0.9474	0.0189
	100	0.5345	-0.0318	0.9525	0.0296
	160	0.5349	-0.0316	0.9779	0.0193
Puupahu	040	0.6773	-0.0272	0.9893	0.0107
	100	0.6519	-0.0198	0.9914	0.0064
	160	0.6849	-0.0172	0.9885	0.0063

[a]Correlation coefficient between $\ln(\theta^*)$ and $\ln(t)$.

[b]Standard deviation of the residual θ^*.

Table 6.3

$A^{\wedge}$ and $B^{\wedge}$ of the equation $\theta = A^{\wedge}t^{B^{\wedge}}$ and the correlation coefficient between $\ln(\theta)$ and $\ln(t)$ for a given layer

SITE	DEPTH (cm)	A	B	r^a	s^b
H.poko	040	5.861	-0.0391	0.9663	0.0282
	100	0.4913	-0.0274	0.7410	0.0650
	160	0.5885	-0.0293	0.9057	0.0352
Waiakoa	040	0.5240	-0.0618	0.9936	0.0200
	100	0.5251	-0.0365	0.9804	0.0202
	160	0.5577	-0.0223	0.9807	0.0120
Omaopio	040	0.4577	-0.0217	0.9734	0.0145
	100	0.4569	-0.0144	0.9538	0.0125
	160	0.4435	-0.0139	0.9502	0.0122
Pauwela	040	0.5956	-0.0265	0.8707	0.0393
	100	0.5752	-0.0187	0.9494	0.0152
	160	0.6169	-0.0209	0.9367	0.0188
Kuiaha	040	0.6837	-0.0133	0.9558	0.0114
	100	0.7246	-0.0279	0.9101	0.0339
	160	0.7559	-0.0488	0.9624	0.0359
Makawao	040	0.6769	-0.0458	0.8928	0.0706
	100	0.8815	-0.0521	0.9231	0.0644
	160	0.5779	-0.0281	0.9595	0.0240
Hapapa	040	0.6014	-0.0258	0.9082	0.0356
	100	0.4999	-0.0600	0.9405	0.0631
	160	0.5900	-0.0175	0.9446	0.0174
Olinda	040	0.7759	-0.0245	0.9733	0.0101
	100	0.8304	-0.0242	0.9627	0.0163
	160	0.8426	-0.0408	0.9646	0.0261
Puupahu	040	0.6694	-0.0295	0.9748	0.0171
	100	0.7969	-0.0108	0.9686	0.0068
	160	0.6326	-0.0191	0.8694	0.0261

[a]Correlation coefficient between $\ln(\theta)$ and $\ln(t)$.

[b]Standard deviation of the residual θ.

Table 6.4

A' and B' of the equation $\theta^* = A' + B' \ln(t)$ and the correlation coefficient between θ^* and $\ln(t)$ for an average water content above a specified depth

SITE	DEPTH (cm)	A	B	r^a	s^b
H.poko	040	0.4957	-0.0188	0.9614	0.0146
	100	0.4666	-0.0137	0.9075	0.0166
	160	0.4788	-0.0143	0.9389	0.0134
Waiakoa	040	0.4352	-0.0224	0.9895	0.0092
	100	0.4403	-0.0231	0.9978	0.0042
	160	0.4554	-0.0189	0.9984	0.0029
Omaopio	040	0.4433	-0.0092	0.9908	0.0036
	100	0.4367	-0.0079	0.9901	0.0031
	160	0.4339	-0.0076	0.9852	0.0036
Pauwela	040	0.5193	-0.0148	0.9334	0.0145
	100	0.5186	-0.0103	0.9379	0.0094
	160	0.5380	-0.0106	0.9667	0.0067
Kuiaha	040	0.5679	-0.0088	0.9837	0.0045
	100	0.6193	-0.0120	0.9420	0.0114
	160	0.6212	-0.0168	0.9783	0.0093
Makawao	040	0.5492	-0.0220	0.9271	0.0273
	100	0.6187	-0.0257	0.9378	0.0282
	160	0.5736	-0.0226	0.9631	0.0184
Hapapa	040	0.6963	-0.0268	0.9846	0.0118
	100	0.7217	-0.0215	0.9890	0.0077
	160	0.7219	-0.0233	0.9854	0.0094
Olinda	040	0.6388	-0.0116	0.9408	0.0125
	100	0.5362	-0.0162	0.9388	0.0173
	160	0.5360	-0.0159	0.9703	0.0113
Puupahu	040	0.6366	-0.0173	0.9904	0.0061
	100	0.6522	-0.0124	0.9920	0.0039
	160	0.6850	-0.0114	0.9893	0.0040

[a]Correlation coefficient between θ^* and $\ln(t)$.

[b]Standard deviation of the residual θ^*.

standard deviations of less than 0.028. As in the power function model, the correlation coefficient is somewhat lower and the standard deviation somewhat higher in Hamakuapoko (Type 2 profile), Makawao and Olinda (Type 4 profile), and Pauwela (Type 6 profile) than in the other sites. The constant A' is always positive because it indicates θ^* at near saturation. Unfortunately, the average water content at saturation cannot be evaluated because the equation cannot be solved at $t = 0$. The constant B' is always negative, because the average profile water content always decreases with time.

Soil Water Content Redistribution

After cessation of ponding, the water content of a soil layer can be described by the expression

$$(\theta_0 - \theta) = A'' + B'' \ln(t) \qquad (6.25)$$

where θ_0 is soil water content of saturation. The results in Table 6.6 show that changes in soil water content of soil layers is not as smooth as that of the average profile water content, as indicated by Table 6.5. Most of the correlation coefficients for the $(\theta_0 - \theta)$ - $\ln(t)$ relationship are lower than for the θ^* - $\ln(t)$ relationship. The standard deviation from regression of $(\theta_0 - \theta)$ on $\ln(t)$ are generally higher than for the corresponding regression of θ^* on $\ln(t)$. Still, the correlation coefficients for $(\theta_0 - \theta)$ versus $\ln(t)$ are greater than 0.85, except at the 100 cm depth layer in Hamakuapoko, and the regression of $(\theta_0 - \theta)$ on $\ln(t)$ has standard deviations of less than 0.043 in all soils and layers. Hamakuapoko's profile is of the type 2 variety where changes in water content at any depth are

Table 6.5

A" and B" of the equation $(\theta_o - \theta) = A'' + B'' \ln(t)$ and the correlation coefficient between $(\theta_o - \theta)$ and $\ln(t)$

SITE	DEPTH (cm)	A	B	r^a	s^b
H.poko	040	0.1264	0.0184	0.9614	0.0143
	100	0.1172	0.0121	0.7145	0.0309
	160	0.0102	0.0141	0.9143	0.0160
Waiakoa	040	0.1071	0.0229	0.9893	0.0096
	100	0.0321	0.0152	0.9844	0.0075
	160	0.0334	0.0108	0.9840	0.0053
Omaopio	040	0.0195	0.0087	0.9764	0.0055
	100	0.0063	0.0060	0.9544	0.0052
	160	0.0060	0.0057	0.9499	0.0050
Pauwela	040	0.1710	0.0160	0.8537	0.0249
	100	0.0347	0.0096	0.9522	0.0076
	160	0.0178	0.0112	0.9440	0.0094
Kuiaha	040	0.0897	0.0084	0.9598	0.0068
	100	0.1278	0.0173	0.9012	0.0222
	160	0.0262	0.0275	0.9586	0.0213
Makawao	040	0.1326	0.0248	0.8724	0.0425
	100	0.0618	0.0336	0.9188	0.0428
	160	0.0175	0.0135	0.9585	0.0117
Hapapa	040	0.0618	0.0166	0.9865	0.0068
	100	0.0499	0.0174	0.9619	0.0119
	160	0.0527	0.0269	0.9662	0.0167
Olinda	040	0.0843	0.0136	0.8944	0.0203
	100	0.0852	0.0215	0.9141	0.0278
	160	0.0056	0.0092	0.9450	0.0090
Puupahu	040	0.1083	0.0165	0.9787	0.0088
	100	0.0330	0.0080	0.9701	0.0049
	160	0.0242	0.0106	0.8702	0.0144

[a] Correlation coefficient between $(\theta_o - \theta)$ and $\ln(t)$.

[b] Standard deviation of the residual $(\theta_o - \theta)$.

Table 6.6

$A^{\#}$ and $B^{\#}$ of $\ln [z\, d\theta^*/dt] = A^{\#} (\theta_0-\theta) + B^{\#}$ and the correlation coefficient between $(\theta_0-\theta)$ and $\ln [z\, d\theta^*/dt]$

SITE	DEPTH (cm)	$A^{\#}$	$B^{\#}$	r^a	s^b
H.poko	040	-52.8158	6.5904	0.8368	1.7926
	100	-49.9967	5.9666	0.6840	2.3558
	160	-68.1323	1.5804	0.8412	1.7289
Waiakoa	040	-42.0598	4.4687	0.9439	0.9636
	100	-57.5128	2.6035	0.9130	1.0938
	160	-81.2694	3.9763	0.9436	0.8535
Omaopio	040	-99.4629	0.8897	0.8698	1.4272
	100	-129.4177	0.2056	0.8580	1.3411
	160	-129.2828	0.3529	0.8216	1.4310
Pauwela	040	-47.7121	7.7336	0.8127	1.6377
	100	-94.0826	3.4747	0.8313	1.5580
	160	-71.6925	1.8837	0.8412	1.3156
Kuiaha	040	-105.3828	8.3793	0.8049	1.8803
	100	-52.4860	7.1229	0.8498	1.6692
	160	-37.2256	2.3142	0.9376	1.0311
Makawao	040	-35.7631	4.1683	0.8249	2.1291
	100	-28.3207	2.4498	0.8883	1.5887
	160	-78.4359	2.6442	0.9565	0.9826
Hapapa	040	-49.7606	2.9837	0.8726	1.1608
	100	-46.0017	2.9827	0.8476	1.2488
	160	-30.6777	2.5584	0.8238	1.3714
Olinda	040	-59.7071	4.2029	0.8260	1.8521
	100	-41.3520	3.8310	0.8563	1.7095
	160	-106.6264	1.5120	0.9046	1.3900
Puupahu	040	-60.9258	6.7826	0.8926	1.3126
	100	-129.6965	4.9173	0.8772	1.4423
	160	-76.1980	2.5232	0.8479	1.3951

[a]Correlation coefficient between $\ln[zd\theta^*/dt]$ and $(\theta_0-\theta)$.

[b]Standard deviation of the residual $\ln[zd\theta^*/dt]$.

always faster than changes in average water content above the designated depth. For this type of profile, drainage in the middle of the profile could be very uneven causing the poor correlation between water content change and time.

Relationship of Water Flux and Water Content Change

A semilog plot of (a z [dθ/dt]) versus (θ_o - θ), where "a" is calculated from the Equation 6.21, can be used to estimate saturated hydraulic conductivity (Libardi et al., 1980). Since θ is usually more erratic than θ*, particularly at greater depths, and the value of (z dθ/dt) is easier to evaluate than (a z dθ/dt), a soil water flux model which accommodates several desirable features can be written as:

$$\ln [z\, d\theta^*/dt] = A^{\#} (\theta_o - \theta) + B^{\#} \quad (6.26)$$

The correlation between ln [z dθ*/dt] and (θ_o - θ) is mixed. The correlation coefficients ranged from 0.68 to 0.96, but more than half were between 0.80 and 0.85.

Estimation of Hydraulic Conductivity

Working Equations

In the Libardi-θ method, K_o and k were obtained by substituting Equation 6.25 into Equation 6.7 to give

$$K_o = \frac{a\, z}{k} \exp (k\, A'') \quad (6.27)$$

$$k = \frac{1}{B''} \quad (6.28)$$

Values of A" and B" were obtained from Table 6.5 and values of "a" from Table 6.1. Results presented in Tables 6.7 and 6.8 show that K_o ranged from 3.4 to 65.1 cm/hour with Waiakoa > Hapapa > Puupahu > Makawao > Pauwela > Kuiaha > Hamakuapoko > Olinda > Omaopio, and k ranged from 36.4 at Kuiaha to 177.1 at Omaopio.

In the Libardi-Flux method, K_o and k were obtained by substituting Equation 6.26 into Equation 6.9, so that

$$K_o = \exp(B^{\#}) \quad (6.29)$$

$$k = -A^{\#} \quad (6.30)$$

where values of $A^{\#}$ and $B^{\#}$ were obtained from Table 6.6. Results of K_o ranged from 1.4 to 53.3 cm/hour with Waiakoa > Makawao > Hapapa > Puupahu > Kuiaha > Pauwela > Hamakuapoko > Olinda > Omaopio (Table 6.7), and k ranged from 30.7 (Olinda) to 129.3 (Omaopio) (Table 6.8).

Estimates of K_o and k in the Chong-θ method were obtained by assuming that b in Equation 6.5 was equal to $(\theta_o^* - a\,\theta_o)$ and that $((\theta - \theta_o)/\theta_o^*)$ was small (Libardi et al., 1980). If these assumptions hold, K_o and k can be computed from the relationships

$$K_o = -z\,A^{1/B}\,B\,\theta_o^{*\,(B-1)/B} \quad (6.31)$$

$$k = a\,(B - 1)\,/\,B\,\theta_o^* \quad (6.32)$$

where A and B were obtained from Table 6.2 and "a" from Table 6.1. Results presented in Table 6.7 show that K_o varied from 9.5 to 432.6 cm/hour with Hamakuapoko > Kuiaha > Puupahu > Pauwela > Waiakoa > Olinda > Makawao > Hapapa > Omaopio. Results presented in Table 6.8 show that k varied from 30.5 (Kuiaha) to 161.8 (Omaopio).

Table 6.7

Estimated saturated hydraulic conductivity K_o (cm/hour) for the 0-160 cm depth using five simplified methods

SITE	Libardi (θ)	Libardi (Flux)	Chong (θ)	Sisson (θ)	Sisson (θ)	Mean	C.V. (%)
H.poko	4.31	4.86	432.56	4.64	258.05	140.88	140
Waiakoa	65.11	53.32	93.40	37.79	45.86	59.10	37
Omaopio	3.38	1.42	9.49	2.59	3.56	4.09	77
Pauwela	8.12	6.58	220.29	8.75	105.42	69.83	135
Kuiaha	6.82	10.12	371.65	11.39	195.69	119.13	136
Makawao	12.54	14.72	77.05	7.88	31.64	28.77	99
Hapapa	25.95	12.92	31.95	30.59	12.16	22.71	42
Olinda	4.07	4.54	83.72	2.69	36.41	26.29	133
Puupahu	15.27	12.47	246.27	16.65	117.21	81.57	125
MEAN	16.17	13.44	174.04	13.66	89.56	61.37	103
Variance	389	243	22925	158	7704	6284	
C.V.(%)	122	116	87	92	98	76	

Table 6.8

Estimated k for the 0-160 cm depth using five simplified methods

SITE	Libardi (θ)	Libardi (Flux)	Chong (θ)	Sisson (θ)	Sisson (θ)	Mean	C.V. (%)
H.poko	71.05	68.13	53.89	71.05	70.09	66.84	11
Waiakoa	92.34	81.27	74.90	92.34	52.92	78.75	21
Omaopio	177.09	129.26	161.81	177.09	131.17	155.28	15
Pauwela	89.17	71.69	78.09	89.17	94.48	84.52	11
Kuiaha	36.42	37.23	30.47	36.42	59.61	40.03	28
Makawao	73.96	78.44	59.81	73.96	44.31	66.10	21
Hapapa	109.27	106.63	83.01	109.27	62.82	94.20	22
Olinda	37.23	30.68	32.97	37.23	42.89	36.20	13
Puupahu	94.35	76.20	72.84	94.35	87.90	85.13	12
MEAN	86.72	75.50	71.98	86.76	71.80	78.56	17
Variance	1734	912	1511	1734	825	1343	
C.V.(%)	48	40	54	48	40	45	

Estimation of K_o and k in the Sisson-θ method was similar to the Libardi-θ method, i.e. by substitution of Equation 6.25 into Equation 6.13 to obtain

$$K_o = \frac{z}{k} \exp (k A'') \tag{6.33}$$

$$k = \frac{1}{B''} \tag{6.34}$$

where A" and B" were obtained from Table 6.5. There is no need to assume that the average soil water content θ* is linearly related to $\theta_{(z)}$ (Equation 6.5), so that no "a" term appears in Equation 6.33 as in Equation 6.27. Values of K_o vary from 2.6 to 37.8 cm/hour with an order of Waiakoa > Hapapa > Puupahu > Kuiaha > Pauwela > Makawao > Hamakuapoko > Olinda > Omaopio (Table 6.7). Whereas values of k range from 36.4 (Kuiaha) to 177.1 (Omaopio) (Table 6.8).

In the Sisson-W method, K_o and k were obtained by substituting Equation 6.23 into Equation 6.16 to give results of

$$K_o = \frac{z}{k} \exp \{ k (\theta_o - A') - 1\} \tag{6.35}$$

$$k = - \frac{1}{B'} \tag{6.36}$$

where A' and B' were from Table 6.4. Results presented in Table 6.7 and Table 6.8 show that K_o varies from 3.6 to 258.1 cm/hour with Hamakuapoko > Kuiaha > Puupahu > Pauwela > Waiakoa > Olinda > Makawao > Hapapa > Omaopio, and k varies from 42.9 (Olinda) to 131.2 (Omaopio).

Comparison Among the Simplified Methods

As can be seen in Table 6.7, the estimated K_o vary considerably among sites and with the method used at a given site. Coefficient of variation among methods at each site ranged from 37% to 140%. The variation is relatively low in Waiakoa, Hapapa, and Omaopio, but is high in Hamakuapoko, Pauwela, Kuiaha, Olinda, Puupahu, and Makawao. As has been discussed previously, Omaopio (Type 1 profile), Hapapa (Type 3 profile), and Waiakoa (Type 5 profile) have relatively smooth drainage curves. Since the simplified methods are linear models, it can be expected that the smooth linear curves are estimated more accurately than the non-smooth ones. Consequently, the soils at the Omaopio, Hapapa, and Waiakoa sites have lower coefficients of variation.

Mean values of K_o from all sites ranged from 13.4 to 174.0 cm/hour in the order Chong-θ > Sisson-W > Libardi-θ > Sisson-θ > Libardi-Flux. The mean values of K_o determined by the Chong-θ method are consistently higher in all sites than those determined by the other methods. This is caused by the fact that the Chong-θ method assumes a power function relationship between θ^* and time.

In all sites, mean values of K_o estimated by the various methods ranged from 4.1 to 140.9 cm/hour. K_o values in Omaopio are consistently lower for all methods than at the other sites. On the other extreme, the values of K_o in Waiakoa are the highest when estimated by Libardi-θ, Libardi-Flux, or Sisson-θ methods. When they are estimated by the Chong-θ or Sisson-W methods, however, the values of K_o in Hamakuapoko are the highest. A previous study by Green and

Guernsey (1981) in Hapapa (Kula loam) and Omaopio (Keahua silty clay) gave comparable results. Their K_0's computed from the pore-interaction model of Marshall (Green and Corey, 1971) were 32.5 and 10.7 cm/hour for the subsoil of the Kula loam and Keahua silty clay soil respectively, whereas in this study, the calculated values of K_0 were 26.0, 12.9, 32.0, 30.6, and 12.2 cm/hour for the Kula loam soil using Libardi-θ, Libardi-Flux, Chong-θ, Sisson-θ, and Sisson-W respectively, and 3.4, 1.4, 9.5, 2.6, and 3.6 cm/hour for the Keahua silty clay soil.

Values of the constant k vary considerably among sites with Omaopio > Hapapa > Puupahu > Pauwela > Waiakoa > Hamakuapoko > Makawao > Kuiaha > Olinda. The mean values range from 36.2 at Olinda to 155.3 at Omaopio and the variance averages 1343, as shown in Table 6.8. However, there is no appreciable variation in k obtained from the different methods. The average results for all sites range from 71.8 (Sisson-W) to 86.8 (Libardi-θ and Sisson-θ). While the coefficients of variation among methods are less than 28% in all sites. This suggests that K_0 is very sensitive to k.

Estimation of the Spatial Variability of Soil Water Flux

Analytical expressions for mean and variance of soil water flux were calculated from means and variances of K_0 and k. Observations at all sites were combined and estimates of the mean and variance of the soil water flux were developed using Equation 6.19 and Equation 6.20. Results in Table 6.9 show that the mean of soil water flux at steady state varies considerably across five methods. The Libardi-θ, Libardi-Flux, and Sisson-θ methods are similar, but they are lower by 8 to 10 times compared to the Sisson-W method and 11 to 13 times

Table 6.9

Soil water flux at 160 cm profile depth

TIME	METHOD	MEAN (cm/day)	VAR. (cm^2/day^2)	C.V.(%)
0	Libardi-θ	3.88 E+2	2.24 E+5	122
	Libardi-F	3.23 E+2	1.40 E+5	116
	Chong-θ	4.18 E+3	1.32 E+7	87
	Sisson-θ	3.28 E+2	9.10 E+4	92
	Sisson-W	2.15 E+3	4.44 E+6	98
1 hour	Libardi-θ	3.97 E+1	3.18 E+2	45
	Libardi-F	4.39 E+1	2.79 E+2	38
	Chong-θ	5.27 E+1	7.89 E+2	53
	Sisson-θ	3.90 E+1	2.90 E+2	44
	Sisson-W	5.22 E+1	4.16 E+2	39
12 hours	Libardi-θ	3.65	3.02	48
	Libardi-F	4.18	2.73	40
	Chong-θ	4.44	5.74	54
	Sisson-θ	3.65	3.00	47
	Sisson-W	4.45	3.15	40
1 day	Libardi-θ	1.84	7.69 E-1	48
	Libardi-F	2.11	7.00 E-1	40
	Chong-θ	2.22	1.44	54
	Sisson-θ	1.83	7.66 E-1	48
	Sisson-W	2.23	7.91 E-1	40
2 days	Libardi-θ	9.20 E-1	1.97 E-1	48
	Libardi-F	1.06	1.77 E-1	40
	Chong-θ	1.11	3.60 E-1	54
	Sisson-θ	9.20 E-1	1.94 E-1	48
	Sisson-W	1.11	1.98 E-1	40
7 days	Libardi-θ	2.63 E-1	1.59 E-2	48
	Libardi-F	3.02 E-1	1.46 E-2	40
	Chong-θ	3.18 E-1	2.94 E-2	54
	Sisson-θ	2.63 E-1	1.59 E-2	48
	Sisson-W	3.18 E-1	1.62 E-2	40
14 days	Libardi-θ	1.32 E-1	3.99 E-3	48
	Libardi-F	1.51 E-1	3.66 E-3	40
	Chong-θ	1.59 E-1	7.35 E-3	54
	Sisson-θ	1.31 E-1	3.99 E-3	48
	Sisson-W	1.59 E-1	4.05 E-3	40

with the Chong-θ method. Comparing the results in TAble 6.9 with Table 6.7, it is obvious that the mean and variance of the soil water flux at t = 0 day are the same as those for K_o. At this time, the coefficients of variation of the soil water flux for Chong-θ, Sisson-θ, and Sisson-W method are similar, and slightly less than the coefficients of variation for the Libardi-θ and Libardi-Flux methods.

However, the means of the soil water flux drop by 2 to 3 orders of magnitude and the variances by 5 to 7 orders of magnitude within a day after cessation of ponding. The fluxes estimated by all methods continue to decrease and the means become progressively more similar with time. After 14 days, the difference between the highest and lowest flux was only 0.0275 cm/day. At t = 1 day and thereafter, the coefficients of variation remained constant and were similar for all methods.

Conclusions

The assumptions made in developing the simplified methods (Libardi-θ, Libardi-Flux, Chong-θ, Sisson-θ, and Sisson-W methods) for estimating hydraulic conductivity are valid. This is indicated by the high values of correlation coefficient for the relationships used to estimate K_o and k. The correlation coefficients were more than 0.805 for all soils and layers, except for the layer of 100 cm depth in Hamakuapoko site. In other words, at least 65% of the variation in soil water content was explained by change in time.

However, the assumption used to develop each method apparently affects the estimated outcome. The method which assumes a power function (Chong-θ method) gives consistently higher estimates of K_o

than the methods which assume a logarithmic function (Libardi-θ, Sisson-θ, and Sisson-W methods) and an exponential function (Libardi-Flux method). The rank of the calculated values of K_0 was Chong-θ > Sisson-W > Libardi-θ > Sisson-θ > Libardi-Flux methods. On the other hand, variability among methods for estimating hydraulic conductivity is lower when the drainage pattern is smoother. The coefficient of variation of estimated K_0 among methods for each site was Hamakuapoko > Kuiaha > Pauwela > Olinda > Puupahu > Makawao > Omaopio > Hapapa > Waiakoa.

Nevertheless, the differences in hydraulic conductivity estimated by the various methods do not strongly affect soil water flux. The method chosen to describe K(θ) influenced the estimated spatial variation of the soil water flux only at near saturated condition. From day one onward, the estimates of the variation of soil water flux were not influenced appreciably by the choice of method.

The five simplified methods developed by Libardi et al. (1980), Chong et al. (1981), and Sisson et al. (1980) can be used to approximate soil water properties over large areas.

CHAPTER VII

SUMMARY

The capacity of soils to retain and transmit water plays a significant role in determining land quality. However, field measurements of hydraulic parameters are time and labor consuming. On the other hand, simple laboratory determinations generally misrepresent field conditions. To this end a study to test the applicability of procedures to estimate water extractability and hydraulic conductivity was conducted.

Nine experimental sites covering an area of 625 km^2 on the west slope of East Maui, Hawaii, were established to collect the experimental data. Mean annual air temperature of the study area ranged from 14°C, at 1640 m above sea level, to 25°C at sea level. Mean annual rainfall ranges from 380 mm in the rainshadow of Mount Haleakala to 1910 mm on the windward side. At each site, the soils were described to a depth of 150 cm or more. Automatic recording weather stations were installed at each site to collect daily solar radiation, air temperature, and rainfall. A neutron hydroprobe was used to monitor soil water from August 1984 to June 1985. The CERES crop model was employed to test the soil water extractability model, and a simple model for estimating spatial variability of soil water flux was used to test the applicability of the hydraulic conductivity models.

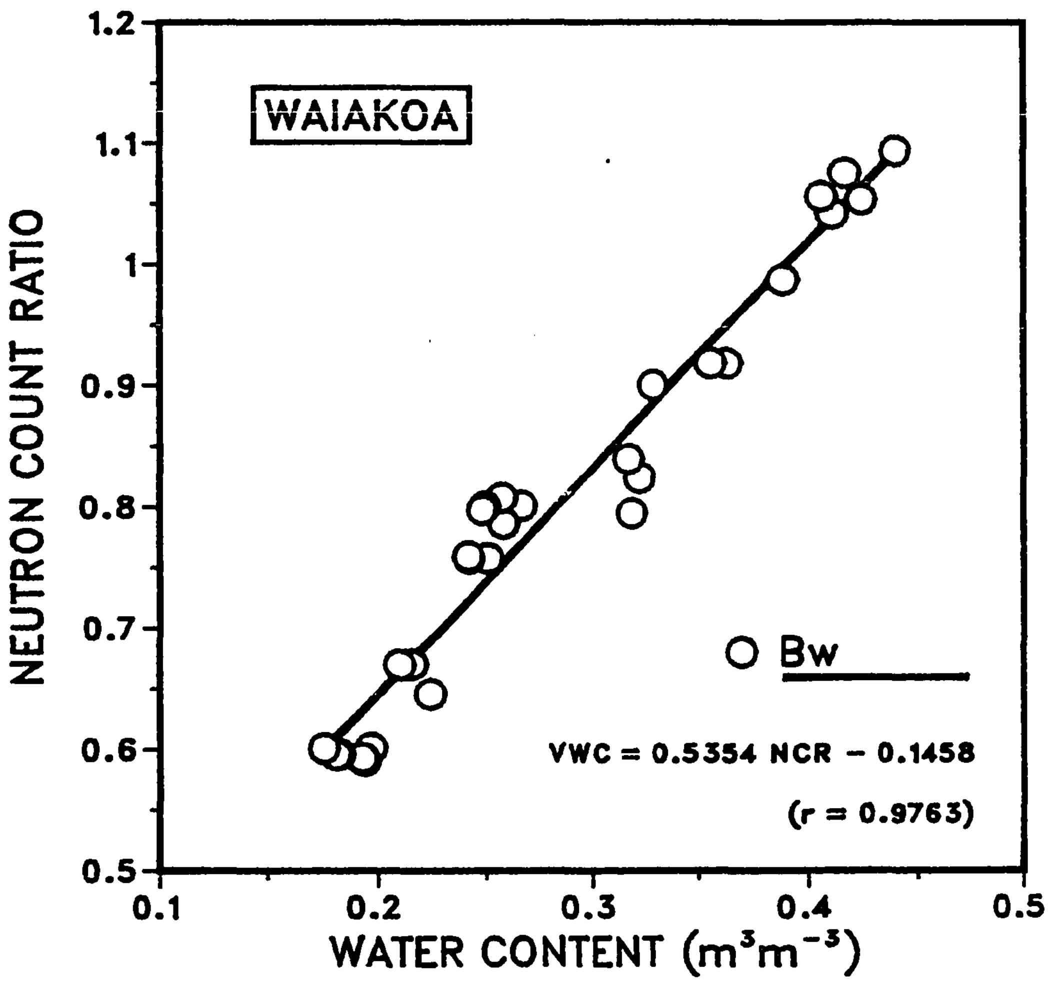
High soil variability necessitates proper field calibration for the neutron hydroprobe. A calibration curve for each site was

developed by regressing neutron count ratio (NCR) on volumetric water content (VWC). To calculate volumetric water content from the corresponding neutron count ratio , the calibration equation was re-written explicitly in water content. This procedure is more accurate than directly regressing volumetric water content on neutron count ratio, especially when the two variables are not highly correlated. For the Ultisols and Andisols and clayey soils investigated, the neutron hydroprobe needed to be calibrated for each soil horizon.

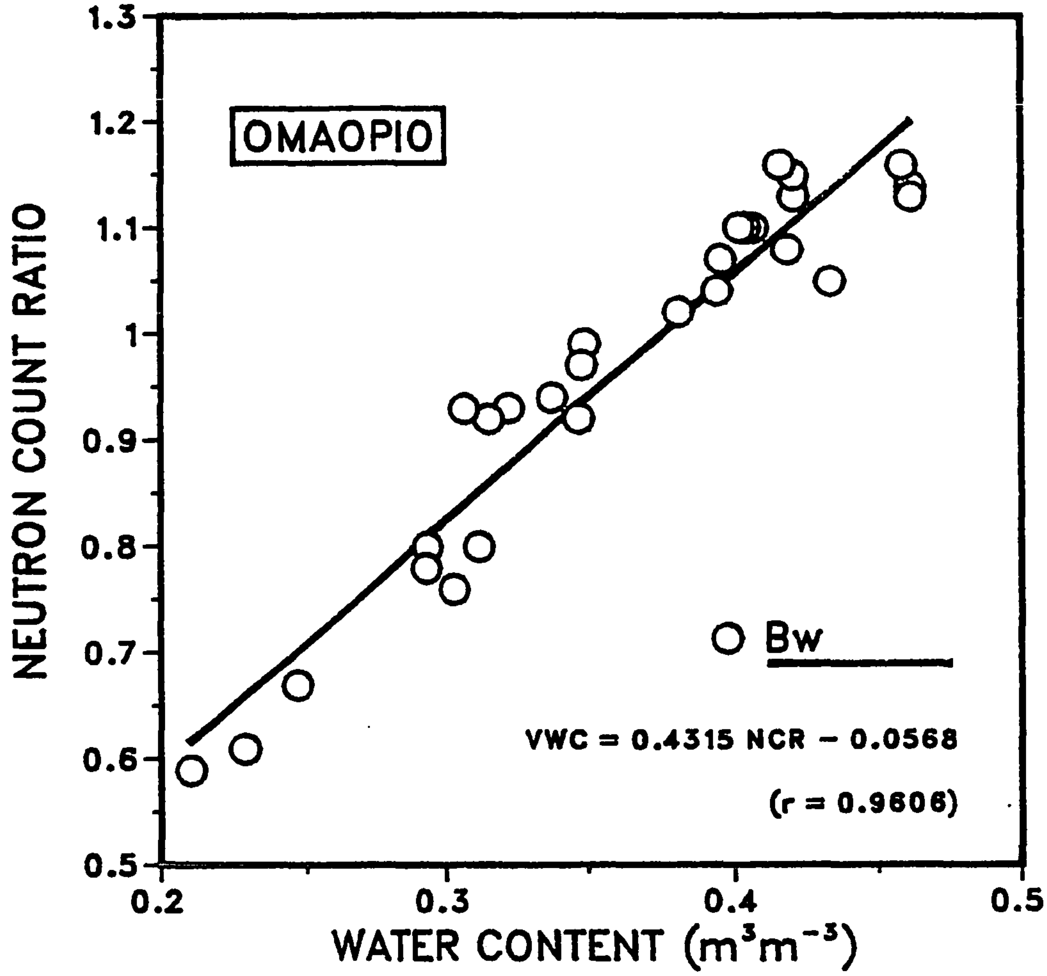
The neutron hydroprobe was used to measure soil water content at various times and depths in the field. The soil water content at the time when the vegetation was permanently wilted was defined as the lower limit (LOL) of soil water extractability. The soil water content measured when the drainage rate attained approximately 0.1 cm/day from the 160 cm deep profile was defined as the upper limit (DUL) of soil water extractability. The difference between DUL and LOL is the plant extractable water (PEXW). Relative to 1.5 MPa and 33 kPa water contents, LOL and DUL were overestimated in Mollisols and underestimated in Ultisols and Andisols by the laboratory methods. However, the plant extractable water was underestimated in Mollisols and overestimated in Ultisols and Andisols relative to the laboratory method. In the final analysis, it turns out that field measured plant extractable water is not significantly different among Mollisols, Ultisols, and Andisols.

The field measured lower limit, upper limit, and plant extractable water were used to calibrate Ritchie's model of soil water extract-ability. The calibrated model requires inputs of bulk density, organic matter content, and 1.5 MPa water content for Andisols, and bulk density, organic matter content, and silt and sand content for other soils. Testing the applicability of the calibrated model with CERES's soil water balance model in an independent set of soils, showed satisfactory results. An average of 72% of the water contents ranging from 0.08 to 0.50 m^3/m^3 were simulated with deviation of less than 0.03 m^3/m^3 from the field measured values. The predicted mean was not significantly different from the measured mean at the 1% level. Measured and predicted values were highly correlated, i.e. with $r = 0.9670$.

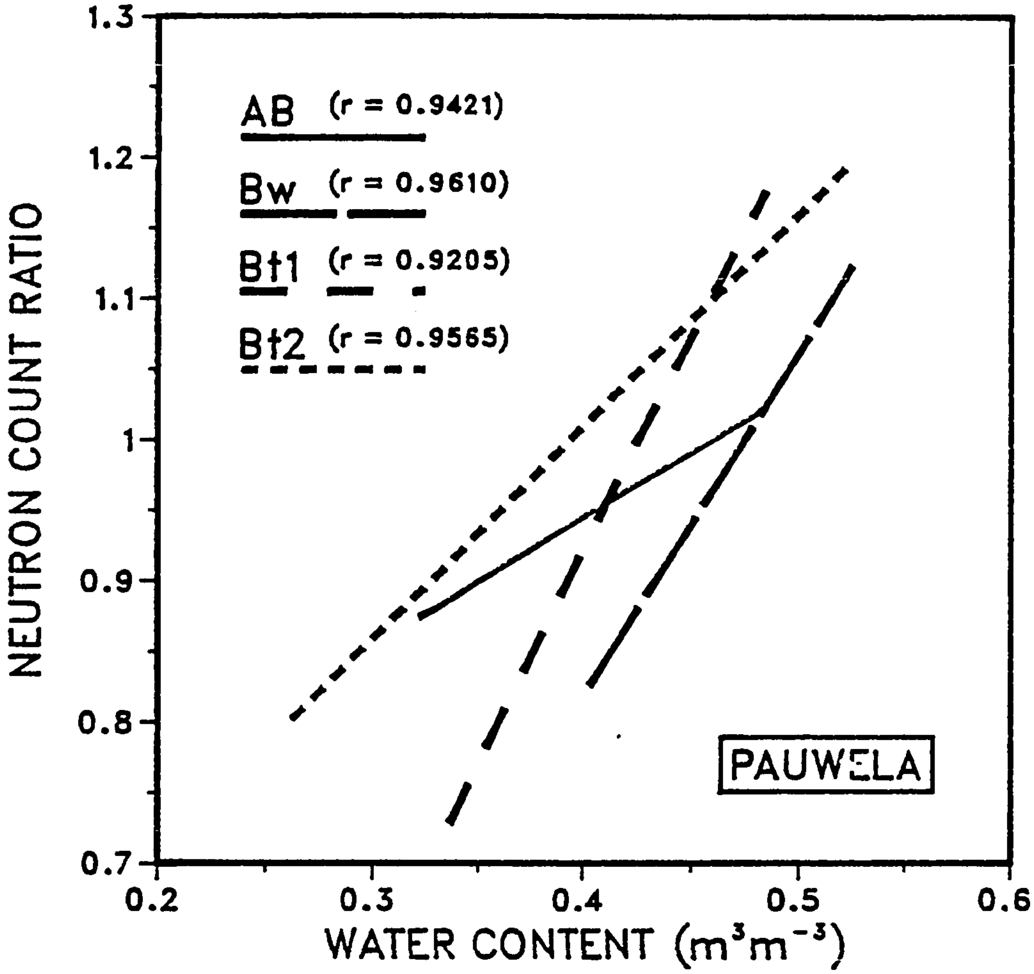
The neutron hydroprobe was also used to monitor soil water content redistribution following cessation of ponding. Conventional procedures in estimating hydraulic conductivity generally require measurement of hydraulic gradients and water content and calculation of water flux. Simple methods for estimating hydraulic conductivity which require only soil water content measurements are, however, available. These simplified methods enable many observations over large areas to be made. All the methods assume that unit hydraulic gradient is maintained during soil water redistribution, and an exponential relationship between hydraulic conductivity (K) and water content (θ). The water content data were used to calculate K_0 and k by each method at the 160 cm depth at each site. Then, the means and variances of K_0 and k were used to estimate the means and variances of soil water flux. Although the assumptions associated with each method are sound as indicated by the high values of the correlation coefficient obtained between water content and time, the form of the model influences the calculated hydraulic conductivity. The method which assumes a power function (i.e. Chong-θ method) gave consistently higher estimates of K_0 than methods which assume a logarithmic function (i.e. Libardi-θ, Sisson-θ, and Sisson-W methods) and an exponential function (i.e. Libardi-Flux method). However, the estimated K_0 only affected the estimated spatial variability of soil water flux at near-saturated conditions. It can be inferred, therefore, that any of the five methods can be used to characterize unsaturated hydraulic properties over large areas. In the wet range, however, the choice of method is uncertain, and further testing is needed.



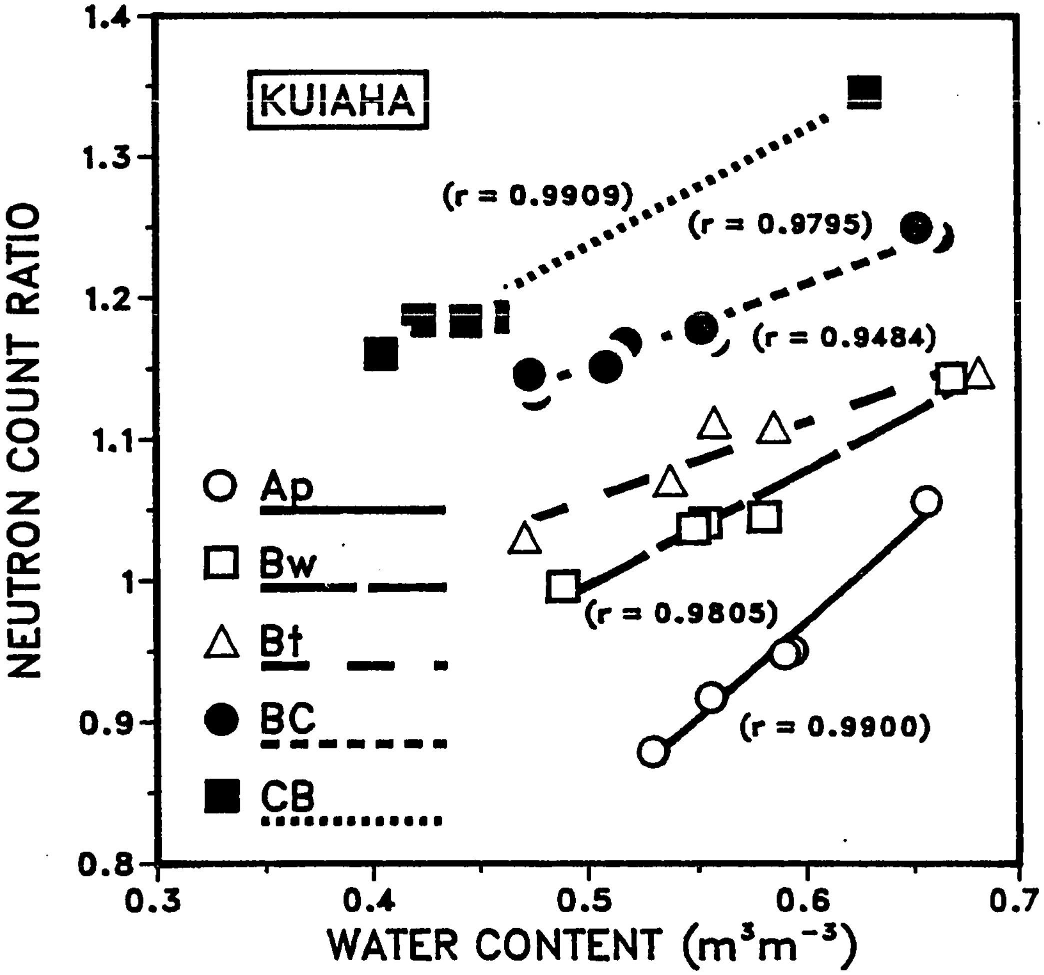
Appendix Figure A.2. Neutron hydroprobe calibration curve for Waiakoa site (Keahua series).



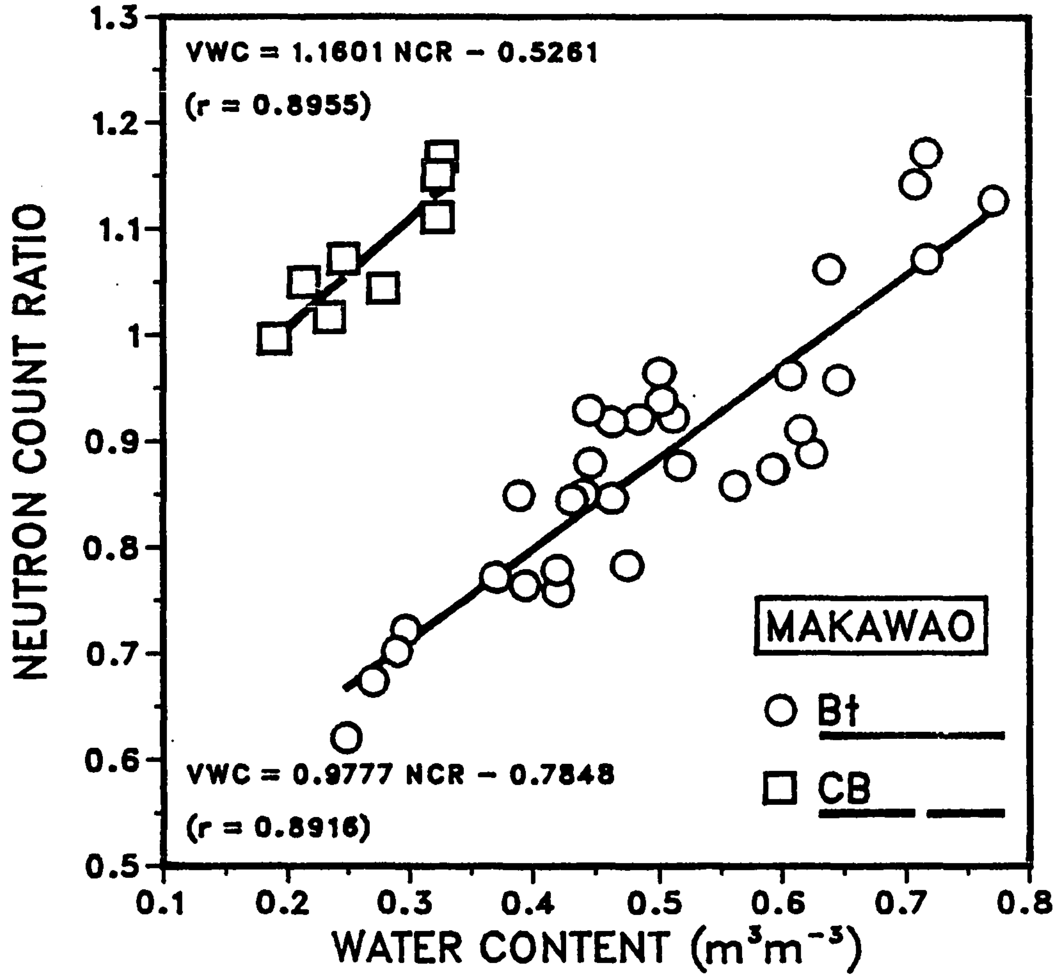
Appendix Figure A.3. Neutron hydroprobe calibration curve for Omaopio site (Keahua series).



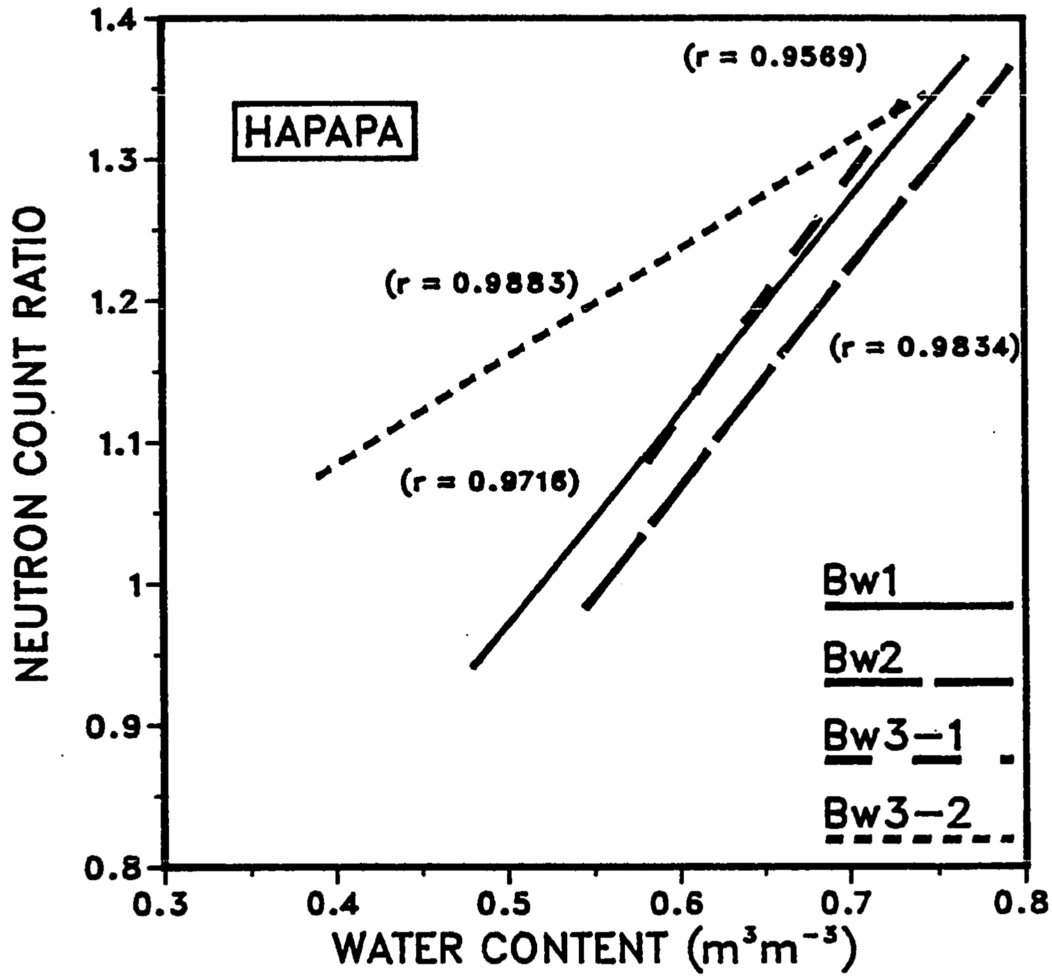
Appendix Figure A.4. Neutron hydroprobe calibration curves for Pauwela site (Haiku series).



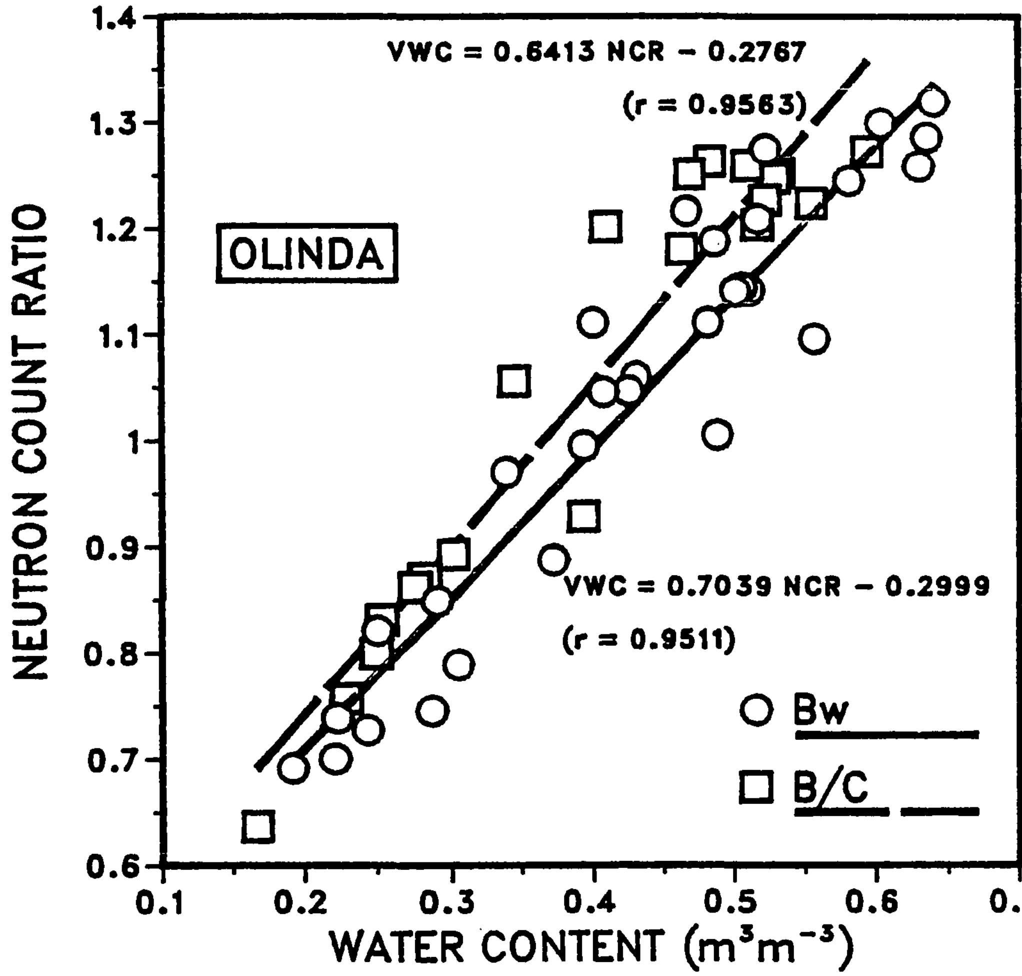
Appendix Figure A.5. Neutron hydroprobe calibration curves for Kuiaha site (Haiku series).



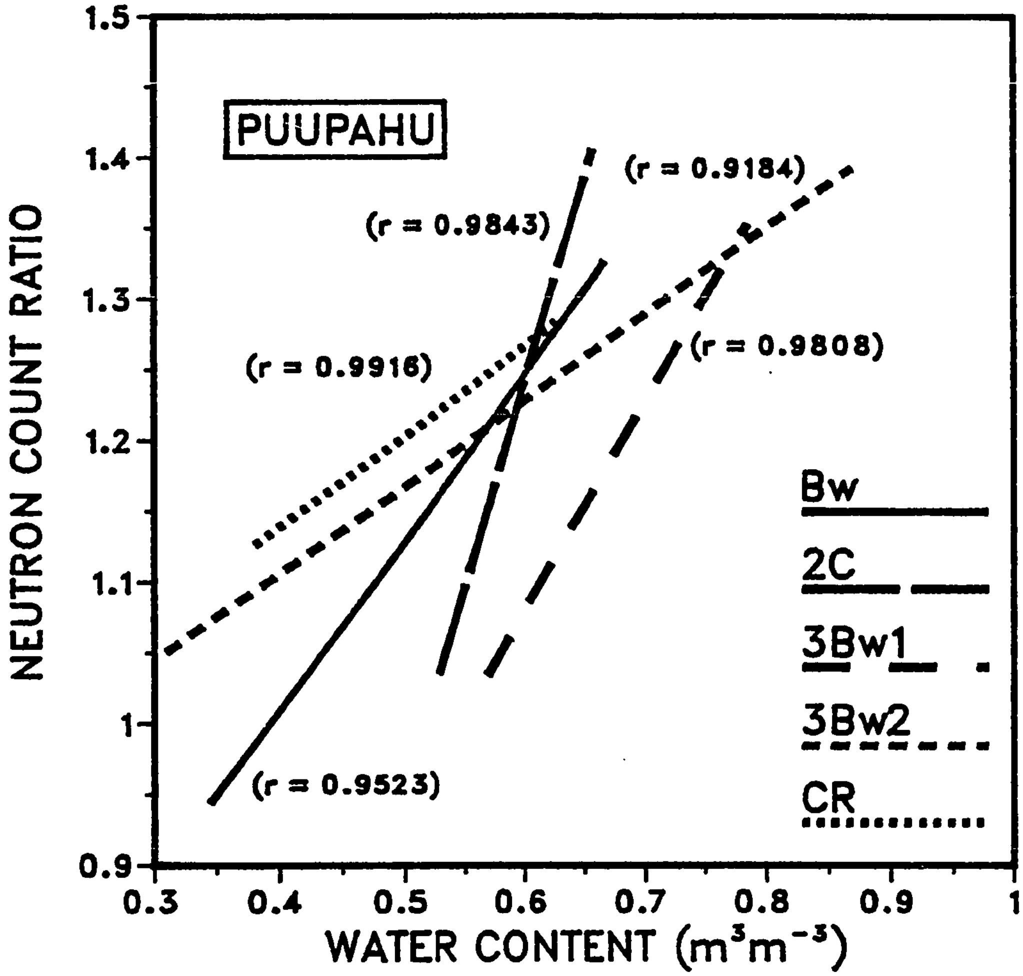
Appendix Figure A.6. Neutron hydroprobe calibration curves for Makawao site (Makawao series).



Appendix Figure A.7. Neutron hydroprobe calibration curves for Hapapa site (Kula series).



Appendix Figure A.8. Neutron hydroprobe calibration curves for Olinda site (Olinda series).



Appendix Figure A.9. Neutron hydroprobe calibration curves for Puupahu site (Kaipoioi series).

Appendix Table A.1

Neutron hydroprobe calibration data set

SITE	DEPTH (cm)	FIELD TEXTURE	WATER CONTENT (% vol.)	NEUTRON COUNT RATIO	HORIZON
H.POKO	30	sic	38.296	0.7846	Ap
	50	sic	34.028	0.8643	Bw1
	70	sic	34.526	0.9014	Bw1
	90	sic	32.180	0.9046	Bw2
	110	sic	33.569	0.8962	Bw2
	130	sic	31.563	0.9013	Bw2
	150	sic	35.279	0.9544	Bw2
	30	sic	32.210	0.8449	Ap
	50	sic	35.183	0.8777	Bw1
	70	sic	35.310	0.9120	Bw1
	90	sic	33.440	0.8960	Bw2
	110	sic	33.650	0.9206	Bw2
	130	sic	31.346	0.8966	Bw2
	150	sic	34.289	0.9529	Bw2
	30	sic	41.214	0.9034	Ap
	50	sic	38.321	0.9456	Bw1
	70	sic	39.598	0.9686	Bw1
	90	sic	37.869	0.9459	Bw2
	110	sic	38.968	0.9405	Bw2
	130	sic	41.308	0.9623	Bw2
	150	sic	39.855	1.0111	Bw2
	30	sic	52.080	1.0578	Ap
	50	sic	45.923	1.0611	Bw1
	70	sic	43.283	1.0329	Bw1
	90	sic	41.751	1.0244	Bw2
	110	sic	46.730	1.0823	Bw2
	130	sic	49.239	1.0857	Bw2
WAIAKOA	30	sicl	17.525	0.6022	1Bw
	50	sicl	19.640	0.6022	1Bw
	70	sicl	21.504	0.6709	1Bw
	90	sicl	25.030	0.7578	2Bw
	110	sicl	25.698	0.8079	2Bw
	130	sicl	26.606	0.8010	2Bw
	30	sicl	18.101	0.5969	1Bw
	50	sicl	19.358	0.5919	1Bw
	70	sicl	20.954	0.6707	1Bw
	90	sicl	24.103	0.7596	2Bw
	110	sicl	24.890	0.8006	2Bw
	130	sicl	25.780	0.7864	2Bw
	30	sicl	42.408	1.0540	1Bw
	50	sicl	41.090	1.0422	1Bw

Appendix Table A.1 (continued) Neutron hydroprobe calibration data set

SITE	DEPTH (cm)	FIELD TEXTURE	WATER CONTENT (% vol.)	NEUTRON COUNT RATIO	HORIZON
	30	sicl	36.334	0.9183	1Bw
	50	sicl	35.565	0.9183	1Bw
	30	sicl	18.225	0.5974	1Bw
	50	sicl	19.242	0.5942	1Bw
	70	sicl	22.345	0.6460	1Bw
	90	sicl	24.144	0.7579	2Bw
	110	sicl	24.767	0.7979	2Bw
	30	sicl	31.665	0.8396	1Bw
	50	sicl	31.846	0.7947	1Bw
	70	sicl	32.218	0.8238	1Bw
	90	sicl	32.857	0.9004	2Bw
	70	sicl	38.870	0.9872	1Bw
	90	sicl	40.613	1.0564	2Bw
	110	sicl	41.669	1.0759	2Bw
	130	sicl	44.012	1.0941	2Bw
OMAOPIO	30	sic	34.657	0.9188	Bw1
	50	sic	34.873	0.9866	Bw1
	70	sic	31.494	0.9244	Bw2
	90	sic	30.633	0.9288	Bw3
	110	sic	32.186	0.9307	Bw3
	130	sic	33.723	0.9402	Bw4
	150	sic	34.756	0.9713	Bw4
	30	sic	46.136	1.1273	Bw1
	50	sic	46.150	1.1392	Bw1
	70	sic	45.841	1.1590	Bw2
	90	sic	41.586	1.1552	Bw3
	110	sic	42.052	1.1464	Bw3
	130	sic	42.093	1.1307	Bw4
	150	sic	40.676	1.1011	Bw4
	30	sic	43.319	1.0488	Bw1
	50	sic	41.850	1.0792	Bw1
	70	sic	40.407	1.1006	Bw2
	90	sic	40.205	1.1011	Bw3
	30	sic	38.093	1.0221	Bw1
	50	sic	39.407	1.0444	Bw1
	70	sic	39.554	1.0740	Bw2
	30	sic	21.019	0.5908	Bw1
	50	sic	22.876	0.6093	Bw1
	70	sic	24.656	0.6724	Bw2
	90	sic	30.253	0.7607	Bw3
	110	sic	31.143	0.8033	Bw3
	130	sic	29.308	0.8043	Bw4
	150	sic	29.261	0.7850	Bw4

Appendix Table A.1 (continued) Neutron hydroprobe calibration data set

SITE	DEPTH (cm)	FIELD TEXTURE	WATER CONTENT (% vol.)	NEUTRON COUNT RATIO	HORIZON
PAUWELA	30	sic	32.172	0.8766	AB
	50	sic	40.347	0.8148	Bw
	70	c	37.053	0.7455	Bt1
	90	sic	31.950	0.7888	Bt2
	110	sic	30.314	0.8625	Bt2
	130	sic	26.249	0.8480	Bt2
	30	sic	33.434	0.8812	AB
	50	sic	40.755	0.8092	Bw
	70	c	33.586	0.7409	Bt1
	90	sic	26.671	0.7526	Bt2
	110	sic	26.540	0.8645	Bt2
	130	sic	28.919	0.8483	Bt2
	30	sic	44.707	0.9641	AB
	50	sic	46.016	1.0378	Bw
	70	c	46.581	1.0753	Bt1
	90	sic	44.886	1.1134	Bt2
	110	sic	47.313	1.1206	Bt2
	130	sic	52.570	1.1345	Bt2
	150	sic	49.505	1.1151	Bt2
	30	sic	44.056	1.0218	AB
	50	sic	52.496	1.0991	Bw
	70	c	46.372	1.1361	Bt1
	90	sic	41.780	1.1086	Bt1
	110	sic	44.149	1.1376	Bt2
	30	sic	48.152	1.0136	AB
	50	sic	52.049	1.1047	Bw
	70	c	48.401	1.1441	Bt1
	90	sic	49.215	1.1762	Bt2
	110	sic	48.525	1.1682	Bt2
	130	sic	51.937	1.1966	Bt2
KUIAHA	30	c	52.955	0.8801	Ap
	50	sic	48.902	0.9959	Bw
	70	sic	47.154	1.0311	Bt
	90	sic	47.578	1.1326	BC
	110	sic	47.341	1.1463	BC
	130	sic	42.194	1.1841	CB
	150	sic	45.660	1.1865	CB
	30	c	55.622	0.9183	Ap
	50	sic	54.855	1.0367	Bw
	70	sic	53.788	1.0710	Bt
	90	sic	52.182	1.1653	BC
	110	sic	50.824	1.1518	BC

Appendix Table A.1 (continued) Neutron hydroprobe calibration data set

SITE	DEPTH (cm)	FIELD TEXTURE	WATER CONTENT (% vol.)	NEUTRON COUNT	HORIZON
	130	sic	40.430	1.1605	CB
	150	sic	44.395	1.1835	CB
	30	c	58.988	0.9491	Ap
	50	sic	55.378	1.0407	Bw
	70	sic	58.520	1.1088	Bt
	90	sic	55.745	1.1695	BC
	30	c	59.348	0.9513	Ap
	50	sic	58.076	1.0452	Bw
	70	sic	55.801	1.1123	Bt
	90	sic	55.183	1.1786	BC
	110	sic	51.715	1.1682	BC
	30	c	65.625	1.0572	Ap
	50	sic	66.820	1.1435	Bw
	70	sic	68.130	1.1481	Bt
	90	sic	66.240	1.2436	BC
	110	sic	65.173	1.2498	BC
	130	sic	62.769	1.3458	CB
MAKAWAO	30	sic	29.682	0.7234	Bt
	50	sic	39.334	0.7656	Bt
	70	sic	46.217	0.8472	Bt
	90	sic	71.620	1.1715	Bt
	110	sic	24.650	1.0718	CB
	30	sic	24.778	0.6217	Bt
	50	sic	36.970	0.7731	Bt
	70	sic	56.060	0.8579	Bt
	90	sic	60.610	0.9620	Bt
	110	sic	21.380	1.0498	CB
	30	sic	28.930	0.7033	Bt
	50	sic	59.156	0.8736	Bt
	70	sic	64.491	0.9578	Bt
	90	sic	63.750	1.0614	Bt
	110	sic	27.920	1.0439	CB
	30	sic	26.937	0.6751	Bt
	50	sic	47.389	0.7836	Bt
	70	sic	62.331	0.8883	Bt
	90	sic	70.720	1.1420	Bt
	110	sic	23.490	1.0169	CB
	30	sic	38.823	0.8502	Bt
	50	sic	41.920	0.7797	Bt
	70	sic	77.152	1.1270	Bt
	110	sic	32.310	1.1108	CB

Appendix Table A.1 (continued) Neutron hydroprobe calibration data set

SITE	DEPTH (cm)	FIELD TEXTURE	WATER CONTENT (% vol.)	NEUTRON COUNT	HORIZON
	30	sic	43.101	0.8458	Bt
	50	sic	59.247	0.8736	Bt
	70	sic	71.689	1.0716	Bt
	90	sic	44.480	0.9302	Bt
	110	sic	18.980	0.9965	CB
	30	sic	49.917	0.9647	Bt
	50	sic	61.451	0.9102	Bt
	30	sic	41.979	0.7599	Bt
	50	sic	51.594	0.8766	Bt
	70	sic	51.066	0.9221	Bt
	90	sic	48.340	0.9214	Bt
	110	sic	32.670	1.1678	CB
	30	sic	44.028	0.8515	Bt
	50	sic	44.561	0.8805	Bt
	70	sic	46.245	0.9192	Bt
	90	sic	50.130	0.9380	Bt
	110	sic	32.370	1.1505	CB
HAPAPA	30	sil	50.409	1.0054	Bw1
	50	sil	55.295	1.0424	Bw1
	70	sil	61.105	1.0822	Bw2
	90	sil	65.603	1.1522	Bw2
	110	sicl	64.086	1.1582	Bw3
	130	sicl	49.174	1.1438	Bw3
	150	sicl	46.832	1.1530	Bw3
	30	sil	52.441	0.9886	Bw1
	50	sil	52.295	1.0063	Bw1
	70	sil	56.370	1.0059	Bw2
	90	sil	64.342	1.1420	Bw2
	110	sicl	58.736	1.1030	Bw3
	130	sicl	44.615	1.1146	Bw3
	150	sicl	41.826	1.1134	Bw3
	30	sil	47.972	0.9869	Bw1
	50	sil	52.193	1.0217	Bw1
	70	sil	54.521	0.9788	Bw2
	90	sil	57.813	1.0393	Bw2
	110	sicl	58.118	1.1033	Bw3
	130	sicl	47.703	1.1224	Bw3
	150	sicl	38.979	1.0905	Bw3
	30	sil	53.649	1.0340	Bw1
	50	sil	51.183	0.9745	Bw1
	70	sil	56.525	1.0290	Bw2
	90	sil	61.003	1.0449	Bw2

Appendix Table A.1 (continued) Neutron hydroprobe calibration data set

SITE	DEPTH (cm)	FIELD TEXTURE	WATER CONTENT (% vol.)	NEUTRON COUNT	HORIZON
	110	sicl	62.436	1.1301	Bw3
	130	sicl	47.820	1.1214	Bw3
	150	sicl	44.283	1.1213	Bw3
	30	sil	64.390	1.1635	Bw1
	50	sil	63.111	1.1437	Bw1
	70	sil	63.923	1.1578	Bw2
	90	sil	65.979	1.1742	Bw2
	110	sicl	61.256	1.1262	Bw3
	130	sicl	45.656	1.1175	Bw3
	150	sicl	41.092	1.0993	Bw3
	30	sil	61.588	1.0917	Bw1
	50	sil	59.614	1.1087	Bw1
	70	sil	62.461	1.1156	Bw2
	90	sil	64.951	1.1198	Bw2
	110	sicl	61.593	1.1843	Bw3
	30	sic	72.328	1.3766	Bw1
	50	sil	76.643	1.3749	Bw1
	70	sil	76.463	1.3526	Bw2
	90	sil	79.249	1.3368	Bw2
	110	sicl	73.119	1.3552	Bw3
	130	sicl	74.360	1.3494	Bw3
	150	sicl	72.141	1.3377	Bw3
OLINDA	30	sicl	30.437	0.7887	Bw
	50	sicl	28.605	0.7456	Bw
	70	sicl	24.266	0.7275	Bw
	90	sil	24.924	0.8000	B/C
	110	sil	27.478	0.8621	B/C
	130	sil	30.113	0.8931	B/C
	30	sicl	37.201	0.8875	Bw
	50	sicl	48.673	1.1880	Bw
	70	sicl	51.688	1.2089	Bw
	90	sil	55.436	1.2235	B/C
	110	sil	46.850	1.2508	B/C
	30	sicl	22.202	0.7388	Bw
	50	sicl	22.044	0.7007	Bw
	70	sicl	19.117	0.6919	Bw
	90	sil	22.891	0.7573	B/C
	110	sil	25.318	0.8316	B/C
	30	sicl	28.971	0.8490	Bw
	50	sicl	50.198	1.1408	Bw
	70	sicl	51.116	1.1417	Bw
	90	sil	51.647	1.2035	B/C

Appendix Table A.1 (continued) Neutron hydroprobe calibration data set

SITE	DEPTH (cm)	FIELD TEXTURE	WATER CONTENT (% vol.)	NEUTRON COUNT	HORIZON
	130	sil	34.926	1.1000	3Bw2
	30	sil	43.020	1.0300	1Bw
	50	sil	45.620	1.0500	1Bw
	70	sil	52.880	1.0400	2C
	90	sil	57.740	1.0700	3Bw1
	110	sil	56.990	1.1400	3Bw2
	130	sil	31.043	1.1000	3Bw2
	30	sil	41.830	1.0100	1Bw
	50	sil	34.550	0.9600	1Bw
	70	sil	53.390	1.0400	2C
	90	sil	61.910	1.0700	3Bw1
	110	sil	51.730	1.1100	3Bw2
	130	sil	31.986	1.0900	3Bw2
	30	sil	39.170	0.9800	1Bw
	50	sil	52.570	1.1100	1Bw
	70	sil	54.100	1.0800	2C
	90	sil	62.670	1.1000	3Bw1
	110	sil	56.840	1.1700	3Bw2
	130	sil	48.430	1.1800	3Bw2
	30	sil	45.280	1.0500	1Bw
	50	sil	51.830	1.1800	1Bw
	70	sil	57.940	1.2000	2C
	90	sil	66.230	1.2000	3Bw1
	110	sil	57.990	1.1900	3Bw2
	130	sil	59.002	1.2800	3Bw2
	30	sil	39.412	1.0397	1Bw
	50	sil	50.021	1.0947	1Bw
	70	sil	55.776	1.1459	2C
	90	sil	67.494	1.1807	3Bw1
	110	sil	69.467	1.2322	3Bw2
	130	sil	62.571	1.2817	3Bw2
	150	sil	38.146	1.1236	CR
	30	sil	65.433	1.3866	1Bw
	50	sil	66.618	1.3789	1Bw
	70	sil	65.638	1.3891	2C
	90	sil	78.436	1.3541	3Bw1
	110	sil	86.824	1.3771	3Bw2
	130	sil	84.180	1.4203	3Bw2
	150	sil	62.536	1.2738	CR
	30	sil	62.840	1.2764	1Bw
	50	sil	65.134	1.2645	1Bw
	70	sil	61.680	1.2865	2C

Appendix Table A.1 (continued) Neutron hydroprobe calibration data set

SITE	DEPTH (cm)	FIELD TEXTURE	WATER CONTENT (% vol.)	NEUTRON COUNT	HORIZON
	110	sil	40.839	1.2011	B/C
	30	sicl	40.741	1.0460	Bw
	50	sicl	63.052	1.2590	Bw
	70	sicl	46.634	1.2158	Bw
	90	sil	52.166	1.2267	B/C
	110	sil	53.175	1.2519	B/C
	30	sicl	43.052	1.0600	Bw
	50	sicl	63.607	1.2858	Bw
	70	sicl	40.037	1.1112	Bw
	90	sil	50.930	1.2590	B/C
	110	sil	52.800	1.2470	B/C
	30	sicl	42.518	1.0468	Bw
	50	sicl	60.431	1.2996	Bw
	70	sicl	58.151	1.2451	Bw
	90	sil	59.404	1.2723	B/C
	110	sil	48.299	1.2626	B/C
	30	sicl	39.382	0.9952	Bw
	50	sicl	48.870	1.0056	Bw
	70	sicl	24.958	0.8211	Bw
	90	sil	16.710	0.6370	B/C
	110	sil	39.293	0.9287	B/C
	130	sil	46.246	1.1806	B/C
	30	sicl	50.603	1.1441	Bw
	50	sicl	55.724	1.0961	Bw
	70	sicl	33.898	0.9699	Bw
	90	sil	28.148	0.8706	B/C
	110	sil	34.484	1.0558	B/C
	30	sicl	48.205	1.1111	Bw
	50	sicl	64.093	1.3201	Bw
	70	sicl	52.246	1.2749	Bw
PUUPAHU	30	sil	39.220	1.0000	1Bw
	50	sil	35.350	1.0100	1Bw
	70	sil	56.410	1.1000	2C
	90	sil	65.750	1.2000	3Bw1
	110	sil	53.360	1.1300	3Bw2
	130	sil	36.065	1.1100	3Bw2
	30	sil	39.040	0.9600	1Bw
	50	sil	41.490	1.0500	1Bw
	70	sil	53.960	1.0500	2C
	90	sil	56.890	1.0300	3Bw1
	110	sil	56.690	1.1400	3Bw2

Appendix Table A.1 (continued) Neutron hydroprobe calibration data set

SITE	DEPTH (cm)	FIELD TEXTURE	WATER CONTENT (% vol.)	NEUTRON COUNT	HORIZON
	90	sil	76.651	1.3215	3Bw1
	110	sil	79.658	1.3485	3Bw2
	130	sil	79.494	1.4014	3Bw2
	150	sil	60.384	1.2692	CR
	30	sil	51.663	1.2134	1Bw
	50	sil	63.191	1.2212	1Bw
	70	sil	60.177	1.2788	2C
	90	sil	75.469	1.3045	3Bw1
	110	sil	78.920	1.3427	3Bw2
	130	sil	78.248	1.3993	3Bw2
	150	sil	55.773	1.2524	CR

APPENDIX B

SUPPORTING DATA FOR CHAPTER V

Computer Program for Soil Water Extractability Model

```
 10 CLS
 15 PRINT:PRINT
 20 PRINT  "Please enter the following information:"
 25 PRINT:PRINT
 30 INPUT "Soil Order (Andisols=1, Ultisols=2, Mollisols=3,
    Others=4:";SO
 40 INPUT "Bulk Density:";D2
 50 INPUT "Organic Matter:";O1
 60 IF SO=1 THEN 280
 70 INPUT "Sand:"; T1
 80 INPUT "Silt:";T2
 90 T3 =100-T1-T2
100 IF T3<0 THEN 420
110 D1=1.5-.01923*T1+.0008324*T1^2-1.083*10^-5*T1^3
    +4.662*10^-8*T1^4
120 IF T1>75 THEN 250
130 W2=.1079+5.004001*10^-4*T2
140 IF T2>70 THEN 230
150 IF SO=2 THEN 210
160 IF SO=3 THEN 190
170 W1=.0542+.00409*T3
180 GOTO 320
190 W1=.127929+.002194*T3
200 GOTO 320
210 W1=1.278654-.12333*T3+.005091*T3^2-8.2393*10^5*T3^3+4.58*10^-7*T3^4
220 GOTO 320
230 W1=.16
240 GOTO 320
250 W1=.19-.0017*T1
260 W2=.429-.00388*T1
270 GOTO 320
280 INPUT "1.5 MPa Water Content:";W15
290 W1=.728128-.572037*D2
300 W2=.04618+.359909*D2
310 D1=1.67-.0300342*W15
320 W3=W1*(1-.01*O1)*(1+D2-D1)+.0023*O1
330 W4=W2*(1-.01*O1)+(D1-D2)*.2+.0055*O1
340 W5=W3+W4
350 PRINT:PRINT
360 PRINT "**********  OUTPUT  **********"
370 PRINT "LOWER LIMIT = ";W3
```

```
380 PRINT "EXTRACTABLE WATER = ";W4
390 PRINT "DRAINED UPPER LIMIT = ";W5
400 GOTO 440
410 PRINT:GOTO 20
420 PRINT "Clay value less than zero.  PLEASE TRY AGAIN !"
430 PRINT:GOTO 15
440 END
```

Appendix Table B.1

Measured and simulated soil water content (m^3/m^3) where the simulated values were obtained with CERES model in Waiakoa site

DATE		SOIL DEPTH	WATER CONTENT (m^3/m^3)	
DT/MO/YR	JULIAN	(cm)	MEASURED	SIMULATED
16/08/84	229	30	0.1762	0.18
		50	0.1737	0.17
		70	0.2214	0.21
		90	0.2556	0.25
12/10/84	286	30	0.1760	0.18
		50	0.1809	0.17
		70	0.2085	0.21
		90	0.2621	0.25
15/11/84	320	30	0.1735	0.18
		50	0.1693	0.17
		70	0.2127	0.21
		90	0.2547	0.25
12/12/84	347	30	0.1789	0.18
		50	0.1739	0.18
		70	0.2042	0.21
		90	0.2576	0.25
19/12/84	354	30	0.1737	0.18
		50	0.1711	0.18
		70	0.2132	0.21
		90	0.2608	0.25
03/01/85	003	30	0.1740	0.18
		50	0.1723	0.18
		70	0.2000	0.21
		90	0.2599	0.25
30/01/85	030	30	0.2153	0.18
		50	0.1899	0.18
		70	0.2196	0.21
		90	0.2647	0.25
17/04/85	107	30	0.1795	0.19
		50	0.1859	0.18
		70	0.2214	0.21
		90	0.2649	0.25
29/06/85	180	30	0.1986	0.19
		50	0.2000	0.18
		70	0.2364	0.21
		90	0.2835	0.25

Appendix Table B.2

Measured and simulated soil water content (m^3/m^3) where the simulated values were obtained with CERES model in Hapapa site

DATE		SOIL DEPTH	WATER CONTENT (m^3/m^3)	
DT/MO/YR	JULIAN	(cm)	MEASURED	SIMULATED
15/11/84	320	30	0.5105	0.51
		50	0.5223	0.53
		70	0.5597	0.52
		90	0.6478	0.57
13/12/84	348	30	0.5162	0.52
		50	0.5443	0.53
		70	0.5127	0.52
		90	0.5721	0.57
20/12/84	355	30	0.5094	0.52
		50	0.5325	0.53
		70	0.5422	0.52
		90	0.5814	0.57
04/01/84	004	30	0.5407	0.52
		50	0.5011	0.53
		70	0.5747	0.52
		90	0.5850	0.57
11/01/85	011	30	0.5304	0.52
		50	0.5518	0.53
		70	0.5781	0.52
		90	0.5825	0.57
15/01/85	015	30	0.6108	0.61
		50	0.6122	0.53
		70	0.6191	0.52
		90	0.6241	0.57
30/01/85	030	30	0.6447	0.66
		50	0.6304	0.59
		70	0.6526	0.52
		90	0.6225	0.57
17/04/85	107	30	0.5542	0.62
		50	0.5739	0.63
		70	0.6131	0.63
		90	0.6280	0.66
17/06/85	168	30	0.5791	0.62
		50	0.5905	0.64
		70	0.6308	0.63
		90	0.6335	0.67

Appendix Table B.3

Measured and simulated soil water content (m^3/m^3) where the simulated values were obtained with CERES model in Puupahu site

DATE		SOIL DEPTH (cm)	WATER CONTENT (m^3/m^3)	
DT/MO/YR	JULIAN		MEASURED	SIMULATED
15/11/84	320	30	0.3575	0.37
		50	0.4337	0.44
		70	0.5337	0.53
		90	0.5997	0.58
13/12/84	348	30	0.4021	0.39
		50	0.4385	0.44
		70	0.5321	0.53
		90	0.5880	0.58
20/12/84	355	30	0.4143	0.39
		50	0.4295	0.44
		70	0.5302	0.53
		90	0.5909	0.58
03/01/85	003	30	0.3969	0.43
		50	0.3541	0.44
		70	0.5299	0.53
		90	0.5949	0.58
30/01/85	030	30	0.5616	0.50
		50	0.5414	0.44
		70	0.5440	0.53
		90	0.5856	0.58
17/04/85	107	30	0.4707	0.46
		50	0.5217	0.52
		70	0.5651	0.60
		90	0.6556	0.70
14/06/85	165	30	0.4900	0.47
		50	0.5329	0.52
		70	0.5693	0.60
		90	0.6569	0.72
26/06/85	177	30	0.4704	0.46
		50	0.5398	0.52
		70	0.5761	0.60
		90	0.6765	0.72
29/06/85	180	30	0.4990	0.47
		50	0.5418	0.52
		70	0.5764	0.61
		90	0.6679	0.72

Appendix Table B.4

Measured and simulated soil water content (m^3/m^3) where the simulated values were obtained with the CERES model that utilized LOL, DUL and PEXW estimated by the modified Ritchie model in the Holopuni site

DATE		SOIL DEPTH (cm)	WATER CONTENT (m^3/m^3)	
DT/MO/YR	JULIAN		MEASURED	SIMULATED
12/10/84	286	30	0.1663	0.13
		50	0.1746	0.16
		70	0.1040	0.16
		90	0.0866	0.07
16/11/84	321	30	0.1494	0.13
		50	0.1472	0.16
		70	0.1713	0.16
		90	0.0792	0.07
14/12/84	349	30	0.1536	0.13
		50	0.1599	0.16
		70	0.1786	0.16
		90	0.0771	0.07
20/12/84	355	30	0.1561	0.13
		50	0.1691	0.16
		70	0.1781	0.16
		90	0.0930	0.07
03/01/85	003	30	0.1661	0.14
		50	0.1454	0.16
		70	0.1829	0.16
		90	0.0849	0.07
12/01/85	012	30	0.1602	0.14
		50	0.1506	0.16
		70	0.1939	0.16
		90	0.0825	0.07
18/01/85	018	30	0.2714	0.16
		50	0.1962	0.16
		70	0.1798	0.16
		90	0.0794	0.07

Appendix Table B.4 (continued) Measured and simulated soil water content (m^3/m^3) where the simulated values were obtained with the CERES model that utilized LOL, DUL and PEXW estimated by the modified Ritchie model in the Holopuni site

DATE		SOIL DEPTH (cm)	WATER CONTENT (m^3/m^3)	
DT/MO/YR	JULIAN		MEASURED	SIMULATED
17/04/85	107	30	0.1808	0.24
		50	0.1954	0.25
		70	0.2323	0.17
		90	0.0902	0.07
25/06/85	176	30	0.2120	0.24
		50	0.2058	0.26
		70	0.2063	0.19
		90	0.1001	0.07
27/06/85	178	30	0.1864	0.24
		50	0.2009	0.25
		70	0.2034	0.20
		90	0.0827	0.07
29/06/85	180	30	0.1955	0.23
		50	0.1883	0.25
		70	0.2144	0.20
		90	0.0864	0.07

Appendix Table B.5

Measured and simulated soil water content (m^3/m^3) where the simulated values were obtained with the CERES model that utilized LOL, DUL and PEXW estimated by the modified Ritchie model in the Haliimaile site

DATE		SOIL DEPTH	WATER CONTENT (m^3/m^3)	
DT/MO/YR	JULIAN	(cm)	MEASURED	SIMULATED
16/08/84	229	30	0.3836	0.37
		50	0.1809	0.20
		70	0.1739	0.17
		90	0.2254	0.21
02/10/85	002	30	0.3991	0.37
		50	0.2475	0.20
		70	0.2024	0.17
		90	0.2137	0.21
12/01/85	012	30	0.4032	0.37
		50	0.2217	0.20
		70	0.1912	0.17
		90	0.2123	0.21
17/01/85	017	30	0.4054	0.37
		50	0.2203	0.20
		70	0.1996	0.17
		90	0.2156	0.21
30/01/85	030	30	0.4447	0.41
		50	0.2594	0.20
		70	0.2177	0.17
		90	0.2289	0.21
17/04/85	107	30	0.4504	0.52
		50	0.2724	0.33
		70	0.2085	0.30
		90	0.2257	0.25
07/06/85	158	30	0.4090	0.39
		50	0.2359	0.22
		70	0.2187	0.20
		90	0.2161	0.24
27/06/85	178	30	0.3736	0.37
		50	0.2268	0.20
		70	0.2121	0.18
		90	0.2313	0.23

Appendix Table B.6

Measured and simulated soil water content (m^3/m^3) where the simulated values were obtained with the CERES model that utilized LOL, DUL and PEXW estimated by the modified Ritchie model in the Kekoa site

DATE		SOIL DEPTH	WATER CONTENT (m^3/m^3)	
DT/MO/YR	JULIAN	(cm)	MEASURED	SIMULATED
12/10/84	286	30	0.3629	0.44
		50	0.3805	0.39
		70	0.4170	0.42
		90	0.4129	0.40
15/11/84	320	30	0.4236	0.44
		50	0.3821	0.39
		70	0.4122	0.42
		90	0.4103	0.40
13/12/84	348	30	0.3973	0.43
		50	0.3814	0.39
		70	0.4175	0.42
		90	0.4052	0.40
10/12/84	355	30	0.4358	0.43
		50	0.3844	0.39
		70	0.4206	0.42
		90	0.4060	0.40
04/01/85	004	30	0.4002	0.43
		50	0.3857	0.39
		70	0.4788	0.42
		90	0.4705	0.40
12/01/85	012	30	0.3857	0.43
		50	0.3853	0.39
		70	0.4197	0.42
		90	0.4063	0.40
16/01/85	016	30	0.4536	0.43
		50	0.4116	0.39
		70	0.4180	0.42
		90	0.4073	0.40
18/01/85	018	30	0.4427	0.43
		50	0.4214	0.39
		70	0.4168	0.42
		90	0.3987	0.40

Appendix Table B.6 (continued) Measured and simulated soil water content (m^3/m^3) where the simulated values were obtained with the CERES model that utilized LOL, DUL and PEXW estimated by the modified Ritchie model in the Kekoa site

DATE		SOIL DEPTH	WATER CONTENT (m^3/m^3)	
DT/MO YR	JULIAN	(cm)	MEASURED	SIMULATED
30/01/85	030	30	0.4968	0.43
		50	0.4509	0.39
		70	0.4214	0.42
		90	0.4013	0.40
17/04/85	107	30	0.4475	0.44
		50	0.4771	0.39
		70	0.4627	0.42
		90	0.4590	0.40
14/06/85	165	30	0.4163	0.44
		50	0.4491	0.39
		70	0.4699	0.42
		90	0.4431	0.40
26/06/85	177	30	0.4077	0.44
		50	0.4301	0.39
		70	0.4536	0.42
		90	0.4384	0.40
28/06/85	179	30	0.4423	0.44
		50	0.4447	0.39
		70	0.4860	0.42
		90	0.4392	0.40
29/06/85	180	30	0.4438	0.44
		50	0.4446	0.39
		70	0.4628	0.42
		90	0.4427	0.40

APPENDIX C

SUPPORTING DATA FOR CHAPTER VI

Appendix Table C.1

Soil water content redistribution after cessation of ponding in the Hamakuapoko site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
010	0.0	60.021	090	0.0	55.850
010	0.5	59.939	090	2.5	55.737
010	6.5	57.269	090	8.5	54.665
010	12.5	55.967	090	14.5	48.432
010	18.5	51.819	090	20.5	42.724
010	24.5	50.969	090	26.5	42.829
010	30.5	49.912	090	32.5	42.522
010	36.5	49.732	090	38.5	41.756
010	42.5	49.320	090	44.5	42.724
010	48.5	48.830	090	50.5	42.756
010	54.5	49.088	090	56.5	42.724
010	60.5	48.340	090	62.5	42.321
010	66.5	49.010	090	68.5	41.982
010	72.5	47.722	090	74.5	42.111
010	78.5	46.975	090	80.5	42.192
010	84.5	45.429	090	86.5	41.651
010	90.5	44.450	090	92.5	41.958
010	102.5	43.909	090	104.5	41.724
010	114.5	43.651	090	116.5	41.845
010	1320.5	42.698	090	1322.5	42.248
010	2615.5	42.571	090	2617.5	41.934
010	3099.5	42.404	090	3101.5	42.046
010	5968.5	41.832	090	5970.5	41.434
010	6308.5	41.722	090	6310.5	41.522
010	9720.5	39.061	090	9722.5	36.394
010	18300.5	39.059	090	18302.5	37.096
010	28440.5	39.043	090	28442.5	36.273
030	0.0	62.783	110	0.0	55.132
030	1.0	62.043	110	3.0	53.214
030	7.0	53.122	110	9.0	52.730
030	13.0	52.721	110	15.0	52.585

Appendix Table C.1 (continued) Soil water content redistribution after cessation of ponding in the Hamakuapoko site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
030	19.0	51.233	110	21.0	50.545
030	25.0	51.045	110	27.0	48.400
030	31.0	51.037	110	33.0	48.456
030	37.0	50.555	110	39.0	48.481
030	43.0	50.119	110	45.0	48.755
030	49.0	49.905	110	51.0	48.206
030	55.0	50.003	110	57.0	47.416
030	61.0	49.602	110	63.0	47.634
030	67.0	48.960	110	69.0	47.392
030	73.0	49.209	110	75.0	47.021
030	79.0	49.138	110	81.0	46.852
030	85.0	49.165	110	87.0	46.828
030	91.0	49.245	110	93.0	46.795
030	103.0	48.541	110	105.0	46.658
030	115.0	48.256	110	117.0	47.078
030	1321.0	47.792	110	1323.0	46.150
030	2616.0	45.172	110	2618.0	45.264
030	3100.0	43.728	110	3102.0	44.191
030	5969.0	43.541	110	5971.0	43.603
030	6309.0	41.456	110	6311.0	43.143
030	9721.0	38.960	110	9723.0	35.959
030	18301.0	38.720	110	18303.0	36.161
030	28441.0	38.666	110	28443.0	35.378
050	0.0	55.541	130	0.0	51.730
050	1.5	49.887	130	3.5	51.174
050	7.5	46.119	130	9.5	50.529
050	13.5	45.494	130	15.5	50.641
050	19.5	45.355	130	21.5	50.738
050	25.5	45.397	130	27.5	50.383
050	31.5	45.336	130	33.5	50.093
050	37.5	45.288	130	39.5	49.714
050	43.5	45.124	130	45.5	50.150
050	49.5	44.924	130	51.5	50.125
050	55.5	45.063	130	57.5	49.384
050	61.5	44.754	130	63.5	48.714
050	67.5	44.748	130	69.5	47.502
050	73.5	44.293	130	75.5	47.513
050	79.5	44.317	130	81.5	47.932
050	85.5	44.184	130	87.5	47.666
050	91.5	44.123	130	93.5	47.747
050	103.5	44.032	130	105.5	47.336

Appendix Table C.1 (continued) Soil water content redistribution after cessation of ponding in the Hamakuapoko site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
050	115.5	44.584	130	117.5	47.118
050	1321.5	43.407	130	1323.5	46.691
050	2616.5	42.813	130	2618.5	45.691
050	3100.5	43.177	130	3102.5	45.078
050	5969.5	41.617	130	5971.5	44.143
050	6309.5	41.805	130	6311.5	43.554
050	9721.5	38.281	130	9723.5	37.717
050	18301.5	38.281	130	18303.5	38.346
050	28441.5	38.038	130	28443.5	38.765
070	0.0	54.109	150	0.0	53.254
070	2.0	53.860	150	4.0	53.286
070	8.0	49.068	150	10.0	53.463
070	14.0	44.226	150	16.0	52.891
070	20.0	44.396	150	22.0	52.899
070	26.0	44.499	150	28.0	53.496
070	32.0	44.323	150	34.0	52.931
070	38.0	44.414	150	40.0	52.657
070	44.0	43.777	150	46.0	52.730
070	50.0	43.577	150	52.0	52.835
070	56.0	43.923	150	58.0	52.044
070	62.0	43.498	150	64.0	52.480
070	68.0	43.553	150	70.0	52.448
070	74.0	43.959	150	76.0	52.504
070	80.0	43.747	150	82.0	52.496
070	86.0	43.929	150	88.0	52.730
070	92.0	43.941	150	94.0	52.222
070	104.0	43.498	150	106.0	52.173
070	116.0	43.619	150	118.0	52.504
070	1322.0	43.959	150	1324.0	52.214
070	2617.0	43.013	150	2619.0	47.852
070	3101.0	42.558	150	3103.0	47.279
070	5970.0	42.157	150	5972.0	46.804
070	6310.0	41.951	150	6312.0	46.513
070	9722.0	39.676	150	9724.0	41.651
070	18302.0	39.270	150	18304.0	40.934
070	28442.0	38.869	150	28444.0	42.530

Appendix Table C.2

Soil water content distribution after cesssation of ponding in the Waiakoa site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
010	0.0	67.711	090	0.0	48.499
010	0.5	61.588	090	2.5	47.759
010	6.5	48.066	090	8.5	47.733
010	12.5	47.727	090	14.5	47.703
010	18.5	46.964	090	20.5	46.254
010	24.5	47.068	090	26.5	46.070
010	30.5	46.441	090	32.5	46.044
010	36.5	46.381	090	38.5	45.733
010	42.5	45.939	090	44.5	45.963
010	48.5	45.852	090	50.5	46.060
010	54.5	45.955	090	56.5	46.029
010	60.5	45.634	090	62.5	46.825
010	66.5	45.606	090	68.5	45.718
010	78.5	45.312	090	80.5	45.713
010	84.5	44.603	090	86.5	45.529
010	90.5	44.401	090	92.5	45.146
010	96.5	44.696	090	98.5	44.815
010	102.5	44.587	090	104.5	44.529
010	1124.5	40.810	090	1126.5	41.345
010	1154.5	40.592	090	1156.5	41.207
010	1184.5	40.262	090	1186.5	40.906
010	2618.5	39.963	090	2620.5	40.745
010	4076.5	39.259	090	4078.5	38.441
010	7200.5	36.100	090	7202.5	37.977
010	8576.5	34.738	090	8578.5	37.712
010	9900.5	33.590	090	9902.5	37.676
010	10072.5	33.498	090	10074.5	37.309
010	15652.5	33.400	090	15654.5	36.283
010	17340.5	33.300	090	17342.5	35.431
010	27480.5	33.210	090	27482.5	34.839
030	0.0	51.770	110	0.0	48.698
030	1.0	50.637	110	3.0	48.698
030	7.0	49.555	110	9.0	48.228
030	13.0	46.565	110	15.0	48.259
030	19.0	42.667	110	21.0	48.320
030	25.0	43.013	110	27.0	48.208
030	31.0	41.411	110	33.0	47.688
030	37.0	41.069	110	39.0	47.978
030	43.0	41.222	110	45.0	47.892
030	49.0	40.625	110	51.0	48.014

Appendix Table C.2 (continued) Soil water content distribution after cessation of ponding in the Waiakoa site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
030	55.0	40.687	110	57.0	47.718
030	61.0	40.636	110	63.0	47.366
030	67.0	40.340	110	69.0	47.024
030	79.0	40.146	110	81.0	46.764
030	85.0	40.110	110	87.0	46.300
030	91.0	39.886	110	93.0	45.835
030	97.0	39.646	110	99.0	45.657
030	103.0	39.692	110	105.0	45.288
030	1125.0	34.298	110	1127.0	42.340
030	1155.0	34.186	110	1157.0	42.422
030	1185.0	34.048	110	1187.0	42.284
030	2619.0	33.262	110	2621.0	42.212
030	4077.0	30.833	110	4079.0	41.289
030	7201.0	30.282	110	7203.0	40.881
030	8577.0	29.629	110	8570.0	40.763
030	9901.0	29.568	110	9903.0	40.559
030	10073.0	29.267	110	10075.0	40.079
030	15653.0	28.746	110	15655.0	39.865
030	17341.0	28.461	110	17343.0	38.743
030	27481.0	27.797	110	27483.0	36.288
050	0.0	50.688	130	0.0	47.718
050	1.5	50.035	130	3.5	46.815
050	7.5	49.305	130	9.5	46.738
050	13.5	49.525	130	15.5	46.192
050	19.5	48.412	130	21.5	46.483
050	25.5	46.437	130	27.5	46.391
050	31.5	44.529	130	33.5	46.167
050	37.5	41.039	130	39.5	46.504
050	43.5	40.620	130	45.5	46.177
050	49.5	40.636	130	51.5	46.279
050	55.5	40.253	130	57.5	46.565
050	61.5	39.533	130	63.5	46.044
050	67.5	39.819	130	69.5	45.948
050	79.5	39.977	130	81.5	45.764
050	85.5	39.630	130	87.5	45.223
050	91.5	39.074	130	93.5	45.458
050	97.5	39.273	130	99.5	45.386
050	103.5	39.391	130	105.5	44.958
050	1125.5	33.523	130	1127.5	43.269
050	1155.5	33.375	130	1157.5	42.993
050	1185.5	33.216	130	1187.5	42.217
050	2619.5	31.874	130	2621.5	42.054

Appendix Table C.2 (continued) Soil water content distribution after cessation of ponding in the Waiakoa site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
050	4077.5	29.798	130	4079.5	41.743
050	7201.5	29.012	130	7203.5	41.738
050	8577.5	28.670	130	8579.5	41.671
050	9901.5	26.772	130	9903.5	41.273
050	10073.5	26.705	130	10075.5	41.182
050	15652.5	26.282	130	15655.5	40.906
050	17341.5	26.246	130	17343.5	39.232
050	27481.5	25.629	130	27483.5	38.345
070	0.0	51.208	150	0.0	54.250
070	2.0	49.678	150	4.0	53.035
070	8.0	49.075	150	10.0	51.887
070	14.0	48.683	150	16.0	51.805
070	20.0	48.274	150	22.0	51.902
070	26.0	48.392	150	28.0	52.224
070	32.0	48.504	150	34.0	52.086
070	38.0	48.183	150	40.0	51.316
070	44.0	48.040	150	46.0	50.800
070	50.0	46.325	150	52.0	51.101
070	56.0	46.305	150	58.0	51.203
070	62.0	46.325	150	64.0	50.795
070	68.0	46.417	150	70.0	50.775
070	80.0	45.417	150	82.0	51.193
070	86.0	45.248	150	88.0	51.066
070	92.0	45.299	150	94.0	50.581
070	98.0	44.907	150	100.0	50.606
070	104.0	44.626	150	106.0	50.642
070	1126.0	37.814	150	1128.0	47.932
070	1156.0	37.788	150	1158.0	47.866
070	1186.0	37.947	150	1188.0	47.784
070	2620.0	37.094	150	2622.0	47.177
070	4078.0	33.732	150	4080.0	45.891
070	7202.0	33.048	150	7204.0	45.866
070	8578.0	32.997	150	8580.0	45.840
070	9902.0	32.196	150	9904.0	45.835
070	10074.0	31.686	150	10076.0	45.703
070	15654.0	29.639	150	15656.0	45.310
070	17342.0	29.440	150	17344.0	43.631
070	27482.0	28.976	150	27484.0	42.998

Appendix Table C.3

Soil water content redistribution after cessation of ponding in the Omaopio site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
010	0.0	53.094	090	0.0	43.712
010	0.5	50.875	090	2.5	43.672
010	6.5	49.520	090	8.5	43.621
010	12.5	48.964	090	14.5	43.740
010	18.5	47.134	090	20.5	43.629
010	24.5	47.027	090	26.5	43.533
010	30.5	47.215	090	32.5	43.541
010	36.5	47.048	090	38.5	43.533
010	42.5	47.010	090	44.5	43.422
010	48.5	47.168	090	50.5	43.406
010	54.5	46.907	090	56.5	43.605
010	60.5	47.022	090	52.5	43.613
010	66.5	47.012	090	68.5	43.577
010	78.5	46.197	090	80.5	43.382
010	90.5	46.137	090	92.5	43.529
010	102.5	46.172	090	104.5	43,067
010	114.5	45.410	090	116.5	42.984
010	1088.5	43.802	090	1090.5	41.375
010	2525.5	43.268	090	2527.5	39.878
010	2698.5	42.546	090	2700.5	39.811
010	7165.5	42.721	090	7167.5	39.962
010	8530.5	42.466	090	8532.5	39.914
010	9659.5	42.293	090	9661.5	40.045
010	11165.5	41.426	090	11167.5	40.041
010	14023.5	41.331	090	14025.5	39.986
010	15948.5	41.305	090	15950.5	39.858
030	0.0	43.864	110	0.0	44.055
030	1.0	43.744	110	3.0	44.019
030	7.0	43.370	110	9.0	44.087
030	13.0	43.565	110	15.0	43.796
030	19.0	42.968	110	21.0	43.963
030	25.0	42.864	110	27.0	43.967
030	31.0	42.375	110	33.0	44.039
030	37.0	42.323	110	39.0	43.756
030	43.0	42.418	110	45.0	44.102
030	49.0	42.231	110	51.0	43.772
030	55.0	42.291	110	57.0	43.868
030	61.0	42.303	110	63.0	43.784
030	67.0	42.418	110	69.0	43.876
030	79.0	42.100	110	81.0	44.079
030	91.0	41.781	110	93.0	43.585

Appendix Table C.3 (continued) Soil water content redistribution after cessation of ponding in the Omaopio site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
030	103.0	42.084	110	105.0	43.179
030	115.0	41.686	110	117.0	43.235
030	1089.0	39.293	110	1091.0	40.137
030	2526.0	38.461	110	2528.0	39.894
030	2699.0	38.274	110	2701.0	39.862
030	7166.0	38.186	110	7168.0	39.986
030	8531.0	38.230	110	8533.0	39.647
030	9660.0	37.266	110	9662.0	39.600
030	11166.0	37.107	110	11168.0	39.428
030	14024.0	36.259	110	14026.0	39.540
030	15949.0	36.403	110	15951.0	39.699
050	0.0	44.306	130	0.0	44.079
050	1.5	44.230	130	3.5	43.963
050	7.5	44.361	130	9.5	43.884
050	13.5	44.063	130	15.5	43.744
050	19.5	44.039	130	21.5	43.808
050	25.5	43.784	130	27.5	43.852
050	31.5	44.035	130	33.5	43.728
050	37.5	43.891	130	39.5	43.895
050	43.5	43.645	130	45.5	43.935
050	49.5	43.350	130	51.5	43.784
050	55.5	43.517	130	57.5	43.728
050	61.5	43.438	130	63.5	43.852
050	67.5	42.864	130	69.5	43.963
050	79.5	42.892	130	81.5	43.891
050	91.5	42.144	130	93.5	43.581
050	103.5	42.247	130	105.5	42.789
050	115.5	42.187	130	117.5	42.554
050	1089.5	40.503	130	1091.5	39.460
050	2526.5	39.886	130	2528.5	39.385
050	2699.5	39.695	130	2701.5	39.600
050	7166.5	39.404	130	7168.5	39.659
050	8531.5	39.118	130	8533.5	39.675
050	9660.5	38.799	130	9662.5	39.460
050	11166.5	38.648	130	11168.5	39.576
050	14024.5	38.290	130	14026.5	39.229
050	15949.5	38.282	130	15951.5	39.321
070	0.0	44.138	150	0.0	42.506
070	2.0	43.967	150	4.0	42.331
070	8.0	43.784	150	10.0	42.434
070	14.0	43.927	150	16.0	42.251

Appendix Table C.3 (continued) Soil water content redistribution after cessation of ponding in the Omaopio site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
070	20.0	43.943	150	22.0	42.383
070	26.0	43.999	150	28.0	42.176
070	32.0	44.110	150	34.0	42.207
070	38.0	44.071	150	40.0	42.502
070	44.0	43.844	150	46.0	42.438
070	50.0	44.055	150	52.0	42.470
070	56.0	43.744	150	58.0	42.506
070	62.0	43.868	150	64.0	42.514
070	68.0	43.899	150	70.0	42.490
070	80.0	43.680	150	82.0	42.199
070	92.0	43.649	150	94.0	42.084
070	104.0	43.537	150	106.0	41.793
070	116.0	42.912	150	118.0	41.375
070	1090.0	41.355	150	1092.0	39.345
070	2527.0	40.686	150	2529.0	39.146
070	2700.0	40.197	150	2702.0	39.062
070	7167.0	40.499	150	7169.0	39.281
070	8532.0	40.296	150	8534.0	39.237
070	9661.0	40.137	150	9663.0	39.209
070	11167.0	39.958	150	11169.0	39.154
070	14025.0	39.683	150	14027.0	38.994
070	15950.0	39.401	150	15952.0	38.648

Appendix Table C.4

Soil water content redistribution after cessation of ponding in the Pauwela site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
010	0.0	64.393	090	0.0	56.781
010	0.5	59.860	090	2.5	55.489
010	6.5	56.033	090	8.5	55.571
010	12.5	54.365	090	14.5	55.429
010	18.5	54.167	090	20.5	55.561
010	24.5	54.202	090	26.5	53.695
010	30.5	53.807	090	32.5	53.270
010	36.5	53.162	090	38.5	53.276
010	42.5	53.044	090	44.5	52.953
010	48.5	53.038	090	50.5	53.312
010	54.5	52.980	090	56.5	53.139
010	60.5	52.965	090	62.5	52.876
010	72.5	53.025	090	74.5	53.049
010	84.5	53.016	090	86.5	52.917
010	96.5	52.977	090	98.5	52.894
010	108.5	52.980	090	110.5	52.337
010	120.5	52.952	090	122.5	52.588
010	1237.5	51.912	090	1239.5	52.140
010	1267.5	51.886	090	1269.5	51.919
010	1297.5	51.963	090	1299.5	50.513
010	1327.5	51.596	090	1329.5	50.902
010	1357.5	51.300	090	1359.5	50.806
010	1387.5	51.485	090	1389.5	50.699
010	1417.5	51.443	090	1419.5	50.621
010	1571.5	51.430	090	1573.5	50.615
010	2880.5	47.400	090	2882.5	48.223
010	9840.5	43.238	090	9842.5	47.242
010	18360.5	42.837	090	18362.5	47.086
010	28500.5	41.518	090	28502.5	46.961
030	0.0	67.379	110	0.0	57.612
030	1.0	67.145	110	3.0	57.415
030	7.0	55.087	110	9.0	56.919
030	13.0	51.593	110	15.0	56.715
030	19.0	52.907	110	21.0	56.464
030	25.0	49.588	110	27.0	56.356
030	31.0	49.228	110	33.0	56.051
030	37.0	49.452	110	39.0	56.087
030	43.0	49.773	110	45.0	56.165
030	49.0	49.023	110	51.0	56.285
030	55.0	49.471	110	57.0	56.129

Appendix Table C.4 (continued) Soil water content redistribution after cessation of ponding in the Pauwela site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
030	61.0	48.761	110	63.0	55.998
030	73.0	48.557	110	75.0	55.501
030	85.0	48.333	110	87.0	55.256
030	97.0	47.301	110	99.0	55.166
030	109.0	48.002	110	111.0	55.160
030	121.0	47.506	110	123.0	54.915
030	1238.0	45.218	110	1240.0	55.112
030	1268.0	45.199	110	1270.0	54.191
030	1298.0	45.180	110	1300.0	52.971
030	1328.0	45.189	110	1330.0	53.384
030	1358.0	45.150	110	1360.0	53.157
030	1388.0	45.160	110	1390.0	53.133
030	1418.0	45.150	110	1420.0	52.864
030	1572.0	45.131	110	1574.0	53.324
030	2881.0	44.936	110	2883.0	50.394
030	9841.0	44.605	110	9843.0	49.156
030	18361.0	43.486	110	18363.0	49.197
030	28501.0	43.136	110	28503.0	48.785
050	0.0	57.797	130	0.0	59.209
050	1.5	57.219	130	3.5	59.137
050	7.5	56.796	130	9.5	59.263
050	13.5	53.193	130	15.5	58.970
050	19.5	53.038	130	21.5	59.251
050	25.5	52.460	130	27.5	59.179
050	31.5	52.543	130	33.5	59.072
050	37.5	52.306	130	39.5	59.425
050	43.5	52.570	130	45.5	59.006
050	49.5	52.313	130	51.5	59.239
050	55.5	52.411	130	57.5	58.886
050	61.5	52.423	130	63.5	48:731
050	73.5	51.921	130	75.5	58.240
050	85.5	51.543	130	87.5	58.300
050	97.5	51.860	130	99.5	58.414
050	109.5	51.630	130	111.5	58.145
050	121.5	51.442	130	123.5	57.690
050	1238.5	51.291	130	1240.5	56.781
050	1268.5	50.985	130	1270.5	56.123
050	1298.5	51.015	130	1300.5	56.111
050	1328.5	50.819	130	1330.5	55.489
050	1358.5	50.717	130	1360.5	55.256
050	1388.5	50.664	130	1390.5	55.076

Appendix Table C.4 (continued) Soil water content redistribution after cessation of ponding in the Pauwela site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
050	1418.5	50.177	130	1420.5	54.999
050	1572.5	50.106	130	1574.5	54.981
050	2881.5	50.015	130	2883.5	52.295
050	9841.5	49.789	130	9843.5	40.854
050	18361.5	49.223	130	18363.5	50.304
050	28501.5	49.147	130	28503.5	50.268
070	0.0	52.270	150	0.0	58.408
070	2.0	52.254	150	4.0	57.834
070	8.0	51.840	150	10.0	57.636
070	14.0	51.843	150	16.0	57.690
070	20.0	50.042	150	22.0	57.373
070	26.0	49.320	150	28.0	57.224
070	32.0	49.270	150	34.0	57.044
070	38.0	48.594	150	40.0	57.080
070	44.0	48.625	150	46.0	57.355
070	50.0	48.535	150	52.0	57.140
070	56.0	48.491	150	58.0	56.931
070	62.0	48.205	150	64.0	56.584
070	74.0	48.205	150	76.0	56.566
070	86.0	48.064	150	88.0	56.608
070	98.0	48.192	150	100.0	56.596
070	110.0	48.092	150	112.0	56.309
070	122.0	48.064	150	124.0	56.021
070	1239.0	48.214	150	1241.0	54.885
070	1269.0	48.043	150	1271.0	54.341
070	1299.0	47.952	150	1301.0	54.275
070	1329.0	47.958	150	1331.0	53.791
070	1359.0	47.747	150	1361.0	53.910
070	1389.0	48.021	150	1391.0	53.850
070	1419.0	47.930	150	1421.0	53.641
070	1573.0	48.033	150	1575.0	53.838
070	2882.0	47.152	150	2884.0	51.045
070	9842.0	46.606	150	9844.0	49.084
070	18362.0	46.497	150	18364.0	48.641
070	28502.0	46.473	150	28504.0	48.306

Appendix Table C.5

Soil water content redistribution after cessation of ponding in the Kuiaha site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
010	0.0	60.528	090	0.0	77.569
010	0.5	55.367	090	2.5	75.438
010	6.5	50.963	090	8.5	69.421
010	12.5	49.232	090	14.5	68.994
010	18.5	49.284	090	20.5	68.222
010	24.5	49.156	090	26.5	65.353
010	30.5	49.001	090	32.5	63.844
010	36.5	48.969	090	38.5	63.025
010	42.5	48.591	090	44.5	62.926
010	48.5	48.607	090	50.5	62.877
010	54.5	48.761	090	56.5	62.074
010	60.5	48.889	090	62.5	63.107
010	84.5	48.798	090	86.5	62.779
010	114.5	47.300	090	116.5	63.041
010	144.5	47.066	090	146.5	62.467
010	174.5	47.156	090	176.5	63.057
010	1437.5	46.884	090	1439.5	61.877
010	1728.5	46.938	090	1730.5	61.713
010	2635.5	45.472	090	2637.5	61.139
010	2977.5	45.450	090	2979.5	60.139
010	10080.5	44.783	090	10082.5	54.695
010	18540.5	43.112	090	18542.5	53.974
010	28680.5	43.017	090	28682.5	53.285
030	0.0	73.739	110	0.0	74.093
030	1.0	66.763	110	3.0	71.831
030	7.0	66.091	110	9.0	72.733
030	13.0	66.127	110	15.0	72.667
030	19.0	66.105	110	21.0	71.224
030	25.0	65.619	110	27.0	67.814
030	31.0	65.440	110	33.0	66.369
030	37.0	64.875	110	39.0	64.795
030	43.0	65.261	110	45.0	64.451
030	49.0	65.554	110	51.0	62.631
030	55.0	64.424	110	57.0	62.844
030	61.0	64.610	110	63.0	61.893
030	85.0	64.803	110	87.0	62.893
030	115.0	64.560	110	117.0	62.270
030	145.0	64.510	110	147.0	62.926
030	175.0	64.281	110	177.0	61.336

Appendix Table C.5 (continued) Soil water content redistribution after cessation of ponding in the Kuiaha site.

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
030	1438.0	62.850	110	1440.0	59.959
030	1729.0	62.514	110	1731.0	59.942
030	2636.0	62.056	110	2638.0	59.795
030	2978.0	62.478	110	2980.0	59.795
030	10081.0	59.087	110	10083.0	54.630
030	18541.0	58.965	110	18543.0	54.368
030	28681.0	58.908	110	28683.0	53.958
050	0.0	72.741	130	0.0	65.529
050	1.5	68.965	130	3.5	65.506
050	7.5	68.063	130	9.5	64.573
050	13.5	67.477	130	15.5	63.452
050	19.5	65.814	130	21.5	63.865
050	25.5	65.545	130	27.5	63.334
050	31.5	65.849	130	33.5	62.649
050	37.5	64.912	130	39.5	62.873
050	43.5	65.404	130	45.5	62.980
050	49.5	64.736	130	51.5	62.342
050	55.5	65.252	130	57.5	57.385
050	61.5	65.369	130	63.5	55.189
050	85.5	64.186	130	87.5	55.071
050	115.5	64.244	130	117.5	55.012
050	145.5	64.162	130	147.5	52.746
050	175.5	62.370	130	177.5	53.914
050	1438.5	62.265	130	1440.5	50.881
050	1729.5	62.031	130	1731.5	50.161
050	2636.5	61.269	130	2638.5	50.244
050	2978.5	61.890	130	2980.5	49.335
050	10081.5	57.134	130	10083.5	45.262
050	18541.5	57.087	130	18543.5	44.837
050	28681.5	56.724	130	28683.5	45.144
070	0.0	79.264	150	0.0	64.750
070	2.0	77.490	150	4.0	65.919
070	8.0	68.231	150	10.0	65.730
070	14.0	65.945	150	16.0	66.415
070	20.0	65.440	150	22.0	64.986
070	26.0	65.701	150	28.0	65.809
070	32.0	62.261	150	34.0	65.140
070	38.0	64.252	150	40.0	64.691
070	44.0	65.212	150	46.0	65.470

Appendix Table C.5 (continued) Soil water content redistribution after cessation of ponding in the Kuiaha site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
070	50.0	64.496	150	52.0	65.211
070	56.0	65.229	150	58.0	64.738
070	62.0	65.619	150	64.0	64.455
070	86.0	64.187	150	88.0	62.366
070	116.0	64.871	150	118.0	56.429
070	146.0	65.554	150	148.0	56.771
070	176.0	64.610	150	178.0	55.107
070	1439.0	65.733	150	1441.0	53.289
070	1730.0	64.740	150	1732.0	52.368
070	2637.0	63.015	150	2639.0	51.790
070	2979.0	63.064	150	2981.0	52.191
070	10082.0	59.614	150	10084.0	46.868
070	18542.0	58.036	150	18544.0	46.702
070	28682.0	57.710	150	28684.0	45.829

Appendix Table C.6

Soil water content redistribution after cessation of ponding in the Makawao site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
010	0.0	71.400	090	0.0	77.980
010	0.5	68.580	090	2.5	77.780
010	5.5	64.420	090	7.5	77.550
010	10.5	53.600	090	12.5	77.470
010	20.5	52.020	090	22.5	78.380
010	30.5	51.800	090	32.5	77.390
010	40.5	51.780	090	42.5	76.160
010	50.5	51.350	090	52.5	76.150
010	60.5	51.020	090	62.5	76.060
010	120.5	50.230	090	122.5	75.670
010	130.5	50.130	090	132.5	75.120
010	150.5	50.000	090	152.5	74.780
010	180.5	49.520	090	182.5	58.840
010	210.5	48.540	090	212.5	56.080
010	1260.5	46.250	090	1262.5	55.810
010	1590.5	46.160	090	1592.5	55.400
010	1650.5	46.140	090	1652.5	55.970
010	2760.5	44.930	090	2762.5	55.910
010	3100.5	44.570	090	3102.5	56.010
010	4160.5	43.980	090	4162.5	55.240
010	4410.5	43.280	090	4412.5	55.820
010	11370.5	43.200	090	11372.5	54.650
010	11860.5	43.120	090	11862.5	54.350
010	12770.5	43.080	090	12772.5	54.550
010	13290.5	43.050	090	13292.5	54.370
010	14240.5	43.010	090	14242.5	54.160
010	18615.5	42.950	090	18617.5	53.440
010	19980.5	42.930	090	19982.5	53.390
010	24560.5	42.920	090	24562.5	53.380
010	28615.5	42.330	090	28617.5	52.900
010	30055.5	41.930	090	30057.5	52.910
010	31630.5	41.820	090	31632.5	52.680
010	37830.5	41.710	090	37832.5	52.160
030	0.0	70.190	110	0.0	47.210
030	1.0	69.390	110	3.0	46.560
030	6.0	69.320	110	8.0	46.330
030	11.0	69.300	110	13.0	46.240
030	21.0	69.270	110	23.0	46.150
030	31.0	62.650	110	33.0	46.140
030	41.0	59.420	110	43.0	46.100

Appendix Table C.6 (continued) Soil water content redistribution after cessation of ponding in the Makawao site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
030	51.0	51.230	110	53.0	46.060
030	61.0	49.770	110	63.0	45.880
030	121.0	49.450	110	123.0	45.750
030	131.0	49.380	110	133.0	45.020
030	151.0	48.960	110	153.0	44.640
030	181.0	47.460	110	183.0	43.410
030	211.0	47.370	110	213.0	42.720
030	1261.0	47.360	110	1263.0	32.430
030	1591.0	47.270	110	1593.0	32.470
030	1651.0	47.260	110	1653.0	32.390
030	2761.0	47.000	110	2763.0	32.160
030	3101.0	46.970	110	3103.0	31.970
030	4161.0	46.750	110	4163.0	32.210
030	4411.0	45.880	110	4413.0	32.150
030	11371.0	44.510	110	11373.0	32.380
030	11861.0	44.310	110	11863.0	31.770
030	12771.0	44.430	110	12773.0	31.790
030	13291.0	44.430	110	13293.0	31.780
030	14241.0	43.850	110	14243.0	32.010
030	18616.0	43.730	110	18618.0	32.120
030	19981.0	43.860	110	19983.0	32.310
030	24561.0	43.720	110	24563.0	31.870
030	28616.0	43.980	110	28618.0	31.920
030	30056.0	43.640	110	30058.0	31.380
030	31631.0	43.580	110	31633.0	31.490
030	37831.0	43.610	110	37833.0	31.160
050	0.0	69.430	130	0.0	54.540
050	1.5	69.460	130	3.5	54.350
050	6.5	69.410	130	8.5	54.320
050	11.5	69.250	130	13.5	54.300
050	21.5	69.230	130	23.5	54.270
050	31.5	68.580	130	33.5	54.100
050	41.5	68.450	130	43.5	53.780
050	51.5	66.960	130	53.5	53.660
050	61.5	63.480	130	63.5	53.640
050	121.5	51.360	130	123.5	53.550
050	131.5	51.200	130	133.5	53.500
050	151.5	50.590	130	153.5	53.320
050	181.5	49.570	130	183.5	53.110
050	211.5	49.290	130	213.5	52.840
050	1261.5	48.840	130	1263.5	47.680
050	1591.5	48.790	130	1593.5	47.540
050	1651.5	48.750	130	1643.5	47.280

Appendix Table C.6 (continued) Soil water content redistribution after cessation of ponding in the Makawao site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
050	2761.5	48.640	130	2763.5	47.060
050	3101.5	48.580	130	3103.5	46.490
050	4161.5	48.270	130	4163.5	46.440
050	4411.5	48.300	130	4413.5	45.740
050	11371.5	48.270	130	11373.5	46.360
050	11861.5	48.380	130	11863.5	46.340
050	12771.5	48.460	130	12773.5	46.290
050	13291.5	48.180	130	13293.5	46.260
050	14241.5	47.960	130	14243.5	46.360
050	18616.5	48.650	130	18618.5	45.350
050	19981.5	48.040	130	19983.5	44.510
050	24561.5	48.520	130	24563.5	43.860
050	28616.5	48.450	130	28618.5	43.420
050	30056.5	48.270	130	30058.5	43.100
050	31631.5	47.960	130	31633.5	42.970
050	37831.5	47.470	130	37833.5	43.040
070	0.0	72.060	150	0.0	53.310
070	2.0	72.320	150	4.0	52.950
070	7.0	72.190	150	9.0	52.870
070	12.0	72.160	150	14.0	52.550
070	22.0	72.100	150	24.0	52.520
070	32.0	72.090	150	34.0	52.400
070	42.0	72.020	150	44.0	52.300
070	52.0	72.010	150	54.0	52.280
070	62.0	71.280	150	64.0	52.270
070	122.0	67.650	150	124.0	52.250
070	132.0	64.470	150	134.0	52.210
070	152.0	61.930	150	154.0	52.240
070	182.0	55.300	150	184.0	52.220
070	212.0	54.580	150	214.0	52.210
070	1262.0	54.500	150	1264.0	45.820
070	1592.0	53.970	150	1594.0	45.480
070	1652.0	53.810	150	1654.0	45.410
070	2762.0	53.870	150	2764.0	45.620
070	3102.0	53.750	150	3104.0	45.410
070	4162.0	53.450	150	4164.0	44.960
070	4412.0	53.580	150	4414.0	44.750
070	11372.0	53.670	150	11374.0	44.250
070	11862.0	53.630	150	11864.0	44.240
070	12772.0	53.680	150	12774.0	44.330
070	13292.0	53.390	150	13294.0	44.170

Appendix Table C.6 (continued) Soil water content redistribution after cessation of ponding in the Makawao site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
070	14242.0	53.340	150	14244.0	43.900
070	18617.0	54.020	150	18619.0	43.850
070	19982.0	53.810	150	19984.0	43.790
070	24562.0	53.870	150	24564.0	44.080
070	28617.0	53.810	150	28619.0	43.450
070	30057.0	53.910	150	30059.0	43.520
070	31632.0	54.150	150	31634.0	43.380
070	37832.0	53.280	150	37834.0	43.440

Appendix Table C.7

Soil water content redistribution after cessation of ponding in the Hapapa site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
010	0.0	78.166	090	0.0	80.248
010	0.5	77.166	090	2.5	78.345
010	6.5	76.723	090	8.5	77.913
010	12.5	76.134	090	14.5	77.462
010	18.5	75.749	090	20.5	77.224
010	24.5	74.772	090	26.5	76.937
010	30.5	70.461	090	32.5	76.918
010	36.5	70.426	090	38.5	77.099
010	42.5	70.486	090	44.5	76.686
010	48.5	69.981	090	50.5	76.561
010	54.5	69.826	090	56.5	77.131
010	60.5	70.117	090	62.5	76.937
010	72.5	69.457	090	74.5	76.530
010	78.5	69.543	090	80.5	76.167
010	84.5	68.995	090	86.5	75.328
010	90.5	68.438	090	92.5	74.182
010	96.5	68.515	090	98.5	73.681
010	102.5	67.580	090	104.5	72.874
010	108.5	67.135	090	110.5	73.193
010	114.5	67.075	090	116.5	72.824
010	1174.5	55.067	090	1176.5	69.180
010	1229.5	54.956	090	1231.5	68.185
010	1288.5	54.656	090	1290.5	68.135
010	5786.5	53.519	090	5788.5	68.148
010	7346.5	51.427	090	7348.5	67.559
010	8394.5	49.884	090	8396.5	66.708
010	9902.5	49.556	090	9904.5	66.276
010	12761.5	48.811	090	12763.5	65.913
030	0.0	76.457	110	0.0	73.877
030	1.0	76.231	110	3.0	73.687
030	7.0	75.828	110	9.0	73.330
030	13.0	72.579	110	15.0	73.194
030	19.0	71.278	110	21.0	73.216
030	25.0	70.976	110	27.0	73.194
030	31.0	70.731	110	33.0	72.934
030	37.0	70.863	110	39.0	73.026
030	43.0	70.693	110	45.0	73.097
030	49.0	70.599	110	51.0	72.902
030	55.0	70.216	110	57.0	72.848

Appendix Table C.7 (continued) Soil water content redistribution after cessation of ponding in the Hapapa site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
030	61.0	70.040	110	63.0	72.885
030	73.0	70.040	110	75.0	73.173
030	79.0	70.360	110	81.0	72.804
030	85.0	70.128	110	87.0	73.216
030	91.0	70.058	110	93.0	72.826
030	97.0	70.228	110	99.0	72.940
030	103.0	70.341	110	105.0	73.075
030	109.0	69.738	110	111.0	73.135
030	115.0	69.128	110	117.0	72.766
030	1175.0	65.231	110	1177.0	65.702
030	1230.0	64.452	110	1232.0	65.729
030	1289.0	64.157	110	1291.0	65.393
030	5787.0	63.214	110	5789.0	65.621
030	7347.0	62.862	110	7349.0	65.171
030	8395.0	61.617	110	8397.0	65.139
030	9903.0	61.643	110	9905.0	65.431
030	12762.0	61.630	110	12764.0	65.182
050	0.0	77.048	130	0.0	76.993
050	1.5	76.557	130	3.5	76.430
050	7.5	76.532	130	9.5	76.111
050	13.5	75.721	130	15.5	74.934
050	19.5	75.413	130	21.5	74.359
050	25.5	74.735	130	27.5	74.410
050	31.5	71.831	130	33.5	74.180
050	37.5	71.397	130	39.5	74.103
050	43.5	70.920	130	45.5	74.141
050	49.5	70.385	130	51.5	73.259
050	55.5	70.278	130	57.5	73.643
050	61.5	69.681	130	63.5	73.387
050	73.5	69.241	130	75.5	73.911
050	79.5	69.707	130	81.5	72.939
050	85.5	69.317	130	87.5	74.065
050	91.5	69.229	130	93.5	73.464
050	97.5	69.732	130	99.5	72.044
050	103.5	69.210	130	105.5	72.850
050	109.5	69.298	130	111.5	71.878
050	115.5	69.191	130	117.5	71.673
050	1175.5	64.974	130	1177.5	56.928
050	1230.5	64.616	130	1232.5	56.724
050	1289.5	64.433	130	1291.5	56.852
050	5787.5	64.578	130	5789.5	57.095

Appendix Table C.7 (continued) Soil water content redistribution after cessation of ponding in the Hapapa site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
050	7347.5	64.157	130	7349.5	54.972
050	8395.5	63.868	130	8397.5	55.023
050	9903.5	63.063	130	9905.5	54.614
050	12762.5	62.856	130	12764.5	54.115
070	0.0	78.721	150	0.0	76.699
070	2.0	78.639	150	4.0	75.650
070	8.0	78.045	150	10.0	74.384
070	14.0	78.013	150	16.0	73.834
070	20.0	77.926	150	22.0	73.694
070	26.0	77.976	150	28.0	72.556
070	32.0	77.206	150	34.0	72.556
070	38.0	77.118	150	40.0	72.747
070	44.0	76.204	150	46.0	72.479
070	50.0	76.104	150	52.0	72.645
070	56.0	73.919	150	58.0	72.568
070	62.0	73.788	150	64.0	72.824
070	74.0	73.606	150	76.0	72.786
070	80.0	73.243	150	82.0	72.632
070	86.0	73.299	150	88.0	71.545
070	92.0	72.993	150	94.0	71.443
070	98.0	73.250	150	100.0	71.648
070	104.0	73.068	150	106.0	71.379
070	110.0	73.249	150	112.0	70.893
070	116.0	72.830	150	118.0	70.458
070	1176.0	69.093	150	1178.0	60.484
070	1231.0	68.830	150	1233.0	59.831
070	1290.0	68.855	150	1292.0	60.087
070	5788.0	68.542	150	5790.0	59.640
070	7348.0	66.689	150	7350.0	58.079
070	8396.0	66.489	150	8398.0	58.399
070	9904.0	66.182	150	9906.0	57.913
070	12763.0	66.182	150	12765.0	58.374

Appendix Table C.8

Soil water content redistribution after cessation of ponding in the Olinda site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
010	0.0	78.970	090	0.0	48.090
010	0.5	77.750	090	2.5	48.030
010	5.5	77.080	090	7.5	47.660
010	10.5	75.620	090	12.5	47.610
010	15.5	74.960	090	17.5	47.160
010	25.5	74.570	090	27.5	46.500
010	35.5	74.490	090	37.5	45.070
010	45.5	73.980	090	47.5	40.030
010	55.5	73.550	090	57.5	36.800
010	75.5	73.260	090	77.5	35.830
010	85.5	72.910	090	87.5	35.840
010	95.5	72.340	090	97.5	35.680
010	105.5	72.390	090	107.5	35.490
010	115.5	72.380	090	117.5	34.910
010	125.5	72.580	090	127.5	34.670
010	135.5	71.830	090	137.5	34.480
010	145.5	71.880	090	147.5	34.880
010	155.5	71.520	090	157.5	34.870
010	165.5	71.690	090	167.5	34.470
010	1315.5	70.260	090	1317.5	31.240
010	1495.5	70.110	090	1497.5	31.310
010	8585.5	69.750	090	8527.5	29.680
010	8945.5	69.630	090	8947.5	29.700
010	9935.5	69.310	090	9937.5	29.490
010	10375.5	69.260	090	10377.5	29.310
010	11383.5	68.740	090	11385.5	29.660
010	11703.5	68.430	090	11705.5	28.880
010	15763.5	67.840	090	15765.5	28.750
010	17127.5	67.560	090	17129.5	28.430
010	21648.5	67.540	090	21650.5	27.590
010	26196.5	67.520	090	26198.5	27.650
010	33538.5	67.460	090	33540.5	27.500
030	0.0	62.700	110	0.0	54.070
030	1.0	62.420	110	3.0	53.590
030	6.0	62.250	110	8.0	53.540
030	11.0	62.210	110	13.0	53.520
030	16.0	56.420	110	18.0	53.770
030	26.0	53.960	110	28.0	53.410
030	36.0	53.270	110	38.0	53.600
030	46.0	53.140	110	48.0	53.420

Appendix Table C.8 (continued) Soil water content redistribution after cessation of ponding in the Olinda site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
030	56.0	52.830	110	58.0	52.340
030	76.0	52.450	110	78.0	48.950
030	86.0	52.480	110	88.0	45.770
030	96.0	52.360	110	98.0	45.930
030	106.0	52.500	110	108.0	45.490
030	116.0	52.190	110	118.0	45.190
030	126.0	52.160	110	128.0	45.190
030	136.0	51.520	110	138.0	45.400
030	146.0	50.900	110	148.0	45.250
030	156.0	50.990	110	158.0	45.400
030	166.0	51.150	110	168.0	45.280
030	1316.0	49.440	110	1318.0	42.330
030	1496.0	49.560	110	1498.0	41.880
030	8526.0	48.940	110	8528.0	40.590
030	8946.0	49.190	110	8948.0	40.430
030	9936.0	49.210	110	9938.0	40.410
030	10376.0	49.120	110	10378.0	40.540
030	11384.0	49.400	110	11386.0	40.630
030	11704.0	49.420	110	11706.0	40.450
030	15764.0	45.920	110	15766.0	40.080
030	17128.0	45.860	110	17130.0	39.140
030	21649.0	45.610	110	21651.0	39.080
030	26197.0	45.470	110	26199.0	39.080
030	33539.0	45.730	110	33541.0	38.590
050	0.0	60.170	130	0.0	58.680
050	1.5	59.880	130	3.5	58.330
050	6.5	59.850	130	8.5	58.110
050	11.5	59.800	130	13.5	57.860
050	16.5	59.640	130	18.5	57.780
050	26.5	51.420	130	28.5	57.440
050	36.5	51.080	130	38.5	57.820
050	46.5	50.920	130	48.5	57.410
050	46.5	50.880	130	58.5	57.300
050	76.5	50.960	130	78.5	56.730
050	86.5	51.140	130	88.5	56.270
050	96.5	51.170	130	98.5	56.190
050	106.5	51.210	130	108.5	55.750
050	116.5	50.280	130	118.5	55.680
050	126.5	49.960	130	128.5	55.430
050	136.5	49.730	130	138.5	55.160
050	146.5	50.050	130	148.5	55.060
050	156.5	49.610	130	158.5	54.960
050	166.5	49.140	130	168.5	53.540

Appendix Table C.8 (continued) Soil water content redistribution after cessation of ponding in the Olinda site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
050	1316.5	47.610	130	1318.5	48.860
050	1496.5	47.180	130	1498.5	48.340
050	8526.5	44.850	130	8528.5	47.320
050	8946.5	44.380	130	8948.5	47.000
050	9936.5	44.190	130	9938.5	47.120
050	10376.5	44.360	130	10378.5	47.070
050	11384.5	44.230	130	11386.5	47.220
050	11704.5	44.460	130	11706.5	47.030
050	15764.5	43.100	130	15766.5	45.130
050	17128.5	42.630	130	17130.5	45.180
050	21649.5	42.040	130	21651.5	44.960
050	26197.5	42.470	130	26199.5	44.840
050	33539.5	42.440	130	33541.5	44.930
070	0.0	57.250	150	0.0	55.480
070	2.0	56.390	150	4.0	55.180
070	7.0	56.060	150	9.0	55.060
070	12.0	55.850	150	14.0	55.020
070	17.0	55.310	150	19.0	54.990
070	27.0	53.480	150	29.0	55.250
070	37.0	46.400	150	39.0	55.180
070	47.0	46.230	150	49.0	55.100
070	57.0	45.950	150	59.0	55.390
070	77.0	45.120	150	79.0	55.530
070	87.0	45.100	150	89.0	55.190
070	97.0	44.740	150	99.0	55.330
070	107.0	44.390	150	109.0	55.280
070	117.0	44.390	150	119.0	55.220
070	127.0	44.060	150	129.0	55.160
070	137.0	44.430	150	139.0	55.060
070	147.0	43.840	150	149.0	55.130
070	157.0	44.040	150	159.0	55.500
070	167.0	43.740	150	169.0	55.060
070	1317.0	40.780	150	1319.0	51.630
070	1497.0	40.280	150	1499.0	51.840
070	8527.0	39.940	150	8529.0	50.940
070	8947.0	39.740	150	8949.0	50.850
070	9937.0	39.720	150	9939.0	50.650
070	10377.0	39.590	150	10379.0	50.060
070	11385.0	39.230	150	11387.0	49.430
070	11705.0	39.210	150	11707.0	49.670
070	15765.0	38.810	150	15767.0	49.240
070	17129.0	38.780	150	17131.0	49.110
070	21650.0	37.180	150	21652.0	48.590

Appendix Table C.8 (continued) Soil water content redistribution after cessation of ponding in the Olinda site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
070	26198.0	36.870	150	26200.0	48.760
070	33540.0	37.440	150	33542.0	48.820

Appendix Table C.9

Soil water content redistribution after cessation of ponding in the Puupahu site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
010	0.0	83.820	090	0.0	79.560
010	0.5	76.240	090	2.5	77.830
010	6.5	73.150	090	8.5	77.890
010	12.5	71.440	090	14.5	77.400
010	18.5	71.110	090	20.5	77.320
010	24.5	70.210	090	26.5	76.910
010	30.5	69.110	090	32.5	76.850
010	36.5	68.830	090	38.5	76.820
010	48.5	68.530	090	50.5	76.980
010	60.5	67.680	090	62.5	75.770
010	72.5	67.990	090	74.5	75.500
010	84.5	67.040	090	86.5	75.850
010	96.5	67.130	090	98.5	75.320
010	108.5	65.710	090	110.5	75.780
010	120.5	65.520	090	122.5	75.770
010	132.5	65.040	090	134.5	75.480
010	144.5	65.410	090	146.5	75.690
010	156.5	65.220	090	158.5	75.450
010	168.5	65.540	090	170.5	75.660
010	180.5	65.000	090	182.5	75.630
010	192.5	65.500	090	194.5	75.820
010	1320.5	63.950	090	1322.5	74.850
010	1350.5	64.000	090	1352.5	74.580
010	1380.5	62.020	090	1382.5	74.190
010	1410.5	61.480	090	1412.5	73.970
010	1440.5	61.340	090	1442.5	74.230
010	1470.5	61.480	090	1472.5	73.950
010	1500.5	61.630	090	1502.5	73.690
010	5691.5	59.250	090	5693.5	71.390
010	7049.5	59.310	090	7051.5	71.900
010	8413.5	59.320	090	8415.5	71.830
010	11367.5	58.650	090	11369.5	71.340
010	15852.5	58.360	090	15854.5	71.560
010	18535.5	58.340	090	18537.5	71.800
010	22903.5	58.310	090	22905.5	71.540
030	0.0	70.200	110	0.0	79.910
030	1.0	62.810	110	3.0	79.620
030	7.0	62.500	110	9.0	79.530
030	13.0	62.180	110	15.0	80.330
030	19.0	61.630	110	21.0	80.190

Appendix Table C.9 (continued) Soil water content redistribution after cessation of ponding in the Puupahu site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
030	25.0	61.370	110	27.0	79.490
030	31.0	61.120	110	33.0	80.340
030	37.0	60.430	110	39.0	79.610
030	49.0	60.130	110	51.0	79.420
030	61.0	60.220	110	63.0	78.670
030	73.0	60.170	110	75.0	78.230
030	85.0	58.830	110	87.0	77.330
030	97.0	58.580	110	99.0	77.430
030	109.0	58.670	110	111.0	78.020
030	121.0	58.040	110	123.0	78.020
030	133.0	58.060	110	135.0	77.530
030	145.0	58.090	110	147.0	76.490
030	157.0	57.890	110	159.0	76.430
030	169.0	58.310	110	171.0	76.100
030	181.0	57.870	110	183.0	76.020
030	193.0	56.660	110	195.0	76.210
030	1321.0	56.300	110	1323.0	75.670
030	1351.0	55.120	110	1353.0	76.540
030	1381.0	54.360	110	1383.0	75.080
030	1411.0	54.250	110	1413.0	74.820
030	1441.0	54.030	110	1443.0	74.500
030	1471.0	54.340	110	1473.0	75.030
030	1501.0	54.070	110	1503.0	75.000
030	5692.0	51.220	110	5694.0	71.890
030	7050.0	51.010	110	7052.0	71.910
030	8414.0	50.600	110	8416.0	71.810
030	11368.0	49.190	110	11370.0	70.990
030	15853.0	49.870	110	15855.0	70.880
030	18536.0	49.410	110	18538.0	70.650
030	22904.0	49.330	110	22906.0	71.020
050	0.0	68.800	130	0.0	87.120
050	1.5	61.870	130	3.5	86.490
050	7.5	61.440	130	9.5	86.250
050	13.5	61.640	130	15.5	85.620
050	19.5	61.570	130	21.5	85.810
050	25.5	59.870	130	27.5	85.910
050	31.5	60.330	130	33.5	84.930
050	37.5	60.440	130	39.5	84.360
050	49.5	60.490	130	51.5	83.740
050	61.5	59.960	130	63.5	83.680
050	73.5	60.370	130	75.5	83.740

Appendix Table C.9 (continued) Soil water content redistribution after cessation of ponding in the Puupahu site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
050	85.5	59.540	130	87.5	84.880
050	97.5	58.370	130	99.5	83.700
050	109.5	58.520	130	111.5	84.350
050	121.5	58.620	130	123.5	84.830
050	133.5	58.890	130	135.5	84.750
050	145.5	59.000	130	147.5	84.760
050	157.5	58.800	130	159.5	84.040
050	169.5	58.750	130	171.5	84.030
050	181.5	57.900	130	183.5	83.200
050	193.5	57.620	130	195.5	83.060
050	1321.5	56.890	130	1323.5	83.490
050	1351.5	56.630	130	1353.5	83.550
050	1381.5	56.250	130	1383.5	82.440
050	1411.5	55.190	130	1413.5	82.390
050	1441.5	54.730	130	1443.5	82.800
050	1471.5	54.190	130	1473.5	82.230
050	1501.5	53.480	130	1503.5	83.520
050	5692.5	52.980	130	5694.5	82.220
050	7050.5	52.740	130	7052.5	82.360
050	8414.5	52.310	130	8416.5	83.020
050	11368.5	52.470	130	11370.5	83.190
050	1583.5	51.960	130	15855.5	83.320
050	18536.5	51.620	130	18538.5	82.950
050	22904.5	51.500	130	22906.5	80.600
070	0.0	64.660	150	0.0	60.940
070	2.0	64.040	150	4.0	60.470
070	8.0	63.960	150	10.0	61.510
070	14.0	63.570	150	16.0	58.480
070	20.0	63.210	150	22.0	58.370
070	26.0	63.220	150	28.0	57.370
070	32.0	63.160	150	34.0	57.960
070	38.0	62.660	150	40.0	58.360
070	50.0	62.650	150	52.0	58.280
070	62.0	62.490	150	64.0	58.740
070	74.0	62.330	150	76.0	57.330
070	86.0	62.360	150	88.0	58.360
070	98.0	62.190	150	100.0	58.020
070	110.0	62.450	150	112.0	58.500
070	122.0	62.180	150	124.0	58.510
070	134.0	62.240	150	136.0	58.660
070	146.0	62.100	150	148.0	58.300
070	158.0	62.180	150	160.0	58.600

Appendix Table C.9 (continued) Soil water content redistribution after cessation of ponding in the Puupahu site

SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)	SOIL DEPTH (cm)	TIME (min)	WATER CONTENT (% vol)
070	170.0	61.930	150	172.0	57.770
070	182.0	62.070	150	184.0	58.420
070	194.0	62.030	150	196.0	57.450
070	1322.0	61.140	150	1324.0	57.700
070	1352.0	61.090	150	1354.0	57.990
070	1382.0	60.940	150	1384.0	57.970
070	1412.0	61.120	150	1414.0	58.660
070	1442.0	60.560	150	1444.0	55.600
070	1472.0	60.510	150	1474.0	53.250
070	1502.0	60.360	150	1504.0	53.140
070	5693.0	60.460	150	5695.0	52.050
070	7051.0	60.360	150	7053.0	52.460
070	8415.0	60.410	150	8417.0	51.990
070	11369.0	60.340	150	11371.0	52.390
070	15854.0	60.120	150	15856.0	51.880
070	18537.0	60.080	150	18539.0	51.560
070	22905.0	59.910	150	22907.0	51.260

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