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ESTIMATING WATER RETENTION FOR MAJOR SOILS IN THE HARARGHE REGION, EASTERN ETHIOPIA

KIBEEBW KIBRET TSEHAI

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ESTIMATING WATER RETENTION FOR MAJOR SOILS IN THE HARARGHE REGION, EASTERN ETHIOPIA

by

KIBEBEW KIBRET TSEHAI

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Dedication

I dedicate this work entirely to my mother, Likelesh Lemma, for the immense and immortal love, encouragement and care she provided. She was a good mentor and friend. Mom, I love you forevermore. Mom, without you, I have always felt down and empty inside. You were the source of happiness in my life.

DECLARATION

I declare that the thesis hereby submitted by me for **Philosophiae Doctor** degree at the University of Free State is my own independent work and has not previously been submitted by me at another university / faculty. I further cede copyright of the thesis in favour of the University of the Free State.

Signed ______________________________

Kibebew Kibret Tsehai

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ABSTRACT

Soil water retention is a fundamental property controlling water storage and movement in the solum. To determine the water retention characteristic curve is time consuming and expensive. Several attempts have been made to establish relationships between easily measurable soil properties, like particle size distribution, organic carbon content, and the water retention characteristic curve. Those relationships are referred to as pedotransfer functions (PTFs). More conveniently, it is described by analytical functions that are suitable in the solution of numerical flow equations as well as in implementation of closed-form methods for predicting other hydraulic properties, such as unsaturated hydraulic conductivity. The objectives of this study were to describe the water retention characteristics of soils from the Hararghe Region, eastern Ethiopia, in relation to certain soil properties; to identify water retention functions for describing the water retention characteristic curves of these soils and to develop a procedure for estimating water content either at certain matric potentials or the complete curve from readily available soil properties. Two approaches, point estimation and parametric estimation techniques, were used for estimating the water content at certain matric potentials and at any matric potential, respectively.

To establish relationships between water retention and relevant soil properties, regression analyses were carried out. From the regression analyses, point PTFs that can be used to estimate the water content at certain matric potentials were developed. This was done firstly by using the complete data set consisting of 216 retention curves and secondly by dividing the complete data set into topsoil and subsoil samples. Due to observed differences in water retention characteristics, the subsoil samples were divided into two groups based on their silt (Si) to clay (C) ratio. The dividing line between these two groups was 0.75. The topsoil and the two subsoil groups were divided into classes based on their silt plus clay content. This resulted in 7 classes for topsoils and subsoils with Si:C ratios < 0.75 and 6 classes for the subsoils with Si:C ratios > 0.75.

For all the point estimation PTFs, the silt plus clay content functions described the variability in water content best. The relationship between water content and silt plus

clay content was curvilinear. In order to quantify the prediction accuracy of these equations, the mean of the mean absolute error (mMAE), the mean of the root mean square error (mRMSE), the mean of the mean bias error (mMBE), d-index of agreement and coefficient of determination (R^2) were used. In some instances, the slopes and intercepts of the 1:1 lines, between measured and predicted values, were used. The silt plus clay content functions for the complete data set explained 78 to 87 % of the variability in water content at specific matric potentials. The mMBE ranged from –0.001 to –0.003 $cm^3 cm^{-3}$, the mMAE 0.022 to 0.034 $cm^3 cm^{-3}$, the mRMSE 0.027 to 0.042 $cm^3 cm^{-3}$. The d-values ranged from 0.838 to 0.867. The silt plus clay content functions for the topsoils explained 88 to 94 % of the variability in water retention with the mMBE ranging from 0 to –0.001 $cm^3 cm^{-3}$, mMAE 0.018 to 0.031 $cm^3 cm^{-3}$, mRMSE 0.024 to 0.036 $cm^3 cm^{-3}$ and the d-values 0.765 to 0.886. The silt plus clay content functions for the subsoils with Si:C ratios < 0.75 were able to explain 78 to 87 % of the variability in water retention with the mMBE ranging from –0.001 to –0.004 $cm^3 cm^{-3}$, mMAE 0.019 to 0.036 $cm^3 cm^{-3}$, mRMSE 0.023 to 0.045 $cm^3 cm^{-3}$ and d-values 0.793 to 0.884. The silt plus clay content function for the subsoils with Si:C ratios > 0.75 explained 86 to 98 % of the variability in water content with mMBE ranging from –0.001 to 0.004 $cm^3 cm^{-3}$, mMAE 0.013 to 0.031 $cm^3 cm^{-3}$, mRMSE 0.015 to 0.038 $cm^3 cm^{-3}$ and d-values 0.737 to 0.991.

Of the three groups, the mean values of the classes were used to develop PTFs with higher R^2-values and lower errors compared with the PTFs developed from the complete data set in each respective group.

From the six water retention functions tested, the Van Genuchten (1980) function, with the restriction $m = 1 - 1/n$, gave the best description of the water retention curves, followed by the Smith (1992) and the ordinary power functions. Over all, the Brooks-Corey (1964) function gave the poorest description of the water retention curves studied. The parameters of the Smith (1992) and Hutson & Cass (1987) functions correlated better with relevant soil properties compared to the parameters of the Van Genuchten function. With the parametric approach the Smith (1992) function estimated water content for topsoils and subsoils with Si:C ratios > 0.75 with a higher accuracy compared with the Van Genuchten and Hutson & Cass functions whereas the Hutson & Cass function was better for the subsoils with Si:C ratios < 0.75.

Testing the functions derived from the point estimation and parameterization techniques on an independent data set indicated that both approaches estimated water content with a reasonable degree of accuracy, although the point estimation techniques gave slightly better results for the subsoils with Si:C ratios > 0.75.

Additional key words: water content, water retention characteristic curve, matric potential, pedotransfer functions, silt plus clay content, silt to clay ratio, water retention functions.

OPSOMMING

Grondwaterretensie is ’n fundamentele eienskap wat die waterhouvermoë en -beweging in die solum beheer. Om die waterkarakteristiekekurwes van gronde te bepaal is ’n omslagtige en tydrowende proses. Verskeie pogings is aangewend om verwantskappe tussen maklik meetbare grondeienskappe, soos deeltjiegrootteverspreiding, koolstofinhoud en waterretensie af te lei. Hierdie verwantskappe word ook pedo-oordragfunksies genoem. Gerieflikheidshalwe moet hierdie funksie analities van aard wees sodat dit gebruik kan word om vloeivergelykings op te los en vir die voorspelling van hidrouliese eienskappe soos die onversadigde hidrouliese geleivermoë. Die doelwitte met hierdie ondersoek was i) om die waterretensie en verwante eienskappe van die gronde van die Hararge Streek in oostelike Ethiopië te bepaal; ii) om die funksie wat die waterretensiekurwes die beste pas te identifiseer en om iii) ’n prosedure te ontwikkel waarvolgens waterretensiekurwes, vanaf maklik bepaalbare grondeienskappe, voorspel kan word. Twee benaderings, nl. die punt- en parametriese beramingstegnieke is gebruik, waarvolgens die waterinhoud by spesifieke matrikspotensiale en die parameters van die waterretensiekurwe onderskeidelik beraam word.

Die verwantskappe tussen waterrensie en die onderskeie grondeienskappe is by wyse van regressie-analieses bepaal. Punt pedo-oordragfunksies is ontwikkel waarmee die waterinhoude by spesifieke matrikspotensiaalwaardes vanaf die slik plus klei-inhoude van gronde beraam kan word. Eerstens is die volledige datastel, bestaande uit 216 retensiekurwes, en tweedens groeperings van die data in bo- en ondergronde, gebruik vir die ontwikkeling van die funksies. Met die interpretasie van die ondergronddata is gevind dat dit in twee populasies, volgens die slik (S) tot klei (K) verhouding verdeel kan word. Die grens tussen die groepe was 0.75. Die groot hoeveelheid retensiekurwes binne elk van die groeperings, nl. bogronde, ondergronde met ’n S:K verhouding <0.75 en ondergronde met ’n S:K >0.75, is verder in 7 silk plus klei persentasieklasse per groep ingedeel. Vir die ondergronde met ’n S:K <0.75 was daar net 6 klasse. Die gemiddelde waterretensie- en tekstuurdata per klas is in die regressie-analieses gebruik. Die afgeleide punt pedo-oordragfunksies tussen waterinhoud en slik plus klei-inhoud, vir elk van die matrikspotensiaalwaardes, was

kromlyning. Die akkuraatheid van die waterinhoudwaardes wat met die afgeleide vergelykings voorspel is, is bepaal deur die voorspelde waardes met die gemete waardes te vergelyk. Die volgende statistiese indikatore, nl. die gemiddelde absolute fout (mMAE), gemiddelde vierkantswortel van die som van kwadrate fout (mRMSE), gemiddelde oorhellingsfout (mMBE), d-indeks van ooreenstremming en die koëffisiënt van bepaling (R^2), is gebruik om die akkuraatheid van die beraamde waterinhoude te bereken.

Die slik plus klei funksies van die volledige datastel het 77.6 tot 87.4% van die variasie in waterinhoud by 'n spesifieke matrikspotensiaal verklaar. Die mMBE het tussen -0.001 tot -0.003 cm^3 cm^{-3}, die mMAE 0.022 tot 0.034 cm^3 cm^{-3}, die RMSE 0.027 tot 0.042 cm^3 cm^{-3} en die d-waarde tussen 0.84 tot 0.87. gewissel. Vir die bogronde alleen het die slik plus klei-inhoude 88 tot 94.3% van die variasie in waterinhoud verklaar met die mMBE wat tussen 0 en -0.001 cm^3 cm^{-3}, mMAE 0.018 en 0.031 cm^3 cm^{-3}, mRMSE 0.024 en 0.036 cm^3 cm^{-3} en die d-waardes 0.77 en 0.89, gewissel het. Vir die ondergronde met S:K verhoudings <0.75 het die slik plus klei-inhoude 78.3 tot 86.9% van die variasie in waterinhoud verklaar met mMBE-waardes tussen -0.001 en -0.004 cm^3 cm^{-3}, mMAE 0.019 en 0.036 cm^3 cm^{-3}, mRMSE 0.023 en 0.045 cm^3 cm^{-3} en d-waardes tussen 0.79 en 0.88. Vir die ondergronde met S:K verhoudings >0.75 was die ooreenstemmende indikatore 85.5 tot 97.6%, mMBE -0.001 tot 0.004 cm^3 cm^{-3}, mMAE 0.013 tot 0.031 cm^3 cm^{-3}, mRMSE 0.015 tot 0.038 cm^3 cm^{-3} en d-waardes tussen 0.74 en 0.99.

Van die ses waterretensiefunksies wat getoets is, het die Van Genuchten (1980) funksie, met 'n beperking van m = 1 – 1/n, die beste passing in alle gevalle gegee, gevolg deur die Smith (1992) en gewone magsfunksies. Oor die algemeen het die Brooks & Corey (1964) funksie die swakste gevaar. Die parameters van die Smith (1992) en Hutson & Cass (1987) funksies het die beste met verskillende grondeienskappe gekorreleer. Met die parametriese benadering het die Smith (1992) vergelyking die waterinhoude van die bogronde en die ondergronde met S:K >0.75, die akkuraatste beraam en vir ondergronde met S:K <0.75 was die Hutson & Cass vergelyking die beste.

Die afgeleide punt en parametriese pedo-oordragfunksies is op 'n onafhanklike datastel getoets. Geen verskil kon tussen die akkuraatheid van die voorspelde waardes van die twee benaderings gevind word nie, hoewel die puntbenadering effens beter voorspellings vir bogronde gegee het.

Sleutelwoorde: waterinhoud, waterretensiekurwe, matrikspotensiaal, pedo-oordragfunksies, slik plus klei-inhoud, slik tot kleiverhouding, waterkarakteristiekekurwe.

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CHAPTER 1

INTRODUCTION

1.1. Background information

If there is magic on this planet, it is in water (Loren Eisley: cited by Miller & Gardiner, 1998).
You never know the worth of water 'till the well runs dry (Benjamin Franklin: cited by Miller & Gardiner, 1998).

Soil and water are two fundamental resources of our agricultural environment. Knowledge of the soil hydraulic properties is indispensable to solve many soil and water management problems related to agriculture, ecology and environmental issues. These hydraulic properties influence, among others, plant growth, soil aeration, soil temperature, drainage, irrigation and trafficability.

The soil water retention curve, being one of the main hydraulic properties, expresses the relationship between the matric potential and the water content of the soil. It can be considered as the soil's fingerprint since the shape of the curve is related to various physical and chemical soil properties, which are unique for each soil. Soil water retention is needed for the study of plant-available water, infiltration, drainage, hydraulic conductivity, irrigation, water stress of plants, and solute movement (Kern, 1995).

While a large number of laboratory and field methods have been developed over the years to measure the soil hydraulic properties (Klute, 1986), accurate *in situ* measurements of these properties have remained relatively costly, time consuming, labour intensive, and difficult to implement. For these reasons, the water retention characteristic is not a readily available property. Thus, cheaper and more expedient methods for estimating the soil water retention are needed if we are to implement improved practices for managing water and chemicals in the unsaturated zone.

One alternative to the direct measurement of water retention characteristics, is the use of analytical functions assumed to describe the water retention function based on other easily obtainable soil characteristics, such as particle-size distribution. Since water retention by soil is affected by other physical and chemical properties, such as texture, bulk density, organic matter, clay mineralogy, etc., the development of empirical relationships to predict soil water retention from these properties is justifiable. Bouma & van Lanen (1987) and Bouma (1989) described these relationships as **Pedotransfer Functions (PTFs)**. A pedotransfer function is, therefore, defined as a function that has as arguments basic data describing the soil (e.g., particle size distribution, bulk density, and organic C content) and yields as a result the water retention function or the unsaturated hydraulic conductivity function (including saturated hydraulic conductivity) (Tietje & Tapkenhinrichs, 1993).

To partially circumvent the measurement problem, several investigators (e.g., Brooks & Corey, 1964; Campbell, 1974; Van Genuchten, 1980) have proposed a closed form analytical expression assumed to describe the water retention curve. These models have the advantage of expressing the hydraulic properties in the form of analytical (nontabular) functions, a feature that facilitates their efficient inclusion into numerical simulation models and also enables the rapid comparison of the hydraulic properties of different soils. Though there could be a considerable deviation between measured and predicted water contents or matric potentials depending on the type of PTF used, the use of analytical functions fitted to the predicted values, has several advantages. They allow for a more efficient representation and comparison of the hydraulic properties of different soils and horizons; they are also more easily used in scaling procedures for characterizing the spatial variability of soil hydraulic properties across the landscape; and, if shown to be physically realistic over a wide range of water contents, analytical expressions provide a method for interpolating or extrapolating parts of the retention curves for which little or no data are available. Analytical functions also permit more efficient data handling in unsaturated flow models, particularly for multidimensional simulations involving layered soil profiles (Van Genuchten *et al.*, 1991).

Results thus far suggest that PTFs work reasonably well for many coarse-textured soils and other porous media having relatively narrow pore-size distributions, but that predictions for many fine-textured and structured field soils remain inaccurate (Van Genuchten *et al.*, 1991). Because of the time-consuming nature of direct field measurement of the hydraulic properties, and in view of the field-scale spatial variability problem, it nevertheless seems likely that predictive models provide the only viable means of characterizing the hydraulic properties of large areas of land, whereas direct measurement may prove to be cost-effective only for site-specific problems (Wösten & Van Genuchten, 1988).

Since every PTF is derived from a database of a limited number of soil samples, it is not always clear to what extend these functions can be used in soil conditions other than those under which they were developed (Cornelis *et al.*, 2001). Further, the dependence of the shape of the water retention curve on soil textural and structural properties varies with the area in which the study was conducted, because of differences in clay mineralogy and in the nature of the organic material (Woodroff, 1950; cited by De Jong *et al.*, 1983; Chen & Schnitzer, 1976).

1.2. Objectives of the study

The problem of obtaining representative samples is complicated by the results of studies (e.g., Nielsen *et al.*, 1973; Russo & Bresler, 1981), which show that soils exhibit significant temporal and spatial variability in their hydraulic properties. The Hararghe Region, which is located in the eastern part of Ethiopia, encompasses areas differing in climate and topography. This has resulted in the development of different soil types. In this region most of the research has been done on the fertility of the different soil types. Hararghe Region is one of the most severely degraded regions in Ethiopia with a water deficit as the main factor limiting crop production. Water use from rainfall has hardly been efficient. Generally speaking, the soil-water relationships are poorly understood. Little work, if any, has been done on characterization of the different soil types in terms of their hydraulic properties. This has for a long time constrained the efficient use of available water for optimum crop production. Lack of appropriate laboratory facilities for measuring the various hydraulic properties, is the major constraint in the poor understanding of the hydraulic properties. Characterization of the soils from Hararghe Region, in terms of their water retention properties, has a high priority. This study was, therefore, initiated with the following main objectives:

1. to describe the water retention characteristics of the Hararghe Region soils, eastern Ethiopia, in relation to certain soil properties;
2. to identify water retention functions for describing the water retention characteristic curves of these soils; and
3. to develop a procedure for estimating water content either at certain matric potentials or the complete curve from readily available soil properties.

1.3. Literature review

1.3.1. Soil water content

Measurement of water content is fundamental to many agricultural, forestry, hydrological, and civil engineering investigations of soils (Gardner *et al.*, 1991). The soil water content, soil wetness or relative water content of the soil is the fractional content of water in the soil expressed in various ways: relative to the total mass of the solids, relative to the total soil mass, relative to the volume of solids, relative to the total volume, and relative to the volume of pores (Hillel, 1980). Soil water content can be expressed either on a gravimetric or a volumetric basis, that is, kilogram per kilogram or cubic meter per cubic meter, respectively (Gardner *et al.*, 1991). In either case, the value derived is dimensionless and can be regarded as a fraction, or a percentage.

(i) On mass basis

$$\theta_m = \frac{M_w}{M_s} \qquad [1.1]$$

with θ_m = water content on mass basis (kg kg^{-1});

M_w = soil water mass in kg;

M_s = dry soil mass in kg.

(i) On volume basis

$$\theta_v = \frac{V_w}{V_t} = \frac{V_w}{(V_s + V_w + V_a)} \qquad [1.2]$$

where θ_v = water content on volume basis ($m^3\,m^{-3}$);

V_w = soil water volume in m^3;

V_t = bulk soil volume in m^3;

V_s = volume of soil solids in m^3;

V_a = volume of soil air in m^3.

The relationship between θ_m and θ_v can be expressed as:

$$\theta_v = \theta_m\left(\frac{\rho_b}{\rho_w}\right) = \theta_m\Gamma_b \qquad [1.3]$$

where ρ_b = bulk density of the soil in kg m^{-3};

ρ_w = density of water kg m^{-3};

Γ_b = bulk specific gravity of the soil (dimensionless).

For many purposes expression of the water content on a volumetric basis is more useful, as multiplying by the soil depth gives the "depth" of water in this depth of soil, a value compatible with the units used to measure rainfall, evaporation, transpiration, drainage, and irrigation. This represents the equivalent depth D_w that soil water would have if it were extracted and then ponded over the soil surface. Thus:

$$D_w = \theta_v z = \theta_m \Gamma_b z \qquad [1.4]$$

where D_w is expressed in mm and z is depth(mm).

Equation 1.4 is especially useful in connection with soils having a nonrigid, swelling and shrinking matrix (Hillel, 1980).

The degree of saturation, S, is the ratio of:

$$S = \frac{V_w}{V_f} = \frac{V_w}{(V_a + V_w)} \qquad [1.5]$$

1.3.2. Driving forces on the soil solution

Soil water potential gradients are being used as the driving force in calculating solute movement in soils. From the theory of irreversible thermodynamics, Stroosnijder (1976) defined driving forces as the difference between the pressure on the soil solution and the gravitational force. Assuming that the solution is homogeneous and the system isothermal, the mathematical expression of the resulting driving force acting on a m^3 soil solution can thus be written as:

$$\sum F = -\nabla p - \rho_{ss} g \nabla Z \qquad [1.6]$$

where p = measurable pressure of the soil liquid phase relative to atmospheric pressure in Pa;

g = acceleration due to gravity in $m\ s^{-2}$;

Z = elevation in m;

ρ_{ss} = density of the soil solution in $kg\ m^{-3}$;

F = force in N.

For practical consideration, because $\sum F$ is difficult to measure, Koorevaar (1975) defined a total potential or hydraulic potential as:

$$\int_{s_0}^{s} \sum F_i ds = \int_{s_0}^{s} \nabla p ds + g \int_{s_0}^{s} \rho_{ss} \nabla Z ds \qquad [1.7]$$

The potential, being an inner vector product, is a scalar quantity, which can be assigned a value if a reference level is given. Considering the density of the solution to be constant, then:

$$P_h = P + \rho_{ss} g \Delta Z \qquad [1.8]$$

where P_h is the total hydraulic pressure potential, P is the soil water pressure potential and $\rho_{ss} g \Delta Z$ is the gravitational potential, all in Pa.

When expressing the potential in energy per unit weight it will have a length dimension and named hydraulic head instead of hydraulic pressure potential. Equation 1.8 can then be written as:

$$H = \frac{P}{\rho_{ss} g} + \Delta Z \qquad [1.9]$$

$$= H_p + \Delta Z \qquad [1.10]$$

where H is the total hydraulic head and H_p the water pressure head, both in meters. The pressure head H_p can easily be determined by means of a tensiometer equipped with a water, mercury, or a Bourdon manometer or a pressure transducer.

1.3.3. Equations governing the soil water flow

The slopes of the water retention curve (C), called the differential water capacity, are being used to calculate water flow in unsaturated soils. Water flow in unsaturated or partly saturated soils is traditionally described with the Richards equation (Richards, 1931: cited by Van Genuchten *et al.*, 1991) as follows:

$$C\frac{\delta h}{\delta t} = \frac{\delta}{\delta z}\left(K\frac{\delta h}{\delta z} + K\right) \qquad [1.11]$$

$$C = \frac{d\theta}{dh} \qquad [1.12]$$

where h is the soil water suction (with dimension L, t is time (T), z is soil depth over which flow occurs (L), K is the hydraulic conductivity (LT^{-1}), and C is the soil water capacity (L^{-1}) approximated by the slope of the soil water retention curve, θ(h), in which θ is the volumetric water content (L^3L^{-3}).

Equation 1.11 may also be expressed in terms of the water content if the soil profile is homogeneous and unsaturated ($h \leq 0$):

$$\frac{\delta\theta}{\delta t} = \frac{\delta}{\delta z}\left(D\frac{\delta\theta}{\delta z} + K(\theta)\right) \qquad [1.13]$$

where D is the soil water diffusivity (L^2T^{-1}), defined as

$$D = K(\theta)\frac{dh}{d\theta} \tag{1.14}$$

The unsaturated soil hydraulic functions in the above equations are the soil water retention curve θ(h), the hydraulic conductivity function K(h) or K(θ), and the soil water diffusivity function D(θ). The availability of water retention relationships is therefore essential for calculating solute fluxes through unsaturated soils.

1.4. Physico-chemical properties of the soil that influence water retention

Several soil properties have been used in the past to predict the hydraulic behaviour of soils. The soil properties affecting hydraulic behaviour of soils are summarized in Table 1.1.

Table 1.1 Summary of soil properties found to affect soil water retention (Rawls *et al.*, 1991)

Particle size properties	Hydraulic characteristic	Morphological properties	Chemical properties
Sand	-33 kPa water	Bulk density	CEC
Silt	-1500 kPa water	Organic carbon	SAR
Clay	Reference	Organic matter	$CaCO_3$
Fine sand	water retention	Porosity	Iron
Very coarse sand	curve	Horizon	
Coarse fragments		Structure	
Particle size distribution		Order	
Median particle size		Colour	
Geometric mean particle size		Clay type	
Standard deviation		Consistence	
Geometric mean particle size			
Water-stable aggregates			

Of these properties bulk density, particle size distribution and organic matter content seem to affect pore size distribution and thus water retention, the most.

1.4.1. Bulk density (ρ_b)

Dry bulk density is defined as the ratio of the mass of dried soil to its total volume (solids plus pores) (Hillel, 1980).

$$\rho_b = \frac{M_s}{V_t} \tag{1.15}$$

where ρ_b = dry bulk density in kg m^{-3};

M_s = dry mass of the soil in kg;

V_t = total soil volume in m^3.

Bulk density is reported to have a great effect on water retention at matric potentials higher than –33 kPa (Rawls *et al.*, 1991). Reeve & Carter (1991) indicated that as the bulk density increases, the amount of water retained between specific matric suctions also increases. This is because compaction reduces the large pores while the amount of intermediate pores increases.

1.4.2. Particle size distribution

Soil texture refers to the proportion of various size ranges of particles in the soil with an upper limit of 2 mm diameter. Soil texture is a permanent, natural attribute of the soil and the one most often used to characterize its physical makeup (Hillel, 1980). As yet there is no universally accepted scheme for the classification of particle sizes, and the various criteria used in different countries are often arbitrary. The different classification systems differ mainly in the particle size limits chosen to separate clay, silt and sand and the percentages of total mass of clay, silt and sand chosen to define a texture class (Shirazi & Boersma, 1984). The generally accepted particle size classes are presented in Table 1.2.

Table 1.2 Several schemes for the classification of soil fractions according to particle diameter ranges

	Soil separates			
Source	Gravel	Sand	Silt	Clay
USDA*	> 2 mm	2 mm – 50μm	50μm - 2μm	< 2μm
ISSS*	> 2 mm	2 mm – 20μm	20μm – 2μm	< 2μm
USPRA*	> 2 mm	2 mm – 50μm	50μm – 5μm	< 5μm

USDA = United States Department of Agriculture, ISSS = International Society of Soil Science, USPRA = United States Public Road Administration.

Sandy soils contain a high fraction of large pores, and the majority of water is released at low suctions. Clay soils, on the other hand, release small amounts of water at low suctions and retain a large proportion of their water even at a high suction.

Soil morphology, specifically aggregation, has a distinct effect on the pore size distribution dominating the soil water characteristic curve as the soil approaches saturation. As soil water content decreases, the water films around soil grains become the dominating soil characteristic influencing water retention. Consequently, in natural soils, aggregation tends to dominate soil water retention only at high water contents, whereas the specific surface area, depending on texture and clay mineralogy, become more important at low water contents. Gardner (1968) found that the soil water content at –1500 kPa was highly correlated with the soil surface area. A number of researchers (Williams *et al.*, 1983; Croney & Coleman, 1954; Sharma & Uehara, 1968) have demonstrated that the presence or absence of soil structure has a dramatic impact on the shape of the water retention curve.

To characterize the granulometric composition of the soil with one value, different parameters have been proposed. Shirazi & Boersma (1984) proposed two statistical properties: the Geometrical Mean Particle Size (GMPS) and the Geometrical Standard Deviation (GSD) of the particle size classes:

$$\mathrm{GMPS} = \mathrm{EXP}\left(0.01\sum_{i=1}^{n} f_i \ln d_i\right) \qquad [1.16]$$

$$\mathrm{GSD} = \mathrm{EXP}\left(\sqrt{\sum_{i=1}^{n} f_i \ln^2 d_i - \left(\mathrm{EXP}\left(0.01\sum_{i=1}^{n} f_i \ln d_i\right)\right)^2}\right) \qquad [1.17]$$

where n = the number of soil separate groups;

f_i = the percentage of the total soil mass having diameters equal to or less than d_i;

d_i = is the arithmetic mean of two consecutive particle-size limits for a particular soil particle class (Krumbein & Pettijohn, 1938).

The smaller the GSD value, the more homogeneous is the material in its composition. For a perfectly homogeneous medium the GSD is equal to one. Using both parameters Shirazi & Boersma (1984) proposed a new textural diagram being able to represent any degree of resolution wanted in the description of the textural composition.

1.4.3. Soil organic matter

According to Allison (1965) soil organic matter is made up of fresh plants and residues. Humus is the vast bulk of resistant organic matter with a high adsorptive capacity and capable of improving structure. It influences the absorption and retention of water, the reserves of exchangeable bases, the capacity of the soil to supply nutrients and the stability of soil structure and aeration. Organic matter increases the amount of water retained in soils, especially at low suctions, but at higher suctions soils rich in organic materials release water rapidly (Reeve & Carter, 1991).

1.5. The water retention characteristic curve

1.5.1. The water retention curve

The relationship between soil water content (L^3L^{-3}) and matric potential, h(L), when plotted on a graph is called the Water Retention Curve (WRC). Because of the wide range of matric potential values Schofield (1935) proposed to log transform the matric potential and call it pF.

The relationship between water content and matric potential is not generally unique for either a group of similar soils or even an individual soil type. In addition to the soil properties, hysteresis plays an important role in affecting the shape and position of the curve. Partial drying followed by rewetting, or partial wetting followed by drying, can result in intermediate curves known as scanning curves, which lie within the hysteresis loop. This implies that the same soil can hold different quantities of water at the same matric potential and, hence, knowledge of the wetting and drying history of a soil is imperative for interpretation of results (Reeve & Carter, 1991). The main reasons for the hysteresis phenomenon, as described by Hillel (1971) are:

1. Pore irregularity. This results in the "ink-bottle" effect.
2. Contact angle. The angle of contact between water and the solid walls of pores tends to be greater for an advancing meniscus than for a receding one. A given water content will tend, therefore, to exhibit greater suction in desorption than in sorption.
3. Entrapped air. This can decrease the water content of newly wetted soil.
4. Swelling and shrinking. Volume changes cause deformation of soil fabric, structure, and pore size distribution, with the result that interparticle contacts differ on wetting and drying.

Because of the hysteresis effect there are actually a family of WRC's for a soil instead of one specific WRC.

1.5.2. Soil water retention functions

As yet, no single theoretical model has been proposed which can estimate the $h(\theta)$ relation from fundamental properties of the soil. This is mainly due to the difficulty in characterizing the complex pore structure inherent in the soil system. Nevertheless, several functions have been proposed to empirically or semi-empirically describe the soil water retention curve. The qualitative effect of different physico-chemical properties as textural composition, clay type, structure and organic matter on the water retention is, however, well known (Hillel, 1982).

Many researchers (Schofield, 1938; Childs, 1940; Russel, 1941) have studied pore size distribution quite intensively, however, no relation has been established with basic soil properties. Attempts made to derive the pore size distribution theoretically were mostly done for particular synthetic media like paper (Vereecken, 1988).

Empirical models for the WRC consist of different forms of mathematical equations relating the measured points of the curve. Vereecken (1988) subdivided them into four major groups based on their functional form: the exponential, the power function, the cosinus hyperbolicus and error function relationships. Semi-empirical models are based on the idea of similarity between the shape of the particle size distribution and the shape of the water retention characteristic.

1.5.2.1. Exponential functions

Rogowski (1971) proposed the following set of equations to describe the WRC.

$$\frac{\theta-\theta_b}{\alpha}=\log(h-h_b+1) \qquad h\geq h_b \qquad [1.18]$$

$$\frac{\theta-\theta_b}{\beta}=\log(h_b-h+1) \qquad h<h_b \qquad [1.19]$$

$$\alpha=\frac{\theta_{15}-\theta_b}{\log(h_{15}-h_b+1)} \qquad h_b<h_{15} \qquad [1.20]$$

$$\beta=\frac{\theta_0-\theta_b}{\log(h_{15}-h_b+1)} \qquad h_b>h_s \qquad [1.21]$$

where θ_b is the soil water content at air entry (L^3L^{-3}), h_b is the matrix potential at air entry (L), h_{15} is the matrix potential at wilting point (L), h_s is the matrix potential at saturation and θ_S is the soil water content at saturation. The pressures are considered in terms of their absolute positive values.

Rewriting Equations 1.18 and 1.19 the following are obtained:

$$h^* = e^{\left(\frac{\theta-\theta_b}{\alpha}\right)} \qquad h > h_b \qquad [1.22]$$

$$h^* = e^{\left(\frac{\theta-\theta_b}{\beta}\right)} \qquad h \leq h_b \qquad [1.23]$$

where $h^* = h - h_b + 1$ [1.24]

Equation 1.19 can be further simplified by setting h equal to h_b for the range between h equal to 0 and h_b so that the water content becomes constant and equal to θ_b within this range. This model overestimates the water content at low pressure heads while having the tendency to underestimate at higher pressure heads (Vereecken, 1988).

Later (Rogowski, 1972) suggested a simplified linear model of the form:

$$\theta = \theta_L + \alpha_L \log\left(\frac{h}{h_L}\right) \qquad h_L \geq 1 \qquad [1.25]$$

$$\alpha_L = \frac{\theta_{15} - \theta_L}{\log(h_{15} - h_L)} \qquad [1.26]$$

θ_L and h_L are suitable values of water content and pressure , respectively, close to saturation.

Rewriting Equation.1.25:

$$\frac{h}{h_L} = e^{\left(\frac{\theta - \theta_L}{\alpha_L}\right)} \qquad [1.27]$$

Taking θ_L and h_L close to saturation ($h_L = 1$, $\theta_L \cong \theta_s$) he obtained:

$$h = e^{\left(\frac{\theta - \theta_s}{\alpha_L}\right)} \qquad [1.28]$$

In contrast to the first model Equations 1.18 and 1.19 this model overestimates the water content at high pressure heads (Rogowski, 1972).

Farrell & Larson (1972) proposed:

$$h = h_{min} e^{\alpha(\theta - \theta_s)} \qquad [1.29]$$

where α is a soil constant. Setting h_{min} equal to 1, the same equation form as Equation 1.28 is obtained.

1.5.2.2. Hyperbolic functions

King (1965) proposed a differential sigmoidal curve between residual and saturated water content as follows:

$$\theta = \frac{\theta_s \delta \left\{ \cosh\left[\left(\frac{h}{h_b} \right)^b + \varepsilon \right] - \gamma \right\}}{\left\{ \cosh\left[\left(\frac{h}{h_b} \right)^b + \varepsilon \right] + \gamma \right\}} \qquad [1.30]$$

where $b < 0$

$h_b > 0$

$0 < \delta < 1$

$\varepsilon > 0$

$0 < \gamma < \cosh(\varepsilon)$ and h^b, b, ε, γ are empirical parameters of the model.

Residual saturation can be defined as:

$$\lim_{h \to \infty} S = [\cosh(\varepsilon) - \gamma] / [\cosh(\gamma) + \gamma] = \theta_r / \theta_s = S_r \qquad [1.31]$$

$$\gamma = [(\theta_s - \theta_r) / (\theta_s + \theta_r)]\cosh(\gamma) \qquad [1.32]$$

Gilham *et al.* (1976) further simplified Equation 1.30 by setting ε equal to zero without loosing flexibility in describing the WRC.

1.5.2.3. Error function models

Starting from a transformed probability distribution of pore diameters, Laliberte(1969) obtained the following equation:

$$S_e = 0.5\mathrm{erfc}\left[\frac{a - b}{\left(c + \frac{h}{h_b} \right)} \right] \qquad [1.33]$$

where a, b and c have a unique relation with λ, the pore size distribution index in the Brooks-Corey equation of 1964. Indeed, Laliberte matched both, Equation 1.33 and the Brooks-Corey equation at low S_e values because he found the latter equation to perform well in the dry region of the WRC. By doing so, the equation looses much of its flexibility in describing WRC data because the wet end is fixed for a certain value. Van Genuchten & Nielsen (1985) suggested to keep at least one or two parameters in addition to h_b flexible in Equation 1.33 (e.g. b, c).

1.5.2.4. Power function models

Most of the equations for the WRC have been expressed in the form of a power function (e.g., Brooks & Corey, 1964; Visser, 1968; Ahuja & Swartzendruber, 1972; Campbell, 1974; Clapp & Hornberger, 1978; Ghosh, 1980; Van Genuchten, 1980; McBride & Mackintosh, 1984). The most popular ones are, however, those developed by Brooks & Corey (1964), Campbell (1974) and Van Genuchten (1980).

The Brooks-Corey equation

The Brooks-Corey equation has been one of the most popular functions used to describe the soil water retention curve. The model is based on theory used in petroleum engineering (Rogowski, 1972). The functional form of the Brooks-Corey equation is described by the following formula:

$$\begin{aligned} \frac{\theta-\theta_r}{\theta_s-\theta_r} &= \left(\frac{h_b}{h}\right)^{\lambda} && h < h_b \\ \theta &= \theta_s && h > h_b \end{aligned} \qquad [1.34]$$

where θ_s = saturated water content,

λ = pore size distribution index,

h_b = bubbling pressure or air entry pressure, and

θ_r = residual water content

Van Genuchten et al. (1991) described this equation as:

$$\begin{aligned} \theta &= \theta_r + (\theta_s - \theta_r)(\alpha h) && (\alpha h > 1) \\ \theta &= \theta_s && (\alpha h \geq 1) \end{aligned} \qquad [1.35]$$

When written in a dimensionless form, Equation 1.35 becomes:

$$S_e = (\alpha h)^{-\lambda} \qquad (\alpha h > 1)$$
$$S_e = 1 \qquad (\alpha h \leq 1) \qquad [1.36]$$

where S_e is the effective degree of saturation, also called the reduced water content ($0 \leq S_e \leq 1$):

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad [1.37]$$

Bubbling pressure, h_b, is approximately equal to the minimum negative pressure of soil water at which, on drainage, the air phase is continuous in the porous material (Brooks & Corey, 1964).

On a logarithmic plot, Equation 1.36 generates two straight lines which intersect at the air entry value, $h_b = 1/\alpha$ (Van Genuchten *et al.*, 1991).

The Brooks-Corey equation has been shown to produce relatively accurate results for many coarse-textured soils characterized by relatively narrow pore- or particle-size distribution (Van Genuchten *et al.*, 1991). Applications to fine-textured and well structured field soils were less successful because of the absence of a well-defined air entry value for these soils. Especially, there seems to be an overestimation of the water content at low matric potentials (Laliberte, 1969). Equations for estimating the parameters for the Brooks-Corey equation developed by Rawls & Brakensiek (1985) and Bloemen (1977) (cited by Rawls *et al.*, 1991) are presented in Table 1.3. Rawls *et al.* (1991) determined the parameters for the Brooks-Corey equation for different soil texture classes (Table 1.4).

Van Genuchten (1980) showed that a discontinuity occurs in the slope of the soil water retention curve, at the bubbling pressure, when the Brooks-Corey function is used. Such a discontinuity sometimes prevents rapid convergence in numerical saturated-unsaturated flow problems.

Brakensiek *et al.* (1981) found a reasonably accurate representation of the water retention curve for tensions greater than 50 cm using the Brooks-Corey function.

Clapp & Hornberger (1978) tried to solve this problem by fitting a parabolic equation through the wet part of the water retention curve.

Setting θ_r equal to zero in Equation 1.35 the equation as proposed by McBride & Mackintosh (1984) is derived:

$$\theta / \theta_s = (\alpha h)^{-mn} \qquad [1.38]$$

$$\theta = \theta_s (\alpha h)^{-mn} \qquad [1.39]$$

$$\log_{10} \theta = \log_{10} \theta_s + \log_{10} (h)^{-mn} - \log_{10} (h_b)^{-mn} \qquad [1.40]$$

with the water content expressed in weight percentage and -mn = $-\lambda$.

They further replaced θ_s by the water content at h_b, which is defined as approximately $0.9\theta_{ms}$, where θ_{ms} is the saturated soil water content in percentage when all the pores are filled:

$$\theta_{ms} = \left\{\left[1 - \left(\frac{\rho_s}{2.65}\right)\right]\right\} 100 \qquad [1.41]$$

and (-mn) is set equal to:

$$-mn = \frac{\log_{10} \theta_{m15} - \log_{10} \theta_{mi}}{\log_{10} h_{15} - \log_{10} h_{mi}} \qquad [1.42]$$

with θ_{m15} = water content at wilting point expressed in weight percentage;θ_{mi} = water content at pressure head i expressed in weight percentage.

Campbell's equation

Campbell (1974) proposed an empirical expression relating water content to water potential for limited ranges of water contents. Campbell's equation is derived from

Brooks-Corey equation (Eq. 1.34) by setting the residual water content equal to zero. His equation is of the form:

$$\frac{\theta}{\theta_s} = \left(\frac{h_b}{h}\right)^{\frac{1}{b}} \qquad [1.43]$$

θ_s = saturated water content;

h_b = bubbling pressure or air entry pressure; and

b = constant (the slope of ln h vs ln θ).

Table 1.3 Estimation equations for water retention equations

A. Brooks-Corey parameters (Rawls & Brakensiek, 1985)
h_b: Brooks-Corey bubbling pressure (cm)
$h_b = e[5.340 + 0.185(C) - 2.484(\phi) - 0.002(C^2) - 0.044(S)(\phi) - 0.617(C)(\phi) + 0.001(S^2)(\phi^2) - 0.00001(S^2)(C) + 0.009(C^2)(\phi) - 0.0007(S^2)(\phi) + 0.00000(C^2)(S) + 0.500(\phi^2)C]$
λ: Brooks-Corey pore-size distribution index
$\lambda = e[-0.784 + 0.018(S) - 1.062(\phi) - 0.00005(S^2) - 0.003(C^2) + 1.111(\phi^2) - 0.031(S)(\phi) + 0.0003(S^2)(\phi^2) - 0.006(C^2)(\phi^2) - 0.000002(S^2)(C) + 0.008(C^2)(\phi) - 0.007(\phi^2)(C)]$
θ_r: Brooks-Corey residual water content (vol. fraction)
$\theta_r = -0.018 + 0.0009(S) + 0.005(C) + 0.029(\phi) - 0.0002(C^2) - 0.001(S)(\phi) - 0.002(C^2)(\phi^2) + 0.0003(C^2)(\phi) - 0.002(\phi^2)(C)$, where S = percentage sand, C = percentage clay and ϕ total porosity.

B. Brooks-Corey parameters (Bloemen, 1977)
$h_b = 2914\ b^{0.79}\ Md^{-0.96}$
$\lambda = 1.512(e^{0.3b} - 1)$
b= grain size distribution index (Eq 1.17)
Md = median grain size (mm)

The values for h_b and b are usually found by plotting water release data on a log-log scale and fitting a straight line to the data (Campbell, 1985). The bubbling pressure is expected to decrease (become more negative) as the mean pore diameter become smaller, and b to increase as the standard deviation of pore size increases. When b is equal to zero, all of the water is held at a single potential, and when b approaches infinity, no change in water content occurs when h changes.

By fitting Campbell's equation to data, Hall *et al.* (1977) and Bache *et al.* (1981) found the following approximate relationships for soils at a bulk density of 1.3 Mg m^{-3}:

$$h_b = -0.5d_g^{-1/2} \quad [1.44]$$

$$b = -2h_b + 0.2\delta_g = d_g^{-1/2} + 0.2\delta_g \quad [1.45]$$

This relationship has been used by Wagner *et al.* (1998) to derive the constant b. The parameters d_g (geometrical mean particle size) and δ_g (geometrical standard deviation) are derived from the main grain size fractions of a soil using the formula of Shirazi & Boersma (1984) (Eq. 1.16 and 1.17).

A similar type of equation has been used by Clapp & Hornberger (1978) to describe the water retention curve:

$$h = h_s W^{-b} \quad [1.46]$$

where W represents the soil wetness and is equal to θ/θ_s, h_s is the 'saturation' suction. The use of this equation implies a sharp discontinuity in suction, or tension, near saturation (Campbell, 1974).

Wagner *et al* (1998) demonstrated that the Campbell equation produced reasonably good correlation ($R^2 = 0.82$) with the measured data of six German soils. They also indicated that the presence of high organic matter might lead to poor model prediction when the Campbell model is used as this model does not account for the effect of organic matter. The parameters for the Campbell model were determined by researchers for the different USDA textural classes (Table 1.5).

Van Genuchten model

Several continuously differentiable (smooth) equations have been proposed to improve the description of soil water retention near saturation. These include functions introduced by King (1965), Visser (1968), Laliberte (1969), Su & Brooks (1975) and Clapp & Hornberger (1978). While these functions were able to reproduce

Table 1.4 Water retention properties for the different soil texture classes

Texture class	Sample size	Total Porosity (ϕ) cm^3 cm^{-3}	Residual water content (θ_r) cm^3 cm^{-3}	Brooks-Corey Parameters				Water Retained at	
				Bubbling pressure (h_b)		Pore size distribution index (λ)			
				Arithmetic (cm)	Geometric (cm)	Arithmetic (cm)	Geometric (cm)	-33 KPa (cm^{3}cm^{-3})	-1500 KPa (cm^3 cm^{-3})
S	762	0.437 (0.374-0.500)	0.020 (0.001-0.039)	15.98 (0.24-31.72)	7.26 (1.36-38.74)	0.694 (0.298-1.090)	0.592 (0.334-1.051)	0.091 (0.018-0.164)	0.033 (0.007-0.059)
LSa	338	0.437 (0.368-0.506)	0.035 (0.003-0.067)	20.58 (-4.04-45.20)	8.69 (1.80-41.85)	0.553 (0.234-0.872)	0.474 (0.271-0.827)	0.125 (0.060-0.190)	0.055 (0.019-0.091)
SL	666	0.453 (0.351-0.555))	0.041 (-0.024-0.106)	30.20 (-3.61-64.01)	14.66 (3.45-62.24)	0.378 (0.140-0.616)	0.322 (0.186-0.558)	0.207 (0.126-0.288)	0.095 (0.031-0.159)
L	383	0.463 (0.375-0.551)	0.027 (-0.020-0.074)	40.12 (-20.07-100.3)	11.15 (1.63-76.40)	0.252 (0.086-0.418)	0.220 (0.137-0.355)	0.270 (0.195-0.345)	0.117 (0.069-0.165)
SiL	1206	0.501 (0.420-0.582)	0.015 (-0.028-0.058)	50.87 (-7.68-109.4)	20.76 (3.58-120.4)	0.234 (0.105-0.363)	0.211 (0.136-0.326)	0.330 (0.258-0.402)	0.133 (0.078-0.188)
SaCL	498	0.398 (0.332-0.464)	0.068 (-0.001-0.137)	59.41 (-4.62-123.4)	28.08 (5.57-141.5)	0.319 (0.079-0.559)	0.250 (0.125-0.502)	0.255 (0.186-0.324)	0.148 (0.085-0.211)
CL	366	0.464 (0.409-0.519)	0.075 (-0.024-0.174)	56.43 (-11.44-124.3)	25.89 (5.80-115.7)	0.242 (0.07-0.414)	0.194 (0.100-0.377)	0.318 (0.250-0.386)	0.197 (0.115-0.279)
SiCL	686	0.471 (0.418-0.524)	0.040 (-0.038-0.118)	70.33 (-3.26-143.9)	32.56 (6.68-158.7)	0.177 (0.039-0.315)	0.151 (0.090-0.253)	0.366 (0.304-0.428)	0.208 (0.138-0.278)
SaC	45	0.430 (0.370-0.490)	0.109 (0.013-0.205)	79.48 (-20.15-179.1)	29.17 (4.96-171.6)	0.223 (0.048-0.398)	0.168 (0.078-0.364)	0.339 (0.245-0.433)	0.239 (0.162-0.316)
SiC	127	0.479 (0.425-0.533)	0.056 (-0.024-0.136)	76.54 (-6.47-159.6)	34.19 (7.04-166.2)	0.150 (0.040-0.260)	0.127 (0.074-0.219)	0.387 (0.332-0.442)	0.250 (0.193-0.307)
C	291	0.475 (0.427-0.523)	0.090 (-0.015-0.195)	85.6 (-4.92-176.1)	37.30 (7.43-187.2)	0.165 (0.037-0.293)	0.131 (0.068-0.253)	0.396 (0.326-0.466)	0.272 (0.208-0.336)

* Sa = sand; LSa = loamy sand; SaL = sandy loam; L= loam; SiL = silt loam; SiCL = silty clay loam; SaCL = sandy clay loam; CL = clay loam; SaC = sandy clay; SiC = silty clay; C = clay.

Table 1.5 Representative Campbell equation parameters for USDA soil texture classes

Texture	b			h_b			ϕ		
	1*	2*	3*	1	2	3	1	2	3
Sa	1.44	4.05	3.21	15.98	12.10	8.39	0.44	0.40	0.40
LSa	1.81	4.38	4.09	20.58	9.0	12.68	0.44	0.41	0.39
SaL	2.64	4.90	4.78	30.20	21.8	26.03	0.45	0.44	0.39
L	4.51	5.39	6.60	40.12	47.8	26.63	0.46	0.45	0.49
SiL	4.74	5.30	7.34	50.87	78.6	19.41	0.50	0.49	0.48
SiCL	3.13	7.75	7.95	59.41	35.6	13.26	0.40	0.48	0.57
SaCL	4.13	7.12	-	56.43	29.9	-	0.46	0.42	-
CL	5.65	8.52	9.84	70.33	63.0	10.21	0.46	0.48	0.50
SaC	4.48	10.40	-	79.48	15.3	-	0.43	0.43	-
SiC	7.87	10.40	10.26	76.54	49.0	16.98	0.48	0.49	0.53
C	6.06	11.40	12.71	85.60	40.5	12.24	0.48	0.48	0.53

* Sa = sand; LSa = loamy sand; SaL = sandy loam; L= loam; SiL = silt loam; SiCL = silty clay loam; SaCL = sandy clay loam; CL = clay loam; SaC = sandy clay; SiC = silty clay; C = clay. 1= Rawls *et al.* (1982), 2 = Clapp & Hornberger (1978), 3 = De Jong (1982).

observed soil water retention data more accurately, most are mathematically too complicated to be easily incorporated into predictive pore-size distribution models for the hydraulic conductivity, or possess other features that make them less attractive in soil water studies (Van Genuchten & Nielsen, 1985). A smooth function with attractive properties is the equation of Van Genuchten (1980).

$$S_e = \left(\frac{1}{1+(\alpha h)^n} \right)^m \qquad [1.47]$$

where S_e is the effective degree of saturation (Eq. 1.37) and α, n and m are empirical constants affecting the shape of the retention curve. θ_r is generally defined as the water content where the soil solution does not contribute anymore to the flow (Brooks & Corey, 1964; Brutsaert, 1966). Van Genuchten (1980) defined θ_r as the water content at which the gradient ($d\theta/dh$) becomes zero, excluding the region near θ_s which also has a zero gradient. It can be measured experimentally, for example, by determining the water content of air dry soil. For practical reasons it seems sufficient to define θ_r as the water content at some large negative value of the pressure head, e.g., at the permanent wilting point (h = -1500 cm) (Van Genuchten, 1980). Even in that case, however, significant decreases in h are likely to result in further desorption of water, especially in fine-textured soils. Rather than being a quantity that can be measured experimentally, θ_r is regarded as a parameter, which has to be obtained through data fitting (Brooks & Corey, 1964; Laliberte, 1969; Van Genuchten, 1980).

Equation 1.47 with m = 1 has been used successfully earlier by Ahuja & Swartzendruber (1972), Endelman *et al.* (1974), Haverkamp *et al.* (1977) and Varallyay & Mironenko (1979), amongst others. Recently it has been used by Vereecken *et al.* (1989), Minasny *et al.* (1999); Scheinost *et al.* (1997); Wösten *et al.* (1999) and van den Berg *et al.* (1997). Equations that can be used to estimate the parameters for the van Genuchten equation were proposed by Vereecken (1988) (Table 1.6).

Table 1.6 Parameter estimation equations for the Van Genuchten's water retention equation

C. Van Genuchten parameters (Vereecken, 1988)
$\theta_r = 0.015 + 0.005(C) + 0.014(Ca)$
$\alpha = 10^{(-2.486 + 0.025(S) - 0.351(Ca) - 2.617(bd) - 0.023(C)}$
$n = 10^{\left(0.053 - 0.009(S) - 0.013(C) + 0.00015(S^2)\right)}$
$m = 1 - 1/n$,
where: S = percentage sand, C = percentage clay, Ca = percentage organic carbon content and bd = bulk density (g/cm^3)

1.6. Approaches for estimating soil water retention from soil properties and characteristics

Since water retention by a soil is affected by other physical properties, such as texture and structure, it is possible to develop empirical relationships to predict soil water retention (Minasny *et al.*, 1999). Bouma (1989) introduced the term pedotransfer function (PTF), which he described as translating data we have into what we need, i.e.

predictive functions of certain soil properties from other easily, routinely, or cheaply measured properties.

Minasny *et al.* (1999) divided the PTFs for predicting the water retention curve into three types.

1. Point estimation: This approach estimates the water content of the soil at certain predefined matric potentials using multiple linear regression (Husz, 1967; Renger, 1971; Gupta & Larson, 1979; Rawls & Brakensiek, 1982; Puckette *et al.*, 1985; Minasny *et al.*, 1999; van den Berg *et al.*, 1997; Hutson, 1986; Gaiser *et al.*, 2000) or artificial neural networks (Pachepsky *et al.*, 1996).
2. Parametric estimation: This approach estimates the parameters of a hydraulic model that is a closed-form equation, assumed to describe the h(θ) relationship (e.g., Brooks & Corey, 1964; Rawls & Brakensiek, 1985; Campbell, 1974; van Genuchten, 1980; Pachepsky *et al.*, 1982; Cosby *et al.*, 1984; Nicolaeva *et al.*, 1986; Vereecken *et al.*, 1989; Minasny *et al.*, 1999; Scheinost *et al*, 1997, Wösten *et al.*, 1999, van den Berg *et al.*, 1997). This is done through multiple linear regression (Vereecken *et al.*, 1989; Scheinost *et al.*, 1997; Minasny *et al.*, 1999; Wösten *et al.*, 1999) or artificial neural networks (Pachepsky *et al.*, 1996; Schaap & Leij, 1998; Minasny *et al.*, 1999; Schaap *et al.*, 1999).
3. Physico-empirical models: In this approach the water retention curve is derived from physical attributes (Arya & Paris, 1981; Haverkamp & Parlange, 1986) and the use of fractal mathematics and scaled similarities (Tyler & Wheatcraft, 1989; Comegna *et al.*, 1998). Arya & Paris (1981) translated the particle-size distribution into a water retention curve by converting the solid mass fractions into water content, and pore-size distribution into hydraulic potential by means of a capillary equation. The problem with this method is that it needs information about the packing of soil particles.

Although the point estimation method is used extensively, it has some serious limitations. One of the major disadvantages is that through its application no physical insight is acquired in the behaviour of the specific hydraulic property under study (Vereecken, 1988). The relationships between the hydraulic and other soil properties are merely exercises of applying statistical tools, trying to find the best equations. If the complete hydraulic behaviour of the soil is envisaged, it is still necessary to fit a line through the estimated data points, either by hand or some kind of curve fitting technique. The estimated data points, based on regression, will not always guarantee a sound physical behaviour unless enough precautions are taken to prevent this, like pre-smoothing. Point estimation further hampers comparing hydraulic behaviour of different soils, unless visual comparison of the smoothed curves is satisfactory.

In the parameterization method the need exists to find an appropriate model describing the water retention curve. In the best case, the model can be linearized, reducing the estimation problem to linear regression analyses. In other cases, the models can be intrinsically non-linear, needing a non-linear parameter estimation technique. These techniques are often difficult to handle and do not always converge.

Although this is a limitation of concern, especially when large datasets and different competitive models with varying degree of complexity are involved, the parameterisation approach offers a lot of possibilities compared to point estimation. The complete measuring range for water retention properties can be generated from only a few measurements. It enhances the interpretation of water retention properties, and their mutual comparison, on the basis of parameters. Because a mathematical model for the physical behaviour has to be assumed, the physical soundness of the estimated water retention is guaranteed. A mathematical model for water retention, using the parameterisation method, offers the advantage of a large flexibility in mathematical operations. An appropriate choice of a model for water retention characteristic could for instance result in closed form equations for the different $K(\theta)$ models.

1.7. Approaches in parameter estimation

Unsaturated soil hydraulic properties are commonly represented by empirical equations, which define the relationship between wetting fluid conductivity, saturation and capillary pressure. The estimation of soil hydraulic properties then reduces to estimating parameters for the appropriate constitutive model (Mishra *et al.*, 1989). Estimation of the parameters, given a set of measured or observed responses, known to be dependent on a set of independent variables or predictor variables with a known or unknown model structure, is, however, difficult. Mathematically this can be written as:

$$\bar{Y} = f(X, \bar{\beta}, \bar{\varepsilon}) \quad [1.48]$$

where $\bar{Y}$ is the column vector representing the dependent variable (nx1);
X is the design matrix of the independent variable(s) assumed non stochastic in most problems of parameter estimation;
$\bar{\beta}$ is the column vector of unknown parameters (px1); and
$\bar{\varepsilon}$ is the error term which is mostly unknown.

If the model is correct, the error term represents the variation in the dependent variable due to measurement errors or stochastic variation. If there are errors in the model equation, a model error component has to be considered. The model is then known to be inexact (Bard, 1974). An inexact model describes approximately the true values of the variables due to neglecting some processes in the model. Assuming the errors additive, we can write:

$$\bar{Y} = f(X, \bar{\beta}) + \bar{\varepsilon} \quad [1.49]$$

If the dependent variables are measured without error, the model is reduced to what is called the standard model (Bard, 1974) or commonly known as a regression model. This is a group of models for which the parameter estimates are easiest to obtain. Equation 1.49 can represent both a linear and a non-linear model. A model is defined to be linear if the parameters can be written in the following form:

$$\bar{Y} = X\bar{\beta} \quad [1.50]$$

In other words, linear estimation problems are problems where the model is a linear or linearizable expression of the unknown parameters. Bard (1974) clearly points out that even when a model is linear, the estimation procedure can be a non-linear estimation procedure depending upon the chosen object function. If this is not of the quadratic form (least squares), the resulting equations, which have to be solved, are no longer linear.

Many parameter estimation problems can be formulated as a weighted least-squares minimization problem (Kool *et al.*, 1987):

$$\min O(b) = 1/2[q^* - q(b)]^T W[q^*-q(b)] + 1/2[b^*-b)^T V(b^*-b) \qquad [1.51]$$

where the objective function (or performance index), O(b) is a function of the model parameters b, $b = \{b_1, \ldots, b_m\}^T$; $q^* = \{q_1, \ldots, q^*_n\}^T$ is the observation vector whose elements represent measured heads, water contents, concentrations or fluxes; $q(b) = \{q1(b), \ldots, q_n(b)\}T$ represents the predicted response for a given parameter vector b; b* represents direct estimates or measurements of the parameters b ; and W and V are symmetric weighting matrices. The coefficient 1/2 is purely for notational convenience.

The objective is to find the parameter vector b^f that minimizes Equation 1.51 or, in other words, results in a best fit between the model and available data. If the problem has a unique solution, the final parameter values b^f are also best estimates for the unknown model parameters b.

The weighting matrices W and V contain information about measuring accuracy, as well as possible correlations between measuring errors and between parameters. In the absence of any additional information besides the observations q*, the simplest and recommended (Beck & Arnold, 1977) approach is to set W equal to the identity matrix and V to zero:

$$W = 1, V = 0 \qquad [1.52]$$

In this case, Equation 1.51 reduces to the well-known Ordinary Least-Squares (OLS) procedure:

$$\min O(b) = \frac{1}{2}\left[q^* - q(b)\right]^T\left[q^* - q(b)\right] = \frac{1}{2}\sum_{i=1}^{n}\left[q^* - q(b)\right]^2 \qquad [1.53]$$

The OLS formulation has probably been the most widely used procedure for parameter estimation. Its advantage is due to its simplicity and because it requires a minimum amount of information. When observation errors are normally distributed, are uncorrelated and have a constant variance, the OLS possess optimal statistical properties (Bard, 1974). When these conditions are not met, the OLS method will no longer yield optimal parameter estimates in terms of precision and minimum variance. When the normality assumption alone is violated, OLS can still be used with good results (Beck & Arnold, 1977).

More serious difficulties arise due to violation of the constant variance and uncorrelated errors assumptions. The remedy is to use weighting through the matrices W and V. In what is generally called the weighted least squares (WLS) method, W is the diagonal matrix which corrects for unequal error variances, and V is taken as zero. The elements of W are chosen such that the most accurate measurements receive the most weight. The elements of W and V may be chosen by the modeller based on knowledge and understanding of the physical system. Since subjective procedures may lead biased parameter estimates, a preferred method is to base the weighting on statistical considerations. This leads to selection of the inverse of the error covariance matrix as the weighting matrix:

$$W = C_q^{-1} \tag{1.54}$$

$$C_q = E[(q^* - \bar{q})(q^* - \bar{q})^T] \tag{1.55}$$

$$\bar{q} = E(q^*) \tag{1.56}$$

where E denotes expectation. The diagonal elements of W account for unequal error variances, and off-diagonal elements for correlated errors. In case the off-diagonal elements of W are also taken into account, the method is classified as generalized least squares (GLS). Often, when a method is described as WLS or GLS, no prior information on the parameters themselves is presumed and the objective function consists of only the first term of Equation 1.51.

CHAPTER 2

MATERIALS AND METHODS

2.1. Sites

Before describing the sites from which samples were collected, it was felt necessary that due to the effect of parent material on soil characteristics to give a brief description on the geology of the Hararghe Highlands, from where most of the samples were collected.

Geology and soils of Hararghe Highlands

The Hararghe Highlands lie over the crystalline bedrock of the pre-historic Gondwana continent that became fractured at a much later time (Mohr, 1964: cited by Tamirie et al, 1986). The hard rocks of the Gondwana continent (granite and gneiss) which were formed during the pre-Cambrian period lay as peneplains below sea level for a long period, resulting in the deposition of very ancient sedimentary rocks in eastern Ethiopia, as throughout Ethiopia. These limestones and sandstones were laid down during the Triassic, when the sea again covered the eastern part, and the Jurassic and Cretaceous periods. The sandstones were formed in the deeper areas of the sea, with the limestones being deposited in the shallower parts. The last small deposits were formed at the end of the Miocene period. The thickness of the deposits varies; at Hakim Gara, the southern edge of Harar city, the sandstone-formation is 50 meters thick and contains a thin band of limestone containing fish fossils. Volcanic material is found mixed in the beds above the old crystalline rocks. In many places, the most recently formed rocks have been eroded and those of the original continent were exposed once more. In the region surrounding the city of Harar, mostly eroded remains of the eastern plateau are being found (Mohr, 1964; Murphy, 1959, 1963 and 1968).

The pre-Cambrian metamorphic rocks, granite, and to a lesser extent gneiss and micaschists, are particularly exposed throughout the Alemaya, Hundene, Fedis, Jarso, Kombolcha, Kersa-Dengego areas and all along the main highways throughout the Hararghe Highlands (Mohr, 1964; Tamirie, 1974).

Though there is a general similarity in the geology of the Hararghe Highlands, the unique combination of soil forming factors and processes resulted in the formation of different types of soils in the region. As a result, different types of soil units occur in different landscapes of the region. Rock outcrops cover most of the top parts of the highlands. The soils that developed there are mostly shallow and have only an A-horizon overlying the bedrock (Tamirie, 1981). The general sequence of soil orders from the top of the highlands down to the valley bottoms, as reported by Tamirie (1981), are Lithosols, Regosols, Alfisols, Cambisols, Fluvisols and Vertisols.

There is no suitable soil map of the region available. According to the reconnaissance survey made by Tamirie (1981), the dominant soil orders that occur in Hararghe Region are Lithosols, Regosols, Yermosols, Fluvisols, Cambisols, and Vertisols and in some places Alfisols. Different associations of these and other soil orders were described.

In selecting sampling sites for this study, major emphasis was placed on the type of soils that occur at those sites. Care was taken that the selected soil types represented the major textural classes and horizons in the profiles. This was done to secure a large variation in soil properties, reinforcing the generalization capacity of the derived models.

From the general information on soil types, occurring in Hararghe Region (Tamirie, 1981), a total of 14 sites were selected from west and east Hararghe, Dire Dawa and Jijiga regions (Figures 2.1 and 2.2). Within these 14 sites, a total of 26 profiles were opened. At some sites where there were several different soil types, 2 to 5 profiles were opened. The sites selected were: Gelemso, Bedessa, Chiro, Hirna, Karamille, Langae, Kersa, Adele, Dire Dawa, Alemaya University Campus, Hamaresa, Kombolcha, Babile and Jijiga (Figure 2.3). Table 2.1 shows the number of profiles opened at each site. A brief description of each profile is given in Appendix 2.1.

Table 2.1 List of sites and number of profiles opened at each site

Site	Wereda	Code	Number of profiles
Gelemso	Habro	GP1-2	2
Bedessa	Kuni	BEP1-2	2
Chiro Jello Catchment	Chiro	CJP1-5	5
Hirna	Tulo	HP1-2	2
Karamille		KP	1
Langae	Kersa	LP	1
Kersa	Kersa	KE	1
Adele	Kersa	AD	1
Dire Dawa	Dire Dawa	DP	1
Alemaya University Campus	Alemaya	AUP1-4	4
Hamaresa	Hundene	HA	1
Kombolcha	Kombolcha	KO	1
Babile	Babile	BA	1
Jijiga	Jijiga	JP1-3	3

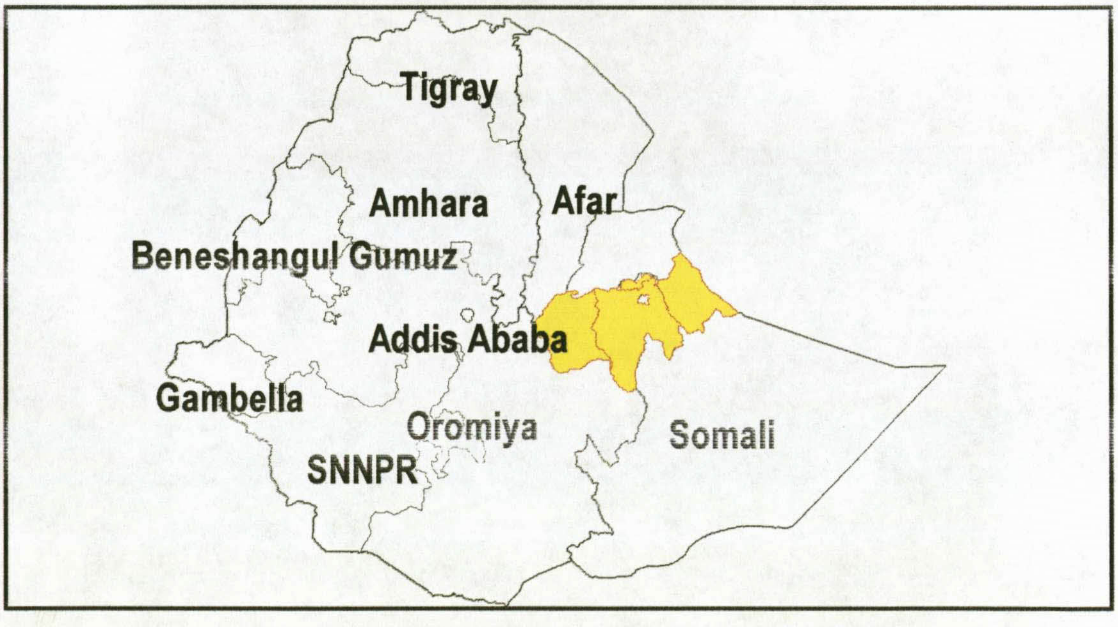


Fig. 2.1. Map of Ethiopia showing the study sites (shaded areas) in Hararghe Region.

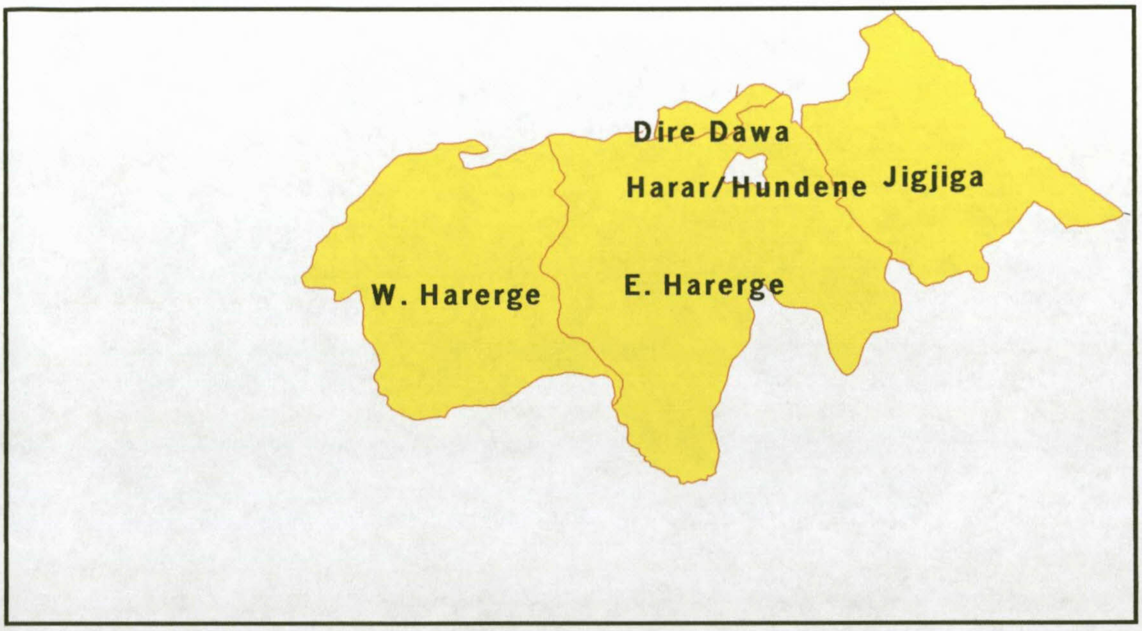


Figure 2.2 Map of the study sites in Hararge Region.

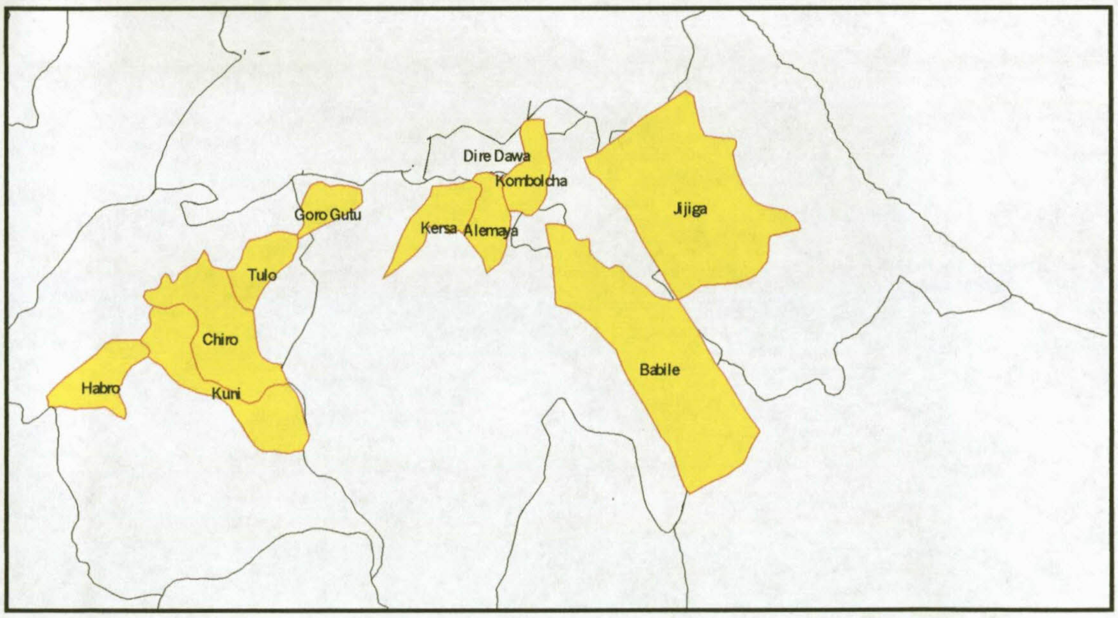


Figure 2.3 Map of sampling sites (shaded areas) in the study areas.

2.2. Soil sampling

A total of 230 disturbed and 230 undisturbed samples were collected in duplicate from the 26 profiles giving a total of 460 samples. As there was a difference in the number of horizons in each profile, the number of samples collected from the different profiles varied.

Undisturbed samples were taken with a soil sampler similar to the procedure described by Blake & Hartge (1986a). To minimize compaction during sampling, three sample holders (3 cm long and 5 cm in diameter) were inserted into the soil sampler. The sampler had a 10 cm cylindrical end to accommodate the three core holders. The middle sample holder was retained for soil water retention measurements. Undisturbed and disturbed samples were taken at 10 cm depth increments for each horizon. Horizons with a thickness less than 10 cm were skipped.

After the particle size distribution analyses were done, 14 samples were discarded because their texture were exactly the same, leaving a total of 216 samples.

2.3.1. Water retention curves

To ensure a representative water retention curve, the water contents were measured at nine matric potentials namely -1, -5, -8, -10, -30, -60, -100, -300 and -1500 kPa. The samples were saturated from the bottom in order to remove entrapped air. The appearance of a thin layer of free water on the surface of the core samples was taken as an indicator of saturation. The samples were weighed for later water content calculations. Since 100 % saturation is difficult to attain, it was assumed that the matric potential at this water content was approximately -1 kPa. The higher matric potentials (-5 and -8 kPa) were determined using a sand suction table (Stakman *et al.*, 1969). The samples were saturated as described above and placed in hydraulic contact with the suction table before suction was applied. The suction was applied with a vacuum pump with a vacuum regulator. The equilibrium weight was recorded so that the water content could be calculated after the samples were oven-dried at the end of all the measurements. The same undisturbed samples were resaturated and used in a pressure plate extractor for measuring water contents corresponding to matric potentials of -10, -30,- 60, and -100 kPa. The samples were then removed from the soil cores and dried at 105 °C for 24 hours and weighed to calculate the water contents and bulk densities. From these disturbed samples were placed in a pressure plate extractor for determining the water content at -300 kPa and in a ceramic plate extractor for the water content at -1500 kPa. The water contents corresponding to these matric potentials were determined gravimetrically.

2.3.2. Particle size analysis

Subsamples from the disturbed samples were used to determine the particle size distribution with the pipette method (Day, 1965). The following six granular fractions 2000 to 500, 500 to 250, 250 to 50.3, 50.3 to 20.0, 20.0 to 2, and < 2 μm were separated. The samples were dispersed; the silt and clay fractions were separated from the sand after which the sand was further separated by dry sieving. For the characterization of the particle size distributional properties the six particle size classes were used to calculate the geometrical mean particle size (GMPS) and the geometrical standard deviation (GSD) were calculated using the method of Shirazi & Boersma (1984) (Eq. 1.16 and 1.17) with n equal to 6.

2.3.3. Dry bulk density

The dry bulk density was calculated from the oven dry mass and volume of the undisturbed soil cores that were used for the determination of the water retention curve.

2.3.4. Organic carbon content

The organic carbon content was determined on subsamples of the disturbed sample with means of the Walkley & Black (1934) method.

CHAPTER 3

EFFECT OF SOIL PROPERTIES ON SOIL WATER RETENTION

3.1. Introduction

Soil water retention relationships are not unique and are affected by a number of environmental and soil factors. Childs (1940) (cited by Williams *et al.*, 1983) indicated that the characteristics of soil water retention curves are related to morphological soil properties like texture and structure, and to the nature and amount of colloidal material contained both as organic matter and as clay-sized minerals. Ekern (1963) and Cagauan & Uehara (1965) found definite patterns between water retention curves with changes in soil structure. Rawls *et al.* (1991) described irregular pore geometry and discontinuity, and variations in texture and mineralogy as the primary soil properties influencing soil water retention. Sharma & Uehara (1968) mentioned soil composition, pore-size distribution, and temperature as important factors that control water retention in soils. They further indicated that soil composition is influenced by differences in mineralogy, organic matter and soluble salt content and pore-size distribution as affected by texture and structure of the soil system. In their study, they demonstrated that the role of texture becomes less important with increasing structural development. This implies that in strongly structured soils, soil water retention cannot be predicted from texture alone.

Different factors influence water retention at different suctions. The amount of water retained at low suctions (0-100 kPa) depends primarily upon the capillary effect and, in non-shrinking soils, on pore size distribution, and hence is strongly affected by the structure of the soil (Reeve & Carter, 1991). Sandy soils contain many macro pores, and the majority of the water is released at low suctions. Clay soils on the contrary contain less macro pores and release small amounts of water at low suctions and retain a large proportion of their water. On the other hand, water retentions at high suctions are a function of adsorption and are thus influenced by the specific surface of the soil material.

Clay mineralogy is also important. Smectitic clays (2:1) with a high cation exchange capacity and specific surface have larger adsorption forces than 1:1 kaolinitic clays (Lambooy, 1984). Baumer & Brasher (1982) indicated that clay mineralogy is an important factor influencing soil water retention in soils containing more than 10 % clay. In addition, the cation exchange capacity, which is determined by clay type and content, may also be important (Baumer & Brasher, 1982; Kutilek, 1973). El Ashkar *et al.* (1956) and Pachepsky (1989) indicated that sodium hyposulfide-soluble iron oxides and the cation exchange capacity were related to soil water retention. The presence of organic matter increases the amount of water retained, especially at high potentials, but at lower potentials, soils rich in organic materials release water rapidly. The presence of free iron oxides and calcium carbonate has also been shown to affect water retention (Williams *et al.*, 1983; Stakman & Bishay, 1976). The effect of free iron is difficult to separate from the effect of high clay contents and good structural conditions with which it is often associated (Prebble & Stirk, 1959) (cited by Reeve & Carter, 1991).

Soil structure and bulk density have significant effects. Compaction decreases the total pore space of a soil (Archer & Smith, 1972), mainly by reducing the amount of large pores, which is responsible for retaining water at low suctions. Whereas the amount of fine pores remains largely unchanged, the amount of intermediate size pores is sometimes increased, and this can increase the amount of water retained between specific matric suctions of agronomic importance (Reeve & Carter, 1991). Rawls *et al.* (1991) indicated that bulk density has a greater effect on water retention at matric potentials higher than -33 kPa. In natural soils, aggregation tends to dominate soil water retention only at high water contents, whereas texture and clay mineralogy become more important at low water contents. For example, Gardner (1968) found that the soil water content at –1500 kPa was highly correlated with the soil surface area. A number of researchers (Williams *et al.*, 1990; Croney & Coleman, 1954; Sharma & Uehara, 1968) have demonstrated that the presence or absence of soil structure has a dramatic impact on the shape of the water retention curve.

Chemical properties of the soil that affect the integrity of soil aggregates are also important factors that affect soil water retention (Rawls *et al.*, 1991). Baumer &

Brasher (1982) demonstrated that the sodium adsorption ratio is an important field-scale parameter affecting water retention because of its effect on clay dispersion.

Pedotransfer functions (PTFs) are becoming a more common way to predict soil hydraulic properties from soil texture, bulk density and organic matter content (Schaap & Leij, 1998). These functions are used to estimate soil hydraulic properties when direct measurements are too expensive or not available. The functions transform soil properties such as texture, bulk density and organic matter content into water retention values.

Many different types of PTFs have been developed (Rawls *et al.*, 1991) but all need to be calibrated on existing data before true predictions can be made. Consequently, the applicability of a PTF can only be established objectively on independent data, i.e., data not used for calibration. Recently, several such evaluations have been carried out. Tietje & Tapkenhinrichs (1993) tested 13 PTFs for water retention using a German database of 1079 samples. They found that the PTF of Vereecken *et al.* (1989) was applicable to many soils and provided relatively low root mean square residuals (0.05 cm^3 cm^{-3}), but it gave a systematic underestimation of water contents. In another study encompassing more than 25000 samples, Kern (1995) evaluated six water retention PTFs. Results of this study show that water content at pressure heads of –10, -33, and –1500 kPa were often over- or under-estimated. However, all these PTFs have been developed with data sets from temperate or subtropical regions. Van den Berg *et al.* (1997) obtained regression equations for soils of humid tropics.

The testing of models for soils from temperate regions with soil data from humid tropical regions yielded unsatisfactory results (Idike & Ejieji, 1993; Tomasella & Hodnett, 1998). Tomasella & Hodnett (1998) suggested that this is due to the contrasting chemical, physical and biological processes occurring in tropical soils. This indicates that, although some PTFs perform better than others, there seem to be no clearly superior and generally applicable PTFs.

Different approaches have been used to define the water retention characteristic is the compilation of regression equations to predict water content at specified values of matric potential using properties such as bulk density, soil texture and other measured properties such as organic matter content (Ghosh, 1980; Gupta & Larson, 1979; Rawls & Brakensiek, 1982; Rawls *et al.*, 1982; Williams *et al.*, 1992; Rajkai *et al.*, 1996; De Jong *et al.*, 1983; Vereecken *et al.*, 1989; Cosby *et al.*, 1984; Rawls & Brakensiek, 1985; Saxton *et al.*, 1986; van den Berg *et al.*, 1997; Minasny *et al.*, 1999; Paydar & Cresswell, 1996; Tomasella & Hodnett; 1998; Gaiser *et al.*, 2000).

The availability of water retention data in relation to soil type, texture, and organic matter content, for soils of Hararghe Region is generally scarce. As noted by Bastet *et al.* (1997), the performance of published PTFs varied according to the pedological origin of the soil on which they were developed. Consequently, PTFs should not be extrapolated beyond their geographical training area without first assessing their general validity. It would therefore be desirable to develop pedotransfer functions for soils of Hararghe Region in eastern Ethiopia in order to be able to estimate water retention characteristics from easily available soil properties such as texture, bulk density and organic matter content. The objectives of this chapter were therefore to investigate the effect of some basic soil properties on the water retention characteristics of the Hararghe Region soils in eastern Ethiopia, at different matric potential points and to develop empirical relationships (point pedotransfer functions) for predicting water retention from the routinely measured soil properties.

3.2. Materials and Methods

3.2.1. Data set

A total of 216 samples, collected from 26 profiles, were used. The soil samples were collected from east and west Hararghe, Dire Dawa and Jijiga areas. The soil orders include Regosols, Fluvisols, Alfisols, Vertisols, Cambisols and some unclassified soils from Jijiga area.

The volumetric water content-matric potential data pairs for each of the 216 samples represented the mean of two samples. Regression relationships between the volumetric water contents, at each of the matric potentials, and the different soil properties were determined using the data from all the 216 samples.

3.2.2. Statistical analysis

The arithmetic mean, standard deviation, minimum and maximum values of the different soil properties were calculated for all the complete data set.

To establish relationships between soil properties and the volumetric water content at each matric potential, regression analyses were carried out. This was done using the data from the complete data set of 216 samples. The regression analyses were carried out in three ways:

(1) using only one soil property, for example the silt plus clay content, as a predictor variable. Different functions for example linear, logarithmic, power, exponential, quadratic, etc, were fitted to all samples in each group and the function that gave the best and consistent result was chosen.

(2) multiple linear regression on all samples using soil properties selected by stepwise regression was carried out. In this case, gravimetric water content instead of volumetric water content was used. This was done to accommodate bulk density, which was used in calculating volumetric water content.

(3) simple linear or non-linear and multiple linear regressions using only the mean values of the predictor and dependent variables were carried out.

3.2.3. Statistical comparison of measured and predicted values

The pedotransfer functions developed for each matric potential were used to predict a volumetric water content for each sample at that matric potential. The measured and predicted values were compared using several statistical indicators. It has been suggested that the results of different statistical indicators be taken into account simultaneously (Whitmore, 1991; Boucneau *et al.*, 1998; Fox, 1981, Willmott, 1981) as one statistical indicator may lead to erroneous conclusions. The indicators were:

(a) the coefficient of determination (R^2):

$$R^2 = \frac{\left[N\left(\sum \theta_i \theta_{ei}\right) - \left(\sum \theta_i\right)\left(\sum \theta_{ei}\right)\right]^2}{\left[N\sum \theta^2{}_i\right] - \left(\sum \theta_i\right)^2 \left[N\sum \theta^2{}_{ei} - \left(\sum \theta_{ei}\right)^2\right]} \qquad [3.1]$$

where N is the number of water retention data points, θ_i is the measured water content and θ_{ei} is the estimated water content. The R^2 is a measure for the amount of variability explained by the regression model.

(b) the mean bias error (MBE) defined as (Fox, 1981; Gaiser *et al.*, 2000):

$$\mathrm{MBE} = \frac{1}{N}\sum_{i=1}^{n}(\theta_{ei} - \theta_i), \qquad [3.2]$$

indicates whether there is overestimation or underestimation of the measured values.

(c) the mean absolute error (MAE) defined as (Fox, 1981; Gaiser *et al.*, 2000):

$$\mathrm{MAE} = \frac{1}{N}\sum_{i=1}^{N}(|\theta_{ei} - \theta_i|), \qquad [3.3]$$

gives an indication of the mean absolute magnitude of error.

(d) Willmott (1981 & 1982) and Willmott & Wicks (1980) alternatively proposed and used an "index of agreement" (d) of the following form:

$$d = 1 - \frac{\sum_{i=1}^{N}(\theta_{ei}(h_i) - \theta_{mi}(h_i))^2}{\sum_{i=1}^{N}\left(|(\theta_{ei}(h_i) - \bar{\theta}_m)| + |(\theta_{mi}(h_i) - \bar{\theta}_m|\right)^2}, \; 0 \le d \le 1 \qquad [3.4]$$

The magnitude and sign of the slope were used to indicate how much the independent variable influences the water retention at a specific matric potential and the value of the coefficient of determination was used as an indicator of the strength of the relationship between a given basic soil property and water retention.

3.3. Results and discussion

3.3.1. Effect of soil properties on water retention

3.3.1.1. The complete data set

i) General soil properties

The particle size distribution, organic carbon content and bulk density values for the individual samples are presented in Appendix 2.2.

Arithmetic mean, standard deviation, minimum and maximum values and coefficient of variation of the basic soil properties and water retention at nine matric potential points are presented in Table 3.1. Sand content ranged from 2 to 84 %, silt content from 8 to 49 %, clay content from 5 to 78 %, silt plus clay content from 16 to 97 %, total organic carbon content from 0.10 to 2.21 % and bulk density from 0.88 to 1.67 gcm^{-3}. The mean values were: sand content 23 %, silt content 24 %, clay content 52 %, silt plus clay content 76 %, organic carbon content 0.94 % and bulk density 1.19 $g\ cm^{-3}$.

ii) Pedotransfer functions for estimating water content at specific matric potentials

The volumetric water contents at each of the matric potentials for the different samples are given in appendix 2.2. Regression analyses between volumetric water content and different soil properties at each matric potential of the complete data set (n = 216) are given in Table 3.2. These equations revealed that regression with silt plus clay as an independent variable were able to explain, except at –1500 kPa, more than 80 % of the variation in water retention of the soils studied. Only the silt plus clay and clay content were found to be important in explaining the major proportion of the variability in water retention at the nine matric potential values. The relationship between water retention and silt plus clay content at each matric potential value was best explained by an exponential function.

The slopes for the silt plus clay content versus volumetric water content graphs were positive for all the matric potentials. This indicates that silt plus clay content contributed positively to water retention by soils. Moreover, the slopes increased consistently with a decrease in matric potential. This implies that the effect of silt plus clay content increases as the matric potential decreases. This is because water retention at high matric potentials depends primarily on the available pore space, which also depends on the structure of the soil. On the other hand, water retention at low matric potentials is influenced by the specific surface area of the soil. Specific surface area in turn depends on clay mineralogy and clay content (Hajek & Dixon, 1966; Karathanasis & Hajek, 1982a). A higher clay and silt content and a higher available specific surface area will give a higher water retention.

Table 3.1 Arithmetic mean, standard deviation, minimum, maximum values and coefficient of variation of soil properties and water retention for the complete data set (n = 216)

							Matric potential (kPa)								
Variable	Sand (%)	Silt (%)	Clay (%)	OC (%)	BD (gcm^{-3})	Si+C (%)	-1	-5	-8	-10	-30	-60	-100	-300	-1500
Min.	2.72	8.26	5.84	0.10	0.88	16.10	0.313	0.247	0.229	0.180	0.134	0.106	0.077	0.063	0.022
Max.	83.90	48.76	78.30	2.21	1.67	97.28	0.599	0.581	0.565	0.558	0.540	0.533	0.513	0.469	0.363
Ari. Mean	23.31	24.49	52.00	0.94	1.19	76.48	0.512	0.448	0.433	0.418	0.391	0.375	0.361	0.323	0.259
St. dev.	22.01	9.34	17.99	0.43	0.15	22.01	0.071	0.085	0.089	0.093	0.100	0.101	0.101	0.092	0.078
CV (%)*	94.42	38.13	34.60	45.74	12.61	28.78	13.95	18.90	20.61	22.29	25.49	27.01	28.08	28.62	30.14

* *Coefficient of variation*

Pidgeon (1972) used silt plus clay content for estimating water content of ferralitic soils from Uganda at matric potentials of –33 and –1500 kPa with R^2-values of 0.74 and 0.94, respectively. Dijkerman (1988) used the same variable to estimate water content at –1500 kPa for strongly weathered Ultisols and some hydromorphic soils of Sierra Leone with an R^2-value of 0.88. Arruda *et al.* (1987) also used silt plus clay content for estimating volumetric water content at –1500 kPa for soils of South and South East Brazil with an R^2-value of 0.92.

Clay content is another variable found to be important in explaining the variability in water retention of the soils (Table 3.2). The relationship between water retention and clay content at each of the matric potential values was best explained by a power function. McBride & Mackintosh (1984) described gravimetric water content at –1500 kPa as a power function of clay content with an R^2-value of 0.94. Van Antwerpen *et al.* (1994) described the water content for Natal sugar belt soils at field capacity (-10 kPa) and permanent wilting point (-1500 kPa) as a power function of clay content with R^2-values of 0.89 and 0.92, respectively. Gaiser *et al.* (2000) observed that inclusion of soil samples with clay contents > 60 % into their data set increased the non-linearity of the PTFs. Clay content alone explained more than 65 % of the variability in water retention of the soils studied, at all the matric potentials. Hall *et al.* (1977) predicted volumetric water content at –1500 kPa as a quadratic function of the particles smaller than 2 µm. Although not consistently, R^2 increased with a decrease in matric potential (Table 3.2). Hutson (unpublished results) (Schulze *et al.*, 1985) described water retention as a linear function of percentage clay only for five matric potential values (-10, -30, -100, -500 and –1500 kPa) with R^2-values of 0.55, 0.61, 0.69, 0.80 and 0.73, respectively. Many authors (e.g., Lal, 1979 & 1981; Soil Survey Staff, 1975, 1990, 1992; Van den Berg, 1996; Karlsson, 1982; Dijkerman, 1988) used clay content alone for estimating gravimetric water content at –1500 kPa and many others (e.g., Aina & Periaswamy, 1985; Karlsson, 1982; Van den Berg, 1996) used clay content alone for estimating volumetric water content at –1500 kPa.

The slopes of these equations increased with a decrease in matric potential indicating that the influence of clay content on water retention becomes more important at low matric potentials. The positive slopes indicate that clay content contributed positively to water retention and hence the volumes of water retained increased with an increase in clay content.

There are various reasons for the influence of clay content on water retention among which are structure, porosity and clay mineralogy. At high matric potential ranges, structure plays a dominant role while at low matric potential ranges clay mineralogy plays the dominant role. Soils with high clay contents are better structured than soils with low clay contents. At low matric potentials water retention is a function of specific surface area and electrical charge of clay minerals both of which are influenced by clay mineralogy. The larger the specific surface area and the higher the electrical charge, the more water can be adsorbed to clay minerals (Ochiston, 1954; cited by Gaiser *et al.*, 2000). Other studies (e.g., Nielsen & Shaw, 1958) indicated a strong relationship between clay content and water retention as matric potential decreases. Hall *et al.* (1977) explained that as the potential decreases and pore size becomes smaller, the influence of clay content on water retention increases.

The results of multiple linear regression analyses are also presented in Table 3.2. Multiple linear regressions, with bulk density and silt plus clay content as independent variables and gravimetric water content as a dependent variable, were able to explain more than 85 % of the variability in gravimetric water content. Gravimetric water content was used to include bulk density as a predictor variable. Since bulk density is directly related to volumetric water content, it was assumed inappropriate to use volumetric water content, which already includes bulk density as a variable.

Although the independent variable used was gravimetric water content, there were considerable improvements in R^2-values from using bulk density and silt plus clay content as predictor variables compared to using a single variable. The slopes of the multiple regression equations were negative for bulk density at all the matric potentials. The magnitude of the slopes, however, decreased with a decrease in matric potential. The negative signs of the slopes for bulk density indicate that with increasing bulk density water retention decreased at all the matric potentials considered.

Table 3.2 PTFs for estimating water content at different matric potential values from basic soil properties for the complete data set

Dependent variable	Regression equation	R^2
$\theta^*_{-0.1}$	$0.3124 * e^{0.0063(Si+C)}$	0.86
	$0.1907\,(C)^{0.2530}$	0.68
w_*	$0.8982 - 0.4815*BD + 0.0015*(Si+C)$	0.94
θ_{-5}	$0.2266* e^{0.0086(Si+C)}$	0.87
	$0.1132(C)^{0.3510}$	0.70
w	$0.7343 - 0.4222*BD + 0.0020*(Si+C)$	0.90
θ_{-8}	$0.2043 * e^{0.0095(Si+C)}$	0.86
	$0.0968(C)^{0.3818}$	0.68
w	$0.7077- 0.4171*BD+ 0.0022*(Si+C)$	0.89
θ_{-10}	$0.1830 * e^{0.0104(Si+C)}$	0.86
	$0.0815(C)^{0.4160}$	0.68
w	$0.6627- 0.4006*BD+ 0.0023*(Si+C)$	0.89
θ_{-30}	$0.1458* e^{0.0124(Si+C)}$	0.87
	$0.0538(C)^{0.5037}$	0.71
w	$0.6057- 0.3859*BD+ 0.0025*(Si+C)$	0.88
θ_{-60}	$0.1284 * e^{0.0134(Si+C)}$	0.87
	$0.0426(C)^{0.5518}$	0.72
w	$0.5831- 0.3800*BD+ 0.0026*(Si+C)$	0.88
θ_{-100}	$0.1144* e^{0.0144(Si+C)}$	0.86
	$0.0336(C)^{0.6023}$	0.74
w	$0.5414- 0.3591*BD+ 0.0026*(Si+C)$	0.88
θ_{-300}	$0.0969 * e^{0.0150(Si+C)}$	0.83
	$0.0248(C)^{0.6502}$	0.77
w	$0.4067- 0.2745*BD+ 0.0026*(Si+C)$	0.87
θ_{-1500}	$0.0613* e^{0.0179(Si+C)}$	0.78
	$0.0090(C)^{0.8271}$	0.82
w	$0.2775- 0.1967*BD+ 0.0024*(Si+C)$	0.89

**Si+C = silt plus clay content (%), C = clay content (%), BD = bulk density (g cm^{-3}), θ^* = Volumetric water content (cm^3 cm^{-3}), w* = gravimetric water content (gg^{-1}). Equation valid within the following ranges: $16 \leq (Si+C) \leq 97$, $5 \leq C \leq 78$, $0.88 \leq BD \leq 1.67$.*

Soils with low bulk densities retain more water close to saturation than soils with a higher bulk density because the amount of water that can be retained at low suctions depends primarily on the total available pore space, and because soils with a low bulk density are generally better structured (Reeve *et al.*, 1973). This is the reason why there was a negative correlation between bulk density and water retention. The decrease in the influence of bulk density with a decrease in matric potential is due to the fact that at low matric potentials the available surface area rather than the available pore space influences water retention more.

Aina & Periaswamy (1985) and Sharma & Uehara (1968), however, found a strong correlation between water retained at low matric potentials and bulk density. They ascribed this to the larger surface area that is available to retain water at low matric potentials for soils with a high bulk density.

iii) Statistical analyses on the derived PTFs

The equations in Table 3.2 were used to estimate volumetric and gravimetric water contents for each of the 216 samples, which were compared with the measured values. All the data (n = 216) were included in these statistical analyses that were conducted according to the statistical indicators described in Section 3.2.3. The values of the statistical indicators at each matric potential value are presented in Appendix 3.1. The d-index was calculated only for the silt plus clay equations, as they appeared to be the best. The relationships between the estimated and measured values are given in Figures 3.1 for the silt plus clay and clay equations and 3.2 for the multiple regression equations.

The results in Appendix 3.1 show that the mean of mean bias errors (mMBEs) of estimation for silt plus clay content-based PTFs were negative at all the matric potentials. This indicates that there was a systematic underestimation of the measured water content at a given matric potential. The scatter plots in Figure 3.1 show the same phenomenon. These mean underestimations were, however, not for all samples. Most of the underestimations occurred within subsoil samples compared to topsoil samples. For instance at -1kPa, underestimation occurred in 26 % of the topsoil samples, in more than 60 % of the subsoil samples with relatively high clay contents and low silt contents and in 100 % of the subsoil samples with a relatively high silt content and low clay content. This might indicate that the water retention behaviours of these soils are different from each other. Yet, the magnitude of the mMBE is negligibly small indicating that the PTFs can be used to estimate water contents of Hararghe Region soils from their silt plus clay content with reasonable accuracy. Gaiser *et al.* (2000) reported a MBE value of –0.009 for PTFs developed using 194 samples to predict water retention at field capacity and –0.009 for permanent wilting point.

The mean of mean absolute (mMAE) and root mean square errors at each matric potential were relatively small, indicating a reasonable degree of accuracy for estimating water content. Relatively high mMAE and mRMSE values were observed at –10 and –300 kPa. The mean d-index values, which ranged from 0.867 at –1 kPa to 0.838 at –1500 kPa and a mean of 0.854 for the complete curve indicate a reasonably good agreement between measured and estimated water contents. The d-values for individual samples ranged from 0 to 1.

The PTFs developed using bulk density and silt plus clay content as predictor variables and gravimetric water content as a dependent variable resulted in both under- and over-estimations. These PTFs overestimated the water retained at –8, -60 and –1500 kPa and underestimated it for the remaining matric potentials. The magnitudes of the over- and under-estimations were very small (-0.004 – 0.001 cm^3 cm^{-3} of water). Figure 3.2 shows that there were not much scatter except at high water contents where these equations under-estimated the measured values.

The various statistical indicators showed that the derived PTFs can be used for estimating the water contents of Hararghe Region soils at specific matric potentials with minimum prediction error. For wider application, these PTFs need to be tested and validated using an independent data set.

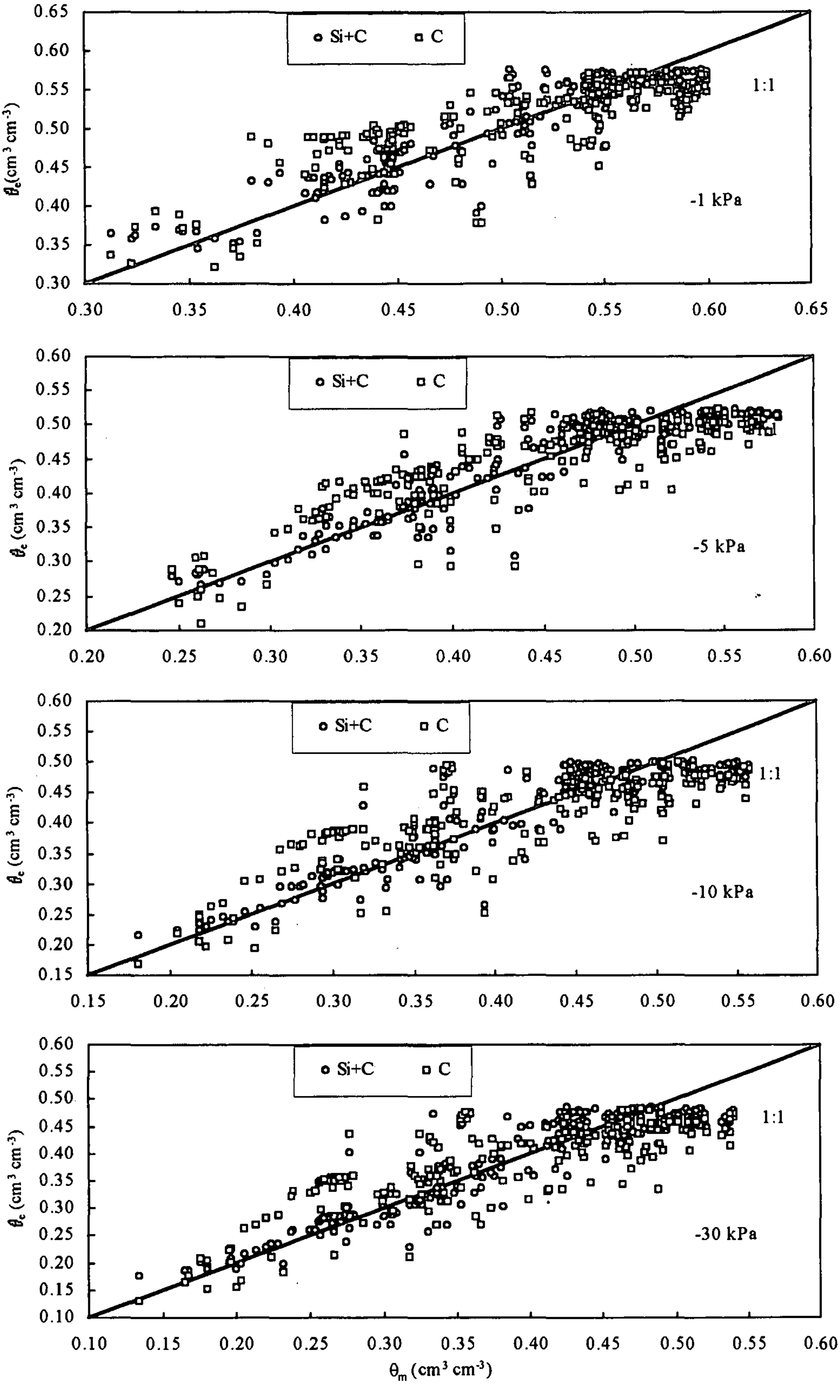


Figure 3.1 continue on next page

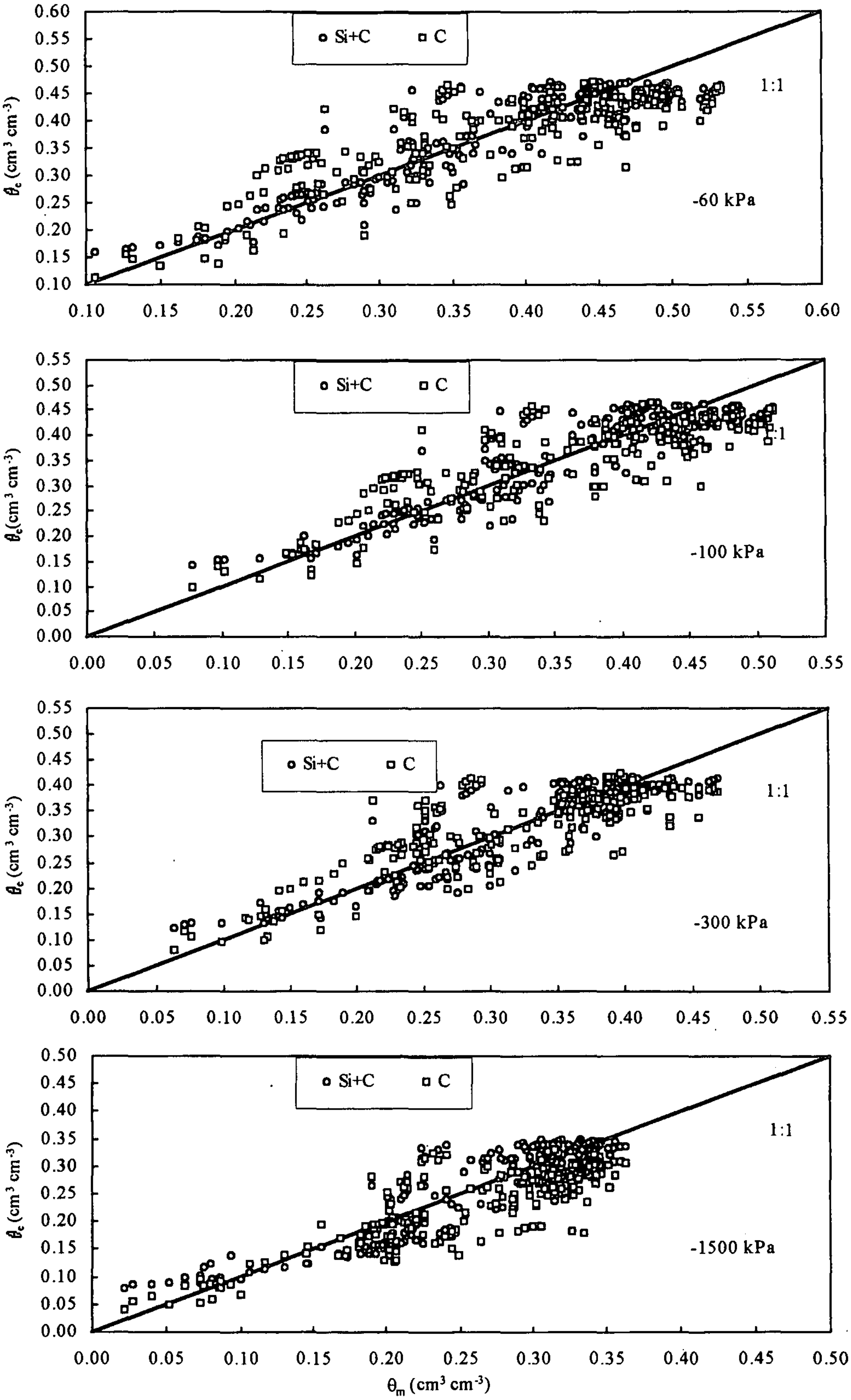


Figure 3.1 The relationship between estimated (θ_e), using the silt plus clay and clay functions, and measured (θ_m) water contents for the complete data set.

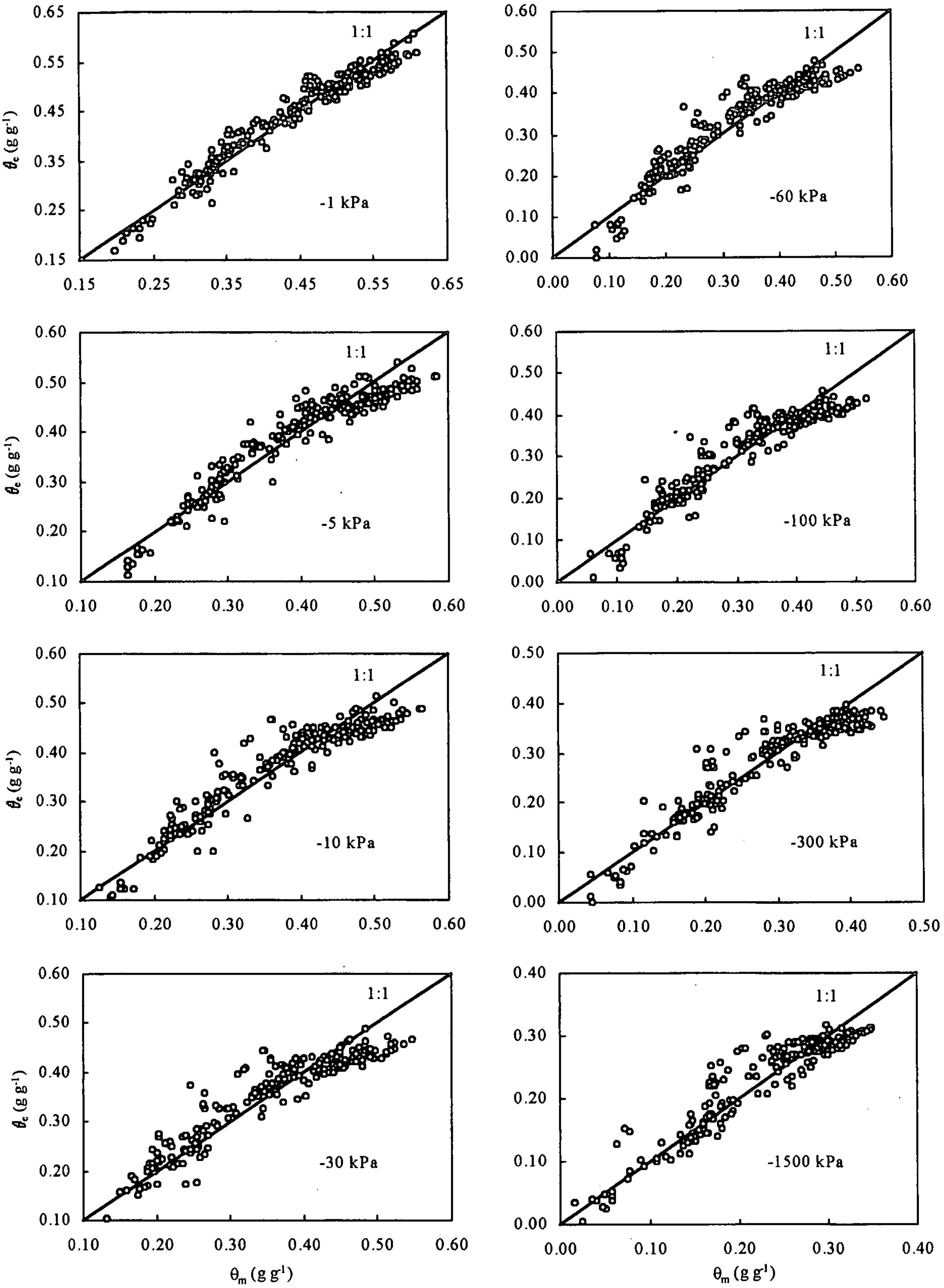


Figure 3.2 The relationship between estimated (θ_e), using the multiple regression equations, and measured (θ_m) water contents for the complete data set.

3.3.1.2. Subdivision of the data set

In an attempt to improve the regression relationships listed in Table 3.2, another approach was used. Accordingly, the complete data set was divided into topsoils with higher organic matter contents (n = 53) and subsoils (n = 163). This was done to separate soil horizons containing more organic matter from those with little organic matter. Within the subsoil group, differences in water retention behaviour of soils with high silt and low clay contents and vice versa were observed. Therefore, the silt to clay ratio (Si:C) was used as a criterion to subdivide the subsoil group into two groups. This ratio was plotted against silt plus clay content (Figure 3.3). This gave two groups of populations with 0.75 being the dividing line. The two groups were therefore those with Si:C ratios < 0.75 (n = 148) and those with Si:C ratios > 0.75 (n = 15). Within each group, silt plus clay content classes were formed using 10 % silt plus clay content increments. This resulted in 7 silt plus clay content classes within each group. Unfortunately some classes contained no or only one sample.

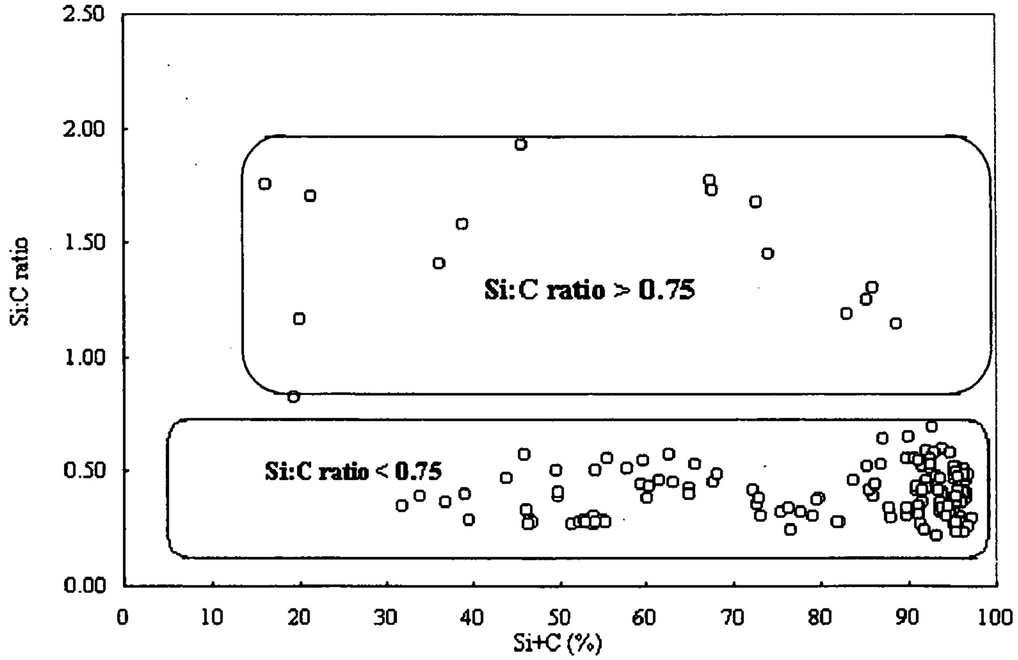


Figure 3.3 The silt to clay ratio used for classifying subsoils into two groups.

3.3.1.3. Topsoils

i) General soil properties

In this group there were 7 silt plus clay classes. Summary statistics of the soil properties and water retention for each class is presented in Tables 3.3 and 3.4, respectively. The sand content (data not indicated) ranged from 3 to 78 %, silt content from 9 to 49 %, clay content from 8 to 73 %, silt plus clay content from 22 to 97 %, organic carbon content from 0.28 to 2.21 % and bulk density from 0.88 to 1.59 gcm^{-3}. The mean values were: sand content 30 %, silt content 28 %, clay content 42 %, organic carbon content 1.31 %, silt pus clay content 70 % and bulk density 1.20 $g\ cm^{-3}$. These soils had a higher mean organic carbon content compared with the subsoil groups (Table 3.3). It should be noted that the soils within a class are from different areas and hence were under different management practices and have different origins, subjected to different soil forming processes and factors and different stages of profile development. The anomalies observed could therefore be due to these reasons.

The mean volumetric water contents of the classes for each of the matric potentials are presented in Table 3.4. With three exceptions, the water retention at specific matric potentials increased consistently with higher silt plus clay contents. The water retained at –1kPa for the 50.01-60 % class was slightly (0.004 cm^3cm^{-3}) lower than for the 40.01-50 % class. This might be because the former has less organic carbon (Table 3.3). The other anomalies were at –300 and –1500 kPa. The 60.01-70 % class retained more water at both points than the 70.01-80 % class. This is because in the latter, there were samples with a high silt and low clay and organic carbon. These soils retained less water than the samples with a high clay and low silt content. The general trend from Table 3.4 is that the water content at a particular matric potential increased with an increase in silt plus clay, clay and organic carbon content and decreased with an increase in sand content and bulk density.

Table 3.3 Arithmetic mean and standard deviation of the soil properties for the 7 silt plus clay classes of the topsoil group

		Sand (%)		Silt (%)		Clay (%)		OC (%)		BD (gcm^{-3})		Si+C (%)	
Class	n*	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
20.01-30	8	74.74	1.96	11.97	2.07	13.30	3.28	0.54	0.20	1.50	0.07	25.26	1.96
30.01-40	-	-	-	-	-	-	-	-	-	-	-	-	-
40.01-50	2	53.05	0.78	19.52	0.76	27.43	0.01	1.62	0.02	1.31	0.18	46.95	0.78
50.01-60	8	44.80	4.08	21.35	6.55	33.86	5.47	1.07	0.26	1.31	0.04	55.21	4.08
60.01-70	6	35.54	3.15	22.95	2.92	41.51	4.72	1.19	0.38	1.27	0.05	64.46	3.15
70.01-80	5	24.13	1.57	31.56	10.58	44.31	10.61	1.35	0.60	1.09	0.16	75.87	1.57
80.01-90	7	12.43	1.89	45.23	3.60	42.33	4.49	1.75	0.28	1.05	0.08	87.57	1.89
90.01-100	17	5.89	2.31	33.25	5.00	60.85	6.64	1.59	0.30	1.07	0.07	94.11	2.31

**number of samples in the class.*

Table 3.4 Arithmetic mean and standard deviation of water retention at 9 matric potential points for the 7 silt plus clay classes of the topsoil group

		-1kPa		-5kPa		-8kPa		-10kPa		-30kPa		-60kPa		-100kPa		-300kPa		-1500kPa	
Class	n	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
20.01-30	8	0.340	0.022	0.264	0.016	0.244	0.012	0.232	0.016	0.197	0.017	0.183	0.016	0.167	0.016	0.136	0.018	0.081	0.011
30.01-40	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
40.01-50	2	0.427	0.030	0.323	0.006	0.308	0.009	0.298	0.007	0.272	0.007	0.257	0.006	0.249	0.006	0.231	0.001	0.170	0.003
50.01-60	8	0.423	0.034	0.350	0.018	0.334	0.021	0.317	0.022	0.287	0.019	0.273	0.020	0.263	0.020	0.246	0.019	0.196	0.025
60.01-70	6	0.451	0.018	0.389	0.011	0.379	0.010	0.362	0.012	0.341	0.013	0.328	0.014	0.317	0.015	0.299	0.008	0.227	0.024
70.01-80	5	0.495	0.020	0.404	0.014	0.392	0.020	0.378	0.024	0.348	0.030	0.335	0.028	0.324	0.032	0.275	0.036	0.221	0.028
80.01-90	7	0.536	0.017	0.475	0.027	0.465	0.027	0.457	0.024	0.437	0.030	0.416	0.026	0.404	0.024	0.355	0.030	0.289	0.019
90.01-100	17	0.538	0.023	0.491	0.031	0.483	0.031	0.469	0.032	0.451	0.034	0.436	0.034	0.424	0.034	0.384	0.043	0.300	0.020

ii) Pedotransfer functions for estimating water contents at specific matric potential for topsoils

Two sets of regression equations for predicting water content at specific matric potential values were developed. For the first set all the 53 individual topsoil samples were included in the regression analyses. The second set of equations were obtained by using only the mean values of the variables (Tables 3.3 and 3.4) for each class in the regression analyses (n = 7).

a) Equations compiled from all the topsoil samples

The PTFs obtained from using the complete topsoil data set that can be used for estimating water contents at specific matric potentials for topsoils are presented in Table 3.5. The regression equations in Table 3.5 show that, except at –300 and –1500 kPa, silt plus clay contents were able to explain more than 90 % of the variability in water retention. Although the regressions for the complete data set and topsoils were done with a different number of samples, the improvement of the R^2 –values ranged from 0.04 at 1 kPa to 0.10 at –1500 kPa. This indicates that the grouping of soils into top and subsoils markedly improved the percentage of variance explained by the silt plus clay content and hence minimized the differences between measured and predicted water content values.

In addition to silt plus clay and clay content, organic carbon content was found to also be important in explaining the variability in water retention for the topsoils. The results in Table 3.5 show that R^2-values ranged from 0.61 at –5 kPa to 0.76 at –1500 kPa. The relationship between organic carbon content and water retention was curvilinear. The slopes of the regression equations increased consistently with a decrease in matric potential, which implies that the effect of organic matter is more pronounced at lower matric potentials. This might be associated with the high specific surface area of organic matter. Mottram *et al.* (1981) used organic matter as one of the predictor variables for estimating water content for topsoils collected from 52 sites in the Mkuzi Game Reserve, Natal, South Africa, at –5 and –1500 kPa matric potentials. The result of their study indicated that the slopes for organic matter in their regression

Table 3.5 PTFs for estimating water content at different matric potential values from basic soil properties for topsoils (complete topsoil data set)

Dependent variable	Regression equation	R^2
$\theta_{-0.1}$	$0.2924 * e^{0.0066(Si+C)}$	0.90
	$0.4424 * (OC)^{0.2942}$	0.66
	$0.1704 * (C)^{0.2770}$	0.74
w	$1.0040 - 0.5399*BD + 0.0008*(Si+C)$	0.97
θ_{-5}	$0.2123 * e^{0.0089(Si+C)}$	0.94
	$0.3719 * (OC)^{0.3760}$	0.61
	$0.1009 * (C)^{0.3776}$	0.79
w	$0.6737 - 0.3770*BD + 0.0019*(Si+C)$	0.94
θ_{-8}	$0.1937 * e^{0.0098(Si+C)}$	0.94
	$0.3571 * (OC)^{0.4163}$	0.63
	$0.0865 * (C)^{0.4108}$	0.78
w	$0.6445 - 0.3685*BD + 0.0020*(Si+C)$	0.94
θ_{-10}	$0.1810 * e^{0.0102(Si+C)}$	0.94
	$0.3424 * (OC)^{0.4425}$	0.65
	$0.0793 * (C)^{0.4246}$	0.77
w	$0.6600 - 0.3830*BD + 0.0019*(Si+C)$	0.94
θ_{-30}	$0.1494 * e^{0.0118(Si+C)}$	0.93
	$0.3127 * (OC)^{0.5222}$	0.67
	$0.0569 * (C)^{0.4949}$	0.77
w	$0.6199 - 0.3741*BD + 0.0020*(Si+C)$	0.93
θ_{-60}	$0.1377 * e^{0.0123(Si+C)}$	0.94
	$0.2982 * (OC)^{0.5316}$	0.64
	$0.0494 * (C)^{0.5210}$	0.78
w	$0.5611 - 0.3425*BD + 0.0022*(Si+C)$	0.93
θ_{-100}	$0.1250 * e^{0.0131(Si+C)}$	0.93
	$0.2837 * (OC)^{0.5799}$	0.67
	$0.0412 * (C)^{0.5600}$	0.80
w	$0.5421 - 0.3359*BD + 0.0022*(Si+C)$	0.94
θ_{-300}	$0.1047 * e^{0.0140(Si+C)}$	0.88
	$0.2492 * (OC)^{0.6522}$	0.70
	$0.0299 * (C)^{0.616}$	0.80
w	$0.4429 - 0.2776*BD + 0.0022*(Si+C)$	0.91
θ_{-1500}	$0.0623 * e^{0.0174(Si+C)}$	0.88
	$0.1820 * (OC)^{0.8419}$	0.76
	$0.0126 * (C)^{0.7755}$	0.82
w	$0.2520 + 0.0282*OC - 0.1762*BD + 0.0018*(Si+C)$	0.96

PTFs valid within the following range: $21 \le (Si+C) \le 97$, $0.28 \le OC \le 2.21$, $8 \le C \le 73$, $0.88 \le BD \le 1.59$.

equations increased with a decrease in matric potential. Their study indicated also that soils with high water retention and relatively low clay contents had high organic matter contents where the upper limit of water retention was concerned. This emphasizes the role organic matter plays in soils with low clay contents.

When the complete data set was used (Section 3.3.1.1, data not shown), the correlation between organic carbon and water retention was poor due to the inclusion of subsoils with lower organic matter contents. Although the effect of organic carbon on water retention has been recognized by several authors (e.g., Salter & Williams, 1965b; Pidgeon, 1972; De Jong & Loebel, 1982), the results obtained by van den Berg *et al.* (1997) indicated little effect. Most of the studies cited included soils with high (>5 %) organic carbon contents, e.g., wet land soils. McBride & Mackintosh (1984) reported that only organic matter contents in excess of about 5 % by weight substantially increased measured gravimetric water content values.

The percentage of variance explained by the clay content of the topsoils improved compared with the complete data set for all matric potentials. The improvements in R^2-values ranged from 0.03 at –300 kPa to 0.10 at –8 kPa. Mottram *et al.* (1981) described water content at –5 and –1500 kPa matric potentials as a linear function of clay content. In their study, clay content was able to explain 71 % of the variation in water content at –5 kPa and 66 % at –1500 kPa.

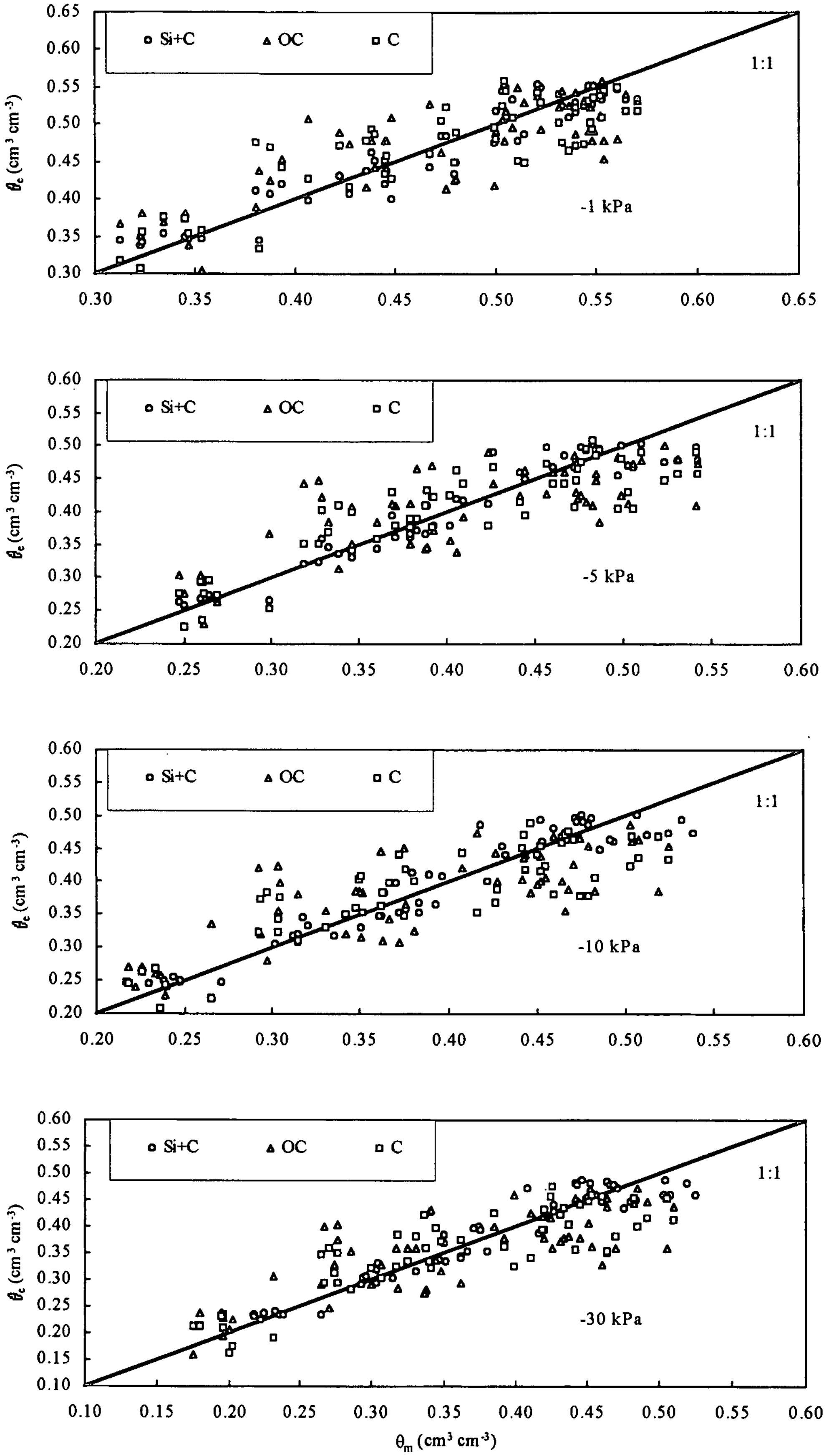
Multiple linear regression equations were also derived using variables selected by stepwise regression and are also given in Table 3.5. These equations also showed an improvement in the percentage of variance explained when compared with those of the complete data set. The improvements in the R^2-values ranged from 0.03 at -1 kPa to 0.07 at –1500 kPa. For the complete data set stepwise regression selected only bulk density and silt plus clay content as predictor variables while for the topsoil data set organic carbon was included as an important variable at –1500 kPa.

iii) Statistical analyses on the derived PTFs

The equations in Table 3.5 were used to obtain estimated values that were compared with the measured values of the topsoil samples. The relationships between the water contents estimated using the equations in Table 3.5 and the measured values are presented in Tables 3.4 and 3.5. The statistical indicators mentioned in Section 3.2.3 were used. The mean values of these indicators for each matric potential are presented in Appendix 3.2. The various indicators showed that the silt plus clay, organic carbon and clay content equations, on average, slightly under-estimated the water contents at all the matric potentials while the multiple regression equations over - (-1, -100, -300 and –1500 kPa) and under- (at the remaining potentials) estimated the water contents. The silt plus clay content equations gave good estimations. The mean of mean absolute (MAE), bias (MBE) and root mean square errors (RMSE) for the complete curve estimated by the silt plus clay content equations were 0.023, -0.001 and 0.028 cm^3 cm^{-3}, respectively. The d-index for individual samples ranged from 0 to 1. The mean d-value for the complete curve was 0.846. This low mean value is due to a few samples with d-values of 0. The equations based on organic carbon content resulted in relatively poor estimation with the mean of mean MAE-, MBE- and RMSE-values of 0.045, -0.004 and 0.056 cm^3 cm^{-3} for the complete curve, respectively. Compared with the organic carbon content equations, the clay content-based equation gave better accuracy with mean MAE-, MBE- and RMSE-values of 0.036, -0.003 and 0.045 cm^3 cm^{-3}. The multiple linear regression equations gave high accuracy with the mean of mean MAE, MBE and RMSE-values of 0.021, 0 and 0.027 cm^3 cm^{-3}, respectively.

The mean of mean MAE-, MBE- and RMSE-values of all the equations in Table 3.5 were lower than the corresponding values for the complete data set. It is obvious that using separate PTFs for topsoils resulted in a better correlation between the relevant soil properties and water retention characteristics. It is clear from the very low error values that a very high degree of accuracy can be expected when these equations are applied for the estimation of water content of a soil at a specific matric potential. The relationships between estimated water contents and measured values are given in Figures 3.4 and 3.5.

It can be concluded that in general the highest accuracies will be obtained by using silt plus clay content as the independent variable for estimating volumetric water content for the topsoils of the Hararghe Region. For estimation of gravimetric water contents the multiple linear regression equations with silt plus clay and bulk density as predictor variables are recommended.



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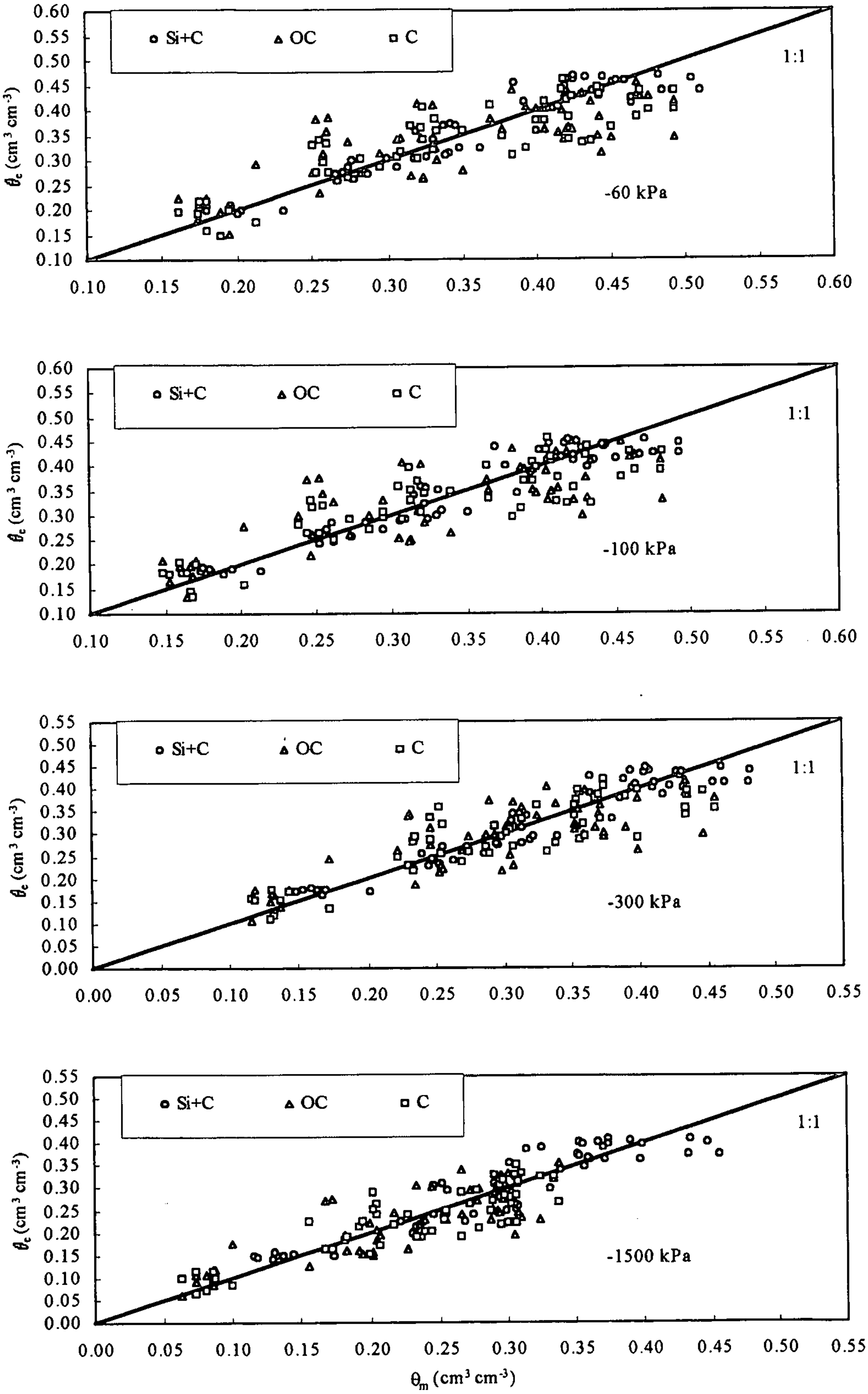


Figure 3.4 The relationship between estimated (θ_e), using the silt plus clay, clay and organic carbon content functions, and measured (θ_m) water contents for the topsoil samples.

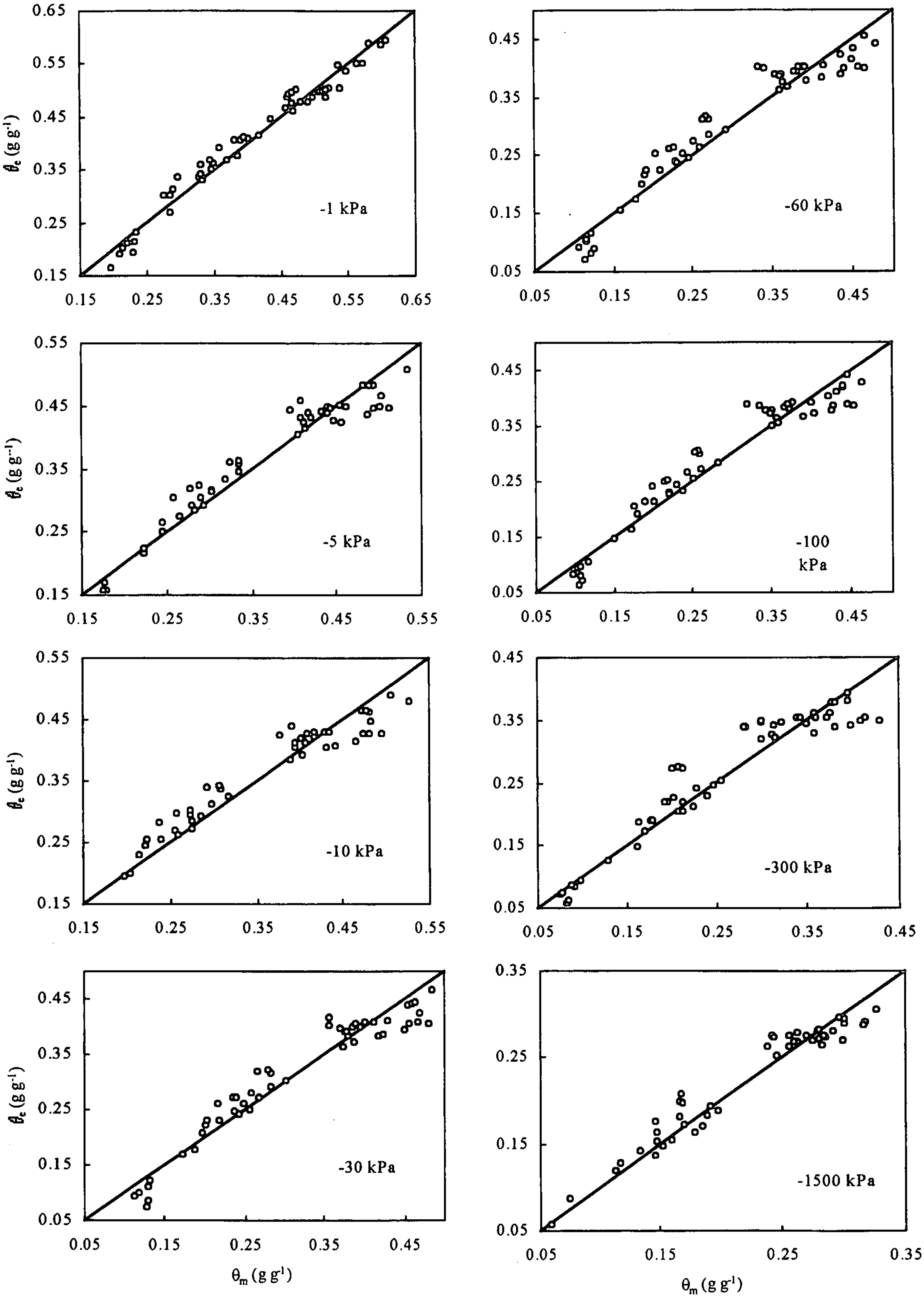


Figure 3.5 Relationship between estimated (θ_e), using the multiple regression equations, and measured (θ_m) water contents for topsoils.

b) Equations based on the mean values for the different classes

In an attempt to make the relationships given in Table 3.5 more universal, the mean values of the predictor variables were regressed against the mean water content values for each class. The mean values of the 7 silt plus clay content classes were used to give a total number of 7 data pairs. The assumption was that means have the characteristic of levelling differences thereby reducing the effect of outliers. Accordingly, four PTFs, for silt plus clay, organic carbon, clay content and bulk densities respectively were developed for each matric potential and the results are presented in Table 3.6.

The results in Table 3.6 show that except for the organic carbon-based PTFs, there were improvements in R^2-values. The accuracy of the equations was tested by comparing the measured values with the corresponding estimated values using the statistical indicators listed in Section 3.2.3 and the values of the indicators for each matric potential are presented in Appendix 3.3.

Generally, the equations in Table 3.6 resulted in a high degree of accuracy for estimating water content compared with the equations in Table 3.5.

3.3.1.4. Subsoils with Si:C ratios < 0.75

i) General soil properties

Similar to the topsoil group, there were 7 silt plus clay content classes for subsoils with Si:C ratios < 0.75. Summary statistics of the soil properties and water retention for each class are presented in Tables 3.7 and 3.8, respectively. The sand content ranged from 2 to 68 %, silt content from 8 to 38 %, clay content from 23 to 78 %, silt plus clay content from 31 to 97 %, organic carbon content from 0.10 to 1.5 % and bulk density from 0.98 to 1.5 gcm^{-3}. The mean values were: sand content 19 %, silt content 23 %, clay content 58 %, silt plus clay content 81 %, organic carbon content 0.84 % and bulk density 1.18 gcm^{-3}. This group represented soil samples from different localities.

Table 3.6 PTFs for estimating water content at different matric potential values using the mean values of the silt plus clay classes for topsoils in Table 3.3 and 3.4

Dependent variable	Regression equation	R^2
$\theta_{-0.1}$	$0.2969*e^{0.0066*(Si+C)}$	0.97
	$0.4220*(OC)^{0.3513}$	0.77
	$0.1510*(C)^{0.3104}$	0.88
w	$0.6646 - 0.0018*C + 0.0029*OC - 0.3364*BD + 0.0031*(Si+C)$	0.99
θ_{-5}	$0.2113*e^{0.0090(Si+C)}$	0.99
	$0.3454*(OC)^{0.4288}$	0.63
	$0.0855*(C)^{0.4189}$	0.88
w	$- 0.0593 - 0.0031*C - 0.0066*OC + 0.0642*BD + 0.0067*(Si+C)$	0.99
θ_{-8}	$0.1929*e^{0.0099*(Si+C)}$	0.99
	$0.3299*(OC)^{0.4726}$	0.64
	$0.0707*(C)^{0.4621}$	0.89
w	$- 0.1309 - 0.0030*C - 0.0050*OC + 0.0981*BD + 0.0069*(Si+C)$	0.99
θ_{-10}	$0.1811*e^{0.0103(Si+C)}$	0.99
	$0.3160*(OC)^{0.4971}$	0.65
	$0.0647*(C)^{0.4765}$	0.88
w	$- 0.1523 - 0.0034*C - 0.0011*OC + 0.1050*BD + 0.0071*(Si+C)$	0.98
θ_{-30}	$0.1504*e^{0.0119(Si+C)}$	0.98
	$0.2856*(OC)^{0.5894}$	0.69
	$0.0448*(C)^{0.5568}$	0.89
w	$- 0.3538 - 0.0036*C + 0.0089*OC + 0.2094*BD + 0.0079*(Si+C)$	0.98
θ_{-60}	$0.1389*e^{0.0123(Si+C)}$	0.98
	$0.2707*(OC)^{0.6133}$	0.68
	$0.0388*(C)^{0.5840}$	0.90
w	$- 0.3310 - 0.0030*C + 0.0070*OC + 0.1927*BD + 0.0073*(Si+C)$	0.98
θ_{-100}	$0.1268*e^{0.0131(Si+C)}$	0.97
	$0.2568*(OC)^{0.6673}$	0.71
	$0.0319*(C)^{0.6275}$	0.91
w	$- 0.3309 - 0.0028*C + 0.0113*OC + 0.1871*BD + 0.0071*(Si+C)$	0.99
θ_{-300}	$0.1090*e^{0.0137(Si+C)}$	0.91
	$0.2256*(OC)^{0.7417}$	0.75
	$0.0232*(C)^{0.6847}$	0.94
w	$- 0.6414 - 0.0019*C + 0.0354*OC + 0.3690*BD + 0.0070*(Si+C)$	0.99
θ_{-1500}	$0.0651*e^{0.0173(Si+C)}$	0.89
	$0.1621*(OC)^{0.9642}$	0.78
	$0.0087*(C)^{0.8803}$	0.95
w	$- 0.4412 - 0.0020*C + 0.0234*OC + 0.2404*BD + 0.0058*(Si+C)$	1.0

** PTFs valid within the following ranges: $25 \leq (Si+C) \leq 94$, $0.54 \leq OC \leq 1.75$, $13 \leq C \leq 61$, $1.05 \leq BD \leq 1.50$*

Only the silt plus clay content and Si:C ratio was used to group the soils and differences within a class in organic matter content and bulk densities, which are highly affected by the management practices occurred. The water contents at specific matric potentials increased consistently with the silt plus clay content except for the 50.01-60 % class, which had slightly (0.013 cm^3 cm^{-3}) lower water contents than the 40.01-50 % class at -1 kPa (Table 3.8). This class had a lower mean organic carbon content (0.47 %). Its mean bulk density was also the highest of all the classes. These two factors might have contributed to the relatively lower water content at -1 kPa.

The profiles from which these samples were collected had a strong structure with features like clay cutans and slickensides deep in their subsoils. This can also affect the water retention properties of the soils.

ii) Pedotransfer functions for estimating water content at specific matric potentials for subsoils with Si:C ratio < 0.75

Similar to the procedure used for topsoil group, one set of equations were derived by including all the 148 samples (Table 3.9) and by using only the mean values of the 7 classes (Table 3.10). Regression analyses were carried out to determine the relationships between basic soil properties and the volumetric water content at different matric potentials. Preliminary analyses indicated that organic carbon content had little effect on water retention and, hence, was not included in the regression analyses.

a) Equations compiled from all the subsoil samples with Si:C ratios < 0.75

The PTFs for the different matric potentials are presented in Table 3.9. The results in Table 3.9 indicate that the R^2-values ranged from 0.78 at –300 kPa to 0.87 at 1 kPa. Compared to the R^2-values using silt plus clay analyses for the complete data set, there was only little improvement at –1 kPa.

Table 3.7 Arithmetic mean and standard deviation of the soil properties for the 7 silt plus clay classes of the subsoil group with a Si:C ratio < 0.75

		Sand (%)		Silt (%)		Clay (%)		OC (%)		BD (gcm^{-3})		Si+C (%)	
Class	n	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
30.01-40	5	63.68	3.31	9.54	1.07	26.79	2.84	0.38	0.26	1.36	0.04	36.32	3.31
40.01-50	9	52.72	2.09	13.05	2.74	34.23	2.88	0.65	0.18	1.30	0.10	47.28	2.09
50.01-60	16	45.20	2.38	14.14	3.74	40.67	2.28	0.47	0.19	1.38	0.07	54.80	2.38
60.01-70	10	36.06	2.84	20.07	2.12	43.87	2.22	0.72	0.14	1.32	0.07	63.91	2.82
70.01-80	11	24.11	2.89	19.19	2.00	56.70	3.24	0.88	0.23	1.19	0.05	75.89	2.89
80.01-90	15	13.40	2.78	25.64	5.66	60.96	5.07	0.66	0.21	1.12	0.07	86.55	2.70
90.01-100	82	5.78	1.75	26.17	4.87	68.04	5.37	1.00	0.29	1.11	0.07	94.22	1.76

Table 3.8 Arithmetic mean and standard deviation of water retention at 9 matric potential (kPa) values for the 7 silt plus clay classes of the subsoil group with a Si:C ratio < 0.75

		-1		-5		-8		-10		-30		-60		-100		-300		-1500	
Class	n	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
30.01-40	5	0.433	0.013	0.317	0.011	0.294	0.015	0.268	0.019	0.229	0.027	0.215	0.020	0.204	0.014	0.162	0.016	0.129	0.018
40.01-50	9	0.443	0.023	0.365	0.026	0.339	0.035	0.314	0.042	0.279	0.040	0.261	0.040	0.251	0.040	0.238	0.035	0.189	0.013
50.01-60	16	0.430	0.022	0.367	0.025	0.344	0.029	0.319	0.034	0.285	0.037	0.265	0.038	0.255	0.037	0.241	0.030	0.209	0.018
60.01-70	10	0.450	0.003	0.381	0.006	0.369	0.010	0.355	0.007	0.333	0.009	0.315	0.023	0.303	0.022	0.266	0.020	0.219	0.004
70.01-80	11	0.510	0.017	0.439	0.024	0.426	0.025	0.413	0.027	0.391	0.029	0.376	0.031	0.354	0.044	0.312	0.050	0.259	0.041
80.01-90	15	0.565	0.038	0.493	0.050	0.480	0.056	0.465	0.059	0.441	0.069	0.431	0.071	0.416	0.071	0.363	0.064	0.301	0.048
90.01-100	82	0.570	0.021	0.517	0.040	0.504	0.046	0.491	0.048	0.468	0.051	0.453	0.051	0.438	0.049	0.393	0.043	0.317	0.033

At the remaining matric potentials, the relationships between silt plus clay content and water content did not improve. The slopes of the equations did not show a specific trend. They increased from -1 kPa to –100 kPa and then decreased. Of the 7 textural classes, the 90.01-100 % silt plus clay content class had the lowest R^2-value. These were soils with high clay contents and strong structure. The clay or silt plus clay content alone may, therefore, not be enough to explain the variation in water content. The inclusion of other parameters like specific surface area or a structure parameter, may describe the variation in water retention better.

The PTFs with only clay contents as variables, gave lower R^2-values than silt plus clay. This implies that for these soils clay content alone was not good enough to fully describe their water retention. Mottram *et al.* (1981) described water content at –5 and –1500 kPa matric potentials as a linear function of clay content alone for subsoils of some Natal soils with R^2-values of 0.61 and 0.76, respectively. Inclusion of silt content and bulk density improved the R^2-values to 0.72 and 0.81, respectively. There might, therefore, be other physical and chemical properties playing a more important role in determining water retention for the subsoils of Hararghe region. A study made by Williams *et al.*, (1983) indicated that besides particle size composition, organic matter content and clay type, the presence or absence of pedality and grade of structure played an important role in determining water retention by soils. Their study indicated that, because aggregation improve with increasing swelling clay content, it simultaneously include the effect of structure. Butler (1955) indicated that the grade of structure can be used as an indicator of structure. On the effect of clay mineralogy, a study on Australian soils by Williams *et al.* (1983) indicated that montmorillonite, iron oxide and vermiculite retained more water per unit mass.

The multiple linear regression PTFs, where bulk density was also included, generally had higher R^2-values. They were able to explain more than 83- 96 % of the variability in water retention.

Table 3.9 PTFs for estimating water content at different matric potential values from basic soil properties for subsoils with a Si:C ratio < 0.75 (n = 148)

Dependent variable	Regression equation	R^2
$\theta_{-0.1}$	$0.3180 * e^{0.0062(Si+C)}$	0.87
	$0.1084 * (C)^{0.3915}$	0.77
w	$0.9277 + 0.0019(Si+C) - 0.0163*OC - 0.5134*BD$	0.96
θ_{-5}	$0.2307 * e^{0.0085(Si+C)}$	0.84
	$0.0507 * (C)^{0.5473}$	0.77
w	$0.8198 + 0.0021 (Si+C) - 0.4927*BD$	0.90
θ_{-8}	$0.2070 * e^{0.0094(Si+C)}$	0.81
	$0.0403 * (C)^{0.5948}$	0.72
w	$0.7808 + 0.0022(Si+C) - 0.4818*BD$	0.88
θ_{-10}	$0.1823 * e^{0.0105(Si+C)}$	0.81
	$0.0295 * (C)^{0.6627}$	0.72
w	$0.7300 + 0.0025(Si+C) - 0.4647*BD$	0.87
θ_{-30}	$0.1496 * e^{0.0121(Si+C)}$	0.81
	$0.0184 * (C)^{0.7636}$	0.72
w	$0.7178 + 0.0025(Si+C) - 0.4759*BD$	0.87
θ_{-60}	$0.1342 * e^{0.0129(Si+C)}$	0.81
	$0.0146 * (C)^{0.8105}$	0.71
w	$0.7164 + 0.0025(Si+C) - 0.4832*BD$	0.86
θ_{-100}	$0.1273 * e^{0.0131(Si+C)}$	0.81
	$0.0137 * (C)^{0.8159}$	0.70
w	$0.6790 + 0.0024(Si+C) - 0.4608*BD$	0.86
θ_{-300}	$0.1161 * e^{0.0129(Si+C)}$	0.78
	$0.0125 * (C)^{0.8123}$	0.69
w	$0.5139 + 0.0025(Si+C) - 0.3513*BD$	0.85
θ_{-1500}	$0.1002 * e^{0.0123(Si+C)}$	0.79
	$0.0116 * (C)^{0.7802}$	0.71
w	$0.4119 + 0.0019(Si+C) - 0.2710*BD$	0.84

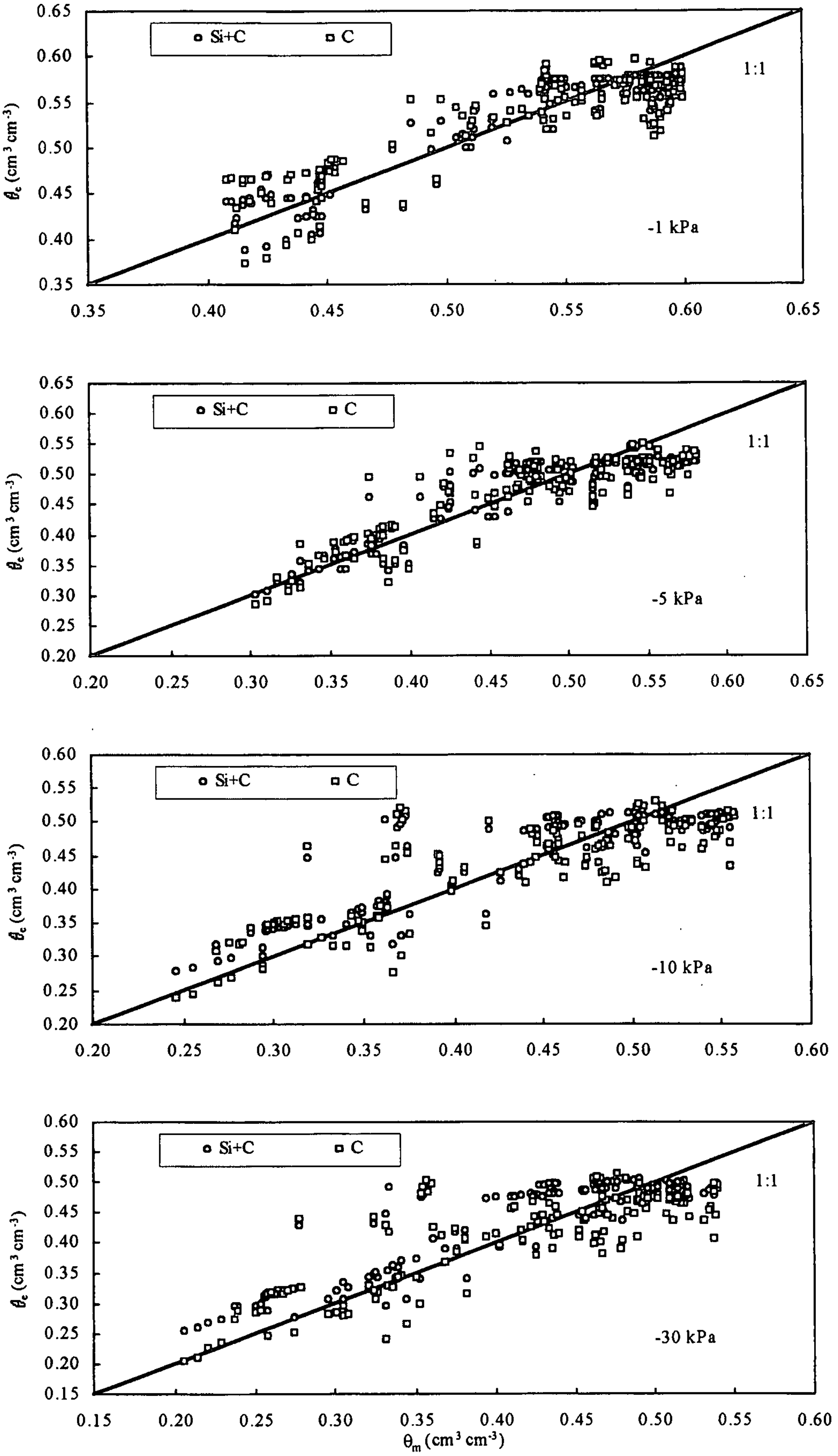
******PTFs valid within the following ranges:* $31 \leq (Si+C) \leq 97$, $23 \leq C \leq 78$, $0.10 \leq OC \leq 1.55$, $0.98 \leq BD \leq 1.50$.

iii) Statistical analyses on the derived PTFs

The values estimated with the equations in Table 3.9 were compared with the measured values. The relationships between estimated and measured values are presented in Figures 3.6 and 3.7. The statistical indicators listed in Section 3.2.3 were calculated for each matric potential and sample and the results are presented in Appendix 3.4. The silt plus clay and clay content equations slightly under-estimated the water contents at all the matric potentials while the multiple linear regression equations under-estimated at –8 and –100 KPa and over-estimated the water contents at the remaining matric potentials.

The mean of mean MAE-, MBE- and RMSE-values for the complete curve were 0.030, -0.003 and 0.038 cm^3 cm^{-3}, respectively for the silt plus clay equations. The corresponding values for the clay equations were 0.035, -0.003 and 0.045 cm^3 cm^{-3}. The multiple linear regression equations gave better accuracy and the mean of mean MAE-, MBE- and RMSE-values were 0.026, 0.002 and 0.034 gg^{-1}, respectively. The mean d-value for the silt plus clay equations was 0.818 and for individual samples ranged from 0 to 1. When compared with the equations based on the complete data set, these equations did not do any better in terms of accuracy for estimating water contents.

It can be concluded that, for this group of soils, the equations based on the silt plus clay content give acceptable accuracy for estimating volumetric water content but the multiple linear regression equations based on bulk density, silt plus clay and organic carbon are recommended.



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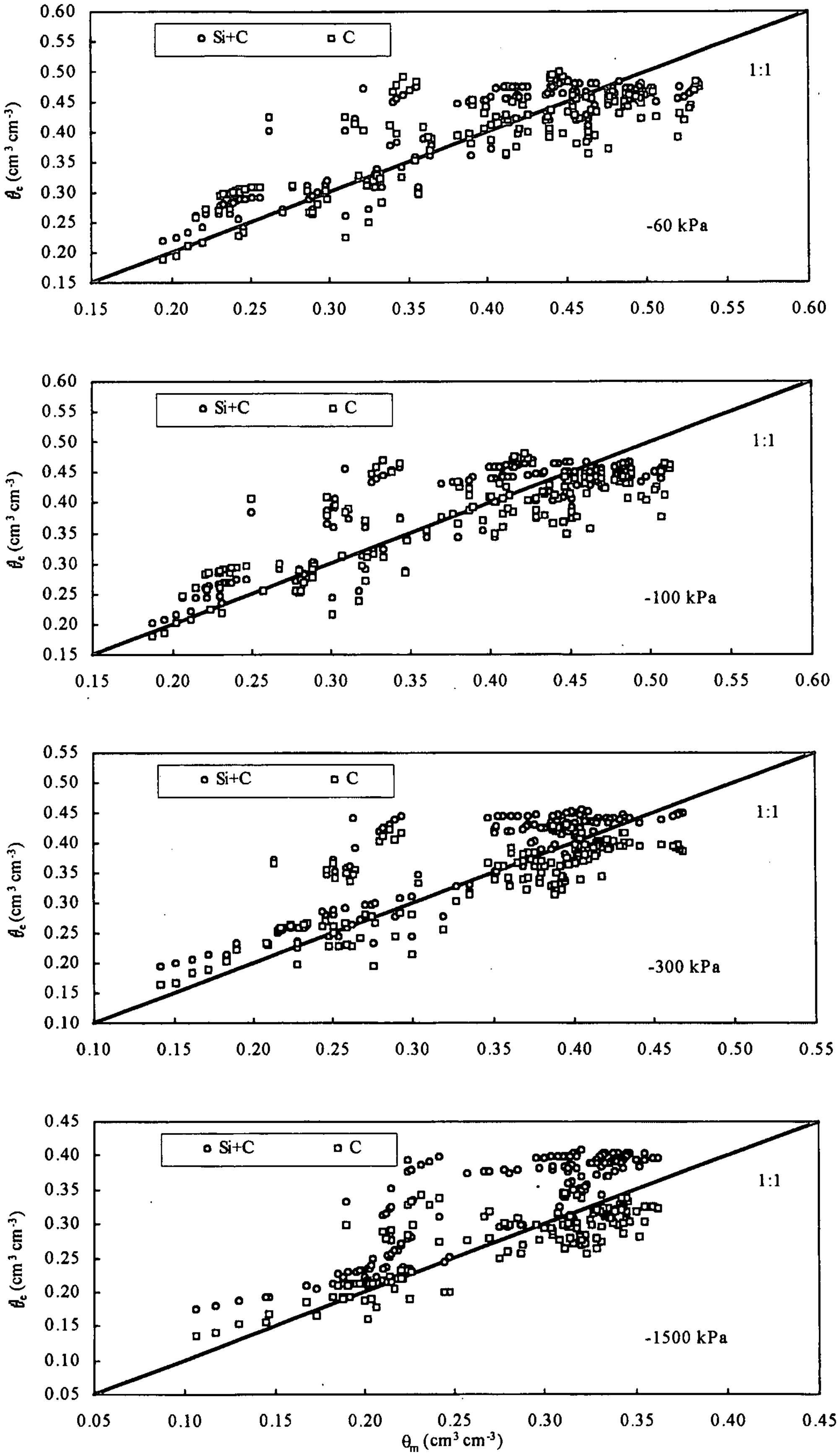

Figure 3.6 The relationship between estimated (θ_e), using the silt plus clay and clay functions, and measured (θ_m) water contents for subsoils with Si:C ratios < 0.75.

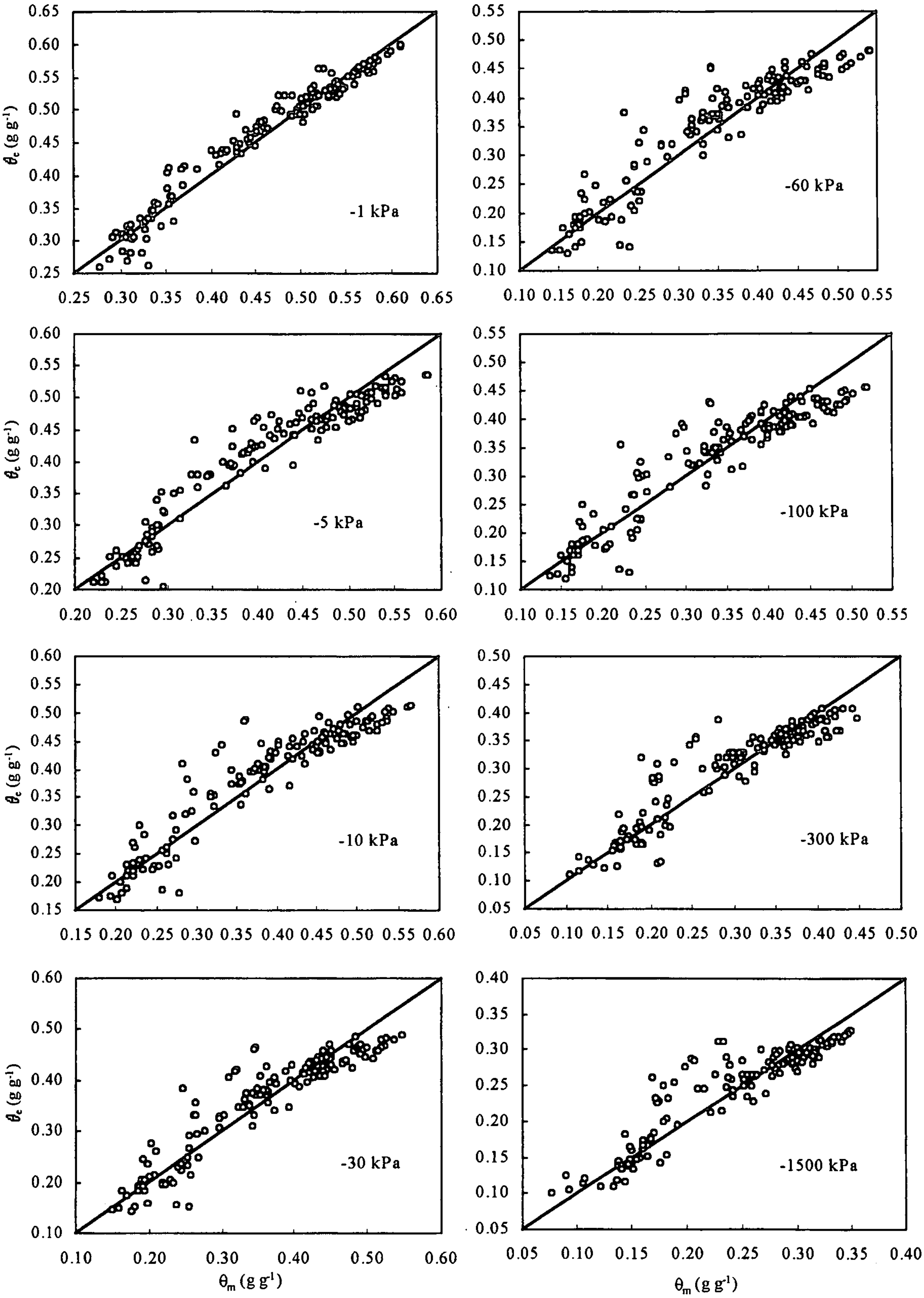

Figure 3.7 Relationship between estimated (θ_e), using multiple regression equations, and measured (θ_m) water contents for subsoils with Si:C ratios < 0.75.

b) Equations based on the mean values for the subsoil group with a Si:C ratio < 0.75

Similar to the topsoil group, equations were developed using the mean class values of the predictor variables and water content. The PTFs are presented in Table 3.10. The results in Table 3.10 indicate that all three PTFs in each matric potential had improved R^2-values compared to the PTFs in Table 3.9.

The accuracy of the equations in Table 3.10 was tested by comparing the actual values with the estimated values. The values of the statistical indicators for each matric potential are presented in Appendix 3.5. These equations gave a much better accuracy compared to the equations in Table 3.9. The mean of mean MAE-, MBE- and RMSE-values for the silt plus clay equations were 0.009, 0 and 0.011 cm^3 cm^{-3}, respectively. The corresponding values for the clay equations were 0.013, -0.001 and 0.015 cm^3 cm^{-3}. The multiple linear regression equations gave even better accuracy with the mean of mean MAE-, MBE- and RMSE-values of 0.006, 0.002 and 0.007 gg^{-1}. The mean d-value for the silt plus clay equations was 0.980 much higher than the one for the equations in Table 3.9.

3.3.1.5. Subsoils with Si:C ratios > 0.75

i) General soil properties

In this group, there were 6 silt plus clay content classes and 15 samples. Summary statistics of the soil properties and water retention for each class are given in Tables 3.11 and 3.12, respectively. The sand content ranged from 11 to 84, silt content from 8 to 48 %, clay content from 5 to 50 %, silt plus clay content from 16 to 88 %, organic carbon content from 0.21 to 1.16 % and bulk density from 1.01 to 1.67 gcm^{-3}. The mean values were: sand 45 %, silt 31 %, clay 23 %, silt plus clay 54 %, organic carbon 0.62 % and bulk density 1.28 gcm^{-3}. For this group, there were only two samples, except the 80.01-90 %, per class and the 40.01-50 % class had only one sample. Because of the small number of samples per class, it was difficult to compare classes.

Table 3.10 PTFs for estimating water content at different matric potential values from the mean values of basic soil properties for subsoils with a Si:C ratio < 0.75 (n = 7)

Dependent variable	Regression equation	R^2
$\theta_{-0.1}$	$0.3359 * e^{0.0055(Si+C)}$	0.88
	$0.1356 * (C)^{0.3331}$	0.80
w	1.2242 + 0.0008*C – 0.0710*OC - 0.6824*BD +0.0006*(Si+C)	0.99
θ_{-5}	$0.2355 * e^{0.0083(Si+C)}$	0.97
	$0.0566 * (C)^{0.5168}$	0.95
w	0.8247 + 0.0014*C – 0.0422*OC - 0.4818*BD + 0.0012*(Si+C)	0.99
θ_{-8}	$0.2103 * e^{0.0093(Si+C)}$	0.99
	$0.0425 * (C)^{0.5795}$	0.96
w	0.7662 + 0.0006*C – 0.0391*OC - 0.4587*BD + 0.0020*(Si+C)	1.0
θ_{-10}	$0.1845 * e^{0.0105(Si+C)}$	0.99
	$0.0302 * (C)^{0.6553}$	0.97
w	0.7092 + 0.0001*C – 0.0256*OC - 0.4386*BD+ 0.0025*(Si+C)	1.0
θ_{-30}	$0.1491 * e^{0.0124(Si+C)}$	0.99
	$0.0174 * (C)^{0.7779}$	0.97
w	0.6180 – 0.0007*C – 0.0140*OC - 0.4019*BD+ 0.0032*(Si+C)	1.0
θ_{-60}	$0.1347 * e^{0.0132(Si+C)}$	0.99
	$0.0138 * (C)^{0.8240}$	0.97
w	0.6558 – 0.0008*C – 0.0248*OC - 0.4331*BD + 0.0033*(Si+C)	1.0
θ_{-100}	$0.1277 * e^{0.0134(Si+C)}$	0.99
	$0.0128 * (C)^{0.8333}$	0.97
w	0.6291 – 0.0020*C - 0.0296*OC - 0.4163*BD + 0.0041*(Si+C)	1.0
θ_{-300}	$0.1098 * e^{0.0138(Si+C)}$	0.95
	$0.0095 * (C)^{0.8797}$	0.96
w	0.4219 – 0.0006*C – 0.0022*OC - 0.2860*BD + 0.0030*(Si+C)	0.99
θ_{-1500}	$0.0888 * e^{0.0140(Si+C)}$	0.93
	$0.0072 * (C)^{0.9028}$	0.97
w	0.2576 + 0.0008*C – 0.0249*OC - 0.1772*BD + 0.0021*(Si+C)	0.99

**PTFs valid within the following ranges: $36 \le (Si+C) \le 94$, $26 \le C \le 68$, $0.38 \le OC \le 1.00$, $1.11 \le BD \le 1.38$*

Table 3.11 Arithmetic mean and standard deviation of the soil properties for the 6 silt plus clay classes of the subsoil group with a Si:C ratio > 0.75

		Sand (%)		Silt (%)		Clay (%)		OC (%)		BD (gcm^{-3})		Si+C (%)	
Class	n	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
10.01-20	2	82.27	2.31	9.50	1.07	8.23	3.38	0.32	0.15	1.53	0.13	17.73	2.31
20.01-30	2	79.24	0.99	12.16	1.92	8.60	0.93	0.41	0.01	1.57	0.14	20.76	0.99
30.01-40	2	62.45	1.94	22.50	1.90	15.05	0.04	0.48	0.21	1.16	0.06	37.55	1.94
40.01-50	1	54.22	0.00	30.14	0.00	15.64	0.00	0.26	0.26	1.22	0.00	45.78	0.00
60.01-70	2	32.47	0.13	42.96	0.23	24.57	0.35	0.53	0.02	1.24	0.06	67.53	0.13
70.01-80	2	26.57	0.95	44.70	1.19	28.73	2.14	0.79	0.24	1.21	0.12	73.43	0.95
80.01-90	4	14.37	2.29	44.75	4.64	40.89	6.36	1.01	0.12	1.15	0.09	85.64	2.29

Table 3.12 Arithmetic mean and standard deviation of water retention at 9 matric potential (kPa) values for the 6 silt plus clay classes of the subsoil group with a Si:C ratio > 0.75

		-1		-5		-8		-10		-30		-60		-100		-300		-1500	
Class	n	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
10.01-20	2	0.363	0.012	0.262	0.000	0.232	0.004	0.192	0.017	0.151	0.023	0.116	0.014	0.087	0.014	0.067	0.006	0.032	0.013
20.01-30	2	0.368	0.009	0.279	0.008	0.248	0.016	0.235	0.024	0.173	0.011	0.140	0.013	0.115	0.019	0.087	0.017	0.040	0.017
30.01-40	2	0.489	0.002	0.417	0.025	0.396	0.036	0.355	0.054	0.270	0.067	0.249	0.058	0.211	0.069	0.164	0.051	0.078	0.004
40.01-50	1	0.440	0.000	0.382	0.000	0.367	0.000	0.333	0.000	0.266	0.000	0.234	0.000	0.206	0.000	0.172	0.000	0.094	0.000
60.01-70	2	0.496	0.026	0.403	0.030	0.386	0.022	0.381	0.025	0.351	0.021	0.336	0.020	0.327	0.022	0.275	0.011	0.206	0.000
70.01-80	2	0.531	0.023	0.418	0.026	0.404	0.019	0.400	0.017	0.368	0.008	0.350	0.004	0.338	0.000	0.303	0.006	0.247	0.004
80.01-90	4	0.556	0.019	0.495	0.033	0.485	0.036	0.475	0.036	0.450	0.038	0.434	0.040	0.417	0.043	0.358	0.025	0.314	0.021

ii) Pedotransfer functions for estimating the water content at specific matric potentials for subsoils with Si:C ratios > 0.75

a) Equations compiled from all the subsoil samples with Si:C ratios > 0.75

The PTFs developed are presented in Table 3.13. The R^2-values indicate that there was a good correlation between soil properties and water retention. The higher R^2-values compared with the complete data set (Table 3.2) reinforced the merit of separating the subsoils into two classes. The R^2-values for clay content were better than the R^2-values for the other groups. This indicates that clay content was a very important variable influencing water retention in this group of soils. Unlike for the other groups, the relationship between water retention and silt plus clay content was best explained by a power equation while the relationship between water retention and clay content was best explained by a logarithmic function except at –30 and –1500 kPa matric potentials where a power function gave the best fit.

iii) Statistical analyses on the derived PTFs

The accuracy of the equations in Table 3.13 was tested by comparing the measured values with the estimated ones. The values of the statistical indicators in Section 3.2.3 for each matric potential are presented in Appendix 3.6. These equations gave high degrees of accuracy with the mean of mean MAE-, MBE- and RMSE-values of 0.022, -0.001 and 0.029 $cm^3 \ cm^{-3}$, respectively, for the silt plus clay equations, 0.025, 0 and 0.031 $cm^3 \ cm^{-3}$ for the clay content equations and 0.031, -0.006 and 0.039 $g \ g^{-1}$ for the multiple linear regression equations. In terms of the MBE-values, the silt plus clay content equations slightly under-estimated the water contents while the clay content equations did not over- or under-estimate the water content. The multiple linear regression equations over-estimated the water contents for –100 to –1500 kPa matric potentials. The mean d-value for the silt plus clay equations was 0.877, indicating a good index of agreement.

Compared with the equations for the complete data set (Table 3.2), the silt plus clay and clay content equations resulted in a much higher degree of accuracy in estimating water content, proving the logic of grouping the soils into different groups.

Table 3.13 PTFs for estimating water content at specific matric potential values from basic soil properties for subsoils with a Si:C ratio > 0.75 (n = 15)

Dependent variable	Regression equation	R^2
$\theta_{-0.1}$	$0.1695*(Si+C)^{0.2656}$	0.91
	$0.341*e^{0.0059(Si+C)}$	0.87
	$0.1154*\ln(C)+0.1349$	0.92
	$0.2217*C^{0.2538}$	0.91
w	$0.7801+0.0033*C-0.3681*BD$	0.97
θ_{-5}	$0.0978*(Si+C)^{0.3559}$	0.86
	$0.2504*e^{0.0078(Si+C)}$	0.80
	$0.1246*\ln(C)+0.0247$	0.84
	$0.1413*C^{0.3373}$	0.84
w	$0.6818+0.0035*C-0.3449*BD$	0.96
θ_{-8}	$0.0726*(Si+C)^{0.4184}$	0.87
	$0.2195*e^{0.0092(Si+C)}$	0.81
	$0.1362*\ln(C)-0.0284$	0.85
	$0.1130*C^{0.3934}$	0.84
w	$0.6564+0.0038*C-0.3425*BD$	0.96
θ_{-10}	$0.0496*(Si+C)^{0.5014}$	0.91
	$0.1863*e^{0.0110(Si+C)}$	0.85
	$0.1520*\ln(C)-0.0938$	0.90
	$0.0837*C^{0.4731}$	0.88
w	$0.5489+0.0049*C-0.2886*BD$	0.96
θ_{-30}	$0.0232*(Si+C)^{0.6561}$	0.94
	$0.1293*e^{0.0147(Si+C)}$	0.92
	$0.1728*\ln(C)-0.2003$	0.93
	$0.0453*C^{0.6251}$	0.94
w	$0.3430+0.0065*C-0.1859*BD$	0.97
θ_{-60}	$0.0126*(Si+C)^{0.7879}$	0.96
	$0.0997*e^{0.0176(Si+C)}$	0.92
	$0.1838*\ln(C)-0.2553$	0.94
	$0.0288*C^{0.7432}$	0.93
w	$0.3248+0.0069*C-0.1895*BD$	0.97

Table 3.13 continued...

Dependent variable	Regression equation	R^2
θ_{-100}	$0.0062*(Si+C)^{0.9397}$	0.95
	$0.0737*e^{0.0209(Si+C)}$	0.91
	$0.1925*\ln(C) - 0.3029$	0.93
	$0.0170*C^{0.8806}$	0.92
w	$0.2533 + 0.0073*C - 0.1564*BD$	0.96
θ_{-300}	$0.0037*(Si+C)^{1.0253}$	0.97
	$0.0545*e^{0.0229(Si+C)}$	0.93
	$0.1721*\ln(C) - 0.2845$	0.93
	$0.0113*C^{0.9520}$	0.91
w	$-0.0152 + 0.0038(Si+C)$	0.96
θ_{-1500}	$0.0004*(Si+C)^{1.4965}$	0.98
	$0.0190*e^{0.0338(Si+C)}$	0.96
	$0.1716*\ln(C) - 0.3390$	0.91
	$0.0019*C^{1.4044}$	0.94
w	$-0.0542 + 0.0035*C + 0.0021(Si+C)$	0.99

**PTFs valid within the following ranges:* $16 \leq Si+C \leq 88$, $5 \leq C \leq 50$, $1.01 \leq BD \leq 1.67$.

The multiple linear regression equations resulted in similar degrees of accuracy with the ones for the complete data set.

From the low error values it can be concluded that, for this group of soils, either the silt plus clay or clay content equations can used for estimating water content.

b) PTFs based on the mean values of the classes

Similar to the results obtained so far with mean values of predictors, these PTFs also resulted in better R^2-values compared to the PTFs in Table 3.14. The equations in Table 3.14 indicate that, except at –300 and –1500 KPa, the equations based on the mean clay content resulted in higher R^2-values compared to the silt plus clay content equations. The equations in Table 3.14 were tested for their accuracy by comparing the actual values with the estimated values. The values of the various statistical indicators for each matric potential are presented in Appendix 3.7.

Table3.14 PTFs for estimating water content at different matric potential values from mean values of basic soil properties for subsoils with a Si:C ratio> 0.75 (n = 6)

Dependent variable	Regression equation	R^2
$\theta_{-0.1}$	$0.1706 *(Si+C)^{0.2650}$	0.93
	$0.1214*\ln(C) + 0.1185$	0.94
θ_{-5}	$0.1002*(Si+C)^{0.3480}$	0.87
	$0.1284*\ln(C) + 0.0099$	0.88
θ_{-8}	$0.0742*(Si+C)^{0.4110}$	0.88
	$0.1413*\ln(C) - 0.0476$	0.90
θ_{-10}	$0.0510*(Si+C)^{0.4933}$	0.93
	$0.1571*\ln(C) - 0.1116$	0.95
θ_{-30}	$0.0244*(Si+C)^{0.6439}$	0.99
	$0.1773*\ln(C) - 0.2159$	1.0
θ_{-60}	$0.0130*(Si+C)^{0.7811}$	0.98
	$0.1897*\ln(C) - 0.2743$	1.0
θ_{-100}	$0.0064*(Si+C)^{0.9351}$	0.99
	$0.2003*\ln(C) - 0.3265$	1.0
θ_{-300}	$0.0037*(Si+C)^{1.0259}$	1.0
	$0.1819*\ln(C) - 0.3135$	0.99
θ_{-1500}	$0.0005*(Si+C)^{1.4495}$	0.99
	$0.1767*\ln(C) - 0.3549$	0.96

** PTFs valid within the following ranges: $17 \leq (Si+C) \leq 85$, $8 \leq C \leq 41$.*

The equations resulted in a better degree of accuracy compared with the equations in Table 3.13. The mean MAE-, MBE- and RMSE-values were 0.016, 0 and 0.020, cm^3 cm^{-3} respectively, for the silt plus clay content equations and 0.014, 0 and 0.017 cm^3 cm^{-3}, respectively, for the clay content equations. The mean d-value for the silt plus clay content equations was 0.906, indicating a high degree of agreement between the measured and estimated water contents.

3.3.2 Equations relating matric potential with the intercept (A) and slope (B) of the PTFs developed from basic soil properties

In an attempt to extend the application of the PTFs to matric potential values, not included in their compilation, equations were derived by relating the matric potential value to the intercepts and slopes of the exponential PTFs. The results are given in Table 3.15.

Table 3.15 Equations for predicting water content at a given matric potential

Group	Model	Equation	R^2
All samples	$\theta (h) = A*e^{(B*(Si+C))}$	$A = -0.177*\ln (h^*)+0.3131$	1.0
		$B = 0.0061*(h^*)^{0.7451}$	0.99
Topsoils	$\theta (h) = A*e^{(B*(Si+C))}$	$A = -0.155*\ln (h^{*)} + 0.2939$	1.0
		$B = 0.0065 *(h^*)^{0.6502}$	0.99
Subsoil(Si:C ratio < 0.75)	$\theta (h) = A*e^{(B*(Si+C))}$	$A = 0.3343*(h^*)^{-0.8492}$	0.99
		$B = 0.0067*(h^*)^{0.5456}$	0.86
Subsoil (Si:C ratio > 0.75)	$\theta (h) = A*e^{(B*(Si+C))}$	$A =- 0.2401*\ln(h^*)+0.3553$	0.98
		$B= 0.1530*e^{0.5612 (h*)}$	0.98

h^* = log/h/, h in cm H_2O.

These relationships developed from PTFs in Table 3.2 for the complete data set, Table 3.5 for the topsoils, Table 3.9 for subsoils with Si:C ratios < 0.75 and Table 3.13 for subsoils with Si:C ratios > 0.75. The equations in Table 3.15 can be used to predict the intercepts and slopes from matric potential of the silt plus clay content-water content functions after which they can be used for estimating the water content at a matric potential value.

3.4. Conclusions

An Investigation into the effects of some soil properties on water retention characteristics of soils in Hararghe Region, eastern Ethiopia, and development of point pedotransfer functions using routinely measured soil properties (e.g., particle size composition, organic carbon content, bulk density) for predicting the water content at a given matric potential, have been the objectives of this chapter.

The pedotransfer functions that can be used to estimate volumetric water content at a range of matric potentials from silt plus clay content were obtained using regression analyses.

For the complete data set, exponential silt plus clay content equations best explained the variability in water content. For predicting gravimetric water content, multiple linear regression equations with bulk density and silt plus clay content as predictor variables also gave high correlations. To improve the correlation coefficients of the point functions, the complete data set was divided into topsoils and the subsoils were further divided into subsoils with silt to clay (Si:C) ratios < and > 0.75.

For the topsoil samples, silt plus clay, clay and organic carbon explained the major proportion of the variability in water retention. Among the equations compiled from these three predictor variables, the silt plus clay equations resulted in the lowest errors of prediction at the different matric potentials. For estimating gravimetric water content, the multiple linear regression equations with bulk density, organic carbon and silt plus clay as predictor variables are recommended as they gave a high degree of accuracy. The equations for the topsoils alone gave a much better accuracy compared to the equations based on the complete data set, proving the logic for separating the total data set into groups.

The equations for the subsoils with a Si:C ratio < 0.75 alone did not improve the relationship between soil properties and water retention characteristics compared with the equations for the complete data set. For this group of soils, silt plus clay and clay content explained the variability in water content. Of the two equations, the silt plus clay equations resulted in lower errors of prediction. For estimating gravimetric water content, the multiple linear regression equations with bulk density and silt plus clay content are recommended as they gave low errors of prediction.

For the subsoils with a Si:C ratio > 0.75, clay content was found to be as important as the silt plus clay content. The equations based on both predictors resulted in high correlations and low errors of prediction.

The samples in the three groups of soils were divided into silt plus clay classes of 10 % increments. The mean values of the silt plus clay classes were used to develop point pedotransfer functions. These equations resulted in higher R^2-values and lower errors of prediction than the respective equations derived from the individual sample data set of each group.

Equations that can be used to estimate water content at any matric potential from soil properties were also developed for the three horizon groups. The advantage of these equations over the ones for specific matric potentials only, is that it combines nine equations into one.

In general, the errors of prediction using soil properties to generate a water retention curve, reported in this study, were not larger than, if any only marginally larger, than those from direct laboratory determinations.

In view of the large spatial variability of soil properties (Nielsen *et al.*, 1973) and the expense and time involved with current direct laboratory methods, application of the derived point functions on soils of Hararghe Region, to generate water retention curves, should improve the value of, for example, irrigation scheduling and water movement studies.

The PTFs in Tables 3.6, 3.9 and 3.10 can be used to estimate a volumetric water content-matric potential data pair for a specific soil horizon from the silt plus clay content. An appropriate water retention function should then be fitted through this data pair. Selecting a water retention function that fits the soils of the Hararghe Region best will be the objective in the next chapter.

CHAPTER 4

IDENTIFICATION AND APPLICATION OF WATER RETENTION EQUATIONS

4.1. Introduction

Equation identification refers to a procedure whereby the best mathematical equation is selected from a multitude of equations used for describing the water retention curve, and of which the parameters can regressed against soil properties. The aim was to establish good links between soil properties and water retention equation parameters. The selected equation is expected to provide the best possible description of the measured water retention curve over a wide range of different soil properties and soil types.

A number of empirical equations (e.g., Brooks & Corey, 1964; King, 1965; Visser, 1968; Laliberte, 1969; Rogowski, 1971 and 1972, Farrell & Larson, 1972; Ahuja & Swartzendruber, 1972; Campbell, 1974; Gilham *et al.*, 1976; Clapp & Hornberger, 1978; Ghosh, 1980; Van Genuchten, 1980; McBride & Mackintosh, 1984) have been developed to describe the water retention curve. These equations vary in their ability to describe the water retention curve since they have different functional forms. Some of them have complex structures with many parameters while others have simple structures with a few parameters and are easy to use. Equations that can also be used to derive analytical solutions for equations of other hydraulic properties, such as hydraulic conductivity, are preferred. There is, therefore, a need to evaluate the most commonly used equations for their accuracy to describe the water retention curve for the soils of the Hararghe Region and their applicability for other modelling purposes. Since it is not possible to evaluate all the available equations, it is essential to identify the equation that best suits the objective of this research. To enhance the practical application of the best equation, it should have a simple structure with the smallest possible number of parameters and should have a physical significance. There are different criteria available that can be used for selecting water retention equations. A brief synopsis of the most commonly used ones follows.

4.2. Identification criteria

Vereecken (1988) used two sets of identification criteria, namely evaluation criteria based on statistical tests and application criteria focusing on the practical use of the equation and the analysis and interpretation of the number of parameters.

4.2.1. Evaluation criteria

Evaluation criteria are used for selecting an equation that:

i) has a mathematical structure able to describe the field data in the best possible way;
ii) produce an equation with the lowest possible number of parameters which can be related to soil properties; and
iii) is able to describe water retention curves of different soil types.

Most authors used power function relationships to characterize soil water retention curves (Visser, 1968; Gregson *et al.*, 1987; Brooks & Corey, 1964; Campbell, 1974; Van Genuchten, 1980). According to Rawls *et al.* (1991), the models most frequently used are the power function models proposed by Brooks & Corey (1964), Campbell (1974), and Van Genuchten (1980) The equation proposed by Van Genuchten (1980) permits a representation of the total soil water retention curve, whereas, the Campbell (1974) and Brooks-Corey (1964) equations do not. The Brooks-Corey (1964) and Campbell (1974) equations have a discontinuity at the air-entry value. Despite this, the Brooks-Corey equation has been widely tested, modified and applied in solving soil-water flow problems (e.g., Lenhard & Bloomsberg, 1979; Russo & Bresler, 1980; Timlin *et al.*, 1999). Similarly, the Campbell (1974) equation has been tested, (e.g., Hall *et al.*, 1977; Cresswell & Paydar, 1996; Wagner *et al.*, 1998), modified (e. g., Hutson & Cass, 1987) and applied to describe water retention curves.

To compare the performance accuracy of the water retention curve equations used in describing measured data, the statistical indicators mentioned in Section 3.2.3 were used.

Lynne & Skaggs (1986) used a frequency count to identify the best equation. They counted the number of times an equation scored best, second best and so on, for a specific criterion. This same procedure was also used by Vereecken (1988) and Cornelis *et al.* (2001) to evaluate the performance of different water retention curve equations and pedotransfer functions, respectively.

4.2.2. Application criterion

The second procedure that can be used for the identification of water retention curve equations is the application criterion. Vereecken (1988) described this criterion as qualitative and as such subjected to more subjective interpretations and evaluations. The application criterion is used when evaluation criteria cannot discriminate between different equations. While evaluation criteria try to select the best equation, application criteria evaluate the capability of the equation in relating soil information to soil hydraulic information. For instance when two equations with different numbers of parameters are found to perform equally well based on evaluation criteria, the equation with the lowest number of parameters, which can be significantly related to soil properties, will be selected. A simpler equation structure will be preferred to a complex one, in view of further practical applications.

From the foregoing it is clear that application criterion relies on the common sense of the researcher, who has to select the best equation that meets his objectives, when pure statistical criteria evaluate the equations to be equally suitable.

4.3. Fitting procedures

4.3.1. Introduction

The equations of Van Genuchten (1980), Brooks & Corey (1964) and Campbell (1974) were fitted to the measured data set with a non-linear, least squares curve-fitting program (RETC; Van Genuchten *et al.*, 1991). RETC was run with MTYPE = 3 ($m = 1- 1/n$) to fit the Van Genuchten equation. Van Genuchten & Nielsen (1985) investigated the ability of the unrestricted Van Genuchten equation to describe a limited set of measured water retention data by using m and n as independent variables and using cases of restricted m- and/or n-values. They found that the best fits were obtained with variable m- and n-values, whilst $m = 1-1/n$ was found to be the best of the restricting assumptions. The Van Genuchten equation is most commonly used with restricting assumptions for m-values because it simplifies the solution for hydraulic conductivity models. The unrestricted Van Genuchten equation has 5 parameters. The empirical prediction of these parameters seems unrealistic. For this reason, and in the light of the results of previous studies by Van Genuchten & Nielsen (1985), it was decided to use the Van Genuchten equation with $m = 1-1/n$, which reduces the number of parameters to four.

RETC was run with MTYPE = 5 to fit the Brooks-Corey and Campbell equations. For the Campbell equation, the residual water content (θ_r) was fixed at zero. The RETC program as used here fits both the $0 > h > h_b$ and the $h < h_b$ sections of the Brooks-Corey and Campbell equations simultaneously to the water retention data. Hence, it was not necessary to exclude the water retention data points at $0 > h > h_b$ from the fitting procedure.

A summary of the water retention equations used during the identification phase and the functional form of the equations used for optimisation purposes are given in Tables 4.1 and 4.2, respectively.

Smith (1992) modified the Brooks-Corey equation to solve the problem of discontinuity at air entry. This equation was fitted to the water retention data using *Solver* of the Microsoft Excel program, which has the same non-linear least squares optimisation process as used in RETC.

Hutson & Cass (1987) modified the Campbell equation to circumvent the problem of discontinuity at the air entry value (h_b). At water contents near saturation, they introduced a parabolic equation. They joined this with the power-law equation of Campbell (1974), which is retained at the dry-end of the curve, to yield a continuous two-piece equation. The two-piece equation requires no additional parameters. The Hutson & Cass (1987) equations are given in Table 4.1. In these equations a is a constant analogous to the air entry potential; (h_i, θi) is the point of inflection where the parabolic and exponential curves meet. The two-piece equation is suitable for soil water simulation (e.g., Ross, 1990) as it has no slope discontinuities and is applicable at all water contents from saturation to wilting point (Hutson & Cass, 1987). This equation was fitted to the measured water retention data using *Solver* of the Microsoft Excel program, which was also used for the power function equation.

Table 4.1 Summary of water retention curve equations studied in the identification phase

No.	Equation	Parameters	Author
1	$S_e = \left(\frac{h_b}{h}\right)^{\lambda}$	Se =$(\theta-\theta_r/\theta_s-\theta_r)$ θ_r, θ_s, h_b, λ	Brooks Corey (1964)
2	$S_e = \left[1+\left(\frac{h}{h_b}\right)^5\right]^{\frac{-\lambda}{5}}$	Se =$(\theta-\theta_r/\theta_s-\theta_r)$ θ_r, θ_s, h_b, λ	Smith (1992)
3	$\frac{\theta}{\theta_s} = \left(\frac{h_b}{h}\right)^{-\frac{1}{b}}$	θ_s, h_b, b	Campbell (1974)
4	$S_e = \left[1+(\alpha h)^n\right]^{-1+\frac{1}{n}}$	Se =$(\theta-\theta_r/\theta_s-\theta_r)$ θ_r, θ_s, α, n	Van Genuchten (1980)
5	$\theta_i = \frac{2b\theta_s}{1+2b}$, $\theta = \theta_s\left(\frac{h}{a}\right)^{-\frac{1}{b}}$ $(h \le h_i)$ $\theta = \theta_s - \frac{\theta_s h^2\left(1-\frac{\theta_i}{\theta_s}\right)}{a^2\left(\frac{\theta_i}{\theta_s}\right)^{-2b}}$ $(h \ge h_i)$	θ_s, b θ_s, b, a Same as above	Hutson & Cass (1987)
6	$\theta = Ah^B$		

In an attempt to reduce the number of parameters in an equation, the measured θ_s was fixed during optimisation and the optimisation process was repeated by allowing the θ_s-value to vary. The R^2- and SSE-values indicated that optimisation by not fixing θ_s at the measured value (θ at-1kPa) described the measured water retention best. Due to this, the parameter θ_s was not fixed but subjected to optimisation similar to the other parameters in an equation. In cases where high correlations between parameters were observed, the optimisation process was repeated by fixing one of the highly correlated parameters alternately and the one that gave better results was retained as the final value of the parameter.

Table 4.2 Mathematical formulation of the water retention curve equations used in the optimisation process and parameter correspondence among the equations

Equation	Formulation	Parameter correspondence
1	$\theta = \theta_r + (\theta_s - \theta_r) \times (\alpha h)^{-\lambda} \quad (\alpha h > 1)$ $\theta = \theta_s \quad (\alpha h \leq 1)$	$\alpha = (h_b)^{-1}$ $\lambda = mn$
2	$\theta = \theta_r + (\theta_s - \theta_r) \times \left[1 + \left(\frac{h}{h_b}\right)^5\right]^{\frac{-\lambda}{5}}$	
3	$\theta = \theta_s \times (\alpha h)^{-\frac{1}{n}}$	b= -1/nm, m =1 $h_b = (\alpha)^{-1}$
4	$\theta = \theta_r + (\theta_s - \theta_r)\left[1 + (\alpha h)^n\right]^{-1+\frac{1}{n}}$	
5	$\theta = \theta_s - \dfrac{\theta_s h^2 \left(1 - \frac{\theta_i}{\theta_s}\right)}{a^2 \left(\frac{\theta_i}{\theta_s}\right)^{-2b}}$	
6	$\theta = Ah^B$	

4.3.2. Data sets used for curve fitting

The six types of water retention curves, listed in Table 4.1, were each fitted to the data sets given in Tables 3.4 (topsoils), 3.8 (subsoils with Si:C ratios < 0.75) and 3.12 (subsoils with Si:C ratios > 0.75). The mean volumetric water contents for each class in these tables, were calculated from a total of 53 samples for the topsoils, 148 samples for subsoils with Si:C ratios < 0.75, and 15 samples for the subsoils with Si:C ratios > 0.75. Each class represented a data pair to which all six types of curves could be fitted. There were a total of 20 data pairs consisting of 7 classes for topsoils and subsoils with Si:C ratios < 0.75 each, and 6 classes for the subsoils with Si:C ratios > 0.75. It was assumed that if a specific water retention function fits the mean data set well it will do the same for individual samples.

4.3.3. Statistical comparison of the goodness of fit for the different water retention equations

After each of the six water retention equations were fitted to each of the 20 data pairs, the equations were used to predict water contents at matric potentials of –1, -5, -8, -10, -30, -60, -100, -300 and –1500 kPa for each class. The predicted and mean measured volumetric water contents were used to calculate the MAE, RMSE, d- and R^2-values for each type of water retention equation, and soil grouping (Table 4.3). The water retention equations were then ranked for each criterion. Frequency count was used to determine the final ranking of the equation.

4.4. Comparison of the applicability of different water retention equations

The values of the various statistical indicators in Table 4.3 show that the accuracy with which the equations estimate the water contents varied within the soil groups. The values of the various statistical indicators for each silt plus clay class and equation are given in Appendices 4.1 (topsoils), 4.2 (subsoils with Si:C ratios < 0.75) and 4.3 (subsoils with Si:C ratios > 0.75).

4.4.1. Brooks-Corey equation

For the topsoil group, the Brooks-Corey equation gave the highest mMAE (0.013cm^3 cm^{-3}) and mRMSE (0.017 cm^3 cm^{-3}) compared with any of the other equations, indicating that it gave the poorest estimates. The Brooks-Corey equation fitted the mean measured values near saturation (-1kPa) for five of the seven water retention curves, but gave a very poor description of the remaining two water retention curves near saturation. The residuals from the Brooks-Corey fitting tend to be positive at –5, -8, -10 and –1500 kPa and negative at the remaining matric potentials. Cresswell & Paydar (1996) evaluated the Brooks-Corey equation for describing the water retention of Australian soils and found negative residuals near saturation and at low water contents and positive residuals in the mid range. They also found high values of the mean absolute error at high water contents. For their topsoil samples they found mMAE- and RMSE-values of 0.009 and 0.011 $cm^3\ cm^{-3}$. For the topsoils with silt plus clay contents > 80 %, the Brooks-Corey equation estimated the same water content for the matric potential range between -1 and -10 kPa. This was because the estimated air entry value was more negative (less than) these matric potentials. This resulted in high residual values near saturation. Van Genuchten & Nielsen (1985) suggested that the Brooks-Corey equation might give less accurate descriptions of water retention curves for structured soils, since the air entry value of these soils is poorly defined. Nonetheless, the values of the mean absolute error and root of mean square error were comparatively small and the d-value indicated a good agreement between measured and estimated water contents. It can, therefore, be said, considering its simple form, that this equation described the measured water retention curves fairly well. A student *t*-test showed that the means of the residuals were not significantly different from zero, indicating the estimated values did not under- or over-estimate the measured values, over the full range of the matric potentials.

For the subsoils with Si:C ratios < 0.75, the residuals near saturation were even higher. For the 70.01-80, 80.01-90 and 90.01-100 % silt plus clay classes, the same water content was estimated between -1 and -10 kPa. The same trend was observed for subsoils with Si:C ratios > 0.75. This equation estimated the water contents of the two groups of subsoils more accurately than the topsoil group, as indicated by the respective mMAE, mRMSE and d-value. The student t-test also showed that the mean of residuals for the two groups of subsoils were not significantly different from zero, indicating that there were no under- or over-estimations of the measured water contents. Cresswell & Paydar (1996) reported mMAE- and mRMSE-values of 0.006 and 0.009 $cm^3\ cm^{-3}$ for the subsoil samples they evaluated. From the frequency count results, this equation gave the poorest estimates of water contents compared to any of the other equations. Campbell & Shiozawa (1992) stated that the Brooks-Corey equation over-estimated water content data at low matric potentials but their observation pertained to matric potentials in the order of -10^5 kPa, which is much lower than those considered here. Ross *et al.* (1991) and Rossi & Nimmo (1994) have each proposed improvements on the Brooks-Corey equation to obtain a better description of water content data at these very low matric potentials.

Table 4.3. Comparison of the water contents estimated with the different water retention equations with the mean measured values in Tables 3.4, 3.8 and 3.12

		Topsoil				
Equation	N*	mMAE	mRMSE	md	mR^2	Rank
Van Genuchten	63	0.010 (3)	0.012(3)	0.992(4)	0.968(4)	3
Brooks-Corey	63	0.013 (6)	0.017(6)	0.991(5)	0.962(5)	6
Campbell	63	0.010(3)	0.013(4)	0.993(3)	0.957(6)	4
Hutson & Cass	63	0.012 (5)	0.015(5)	0.988(6)	0.973(1)	5
Smith	63	0.007(1)	0.011(1)	0.994(1)	0.973(1)	1
Power	63	0.009(2)	0.011(1)	0.994(1)	0.969(2)	2
		Subsoils with Si:C ratio < 0.75				
Van Genuchten	63	0.008(1)	0.009(1)	0.999(1)	0.982(3)	1
Brooks-Corey	63	0.010(4)	0.014(4)	0.997(4)	0.944(5)	4
Campbell	63	0.012(5)	0.015(5)	0.997(5)	0.941(6)	6
Hutson & Cass	63	0.009(3)	0.011(3)	0.999(1)	0.984(1)	2
Smith	63	0.018 (6)	0.021(6)	0.992(6)	0.983(2)	5
Power	63	0.008(2)	0.010(2)	0.999(1)	0.979(4)	3
		Subsoils with Si:C ratio > 0.75				
Van Genuchten	54	0.009 (2)	0.011(2)	0.9988(1)	0.981(3)	2
Brooks-Corey	54	0.012 (4)	0.015(4)	0.9987(3)	0.966(6)	4
Campbell	54	0.009 (3)	0.012(3)	0.9987(3)	0.971(4)	3
Hutson & Cass	54	0.014(6)	0.016(6)	0.9977(5)	0.985(1)	4
Smith	54	0.008(1)	0.010(1)	0.9988(1)	0.984(2)	1
Power	54	0.013(5)	0.016(6)	0.9950(6)	0.971(4)	6

* N = number of estimated and measured volumetric water content data points,
( ) Ranking of the equations.

4.4.2. Smith equation (modified Brooks-Corey)

The Brooks-Corey equation modified by Smith (1992) gave the lowest mMAE (0.009 $cm^3\ cm^{-3}$), mRMSE (0.011 $cm^3\ cm^{-3}$) and the highest d-value (0.994) for topsoils and subsoils with Si:C ratios > 0.75, compared to any of the other equations evaluated. This shows that this equation estimated the water contents with a higher accuracy than any of the other five equations for these groups of soils. Similar to the Brooks-Corey equation, the residuals for the topsoils were positive at –5, -8, -10 and –1500 kPa and negative at the remaining potentials. For subsoils with a Si:C ratio < 0.75, fitting Smith's equation resulted in the highest mMAE and mRMSE and the lowest d-value, indicating that it gave the poorest estimation of the water retention curves for these soils. For the subsoils with a Si:C ratio < 0.75, the residuals were negative at all the matric potentials and mean absolute errors were higher towards the drier end of the curve (-60 to -1500 kPa). For the subsoils with a Si:C ratio > 0.75, the residuals were positive at all the matric potentials, indicating that this equation slightly over-estimated the water contents. Overall, when compared with the Brooks-Corey equation, this equation was able to better describe the water retention curves of the topsoil and subsoils with a Si:C ratio > 0.75. It also has the added advantage of being continuous at the air entry value. A student *t*-test (P = 0.05) showed that there were no significant differences between the evaluation indices of the two equations indicating that they gave a comparable accuracy in describing the water retention curves of the three groups of soils. The *t*-test also showed that the means of residuals from fitting the Smith's equation to the water retention of the three groups of soils were not significantly different from zero. This is in agreement with the d-values that were close to 1.

4.4.3. Campbell equation

While fitting the Campbell equation to the data, it was observed that when the silt plus clay content exceeded 80 % for topsoils and the subsoils with a Si:C ratio < 0.75, the water contents at matric potentials higher than –10 kPa were almost equal to saturation. This was because the matric potential at the air entry value for these soils was less than –10 kPa. Fitting this equation to the water retention curves of the topsoils and subsoils with a Si:C ratio < 0.75, the residuals were negative at –1, -60, -100 and –300 kPa and positive at the remaining potentials. Similar to the Brooks-Corey equation, the highest residuals occurred at the wet-end of the water retention curve for the soils with high silt plus clay contents. The reason for this, as noted by many researchers, is the discontinuity in the slope of this equation at the air entry value and the poor definition of the air entry value for highly structured soils. Cresswell & Paydar (1996) also indicated that errors in the Campbell equation occurred at the wet-end of the water retention curve near the inflection point at the air entry potential. A student *t*-test (P = 0.05) showed that the means of the residuals for the three groups of soils were not significantly different from zero, indicating that over the full range of the matric potentials, the estimated values did not under- or over-estimate the measured values. The d-values for the three groups of soils were close to 1, indicating that there was a good agreement between the measured and estimated values. Overall, the Campbell equation described the measured water retention data better than the Brooks-Corey equation indicating that elimination of the residual water content from the Brooks-Corey equation is acceptable for the majority of the water retention curves of the Hararghe Region soils.

4.4.4. Hutson & Cass equation

Hutson & Cass (1987) modified the Campbell equation in an attempt to solve the discontinuity in the slope of the equation at the air entry value. In this study, this equation did slightly better in estimating the water retention curves of the subsoils with Si:C ratios < 0.75, than the original Campbell equation. For topsoils and subsoils with Si:C ratios > 0.75 , the Campbell equation fitted the measured values better than the Hutson & Cass equation. The student *t*-test (P = 0.05) showed that there were no significant differences between mMAE, mRMSE and mean d-values of the Campbell and Hutson & Cass equations, indicating that they gave the same accuracy in describing the water retention curves of the three groups of soils. The Hutson & Cass equation will be preferred to the Campbell equation because it solves the discontinuity in slope at the air entry value.

4.4.5. Power function

A simple power equation, consisting of only two curve-fitting parameters, also did well in estimating the water contents of the three soil groups. It estimated the water contents of topsoils and subsoils with Si:C ratios < 0.75 better than the other equations except the Smith equation. For the subsoils with a Si:C ratio > 0.75 , fitting this equation gave the highest mean of root mean square error (mRMSE) and the lowest d-value, indicating that it estimated the water contents relatively poorly compared to the other equations. However, considering its simple form and only two curve-fitting parameters, it performed well in estimating water contents of the three soil groups.

4.4.6. Van Genuchten equation

Compared to all the other equations, the Van Genuchten equation with the restriction of $m = 1 - 1/n$ performed very well in estimating the measured water contents of the three soil groups. The mean residuals for the three groups of soils were generally low and it gave better results near saturation. Cresswell & Paydar (1996) found the Van Genuchten equation with this restriction to be the best among the equations they evaluated. They reported mean MAE- and RMSE-values of 0.007 and 0.009 $cm^3\ cm^{-3}$ for topsoil samples and 0.006 and 0.008 $cm^3\ cm^{-3}$ for subsoil samples.

To conclude, the Smith equation performed well next to the Van Genuchten equation. The power function was found to be third best of the six equations evaluated. Student *t*-tests ($P = 0.05$) showed that there were no significant differences among the values of the evaluation indices in Table 4.3, indicating that all the equations did equally well, statistically speaking, in estimating the measured water contents of the three groups of soils.

4.5. Relationships between the parameters of water retention equations and soil properties

All the equations discussed in Section 4.4, described the water retention curves of the Hararghe Region soils with a reasonable degree of accuracy. The next question will be how well can the parameters of these equations be related to relevant soil properties in order to be able to predict it from relevant soil properties, so that reasonable estimates of water content-matric potential relationships can be obtained? In this section this question will be addressed. For this purpose, the Van Genuchten, Smith and Hutson & Cass equations were selected. The Smith and Hutson & Cass equations gave better results than the Brooks-Corey and Campbell equations from which they were derived. They also solved the problem of discontinuity at the air entry value, which is a shortcoming in both the Brooks-Corey and Campbell equations. As regards the power function, there can be no physical significance attached to the two curve-fitting parameters, so it was excluded from further evaluation.

4.5.1. Relationships between equation parameters and soil properties

For the determination of relationships between the parameters of the selected equations and soil properties the following data were used:

(i) The equation parameters obtained with the curve fittings for the individual silt plus clay classes, of the three soil groupings (Section 4.4), were used.

(ii) The mean soil properties of the corresponding classes, summarized in Tables 3.3 (topsoils), 3.7 (subsoils with Si:C ratios < 0.75) and 3.11 (subsoils with Si:C ratios > 0.75), were used.

The parameters of all the water retention equations were related to relevant soil properties with regression analyses. The relevant soil properties that described the parameter of the water retention equation best were selected by either stepwise regression or all-possible regression procedures. The all-possible regressions procedure was used in cases where stepwise regression did not select any soil variable that could be related to the parameters of the equations. To improve the percentage of variance explained by the variable(s), some transformations were also made. After relating the parameters of an equation to a relevant soil property (ies), the predicted parameters were used to estimate water contents at the same matric potentials as the measured water contents. The estimated water contents, using the predicted parameters in the water retention equations, were compared with the measured water contents to determine its accuracy. This was used to select the water retention equation whose parameters can best be predicted from relevant soil properties.

The regression equations that can be used to estimate the parameters of the different water retention equations from relevant soil properties, are given in Table 4.4. The stepwise regression procedure selected only one soil variable for most of the parameters. The ones that were described as a function of more than one variable were from the all-possible regressions procedure. The results of the regression analyses in

Table 4.4 indicate that the soil variable that explains the variance of a parameter best varied with soil groups.

For the equations of Van Genuchten and Smith, θ_r was the most difficult parameter to relate to soil variables. This was because, the optimisation process came up with a value of θ_r equal to zero for the majority of the water retention curves fitted to these equations. Vereecken *et al.* (1989) predicted θ_r from clay percentage and organic carbon content. Van den Berg *et al.* (1997) used only clay content for estimating θ_r and the R^2-value was 0.48. The value of θ_r is related to micropores with a pressure head of –1500 kPa or higher, that in turn are related to the soils high surface area constituents clay and organic matter (Williams *et al.*, 1992). The saturation water content parameter θ_s was related to silt plus clay content except for subsoils with Si:C ratios > 0.75, where it was described best by clay content for the Van Genuchten equation. Compared to the parameters of the Hutson & Cass and Smith equations, the parameters of the Van Genuchten equation were poorly related to soil variables. Many researchers (e.g., Minasny *et al.*, 1999; Tietje & Tapkenhinrichs, 1993) indicated that it is usually difficult to find a relationship between soil properties and the scaling and shape parameters α and n. Puckett *et al.* (1985) found that the values of α were independent of particle size and followed no observable pattern. This was also pointed out by Van Genuchten (1978). Vereecken *et al.* (1989) predicted the logarithm of α from sand, clay, carbon content and bulk density. Campbell (1985) found that $h_b \approx 1/\alpha$ is a function of $d_g^{-0.5}$ (the geometric mean particle diameter) and b is a function of h_b and σ_g (the geometric mean standard deviation). Scheinost *et al.* (1997) proposed that α is related to d_g. The geometric mean particle diameter (d_g) was found to be well related with most of the parameters of the water retention equations. This parameter encompasses all three particle sizes: sand, silt and clay.

4.5.2. Comparisons between measured and estimated water contents

The mean soil properties of the different classes of the three soil groups were used to predict the retention curve parameters with the equations in Table 4.4. The estimated water contents at similar matric potentials were compared with the measured values. Only the Van Genuchten, Smith and Hutson & Cass equations were selected. The comparisons of the water contents estimated from predicted parameters of these three equations and the measured water contents, are given in Table 4.5.

Table 4.4 Estimation equations for the parameters of the different water retention equations

Equation	Topsoils	R^2
Van Genuchten (1980)	$\theta_r = -0.0463 + 21.7542*\%(Si+C)-21.7556*(\% C)-21.7589(\% Si)+1.6561(d_g)+0.0139(\sigma_g)$	0.56
	$\theta_s = 0.3586*e^{0.004*\%(Si+C)}$	0.90
	$\alpha = 0.2985*(1/\log(\%C)) - 0.1228$	0.92
	$n = 1.2153*d_g^{-0.5} + 9.5644$	0.54
Hutson & Cass (1987)	$\theta_s = 0.2831*e^{0.0075*\%(Si+C)}$	0.98
	$a = 0.5125*dg^{-0.5} + 9.4413$	0.68
	$b = 6.9389 + 0.0523*\%(Si+C)-22.7730*d_g$	0.98
Smith (1992)	$\theta_r = 0.013-0.001*\% C-0.3032*d_g+0.0061*\sigma_g$	0.51
	$\theta_s = -0.0190+0.0053*\%(Si+C)+0.9580*dg+0.010*\sigma_g$	0.96
	$h_b = 58.4349+985.467*\%(Si+C)-985.7573*(\% C)-986.1198*(\% Si)-72.55181*dg-1.5864*\sigma_g$	1.0
	$\lambda = 0.2454-0.0019*\%(Si+C)$	0.70
	Subsoils with a Si:C ratio < 0.75	
Van Genuchten (1980)	$\theta_r = -0.0031*\%(Si+C) + 0.2784$	0.71
	$\theta_s = 0.0025*\%(Si+C) + 0.3671$	0.52
	$\alpha = -1.6285+0.0346*\%(Si+C)-0.0633*(\%Si)+6.4893*dg+0.0423*\sigma_g$	0.56
	$n = 4.1769*\%(Si+C)^{-0.3034}$	0.82
Hutson & Cass (1987)	$\theta_s = 0.3138*e^{0.0067*\%(Si+C)}$	0.90
	$a = 0.5574*d_g^{-0.5} + 4.5859$	0.90
	$b = -83.109*d_g + 11.7340$	0.91
Smith (1992)	$\theta_r = -0.0067*(\%Si) + 0.1636$	0.60
	$\theta_s = 0.1155 + 0.0049*\%(Si+C)+2.3367*d_g$	0.96
	$h_b = -3.4349-68.4299*(\% C)-68.5963*(\% Si)+68.6785*(\%Si+C)+122.8086*d_g$	0.81
	$\lambda = 0.5415*e^{-0.0748*\%(Si+C)}$	0.83

Table 4.4 Continued...

	Subsoils with a Si:C ratio > 0.75	
Van Genuchten (1980)	$\theta_r = 0.0019 * \% \, C - 0.0064$	0.10
	$\theta_s = 0.1121 * LN \, (\% \, C) + 0.1689$	0.93
	$\alpha = 0.0017 * \% \, clay + 0.0306$	0.65
	$n = 0.0662 * LN(d_g) + 1.4299$	0.79
	$\theta_s = 0.2229 * \%(Si+C)^{0.2097}$	0.81
Hutson & Cass (1987)	$a = 24.1170 \, e^{-0.011 * \%(Si+C)}$	0.44
	$b = 1.4872 * (1/sqrt(dg))^{0.8840}$	0.98
	$\theta_r = 0.0016 * (\% \, Si) - 0.0222$	0.20
Smith (1992)	$\theta_s = 0.1696 * \%(Si+C)^{0.2678}$	0.94
	$h_b = 87.74 - 1.7 \, (\% \, Si) - 199.51 * dg$	0.91
	$\lambda = 0.0702 * Ln \, (d_g)) + 0.4143$	0.94

θ_r = residual water content (cm^3 cm^{-3}), θ_s = water content at saturation, α = scaling parameter (cm^{-1}), n = shape parameter (dimensionless), h_b = air entry pressure (cm), λ = pore size distribution index (dimensionless), b = a constant ($1/\lambda$), a = a constant analogous to h_b (cm)

(i) Topsoil

The values of the various statistical indicators for the 7 silt plus clay classes and the three equations are given in Appendix 4.4. For topsoils, the water contents estimated from the predicted parameters of the Hutson & Cass equation gave the lowest mean RMSE (0.009 cm^3 cm^{-3}) and highest d-value (0.998) compared to the water contents estimated from the predicted parameters of the Van Genuchten (0.028 cm^{3}cm^{-3} and 0.984, respectively) and Smith (0.017 cm^3 cm^{-3} and 0.982, respectively) equations. The mean RMSE suggests that the water content estimated with the predicted parameters of the Hutson & Cass equation was, on average, 0.020 cm^3 cm^{-3} and 0.009 cm^3 cm^{-3} closer to the measured water contents than the water contents estimated using the predicted parameters of the Van Genuchten and Smith equations, respectively. The index of agreement suggests that the Hutson & Cass equation was 1.45 and 1.64 % more accurate than the Van Genuchten and Smith equations, respectively. The student *t*-test, also, showed that the mean RMSE of the water contents estimated with the predicted parameters of the Hutson & Cass equation was significantly smaller than the mean RMSE of the water contents estimated with the predicted parameters of the Van Genuchten and Smith equations. The index of agreement, however, was not significantly higher than those of the Van Genuchten and Smith equations. It is important to note that the R^2 suggested that the parameters of the Smith equation had a better accuracy. Analyses of slopes and intercepts of the three equations of the 1:1 line (plotting estimated water content against measured content and fitting a straight line through the data) showed that the mean slope (0.902) and intercept (0.037cm^3 cm^{-3}) of the water contents estimated from the predicted parameters of the Hutson & Cass equation were significantly ($P = 0.05$) lower than 1 and zero, respectively, indicating that the predicted parameters of this equation, over-estimated the measured water contents. On the other hand, the mean slope and intercept of the water contents estimated from the predicted parameters of the Van Genuchten equation were not significantly different from 1 and zero, indicating that the predicted parameters of this equation did not over-or under-estimate the measured water contents and that there was a perfect match between the estimated and measured water contents on the 1:1 line. For the water contents estimated from the predicted parameters of the Smith equation, only the intercept was significantly different from zero (Figure 4.1).

Using frequency count to select the best equation, the Smith equation appeared to be the best in giving better estimates of the measured water contents of topsoils followed by the Hutson & Cass and Van Genuchten equations. This implies that the predicted parameters of the Smith equation were better for estimating water content from relevant soil properties compared to the predicted parameters of the Huston & Cass and Van Genuchten equations (Table 4.4).

From the foregoing discussions, it can be concluded that the predicted parameters of the three equations gave reasonably good estimates of the measured water contents albeit the predicted parameters of the Smith equation were found to be more accurate for estimating water content from the relevant soil properties of the Hararghe Region soils.

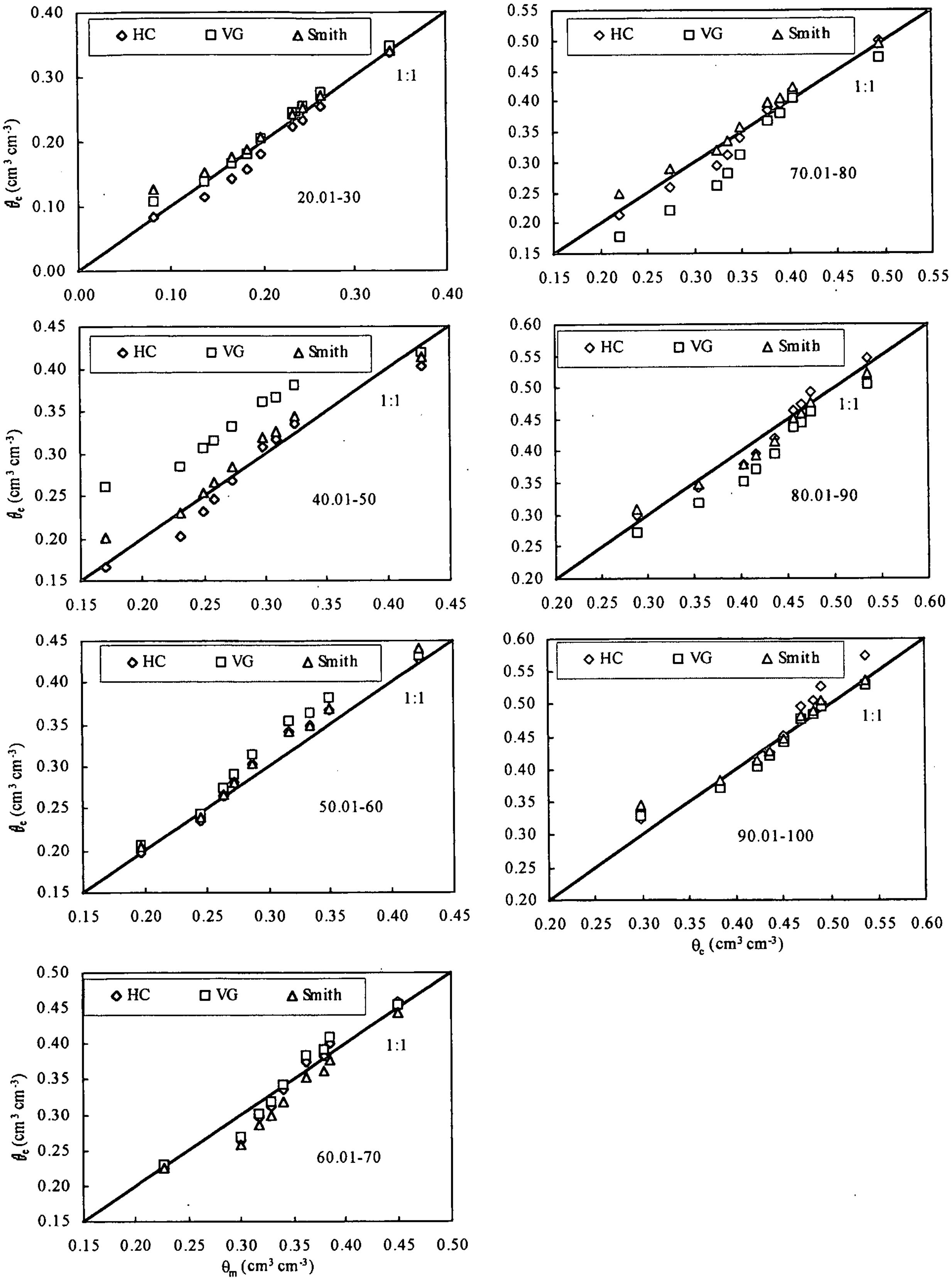

Figure 4.1 The relationship between estimated (θ_e), from predicted parameters of water retention equations, and measured (θ_m) water contents for the 7 topsoil silt plus clay classes.

Table 4.5 Comparison of water contents estimated from predicted parameters of water retention equations with the corresponding measured values

	Topsoils					
Equation	mMAE*	mRMSE	md	Slope	Intercept	R^2
Van Genuchten	0.025(3)	0.028 (3)	0.984(2)	0.996^{ns}	-0.002^{ns}	0.962(3)
Hutson & Cass	0.014 (2)	0.009(1)	0.998 (1)	0.902*	0.037*	0.967(2)
Smith	0.014(1)	0.017 (2)	0.982(3)	1.034^{ns}	0.032*	0.971(1)
	Subsoils with Si:C ratio < 0.75					
Van Genuchten	0.034 (3)	0.038(3)	0.975 (3)	1.034^{ns}	-0.008^{ns}	0.977(3)
Hutson & Cass	0.015 (1)	0.019(1)	0.989 (1)	0.962^{ns}	0.017^{ns}	0.980(2)
Smith	0.019(2)	0.021 (2)	0.988 (2)	0.937^{ns}	0.034^{ns}	0.982(1)
	Subsoils with Si:C ratio > 0.75					
Van Genuchten	0.025(3)	0.028 (3)	0.989 (3)	0.956^{ns}	0.029^{ns}	0.975(3)
Hutson & Cass	0.020 (2)	0.025 (2)	0.993 (2)	0.905*	0.028*	0.977(2)
Smith	0.014(1)	0.016 (1)	0.996(1)	1.006^{ns}	-0.002^{ns}	0.982(1)

*m refers to mean values, ^{ns} = nonsignificant (P = 0.05), * significant (P = 0.05) for H0: slope = 1 and H0:intercept = 0.

(ii) Subsoils with a Si:C ratio < 0.75

The values of the various statistical indicators for each class and water retention equation are given in Appendix 4.5. Comparison of water contents estimated from the predicted parameters of the Hutson & Cass equation with the measured values gave the lowest mean MAE (0.015 cm^3 cm^{-3}), mean RMSE (0.015 cm^3 cm^{-3}) and the highest index of agreement (0.989) compared to the Van Genuchten (0.034 cm^3 cm^{-3}, 0.038 cm^3 cm^{-3} and 0.975, respectively) and Smith (0.019 cm^3 cm^{-3}, 0.021 cm^{3}cm^{-3} and 0.988) equations. This implies that the water contents estimated with predicted parameters of the Hutson & Cass equation were closer to the measured water contents than those estimated with the predicted parameters of the Van Genuchten and Smith equations. The index of agreement showed that with predicted parameters the Hutson & Cass equation gave better estimated water contents than the Van Genuchten and Smith equations for subsoils with Si:C ratios < 0.75. The student *t*-test showed only significant differences between the mean RMSE values of the Hutson & Cass and Van Genuchten equations. A student *t*-test (p = 0.05) showed that the mean slopes and intercepts of 1:1 plots of estimated and measured volumetric water contents for all three equations were not significantly different from 1 and zero, respectively, indicating that, none of these equations over- or under-estimated the measured water contents (Figure 4.2).

The frequency count results in Table 4.5 indicate that the Hutson & Cass equation was better than the Smith and Van Genuchten equations. This means that the predicted parameters of this equation were better correlated with the relevant soil properties and, gave better predictions of water contents compared to the Van Genuchten and Smith equations (Table 4.4).

Since the differences between the values of the evaluation indices for the three equations were not significant, it can be concluded that when using the predicted parameters all these three equations can be used for estimating water contents at required matric potentials. For better accuracy, however, the Hutson & Cass equation appears to be more suitable for subsoils with Si:C ratios < 0.75 of the Hararghe Region.

(iii) Subsoils with Si:C ratios > 0.75

The values of the various statistical indicators for each class and equation are given in Appendix 4.6. The water contents estimated with the predicted parameters of the Smith equation compared with the measured values gave the lowest mean MAE (0.014 cm ^{3} cm^{-3}), mean RMSE (0.016 cm^3 cm^{-3},) and the highest d-value (0.996) compared to the Hutson & Cass (0.020 cm^3 cm^{-3}, 0.025 cm^3 cm^{-3} and 0.993, respectively) and the Van Genuchten (0.025 cm^3 cm^{-3}, 0.028 cm^3 cm^{-3} and 0.989, respectively) equations. The student *t*-test showed that the mean MAE and RMSE values for the Smith equation were significantly smaller than the corresponding values for the Hutson & Cass and Van Genuchten equations. This implies that the water contents estimated with the predicted parameters of the Smith equation were closer to the measured water contents than the ones estimated with the predicted parameters of Huston & Cass and Van Genuchten equations. Analyses of slopes and intercepts of the 1:1 plots indicated that the mean slopes and intercepts of the Smith and Van Genuchten equations were not significantly (P = 0.05) different from 1 and zero, respectively, while those of the Hutson & Cass equations were significantly different (Figure 4.3).

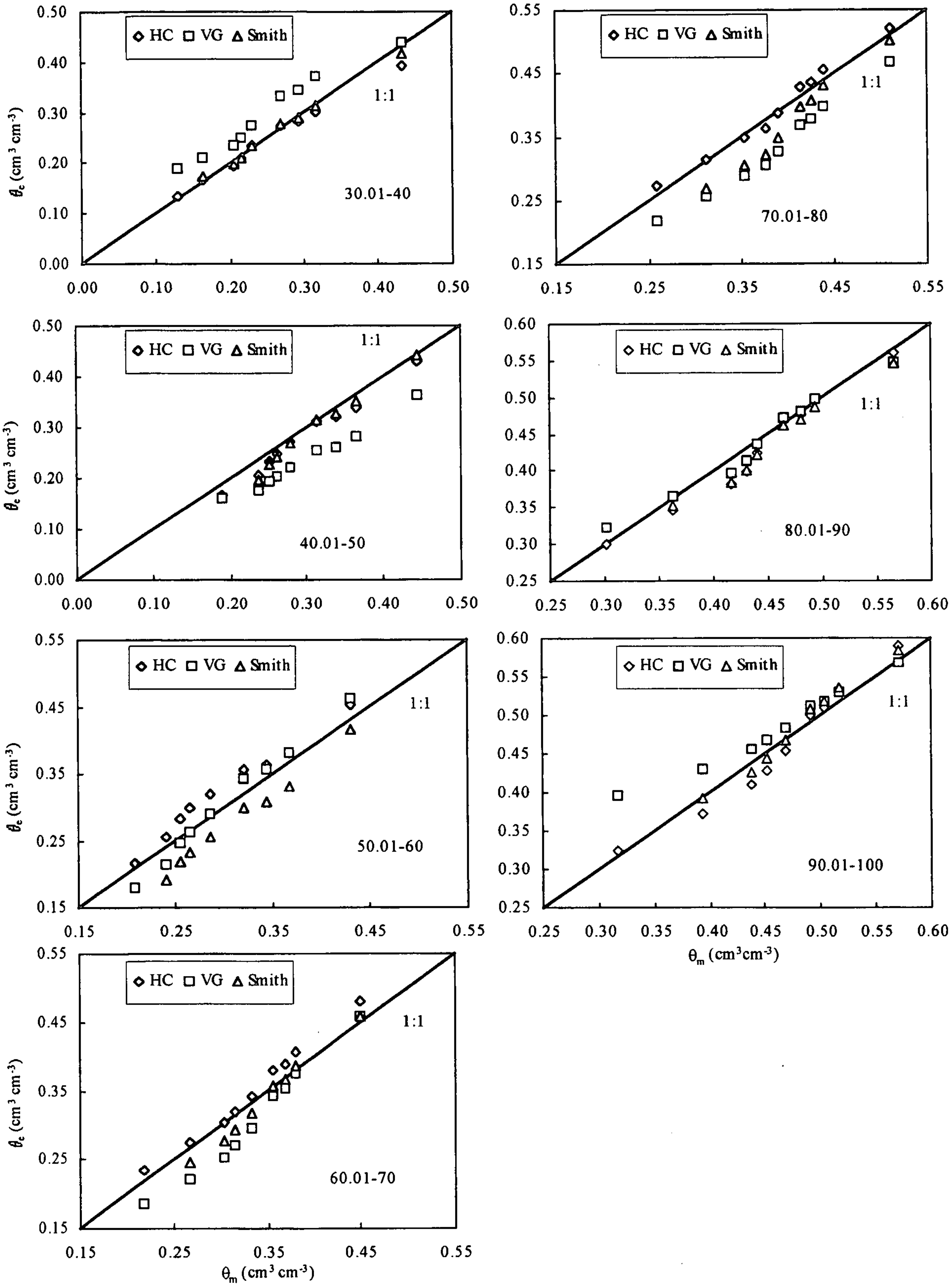

Figure 4.2 Relationship between estimated (θ_e), from predicted parameters of water retention equations, and measured (θ_m) water contents for the 7 silt plus clay content classes of subsoils with Si:C ratios < 0.75.

The frequency count results in Table 4.5 indicate that, for subsoils with Si:C ratios > 0.75, using predicted parameters for the Smith equation gave the best estimated water contents followed by the Hutson & Cass and Van Genuchten equations, for Hararghe Region soils.

To conclude, for better accuracy, the Smith equation is recommended for topsoils and subsoils with a Si:C ratio > 0.75 and Hutson & Cass for subsoils with a Si:C ratio < 0.75 of the Hararghe Region.

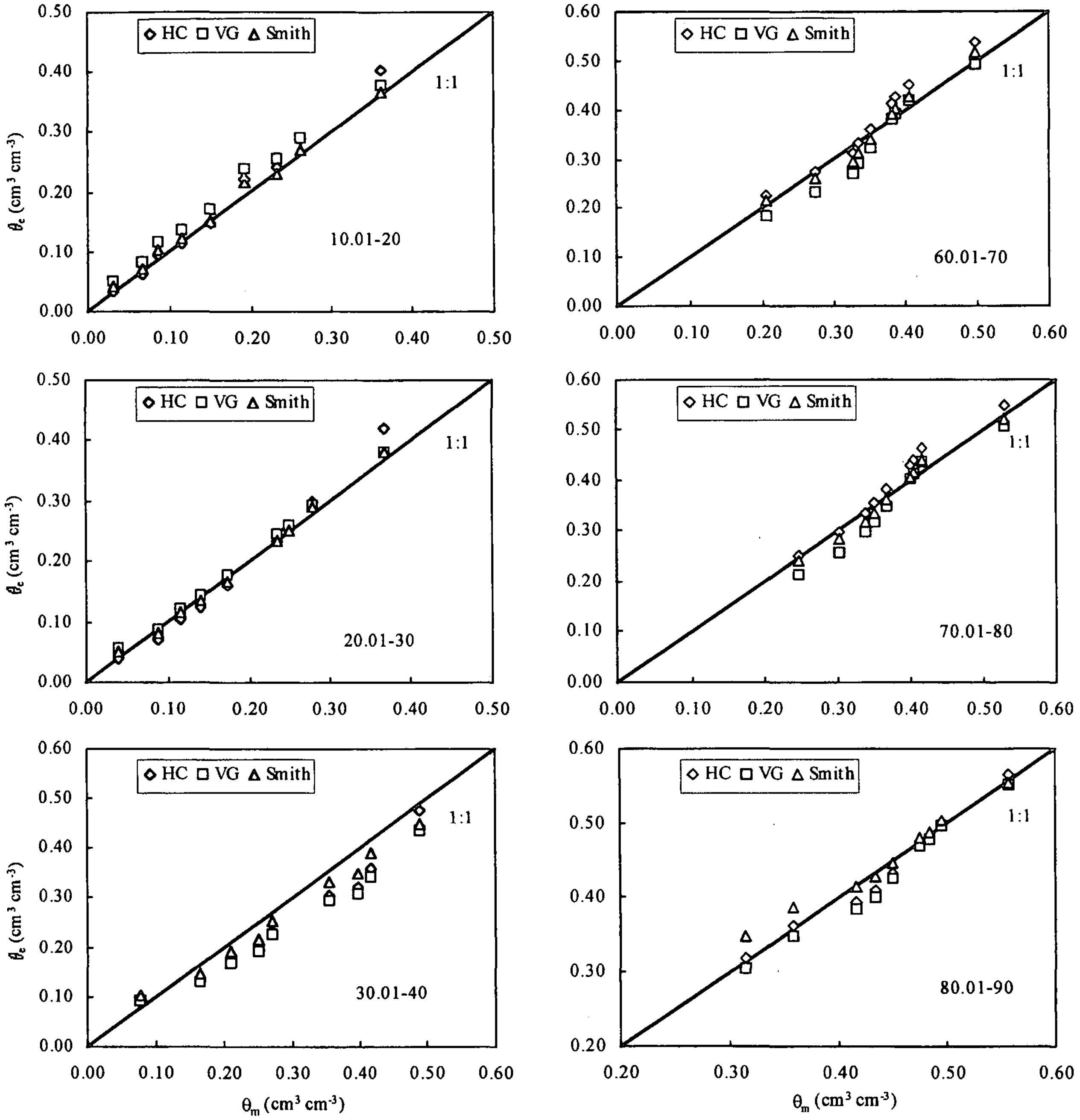

Figure 4.3 The relationship between estimated (θ_e), from predicted parameters of water retention equations, and measured (θ_m) water contents for the 6 silt plus clay content classes of the subsoils with Si:C ratios > 0.75.

4.7. Conclusions

The objectives of this chapter were firstly to select the best water retention equation with a mathematical structure suitable for describing the measured water retention curves of the Hararghe Region soils in the best possible way. Secondly to select an equation with the lowest possible number of parameters that can be related to soil properties.

Six water retention equations were selected for evaluation. Overall, the Van Genuchten equation was found to fit the measured water contents of the Hararghe Region soils best compared to the Brooks-Corey, Campbell, Huston & Cass, Smith and simple power equations. Following the Van Genuchten equation, the Smith and simple power equations also fitted the measured water contents of the Hararghe Region soils well. The Brooks-Corey equation gave the poorest fit.

The parameters of the Van Genuchten equation correlated poorly with soil properties compared to the parameters of the Smith and Hutson & Cass equations which gave better correlations. For this reason, using the parameters of the Van Genuchten equation, predicted from soil properties, gave the poorest estimates of the water contents for the Hararghe Region soils. The predicted parameters of the Smith (1992) equation gave the best estimates of the water contents for the topsoils and subsoils with a Si:C ratio < 0.75 while the predicted parameters of the Hutson & Cass equation gave the best estimates for the subsoils with a Si:C ratio > 0.75.

CHAPTER 5

VALIDATION OF THE POINT AND PARAMETRIC APPROACHES FOR ESTIMATING A WATER RETENTION CURVE FROM SOIL PROPERTIES

5.1. Introduction

In chapter one it was mentioned that in general two types of estimation procedures have been used in literature, namely, point estimation and parameterization techniques. The point estimation method deals with the estimation of the water content at specific matric potential values from common soil properties by means of empirical models. When the different water content-matric potential data pairs were estimated from the relevant soil properties, a complete water retention curve can be fitted through the data points (Vereecken, 1988).

With the parameterization method the parameters of a specific water retention curve equation are estimated with empirical equations using relevant soil physical properties.

Cornelis *et al.* (2001) validated pedotransfer functions (PTFs), developed by nine authors, on a data set of 298 undisturbed 100-cm^3 soil samples, collected from 69 different soils covering a wide range of textures within Flanders, Belgium. The nine functions they validated represented both the point (Gupta & Larson, 1979; Rawls & Brakensiek, 1982) and parametric approaches (Rawls & Brakensiek, 1985; Vereecken et al., 1989; Wösten *et al.,* 1994; Scheinost *et al.*, 1997; Schaap *et al.*, 1999; Wösten *et al.*, 1999). The validated PTFs showed good to poor prediction accuracy with the mean of the mean absolute error values ranging from 0.0312 cm^3 cm^{-3} for the Vereecken *et al.* (1989) PTFs to 0.0603 cm^3 cm^{-3} for the Rawls & Brakensiek (1985) PTFs and the mean of root mean squared errors ranging from 0.0412 cm^3 cm^{-3} for the Vereecken *et al.* (1989) to 0.0774 cm^3 cm^{-3} for the Rawls & Brakensiek (1985) PTFs. These PTFs used particle size distribution, bulk density and organic matter content, as variables.

Kern (1995) validated six models that included functions with various combinations of particle size distribution, bulk density and soil organic matter using data from nearly 6000 pedons sampled throughout the USA. The Rawls model, which requires particle size distribution and organic matter data, had the lowest overall absolute mean error values of 0.020, 0.001 and 0.007 $cm^3 cm^{-3}$ at matric potentials of –10, -33 and –1500 kPa, respectively. The Saxton *et al.* (1986) model, which requires particle size distribution data only, had mean absolute errors of 0.018 and 0.007 $cm^3 cm^{-3}$ at –10, –1500 kPa, and a mean absolute error of 0.017 $cm^3 cm^{-3}$ at –33 kPa. The Vereecken model, which requires bulk density, particle size distribution and organic matter data, had mean absolute errors of 0.016 and 0.009 $cm^3 cm^{-3}$ at matric potentials of –10 and –33 kPa and a mean absolute error of 0.020 $cm^3 cm^{-3}$ at –1500 kPa.

Tietje & Tapkenhinrichs (1993) validated 13 pedotransfer functions against test data sets with a wide range of soils from Germany. After the application of several PTFs to many soils in the data set, the average root mean squared error was found to be in the range of 0.04 to 0.13 $cm^3 cm^{-3}$ depending on the PTF used.

In chapter three, equations were compiled that can be used to estimate the water content at 9 matric potential values. The equations derived from silt plus clay contents were found to give the best predictions. In chapter four, different water retention equations were evaluated and the parameters of the equations that gave the best fit were related to relevant soil properties. The Smith equation gave estimates of water contents with a high degree of accuracy for the topsoil and subsoils with Si:C ratios > 0.75 and the Hutson & Cass equation gave good estimates of water contents for the subsoils with Si:C ratios < 0.75. Vereecken (1988) described the advantages and disadvantages of both the point estimation and parameterization procedures and indicated that comparison of the results of the two methods has never been made. The objective with this chapter is to compare the accuracy of the two techniques on a data set that was not directly used for developing the equations.

5.2. Materials and methods

From the complete data set of 216 individual samples, representing the mean of duplicate measurements, 25 topsoils, 88 subsoils with a Si:C ratio < 0.75 and all (15) of the subsoils with Si:C ratios > 0.75 were selected to represent a full range of Si+C-values. The measured volumetric water contents, at each of the matric potentials, were compared to the values predicted with the following equations. For the point estimation approach, the equations using only silt plus clay as independent variable (Tables 3.6, 3.10 and 3.14) were used to estimate the water content at each of the matric potentials using the silt plus clay contents of the individual samples. For the parametric approach, the parameters of the Smith equation were predicted from the relevant individual soil property values for the topsoil and subsoils with Si:C ratios > 0.75 and the Hutson & Cass equation for subsoils with Si:C ratios < 0.75, using the equations in Table 4.4. The predicted parameters were then used to estimate water content at each of the matric potentials for individual samples. The estimated water contents were then compared with the measured water contents in Figures 5.1, 5.2 and 5.3 and the statistical comparisons are given in Tables 5.1, 5.2 and 5.3.

5.3. Results and discussion

5.3.1. Topsoils

The comparison of water contents, estimated with the point estimation and parametric (Smith equation) approaches, with the corresponding measured values for topsoils is presented in Figure 5.1. The figure shows that both approaches over-estimated the water contents of some individual samples and under-estimated the water contents of some other individual samples. From the figure it can be seen that, except at –1500 kPa, both approaches under-estimated the high water contents at each matric potential. At –1500 kPa the parametric (Smith equation) approach over-estimated the water contents of 60 % of the samples while the point estimation approach over-estimated the water content of 40 % of the samples.

Further statistical comparison of the two approaches is presented in Table 5.1. The results in Table 5.1 comply with the trends observed in Figure 5.1. For the point estimation approach, the mean bias errors (MBE) are negative at all the matric potentials indicating that this approach, on average, under-estimated the water content at each matric potential.

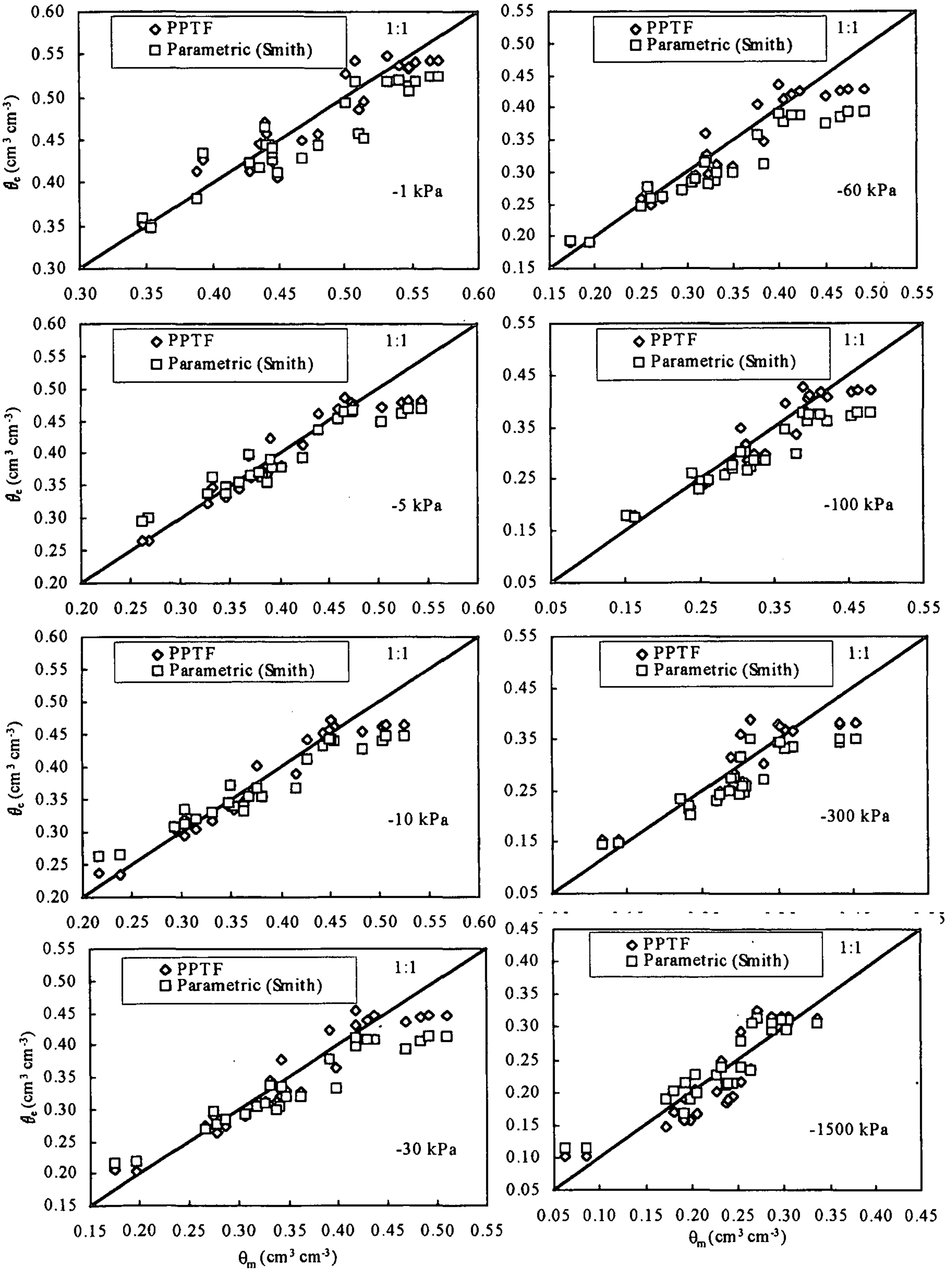

Figure 5.1 Comparison of water contents, estimated (θ_e) with the point and parametric (Smith equation) approaches, with the corresponding measured (θ_m) values for topsoils.

The mean absolute error (MAE) and the root mean square residuals (RMSE) indicate that the highest error of prediction occurred at –300 kPa (0.033 and 0.038 cm^3 cm^{-3}, respectively) and the lowest at –1 kPa (0.018 and 0.021 cm^3cm^{-3}, respectively). For the parametric (Smith equation) approach, the mean bias errors were negative at all matric potentials except at –1500 kPa. The values of the mean absolute (MAE) and root mean square residual (RMSE) indicate that the highest error of prediction occurred at –300 kPa (0.037 and 0.045 cm^3 cm^{-3}, respectively) and the lowest at –1500 kPa (0.021 and 0.024 cm^3cm^{-3}, respectively). This values and Figure 5.1 indicate that the parametric approach gave better accuracy than the point estimation approach at –1500 kPa.

Table 5.1. Comparison of water contents, estimated with point and parametric (Smith) approaches, with the corresponding measured values for topsoils

Approach		Matric potential (kPa)							
		-1	-5	-10	-30	-60	-100	-300	-1500
PPTF	MBE	-0.002	-0.008	-0.007	-0.007	-0.010	-0.008	-0.010	-0.006
	MAE	0.018	0.019	0.019	0.024	0.024	0.025	0.033	0.028
	RMSE	0.021	0.024	0.023	0.028	0.029	0.029	0.038	0.033
	d	0.94	0.95	0.95	0.94	0.92	0.92	0.91	0.97
	R^2	0.89	0.91	0.93	0.91	0.90	0.89	0.78	0.80
	Slope	0.881	0.864	0.868	0.859	0.869	0.879	0.819	1.020
	Intercept	0.054	0.048	0.044	0.043	0.035	0.032	0.044	-0.008
Parametric (Smith)	MBE	-0.017	-0.011	-0.013	-0.024	-0.030	-0.031	-0.029	0.005
	MAE	0.025	0.023	0.025	0.031	0.033	0.036	0.037	0.021
	RMSE	0.030	0.031	0.033	0.041	0.043	0.045	0.045	0.024
	d	0.93	0.94	0.97	0.92	0.91	0.91	0.90	0.96
	R^2	0.86	0.91	0.92	0.92	0.91	0.91	0.82	0.86
	Slope	0.755	0.687	0.676	0.661	0.693	0.687	0.692	0.859
	Intercept	0.099	0.116	0.111	0.097	0.075	0.072	0.064	0.038

The d-values at all the matric potentials were > 0.90 indicating that there was a good agreement between measured and estimated water contents. A student t-test ($P = 0.05$) indicated that the mean slopes and intercepts of the 1:1 plot between estimated and actual water retention curves for both approaches were not significantly different from 1 and 0, respectively. The slopes for the 1:1 plot at each matric potential in Figure 5.1, however, indicate that the parametric approach under-estimated the measured water contents more than the point estimation approach.

The results in Figure 5.1 and the values of the various statistical indicators in Table 5.1 indicate that both approaches gave a comparable degree of accuracy, although the point approach seemed to give better accuracy than the parametric (Smith equation) approach.

5.3.2. Subsoils with a Si:C ratio < 0.75

A comparison of the water contents, estimated with the point and parametric (Hutson & Cass equation) approaches, with the corresponding measured water contents for subsoils with a Si:C ratio < 0.75 is presented in Figure 5.2. A student *t*-test indicated that the mean slopes and intercepts of the 1:1 plot between the estimated and actual water retention curves were note significantly different from 1 and 0, respectively, for the point estimation approach and different from 1 and 0 for the parametric approach.

Figure 5.2 shows that both approaches over-estimated the water content of some individual samples and under-estimated the water contents of other samples. At –1 kPa, the parametric (Hutson & Cass equation) approach over-estimated the high water contents while the point estimation approach under-estimated it. At the other potentials, the two approaches gave similar results by either over- or under-estimating the water contents.

Further statistical comparisons, using different statistical indicators, are presented in Table 5.2. For the point estimation approach, the mean bias errors (MBE) were positive at all the matric potentials, indicating that this approach, in most cases, over-estimated water contents. The mean absolute (MAE) and root mean square errors (RMSE) indicate that the highest errors of prediction occurred at –60 and –100 kPa, with MAE and RMSE values of 0.037 and 0.044 cm^3cm^{-3}, respectively.

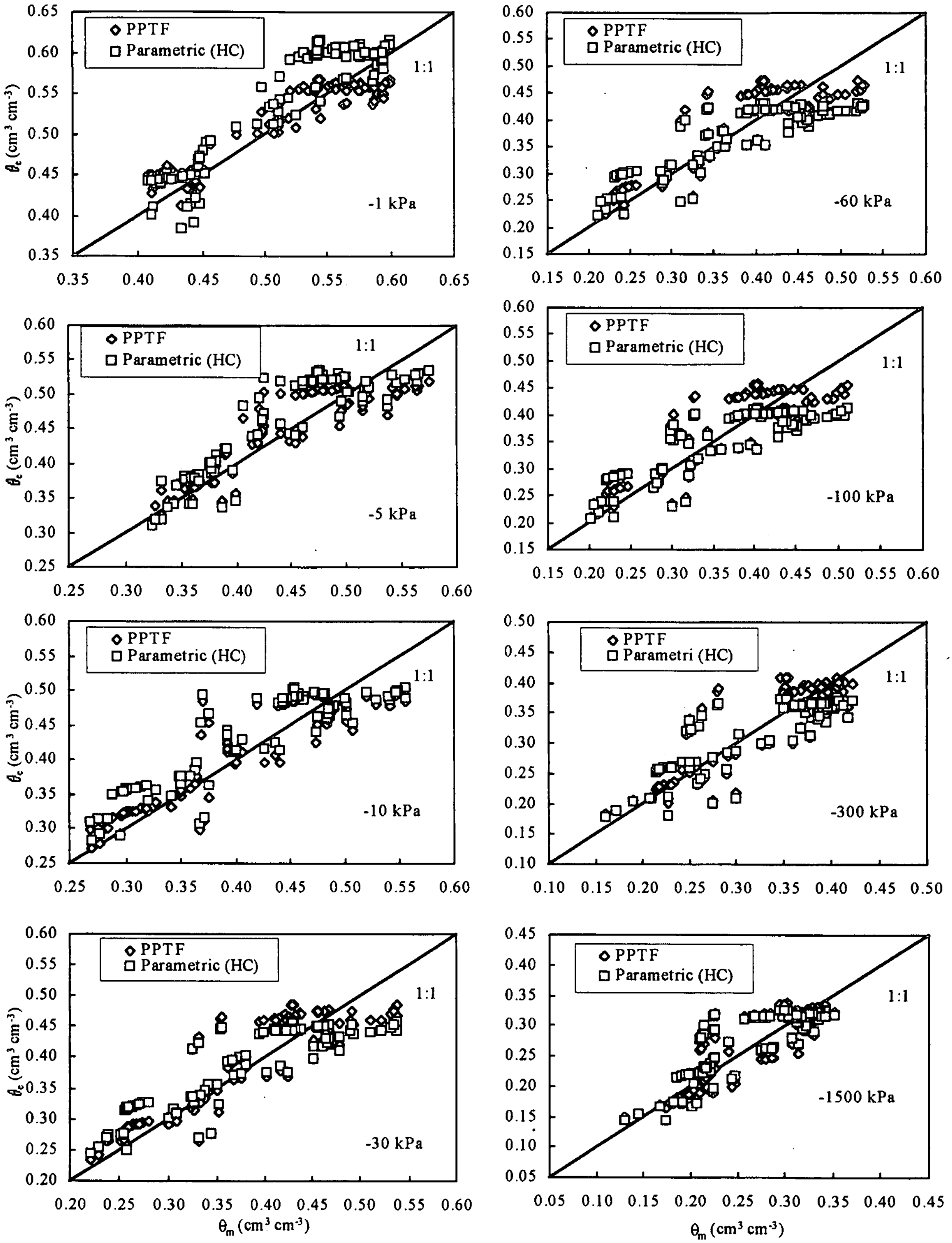

Figure 5.2 Comparison between water contents, estimated (θ_e) with the point and parametric (Hutson & Cass equation) approaches, and with the corresponding measured (θ_m) water content values for subsoils with a Si:C ratio < 0.75.

Table 5.2 Comparison of water contents, estimated with the point and parametric (Hutson & Cass equation) approaches, with the corresponding measured values for subsoils with a Si:C ratio < 0.75

Approach		Matric potential (kPa)							
		-1	-5	-10	-30	-60	-100	-300	-1500
PPTF	MBE	0.001	0.005	0.005	0.006	0.007	0.006	0.004	0.002
	MAE	0.022	0.027	0.030	0.034	0.037	0.037	0.027	0.025
	RMSE	0.026	0.032	0.036	0.042	0.044	0.044	0.037	0.032
	d	0.95	0.94	0.94	0.94	0.93	0.93	0.93	0.92
	R^2	0.86	0.79	0.81	0.78	0.77	0.77	0.76	0.73
	Slope	0.711	0.817	0.811	0.811	0.798	0.785	0.869	0.912
	Intercept	0.149	0.086	0.083	0.079	0.082	0.083	0.045	0.025
Parametric (HC)	MBE	0.020	0.016	0.018	0.003	-0.006	-0.010	-0.005	0.007
	MAE	0.028	0.031	0.037	0.037	0.040	0.041	0.033	0.025
	RMSE	0.035	0.037	0.042	0.045	0.049	0.050	0.040	0.032
	d	0.94	0.93	0.92	0.91	0.89	0.88	0.90	0.91
	R^2	0.86	0.79	0.78	0.75	0.74	0.72	0.71	0.7
	Slope	1.063	0.885	0.730	0.635	0.591	0.578	0.663	0.779
	Intercept	-0.012	0.067	0.129	0.144	0.146	0.140	0.102	0.065

For the parametric approach, the mean bias errors were negative between –1 and –30 kPa and at –1500 kPa and positive at the remaining potentials. The mean absolute and root mean square errors (RMSE) indicate that the highest error of prediction occurred at –100 kPa with MAE and RMSE values of 0.041 and 0.050 cm^3cm^{-3}, respectively. The d-values for the point estimation approach were > 0.90, at all the matric potentials, whereas for the parametric (Hutson & Cass equation) approach the d-values were < 0.90 at –60 and –100 kPa, resulting in high errors of prediction.

The results in Figure 5.2 and the values of the various statistical indicators indicated that the point estimation approach gave slightly better estimations than the parametric (Hutson & Cass equation) approach. Both approaches estimated the water contents with a reasonable degree of accuracy.

5.3.3. Subsoils with a Si:C ratio > 0.75

A comparison between the volumetric water contents, estimated with the point and parametric (Smith equation) approaches, with the corresponding measured values for subsoils with Si:C ratios > 0.75, is presented in Figure 5.3. Figure 5.3 shows that both approaches gave the same scatter in estimated water contents at all the matric potentials, illustrating that both approaches consistently over- and under-estimated the water contents. At –1500 kPa, both approaches over-estimated the water contents of the majority of the samples.

Further statistical comparisons, using different statistical indicators, are presented in Table 5.3. Mean bias error (MBE) for the point approach indicate that this approach slightly over-estimated the water content at –1 and –1500 kPa and under-estimated it at –5, -10, -30 and –300 kPa and at –60 and –100 kPa it fitted the measured values best. The mean absolute error (MAE) and root mean square error (RMSE) show that the highest error of prediction occurred at –5 kPa (0.028 and 0.037 cm^3cm^{-3}, respectively), a feature that can be seen in Figure 5.1, and the lowest MAE and RMSE occurred at –1500 kPa (0.015 and 0.017 cm^3cm^{-3}, respectively). The d-values were > 0.94 at all the matric potentials indicating a good agreement between measured and estimated water contents. The mean bias errors for the parametric approach showed that this approach under-estimated the water contents at –1, -30, -60 and –100 kPa and over-estimated it at the remaining potentials. The mean absolute error (MAE) and root mean square error (RMSE), indicate that the highest error of prediction occurred at – 100 kPa and the lowest at –1 kPa. The d-values for this approach were also > 0.95 indicating a good agreement between estimated and measured values. A student *t*-test confirmed for both approaches that the mean slopes and intercepts, of the 1:1 plot between estimated and measured water contents, were not significantly (P= 0.05) different from 1 and 0, respectively.

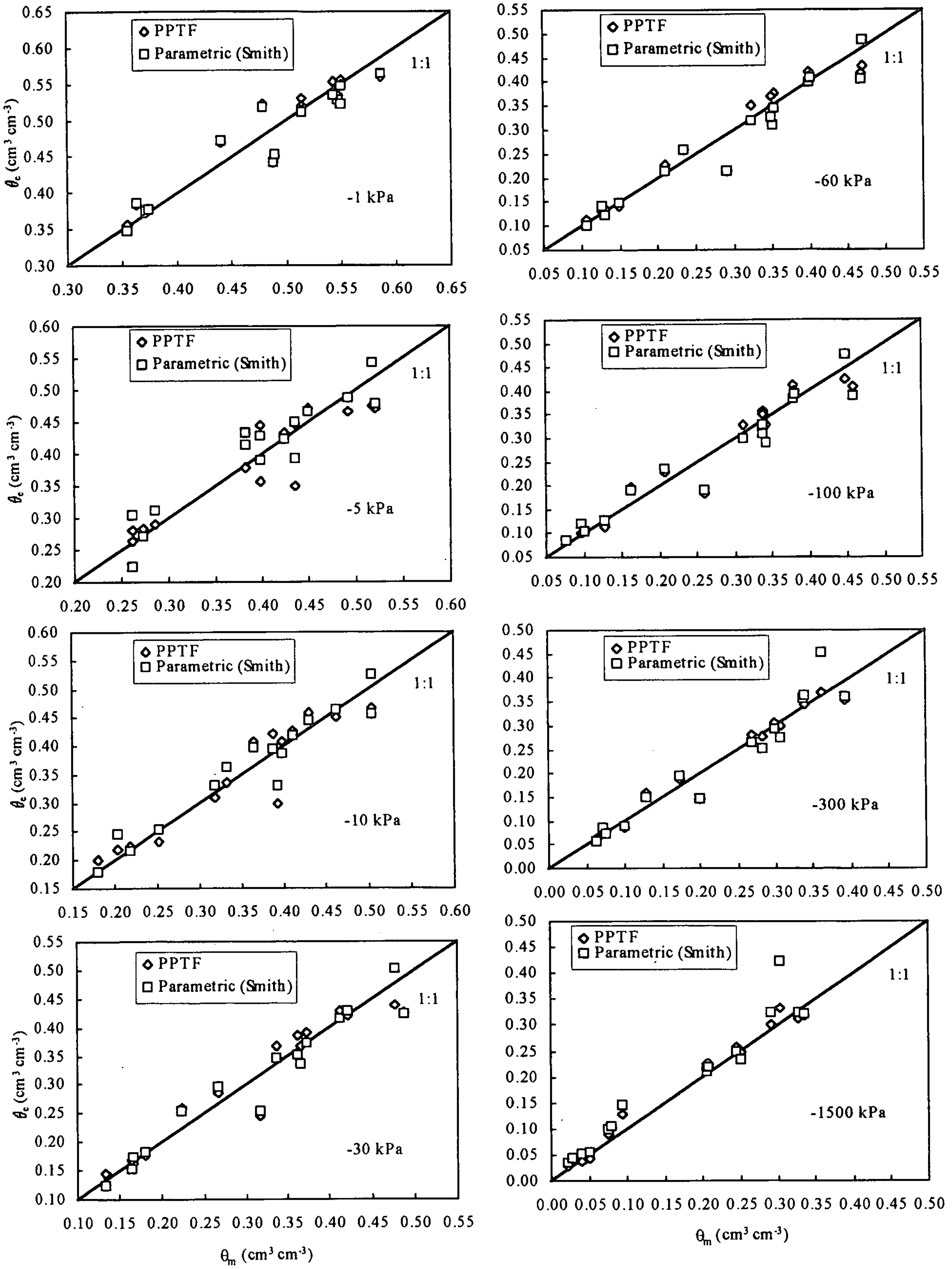

Figure 5.3 Comparison between water contents, estimated (θ_e) with point and parametric (Smith equation) approaches and the corresponding measured (θ_m) values, for subsoils with a Si:C ratio > 0.75.

Table 5.3 Comparison of water contents estimated with point and parametric (Smith) approaches with the corresponding measured values, for subsoils with a Si:C ratio >0.75

Approach		Matric potential (kPa)							
		-1	-5	-10	-30	-60	-100	-300	-1500
PPTF	MBE	0.001	-0.004	-0.003	-0.001	0.000	0.000	-0.001	0.009
	MAE	0.018	0.028	0.026	0.023	0.022	0.024	0.015	0.015
	RMSE	0.024	0.037	0.035	0.031	0.029	0.030	0.021	0.017
	d	0.98	0.95	0.97	0.98	0.98	0.99	0.99	0.99
	R^2	0.90	0.82	0.88	0.93	0.94	0.94	0.97	0.98
	Slope	0.913	0.811	0.889	0.903	0.937	0.952	0.972	0.979
	Intercept	0.043	0.070	0.037	0.029	0.018	0.013	0.006	0.012
Parametric (Smith)	MBE	-0.005	0.007	0.004	-0.005	-0.011	-0.007	0.001	0.019
	MAE	0.018	0.025	0.020	0.021	0.020	0.026	0.024	0.023
	RMSE	0.024	0.030	0.027	0.029	0.030	0.034	0.033	0.037
	d	0.97	0.97	0.98	0.98	0.98	0.98	0.98	0.97
	R^2	0.91	0.89	0.93	0.94	0.94	0.93	0.93	0.93
	Slope	0.866	0.936	0.925	0.946	0.936	0.903	1.023	1.014
	Intercept	0.060	0.032	0.030	0.012	0.008	0.019	-0.005	0.017

The results in Figure 5.3 and the values of the various statistical indicators in Table 5.3 indicate that both approaches can be used to predict water content for the Hararghe Region subsoils with a Si:C ratio > 0.75 with a reasonable accuracy.

5.4. Conclusions

The results from this study can be used in two ways to estimate a water retention curve for a soil from certain properties. With the point estimation approach water content at each of a range of matric potential values between -1 and –1500 kPa can be calculated with the corresponding empirical pedotransfer functions. The generated water content-matric potential data pair can then be fitted to an acceptable water retention function. The actual parameters obtained by fitting the data pair to the water retention equation can then be used to calculate water content at any matric potential or matric potential at any given water content. With the second or parametric approach the parameters of an acceptable water retention function can be calculated directly from the relevant soil properties. The calculated parameters can then be used for calculating water content at any matric potential or matric potential at a given water content.

Ranges of individual samples for the three soil groupings, representing the full silt plus clay content range, were selected for comparing the applicability of the point and parametric approaches. For the topsoils, both point estimation and parametric (Smith equation) approaches gave reasonably good accuracy. For the subsoils with Si:C ratios <, the point estimation approach gave slightly better accuracy than the parametric (Hutson & Cass equation) approach. For the subsoils with Si:C ratios > 0.75, both approaches gave a comparable accuracy and the difference was small. The values of the various statistical indicators for the three groups of soils were comparable to the values mentioned in literature.

From the results obtained from the comparison, it can be concluded that both approaches can be used to predict water content with a reasonable degree of accuracy from relevant properties for the soils of the Hararghe Region.

CHAPTER 6

EXTENSION OF THE PEDOTRANSFER FUNCTIONS TO INCLUDE MORE SANDY SOILS

6.1. Introduction

In Chapter 3, pedotransfer functions for estimating water contents at specific matric potentials were developed for soils of Hararghe Region, eastern Ethiopia. In Chapter 4, parametric pedotransfer functions were developed for the same soils. The majority of the soils from Hararghe Region, used for this study, have relatively high clay and silt plus clay contents. Experience indicates that most of the PTFs compiled by many researchers give reasonable estimates within the range of soil properties from which they were derived. In other words, the regression equations are range-dependent. The extension of the applicability of the PTFs derived from soils of Hararghe Region to include more sandy soils is therefore, imperative. The objective of this chapter is therefore to revise the PTFs developed in Chapter 3 by including soils with higher sand contents.

6.2. Materials and methods

6.2.1. Data set

A total of 216 samples were used for deriving the PTFs for the Hararghe Region. Forty samples were added to the previous complete data set. These 40 samples represented sandy South African soils collected from areas where smectitic clay types dominate the clay fraction (Van Rensburg, 1988).

6.2.2. Statistical analyses on the derived PTFs

The pedotransfer functions derived for each of the matric potential values were evaluated for their precision using the mean absolute bias (MAB) and root mean square error (RMSE) as described in Section 3.2.3.

6.3. Results and discussion

6.3.1. Complete data set

Regression equations, using different relevant soil properties as independent variables, were carried out to quantify the effect of the relevant soil properties on water retention at specific matric potential values and the results are given in Table 6.1.

Inclusion of 40 samples of mainly sandy South African soils improved the relationship between water retention and the relevant soil properties. At all the matric potentials, the R^2-values were higher than the values in Table 3.2. Different functional forms (linear, exponential, power, etc) were given. This was because the function that described the relationship between water content and relevant soil properties varied within the range of matric potentials.

The accuracy of the silt plus clay functions was tested by comparing the measured water content values with the estimated values. The mean of mean absolute bias (mMAB) and root mean square errors (mRMSE) at each matric potential are presented in Appendix 6.1. From the different forms of the silt plus clay functions, the linear functions resulted in relatively low mean of mean absolute bias and root mean square error compared with the power and exponential forms which indicates that the linear equations are more suitable for prediction purposes.

The results indicated that, within the range of soil variables indicated in the footnote of Table 6.1, the silt plus clay functions can be used for estimating water content at the indicated matric potential values with a reasonable degree of accuracy.

6.3.2. Topsoil

For the topsoil group two additional classes (0-10 and 10.01-20 %) were added to the previous classes (Table 3.3). The total number of samples in this group increased from 53 to 67. Equations were derived for estimating the water content at specific matric potential values and are presented in Table 6.2.

Table 6.1 Pedotransfer functions for estimating water contents at different matric potential values from relevant soil properties for the complete data set

h (kPa)	(Si+C) content functions	R^2	Clay content functions	R^2
-1	$\theta = 0.003\,(Si+C) + 0.2795$	0.92	$\theta = 0.0038(C) + 0.3126$	0.82
	$\theta = 0.2983e^{0.0069(Si+C)}$	0.91	$\theta = 0.3222e^{0.0085(C)}$	0.80
	$\theta = 0.1408(Si+C)^{0.3}$	0.89	$\theta = 0.1945(C)^{0.2469}$	0.79
-10	$\theta = 0.0038(Si+C) + 0.126$	0.89	$\theta = 0.0047(C) + 0.1681$	0.79
	$\theta = 0.1601e^{0.012(Si+C)}$	0.88	$\theta = 0.1842e^{0.0147(C)}$	0.76
	$\theta = 0.04(Si+C)^{0.5436}$	0.91	$\theta = 0.0722(C)^{0.4458}$	0.81
-30	$\theta = 0.0041(Si+C) + 0.0739$	0.91	$\theta = 0.0052(C) + 0.1186$	0.81
	$\theta = 0.1189e^{0.0148(Si+C)}$	0.90	$\theta = 0.1407e^{0.0183(C)}$	0.79
	$\theta = 0.0217(Si+C)^{0.6672}$	0.93	$\theta = 0.0436(C)^{0.555}$	0.85
-60	$\theta = 0.0042(Si+C) + 0.0532$	0.91	$\theta = 0.0052(C) + 0.0983$	0.82
	$\theta = 0.1022e^{0.0162(Si+C)}$	0.91	$\theta = 0.1227e^{0.0199(C)}$	0.80
	$\theta = 0.0161(Si+C)^{0.7256}$	0.93	$\theta = 0.0344(C)^{0.604}$	0.85
-100	$\theta = 0.0042(Si+C) + 0.0377$	0.91	$\theta = 0.0052(C) + 0.0831$	0.82
	$\theta = 0.0881e^{0.0175(Si+C)}$	0.90	$\theta = 0.1073e^{0.0215(C)}$	0.79
	$\theta = 0.0118(Si+C)^{0.7876}$	0.93	$\theta = 0.0265(C)^{0.6597}$	0.86
-300	$\theta = 0.0039(Si+C) + 0.0242$	0.91	$\theta = 0.0049(C) + 0.065$	0.82
	$\theta = 0.0695e^{0.019(Si+C)}$	0.88	$\theta = 0.0859e^{0.0234(C)}$	0.77
	$\theta = 0.0075(Si+C)^{0.8659}$	0.93	$\theta = 0.0184(C)^{0.7231}$	0.85
-1500	$\theta = 0.0032(Si+C) + 0.017$	0.91	$\theta = 0.004(C) + 0.0498$	0.83
	$\theta = 0.0529e^{0.0197(Si+C)}$	0.85	$\theta = 0.0654e^{0.0244(C)}$	0.76
	$\theta = 0.0054(Si+C)^{0.8921}$	0.89	$\theta = 0.013(C)^{0.7557}$	0.84

**Equations valid within the following ranges: $6 \leq silt + clay \leq 97$, $3 \leq clay \leq 78$ and Si+C = silt plus clay content (%) and C = clay content (%).*

The results in Table 6.2 indicate that the inclusion of samples with higher sand contents increased the R^2-values given in Table 3.5, except at –30 kPa. The variables for the multiple linear regression equations were selected by stepwise regression procedures. The R^2-values have improved at all the matric potential values compared with the R^2-values for the complete data set. Graphical representations of the linear equations in Table are given in Figure 6.1.

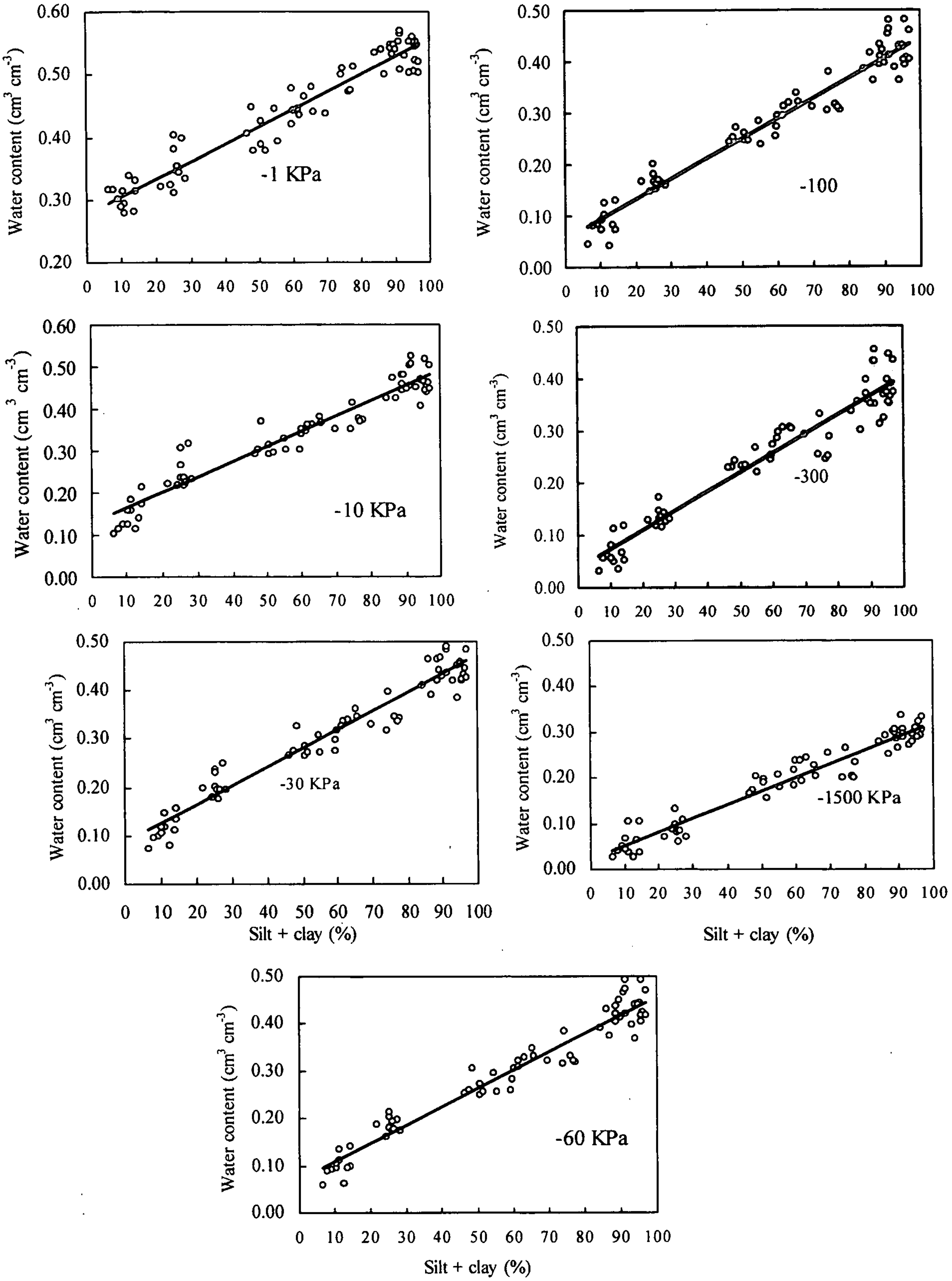

Figure 6.1 The relationship between water content at different matric potential points and silt plus clay content for topsoils.

Table 6.2 Pedotransfer functions for estimating water content at different matric potential values from relevant soil properties for the topsoil group

h (kPa)	(Si+C) content functions	R^2
-1	$\theta = 0.0028(Si+C) + 0.2771$	0.93
	$\theta = 0.2911e^{0.0067(Si+C)}$	0.92
	$\theta = 0.1596(Si+C)^{0.2592}$	0.88
	$\theta = 0.4977 - 0.0022*S + 0.0015*Si$	0.94
-10	$\theta = 0.0036(Si+C) + 0.1269$	0.93
	$\theta = 0.0422(Si+C)^{0.5237}$	0.94
	$\theta = 0.1496e^{0.0127(Si+C)}$	0.87
	$\theta = 0.5886 - 0.0047*S - 0.0016*C$	0.93
-30	$\theta = 0.0039(Si+C) + 0.0862$	0.94
	$\theta = 0.0258(Si+C)^{0.6223}$	0.95
	$\theta = 0.1159e^{0.0151(Si+C)}$	0.88
	$\theta = 0.5593 - 0.0048*S - 0.0014*C$	0.95
-60	$\theta = 0.0039(Si+C) + 0.0697$	0.95
	$\theta = 0.0199(Si+C)^{0.6729}$	0.95
	$\theta = 0.101e^{0.0163(Si+C)}$	0.88
	$\theta = 0.5149 - 0.0045*S - 0.0010*C$	0.95
-100	$\theta = 0.0039(Si+C) + 0.0541$	0.95
	$\theta = 0.0146(Si+C)^{0.7353}$	0.94
	$\theta = 0.0866e^{0.0178(Si+C)}$	0.86
	$\theta = 0.4998 - 0.0045*S - 0.0009*C$	0.95
-300	$\theta = 0.0037(Si+C) + 0.0375$	0.93
	$\theta = 0.0092(Si+C)^{0.8189}$	0.93
	$\theta = 0.0673e^{0.0196(Si+C)}$	0.84
	$\theta = 0.4040 - 0.0037*S$	0.93
-1500	$\theta = 0.003(Si+C) + 0.0225$	0.94
	$\theta = 0.0065(Si+C)^{0.8387}$	0.91
	$\theta = 0.0491e^{0.0205(Si+C)}$	0.86
	$\theta = 0.3677 - 0.0035*S - 0.0008*C$	0.95

Equations valid within the following ranges: $6 \leq Si+C \leq 97$, $3 \leq silt \leq 49$, $3 \leq clay \leq 73$.

The accuracy of the equations in Table 6.2 was evaluated by comparing the measured water contents with those estimated using the equations. The mean of mean absolute bias (mMAE) and root mean square error (mRMSE) at each matric potential are presented in Appendix 6.2. The results in Appendix 6.2 indicate that, from the different forms of the silt plus clay functions, the linear and power forms gave better results. The exponential forms resulted in relatively large mean of mean absolute and root mean square errors. The multiple linear regression equations gave slightly better accuracy compared with the other three forms of the silt plus clay functions.

The equations in Table 6.2 for topsoils only gave a higher accuracy compared with the equations in Table 6.1 for the complete data set, indicating that dividing the total samples into groups improved the relationships.

6.3.3. Subsoils with a Si:C ratio < 0.75

Two additional classes, 0-10 and 10.01-20 % silt plus clay content, were added to the previous samples in this group (Table 3.7) and the total number of samples increased from 148 to 164.

Two sets of equations were developed for estimating the water content at a specific matric potential for subsoil samples with a Si:C ratio < 0.75 and the results are presented in Table 6.3. Stepwise regression did not add additional variables or improve the R^2-values. The relationships between volumetric water content and percentage silt plus clay, at the different matric potentials, are illustrated in Figure 6.2.

The accuracy of the equations in Table 6.3 was evaluated by comparing the measured water contents with the estimated water contents using these equations. The values of the mean of mean bias error (mMBE) and root mean square error (mRMSE) at each matric potential are presented in Appendix 6.3. The results in Appendix 6.3 indicate that the accuracy of the three forms of the silt plus clay functions were not much different except at –300 and –1500 kPa where the exponential form gave a higher mean of the mean absolute bias and root mean square error. In terms of the mean of the mean absolute bias and root mean square error, the equations in Table 6.3 for subsoils with a Si:C ratio < 0.75 were very similar to the equations in Table 6.1 derived from the complete data set.

Table 6.3 Pedotransfer functions for estimating water content at specific matric potential values from relevant soil properties for the subsoils with a Si:C ratio < 0.75

h (kPa)	(Si + C) content functions	R^2	Clay content functions	R^2
-1	$\theta = 0.0033(Si + C) + 0.2646$	0.93	$\theta = 0.0044(C) + 0.273$	0.89
	$\theta = 0.2899e^{0.0073(Si + C)}$	0.93	$\theta = 0.1311(C)^{0.3445}$	0.89
	$\theta = 0.1176(Si + C)^{0.3439}$	0.91	$\theta = 0.2953e^{0.0097(C)}$	0.88
-10	$\theta = 0.0041(Si + C) + 0.1079$	0.87	$\theta = 0.0054(C) + 0.1188$	0.83
	$\theta = 0.1556e^{0.0124(Si + C)}$	0.89	$\theta = 0.0393(C)^{0.5924}$	0.88
	$\theta = 0.0326(Si + C)^{0.5914}$	0.90	$\theta = 0.1611e^{0.0165(C)}$	0.84
-30	$\theta = 0.0043(Si + C) + 0.0638$	0.87	$\theta = 0.0057(C) + 0.0764$	0.82
	$\theta = 0.1201e^{0.0147(Si + C)}$	0.89	$\theta = 0.0233(C)^{0.7043}$	0.88
	$\theta = 0.0185(Si + C)^{0.7051}$	0.91	$\theta = 0.1255e^{0.0195(C)}$	0.84
-60	$\theta = 0.0044(Si + C) + 0.0426$	0.88	$\theta = 0.0058(C) + 0.0562$	0.82
	$\theta = 0.1042e^{0.0159(Si + C)}$	0.90	$\theta = 0.018(C)^{0.7573}$	0.88
	$\theta = 0.0139(Si + C)^{0.7617}$	0.92	$\theta = 0.1096e^{0.021(C)}$	0.85
-100	$\theta = 0.0043(Si + C) + 0.0337$	0.87	$\theta = 0.0057(C) + 0.0485$	0.81
	$\theta = 0.0948e^{0.0166(Si + C)}$	0.90	$\theta = 0.0151(C)^{0.7907}$	0.88
	$\theta = 0.0114(Si + C)^{0.7972}$	0.919	$\theta = 0.1003e^{0.0219(C)}$	0.835
-300	$\theta = 0.0039(Si + C) + 0.022$	0.875	$\theta = 0.0052(C) + 0.035$	0.816
	$\theta = 0.0746e^{0.0181(Si + C)}$	0.864	$\theta = 0.0095(C)^{0.8793}$	0.879
	$\theta = 0.0069(Si + C)^{0.8868}$	0.918	$\theta = 0.0792e^{0.0239(C)}$	0.805
-1500	$\theta = 0.0031(Si + C) + 0.0263$	0.883	$\theta = 0.0041(C) + 0.0374$	0.817
	$\theta = 0.064e^{0.0175(Si + C)}$	0.843	$\theta = 0.0086(C)^{0.8537}$	0.866
	$\theta = 0.0063(Si + C)^{0.8612}$	0.905	$\theta = 0.0679e^{0.0231(C)}$	0.784

Equations valid within the following ranges: $9 \leq silt + clay \leq 97$, $6 \leq clay \leq 78$.

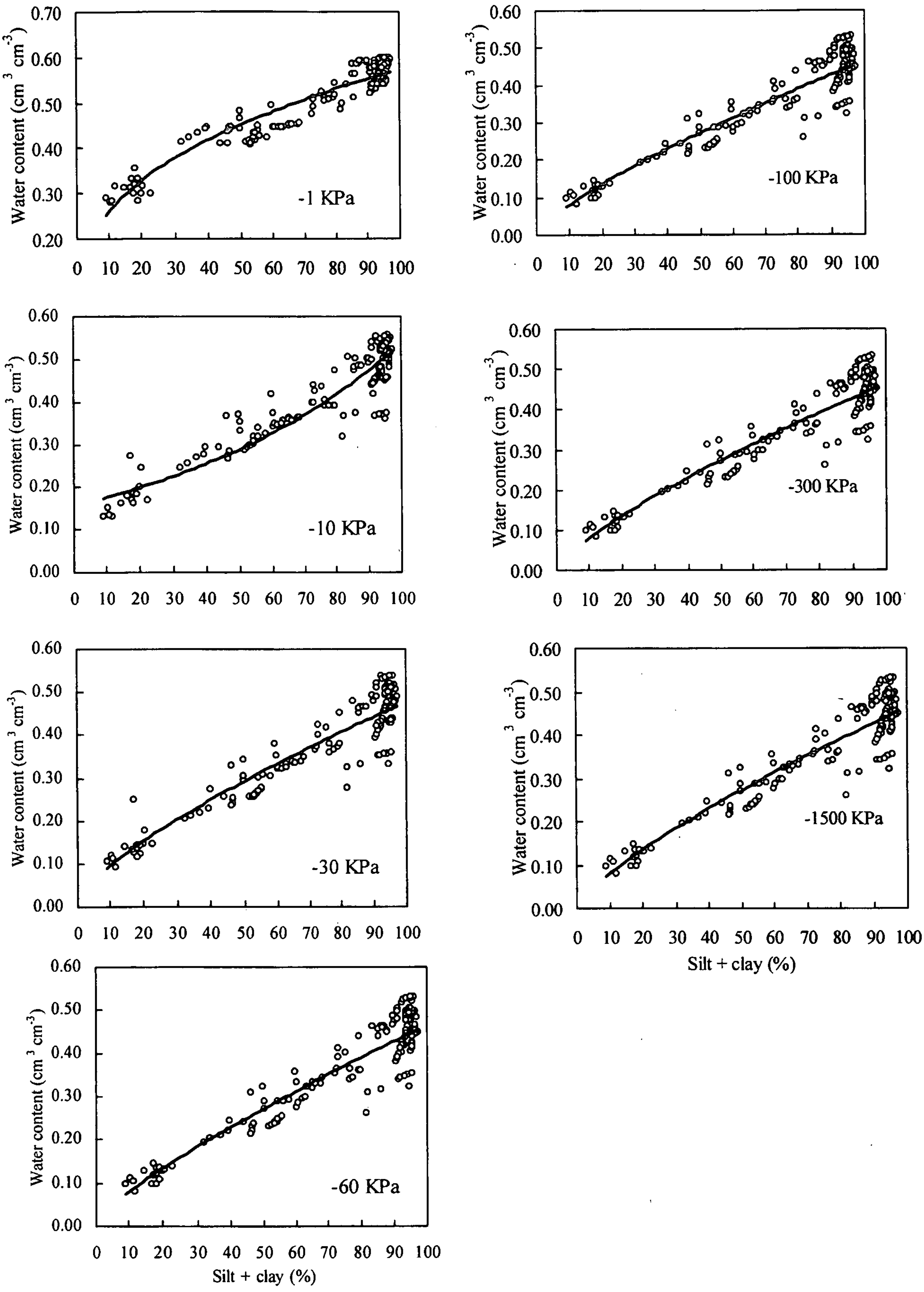

Figure 6.2 The relationship between measured water content at different matric potential points and silt plus clay content for subsoils with Si:C ratios < 0.75.

6.3.4. Subsoils with a Si:C ratio > 0.75

Ten samples were added to this group of soils and the total number of samples increased from 15 to 25. Graphical representations of the relationships are given in Figure 6.3.

Equations were developed for estimating the water content at specific matric potential from relevant soil properties, and the results are presented in Table 6.4. Graphical representations of the relationships are given in Figure 6.3.

The equations were evaluated for their accuracy by comparing the measured water contents with those estimated using these equations. The mean of mean absolute error (mMAE) and root mean square error (mRMSE) at each matric potential are presented in appendix 6.4.

The results in Appendix 6.4 indicate that both the linear or exponential functions gave the same accuracy in terms of the mean of mean absolute bias and root mean square error.

The equations in Table 6.4 for the subsoils with a Si:C ratio > 0.75 gave better accuracies compared with the equations in Table 6.1 for the complete data set, indicating that dividing the complete data set into three groups had resulted in a higher accuracy in estimating water contents from the relevant soil properties.

Table 6.4 Pedotransfer functions for estimating water content at specific matric potentials from relevant soil properties for subsoils with a Si:C ratio > 0.75

h (kPa)	(Si + C) content functions	R^2
-1	$\theta = 0.0029(Si + C) + 0.3163$	0.915
	$\theta = 0.3291e^{0.0063(Si + C)}$	0.906
-10	$\theta = 0.0035(Si + C) + 0.1631$	0.888
	$\theta = 0.1867e^{0.011(Si + C)}$	0.842
-30	$\theta = 0.0042(Si + C) + 0.0751$	0.933
	$\theta = 0.1179e^{0.0158(Si + C)}$	0.905
-60	$\theta = 0.0044(Si + C) + 0.048$	0.936
	$\theta = 0.0967e^{0.0178(Si + C)}$	0.905
-100	$\theta = 0.0045(Si + C) + 0.0185$	0.942
	$\theta = 0.0744e^{0.0207(Si + C)}$	0.909
-300	$\theta = 0.004(Si + C) + 0.0111$	0.954
	$\theta = 0.0612e^{0.0213(Si + C)}$	0.914
-1500	$\theta = 0.0035(Si + C) - 0.0064$	0.897
	$\theta = 0.0395e^{0.0242(Si + C)}$	0.755

Equations valid within the following ranges: 15 ≤ silt + clay ≤ 88.

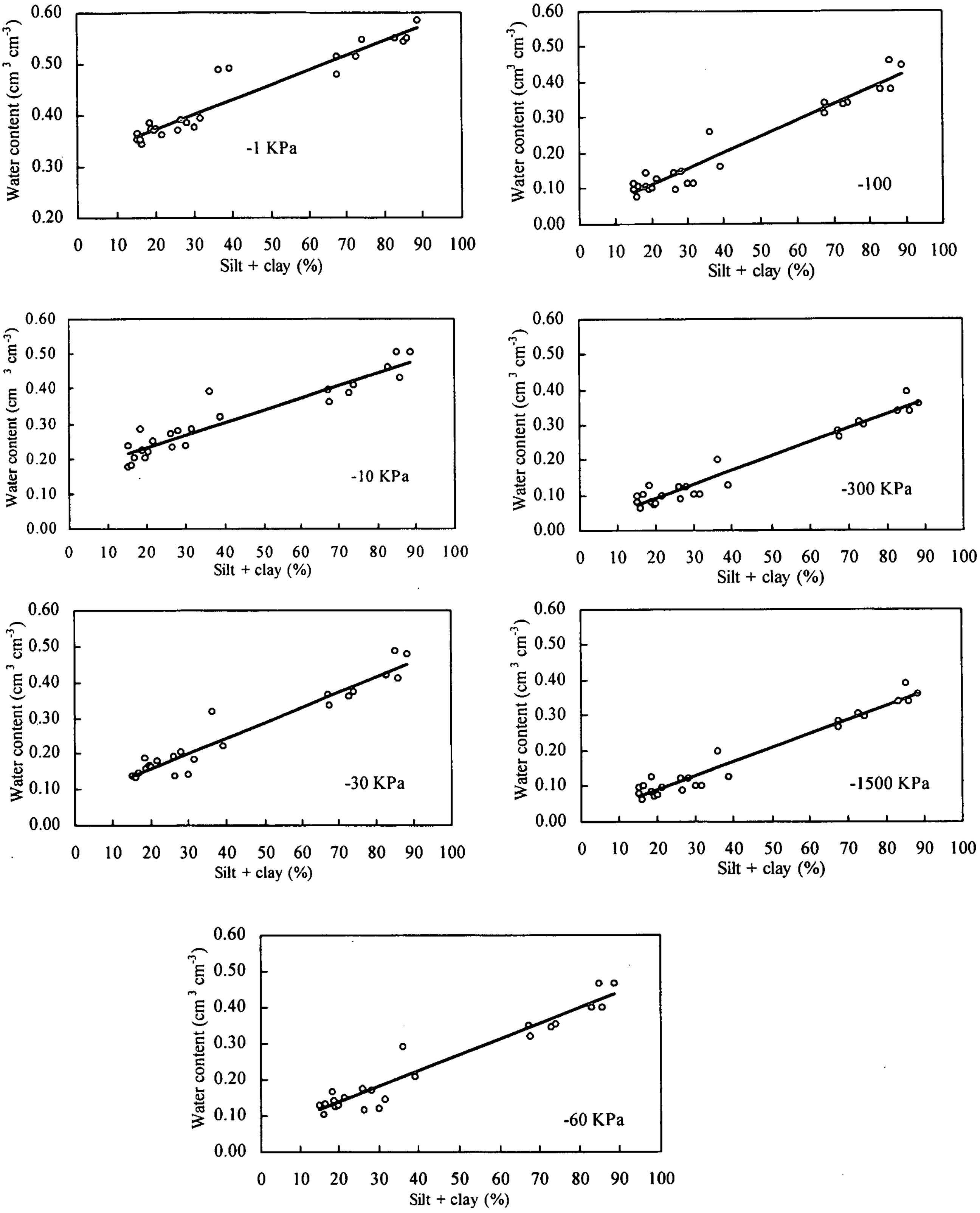

Figure 6.3 The linear relationship between measured water content at 7 matric potential points and silt plus clay content for subsoils with Si:C ratios > 0.75.

6.4. Conclusions

Most of the pedotransfer functions developed for estimating the water content at specific matric potential values are based on a certain range of predictor variables. Experience showed that these equations give better results for the range of predictor variables within which they were derived. Those pedotransfer functions developed from a wider range of predictor variables should be more widely applicable. The objective of this chapter was to extend the range of applicability of the pedotransfer functions developed mainly from soils with relatively high silt plus clay contents. To achieve this goal, 40 soil samples with relatively low silt plus clay contents (6 – 30 %) were added to the previous data set consisting of silt plus clay contents ranging from 16-97 %.

A set of pedotransfer functions were developed for the complete data set, topsoils, subsoils with Si:C ratios of < 0.75 and > 0.75. The accuracy of the functions were evaluated using the mean of mean absolute bias and root mean square error as criteria. For the complete data set, the linear forms of the silt plus clay functions gave a higher accuracy compared with the other forms. For the topsoil samples alone, the multiple linear regression functions gave slightly better results compared with the other functions. For the subsoils with a Si:C ratio < 0.75, the linear and power forms of the silt plus clay functions gave better results. For the subsoils with a Si:C ratio > 0.75, all the equations gave a comparable accuracy.

Except for the subsoils with a Si:C ratio < 0.75, dividing the complete data set into groups has resulted in a higher accuracy compared with the complete data set.

Generally, the differences between measured and estimated water contents at different matric potential values with the different functions, were not larger than the standard deviations of the actual measured water contents. Therefore, in view of the larger spatial variability of soil properties and the expense, labour and time involved with direct laboratory methods for water retention, the use of these functions for estimating water contents at different matric potentials is justifiable. Care should be taken to apply these equations only to soils with similar smectitic clay mineralogy.

CHAPTER 7

GENERAL DISCUSSION AND CONCLUSIONS

While a large number of laboratory and field methods have been developed over the years to measure the soil hydraulic properties (Klute, 1986), most accurate *in situ* measurements of these properties have remained relatively costly, time consuming, labour intensive, and difficult to implement. The measurement of the water retention characteristic is not an exception. Thus, cheaper and more expedient methods for estimating the soil water retention characteristics are needed. Since the water retention characteristics are affected by other physical and chemical properties, such as texture, bulk density, organic matter content, clay mineralogy, etc., the development of empirical relationships to predict soil water retention from these properties is justifiable. In land evaluation, such relationships are called pedotransfer functions.

Results thus far suggested that predictive models work reasonably well for sandy soils, but that predictions for more clayey and structured field soils remain inaccurate due mainly to the poor definition of the air entry value for these soils.

Since every pedotransfer function (PTF) is based on the data from a limited number of soil samples, it is not always clear to what extend these functions can be used in soil conditions other than those under which they were developed. Furthermore, the dependence of the shape of the water retention curve on soil textural and structural properties varies with the area in which the study was conducted, because of differences in clay mineralogy and in the nature of the organic material.

One usually finds that, even though the correlations fit the data from which they were developed quite well, they give relatively poor fits to data from other studies. There are several reasons for the failure of these correlations (Campbell, 1985). The first is that pore-size distribution, and not particle-size distribution, determines water retention. The two are related but particle packing, shape, orientation, etc., are also important. A second problem is that the water release data themselves may not be reliable. Most of the data used in correlations are obtained from pressure plates. Pressure plate equilibration is usually far from complete, even when outflow has apparently stopped, because of the low hydraulic conductivity of soil at low water potentials. These demerits in the laboratory measurement methods call for an improvement or modification of the existing methods so that more reliable data will be obtained. The existing laboratory methods also give better results for non-swelling soils whereas the determination of water retention for swelling soils is not clearly defined.

Research relating soil physical properties and characteristics to water retention characteristics has been limited to mostly soil properties such as particle size distribution, bulk density and organic matter content. Most published PTFs used these properties as predictor variables for estimating either water content at a specific matric potential or the parameters of water retention functions. Only few have tried to relate other important soil properties such as clay type (Baumer & Brasher, 1982; Williams *et al.*, 1983; Williams *et al.*, 1990; Gaiser *et al.*, 2000), soil structure (De Jong *et al.*, 1983; McBride & Mackintosh, 1984; Williams *et al.*, 1983; Peterson *et al.*, 1968a, b;) and water-stable aggregates (Mungare *et al.*, 1983) to soil water retentivity.

As noted by Bastet *et al.* (1997), the performance of published PTFs varied according to the pedological origin of the soils from which they were developed. Idike & Ejieji (1993) and Tomasella & Hodnett (1998) tested PTFs for soils from temperate regions on soil data from humid tropical regions and found that it yielded unsatisfactory results, the main reasons being the contrasting chemical, physical, and biological processes operating within the two geographical locations.

Most studies included a large number of soil samples collected from different areas, either as a whole or classifying them according to their textural class. It must, however, be noted that a textural class embraces a wide range of soils and, hence, it is desirable to discriminate between soils within a class. Gaiser *et al.* (2000) classified the soil samples they studied according to their clay mineralogy, which improved the correlation between the water retention characteristics and the relevant soil properties. In this study, classifying the complete data set into topsoils and subsoils and the subsoils into those with silt (Si) to clay (C) ratios larger and smaller than 0.75 gave better results compared with treating the complete data set as a unit. Williams et al.

(1983) pointed out that soils with a high clay content (clay loam and clay) should be separated from soils with lower clay contents (sand, sandy loam, loam) when water retention characteristics are to be evaluated. Gaiser *et al.* (2000) observed that inclusion of soil samples with clay contents > 60 % into their data set caused the PTFs to have a non-linear character.

In the Hararghe Region, eastern Ethiopia, water deficit is the main factor limiting crop production. In most of the areas in the Region, the rainfall pattern is so erratic and sporadic that, every year, crop failure is becoming a serious threat. The increasing human population is becoming more and more prone to drought and famine. The absence of sound water management practices is exacerbating the situation year after year. It is high time for designing or devising a scenario for efficient use of the meagre amount of water either from rainfall or ground water sources. Understanding the hydraulic behaviour of the soils within the region is a key factor to the success of such scenarios. Water retention is one of the most important hydraulic characteristics of the soil in agriculture and other environmental studies. The study of the water retention characteristics of the Hararghe Region soils, in relation to their physical and chemical properties was, therefore, deemed to be necessary. To this effect, the water retention characteristics of soils collected from 14 sites and 26 profiles were measured at 9 matric potential values, -1, -5, -8, -10, -30, -60, -100, -300 and –1500 kPa.

Experience showed that measuring water retention on a large scale is expensive and time consuming. It is therefore important to find a means by which the information on water retention, obtained from the 14 selected sites, can be extrapolated to other areas with similar soil types. To achieve this, two approaches were used for relating water content, as a function of matric potential, $\theta(h)$, to the relevant soil properties. In the first approach, referred to as the point estimation technique, pedotransfer functions for estimating the water content at specific matric potential values from relevant soil properties were compiled. In the second approach, called the parametric technique, the parameters of individual water retention equations were related to soil properties, which can be used for estimating the water content at any matric potential.

To establish relationships between relevant soil properties and water retention, regression analyses were carried out. This was done for the complete data set, topsoils and subsoils separately. To accommodate the effect of organic matter on water retention, the complete data set was divided into topsoils with a higher organic matter contents and subsoils with low organic matter contents. Within subsoils, differences in the water retention characteristics were observed. The difference was between soils with high clay and low silt contents and vice versa. Presumably, these two groups differ in their structure, which has a bearing on pore size distribution. Differences in pore size distribution can result in differences in water retention characteristics, especially at high matric potentials. The soils with high clay contents had well-developed structure and those with high silt contents had medium to weak structure. To separate these groups, the silt (Si) to clay (C) ratio was used as a criterion. Plotting the Si:C ratio against silt plus clay content revealed two distinct populations, one with Si:C ratios < 0.75 and the other with > 0.75 (Figure 3.3). This showed that, besides the silt plus clay content, the ratio of silt to clay content is also important in water retention characteristic studies and needs to be considered critically in future studies. Although different predictor variables were used, the silt plus clay content alone was able to explain the variability in water retention within the groupings reasonably well. The use of many variables in multiple regressions for estimating volumetric water content didn't improve the correlation significantly and hence were not included. This study also indicated that the relationship between water retention and soil properties is not always linear as is cited in many studies. It was the curvilinear functions that gave better correlations compared with the linear ones.

Statistical comparisons of the different pedotransfer functions revealed that the grouping of the soils resulted in a better correlation between the relevant soil properties and water retention characteristics. For relating water retention with relevant soil properties, it seemed necessary to group soils according to their water retention characteristics before conducting the regression analyses. This grouping will help to identify the soil variable that was predominantly influencing water retention. For example, for the topsoils (Table 3.5) organic matter content alone was able to explain from 61 to 76 % of the variability in water retention whereas for the subsoils it explained only 25 % or less (equation not indicated) of the variability in water retention. This indicates that, besides clay and silt contents, organic matter also played an important role in water retention by the topsoils.

The point pedotransfer functions can be used to predict water content at the corresponding matric potential values, from relevant soil properties. This will give a set of water content-matric potential data pairs for a specific soil layer. This data pair can be fitted to any water retention equation, which can then be used for estimating water content at any matric potential value. The Van Genuchten equation, with a restriction $m = 1 - 1/n$, can be used for this purpose, when a further application of these functions is envisaged. The RETC program (Van Genuchten *et al.*, 1991) can be used for fitting the estimated water contents to this equation. For the parametric approach, the parameters of the water retention functions can be predicted from relevant soil properties using the equations in Table 4.4. The water retention curve with predicted parameters can then be used for estimating the water content at any matric potential.

From the six water retention functions chosen for identification, the Van Genuchten function, with the restriction $m = 1 - 1/n$, gave the best overall description of the water retention curves followed by the Smith and simple power functions. The Brooks-Corey function gave the poorest description of the water retention curves. The parameters of the Smith and Hutson & Cass functions could be predicted from relevant soil properties more accurately compared with the parameters of the Van Genuchten function. Due to this reason, the Smith equation for topsoils and subsoils with Si:C ratios > 0.75 and the Hutson & Cass equation for the subsoils with Si:C ratios < 0.75, are recommended as functions for the water retention curves of the soils.

Comparison of the applicability of the point and parametric estimation techniques showed that the derived pedotransfer functions can be applied with a high degree of accuracy.

The following step-by-step procedures can be followed to estimate a water retention curve of a soil sample, using either of the point estimation or parametric approaches:

(i) Point estimation approach

1. Collect representative soil samples.
2. Determine the particle size distribution and organic carbon content of the samples. During the particle size analyses, it is necessary to have as many size fractions, for example, coarse, medium, fine, very fine sand,) as possible including the percentage particles < 0.05 μm and the clay content.
3. Classify the soils into those with a higher organic carbon content (topsoil) and those with a lower organic carbon content (subsoil).
4. When it is a subsoil sample, calculate the ratio between the percentages silt to clay. Use the relevant subsoil pedotransfer functions for Si:C ratios < than 0.75 or > than 0.75.
5. Select the relevant pedotransfer functions for topsoils in Tables 3.6 Or 6.2, subsoils with Si:C ratios < 0.75 in Tables 3.10 or 6.3 and subsoils with Si:C ratios > 0.75 in Tables 3.14 or 6.4. The functions in Tables 6.2 to 6.4 accommodate a wider range of texture classes. Use the pedotransfer functions in the respective Tables to calculate a volumetric water content at –1, -5, -8, -10, -30, -60, -100, -300 and –1500 kPa matric potential.
6. Fit the calculated water contents and corresponding matric potentials to a water retention equation, e.g., Van Genuchten equation using the RETC program, and obtain the parameters of the equation.
7. Calculate the water content at any matric potential, or matric potential at any given water content, using the parameters of the equation in (6).

(ii) Parametric approach

1. From the particle size analyses, calculate the geometrical mean particle size and geometrical standard deviation of the soil sample using Equations1.16 and 1.17.
2. Use the equations in Table 4.4 to calculate the parameters of the appropriate water retention equation using the relevant soil properties for the three groups of soils.

3. Calculate the water content at any matric potential, or matric potential at any given water content, using the calculated parameters in the relevant water retention function.

The estimated water retention curves derived with any of the two approaches can also be used for other applications. With the Van Genuchten function, for instance, the parameters can also be used for estimating the unsaturated hydraulic conductivity if data on saturated hydraulic conductivity are available. This equation, using the RETC program, can also be used to estimate the soil water diffusivity. The program uses the following relationships for estimating unsaturated hydraulic conductivity and soil water diffusivity based on Mualem's (m = 1-1/n) restriction:

$$K(S_e) = K_s S_e^{\ell}\left[1-\left(1-S_e^{1/m}\right)^m\right]^2 \qquad (m = 1\text{-}1/n) \qquad [7.1]$$

in which S_e is given by Equation 1.37, K_s is the hydraulic conductivity at saturation and ℓ is a pore-connectivity parameter (Mualem, 1976a).

The soil water diffusivity corresponding to Equation 7.1 is:

$$D(S_e) = \frac{(1-m)K_s S_e^{\ell-1/m}}{\alpha m(\theta_s-\theta_r)}\left[(1-S_e^{1/m})^{-m}+(1-S_e^{1/m})^m-2\right] \qquad [7.2]$$

where α is the scaling parameter in the Van Genuchten equation.

Therefore, from the estimated water retention curve other hydraulic properties of the soils can also be derived. The predicted soil water diffusivity can be used in modelling water and solute movement in soils. Scullion *et al.* (1986) and Reeve (1986) indicated that at low suctions a knowledge of the release of water by soils could be used in designing drainage and irrigation systems. Besides this, a knowledge of water release characteristics of a soil has many uses such as calculating the available water capacity as the difference between water held at field capacity and the permanent wilting point, determining the optimum frequency and amount of water to be applied by irrigation.

Furthermore, many physically based models depend on the use of water retention data. These models include assessments of soil suitability for disposing municipal sewage sludge (National Soils Hand Book, 1983), prediction of nitrate leaching (Addiscott, 1977), aquifer vulnerability measurements (Carter *et al.*, 1987) and descriptions of the residual behaviour of pesticides (Nicholls, 1989) in the profile. Substances such as nitrate and certain pesticides are readily soluble in water, and their movement in the profile is largely controlled by the water retention characteristics of the soil.

Regional simulations of water availability and soil water fluxes often incorporate water retention data. Predictions of the effect of lowering groundwater on crop production require water retention and hydraulic conductivity data for all soil horizons (Bouma *et al.*, 1986).

Unfortunately, many of these applications require a large amount of data, which may present a formidable barrier to progress. In these cases, the pedotransfer functions developed, using either of the approaches, can be used to generate the necessary data. This briefly indicates the wide range of applications of the measurement or estimation of water retention characteristics for a given soil.

Hararghe Region is one of the regions that are persistently prone to drought. This problem has resulted in a massive famine in the region year after year. For such areas where rainfall is not adequate for sustainable food crop production, practicing irrigation is an immediate surrogate as a source of water. Irrigation scheduling is a key factor for efficient use of the scant water available in such areas. For irrigation scheduling, the knowledge of water retention of the soils is important. The data obtained in this study can provide an insight into the water retention characteristics of the different soil groups in the region. The pedotransfer functions compiled can be used for calculating the available water capacity of soils from the Region and other similar soils. The applications mentioned above can be implemented depending on the problems in a given area. The main contribution of this study in solving water-related problems in the Region is that it provides equations that can be used to estimate water retention curves for the soils studied as an alternative to the time-taking laboratory methods normally used to determine the water retention characteristics of soils. In doing so, it will result in better use of the water for those who are practicing irrigation.

The contribution of this study to the science of pedotransfer function development is that it showed that the proportion of the various soil separates (sand, silt and clay) is an important factor controlling the water retention behaviour of soils. Grouping of subsoils according to the silt to clay ratios improved the estimation of water content from surrogate soil properties. The silt to clay ratio has not been used before by other workers for grouping of soils for pedotransfer function development.

Since the majority of soils from the Hararghe Region were high in silt plus clay content, samples representing more sandy South African soils collected from areas mainly with smectitic clay types (Van Rensburg, 1988) were included to expand the range of applicability of the PTFs. Inclusion of these samples improved the correlations. As a result, these equations can also be used to estimate water retention curves for soils with lower silt plus clay contents.

Although the results of this study seem to be promising, it will be necessary for a wider application, to conduct future research on how to include other important soil attributes that influence water retention by soils. Water retention of soils depends on pore-size distribution, which in turn is influenced by various factors like structure, particle-size composition, organic matter content, clay mineralogy and biological activity. It is, however, expensive and time consuming to measure all these properties. The present study has shown that separating soils according to their water retention behaviour, can result in good correlations between commonly available soil properties and water retention. It is therefore necessary for future research to place more emphasis on clay mineralogy. Once the soils are separated according to differences in clay mineralogy, a more detailed particle size analysis, especially on the sand particles, will be important to improve the understanding of the effect of these fractions on water retention. Presumably, it is very important to consider the ratio of the various soil separates (e.g., silt to clay, clay to silt or other similar ratios) and include these ratios as criteria for classifying soils.

Finally, although the empirical approach for estimating water retention characteristics from soil properties seems adequate, future efforts need to be geared towards developing routine procedures for describing pore geometry and the interaction between soil water and the soil matrix better.

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APPENDIX

Appendix 2.1. Brief descriptions of the profiles from which samples were collected

Profile	Elevation (m)	Slope gradient (%)	Horizons	Depth (cm)	Colour (moist)	Structure	Root abundance
GP1	1640	6	Ap	0-15	2.5YR 3/2	Massive throughout, no cracking	Many root to a depth of 1 m and few roots afterwards
			A2	15-55	2.5YR 3/4		
			B	55-200	2.5YR 3/6		
GP2	1615	2.5	Ap	0-20	10YR 3/1	Granular at the surface and prismatic in B horizon, shiny peds and slickensides	Many roots in the upper 20 cm and only few after wards
			B	20-135	10YR 2/1		
BEP1	1565	1	Ap	0-15	10YR 3/1	Granular at the surface and prismatic with slickensides	Only in the Ap horizon
			A2	15-40	10YR 2/1		
			B	40-80	10YR 3/2		
				80-35	10YR 3/2		
BEP2	1600	6	A	0-35	2.5YR 3/2	Fine granular at the surface and plate-like structures in B horizon	Many roots in the upper 15 cm and only few afterwards
			B	35-155	2.5 YR ¾		
CJP1	2215	9	Ah	0-25	10YR 2/1	Granular and crumb	Many roots throughout
			A2	25-95	10YR 3/2		
CJP2	2180	24	Mollic A	0-25	10YR 2/2	Weak fine granular	Many
			A2	25-40	10YR 3/1	Weak moderate crumby	Many fine
			B	40-70	10YR	Weak fine angular blocky	Very few fine
				70-100		Strong fine-moderate subangular blocky	Very few fine
CJP3	2110	9	Ap-	0-20	-	Weak-moderate crumby	Many fine
			A2	20-60	-	Weak fine granular	Few fine
			AC	60-100	-	Weak fine angular blocky	Very few fine
CJP4	1915	8	Ap	0-10	10YR 3/2	Granular at the surface and subangular blocky structures with shiny faces	Many roots to a depth of 20 cm and few afterwards
			A2	10-25	10YR 3/3		
			B	25-95	10YR 4/3		
CJP5	1840	7	A	0-10	10YR 3/1	Prismatic structure in B horizon	Many roots in the upper 10 cm
			B	10-100	10YR 2/1		
HP1	1720	3	Ap	0-20	-	Weak fine granular	Many
			B	20-100	-	Weak fine angular blocky	Many
HP2	1780	9	A	0-65	-	Structureless	Many roots to a depth of 30 cm
			AC	65-75	-	Structureless	
KP	2110	7	Ap	0-15	10YR 3/1	Weak fine granular	Roots throughout the profile
			A2	15-25	10YR 3/2	Weak crumby	
			AC	25-70	10YR 3/3	Strong coarse columnar	

Appendix 2.1: Continued…

Profile	Elevation (m)	Slope gradient (%)	Horizons	Depth (cm)	Colour (moist)	Structure	Root abundance
LP	1885	3	Ap	0-20	10YR 3/2	Weak fine granular	Many roots in the upper 20 cm
			A2	20-40	10YR 3/1	Weak moderate crumby	
			B	40-100	10YR 3/2	Strong coarse prismatic	
				80+	10YR 3/3		
KE	1885	4	Ap	0-20	Dry, 10YR 3/3	Crumby	Many
			A2	20-50	Dry, 10YR 4/3	Weak coarse angular blocky	Few
			AC	50-85	Dry, 7.5YR 3/4	Strong coarse-moderate subangular blocky	Very few fine roots
DP	1100	1.5	Ap	0-35	10YR 4/2	Structureless	Roots concentrated in the upper 35 cm
			A	35-75	10YR 4/3		
AD	1910	2	Ap	0-35	10YR 2/2	Weak fine granular	Roots concentrated in the upper 35 cm and few reached a depth of 120 cm
			A2	35-105	10YR 3/2	Moderate fine prismatic	
HA	1910	2	A	0-25	2.5YR 3/2	Weak fine granular	Many roots to a depth of 65 cm
			AE	25-40	2.5YR 3/4	Moderate strong massive	
			B	40-100	2.5YR 3/6	Weak fine angular blocky	
				100-170	2.5YR 2.5/4	Strong fine angular blocky	
				170+	10YR 3/2		
KO	2110	2.5	A	0-25	2.5YR 3/6	No distinct structure observed except very fine granules	Many fine
			B	25-50	2.5YR 2.5/4		Many fine
				50-100	2.5YR 3/4		Few fine roots
BAP	1610	2	Ap	0-30	2.5YR 3/4	Weak coarse massive	Roots concentrated in the upper 30 cm
			A2	30-100	2.5YR 3/2	Moderate coarse prismatic	
JKP1	1780	2	A	0-95	10YR 3/2	Granular structure	Roots to a depth of 105 cm
JCHP2	1660	1	A	0-80	10YR 3/2	Weak fine granular	Very fine grass roots to a depth of 125 cm
			B	80-125	10YR 3/3	Moderate fine columnar	
				125+	10YR 4/4	Strong fine prismatic	
JAP3	1660	1	Ap	0-25	10YR 3/2	Strong fine columnar	Very few roots penetrated down the profile
			A2	20-85	10YR 3/3	Strong fine columnar	
			B	85-115	10YR 3/3	Strong coarse-moderate subangular blocky	
			115+	115+	10YR 3/4		

Appendix 2.2. Soil properties and water retention characteristics of some soils from the Hararghe Region

GP1

Depth	Sand	Silt	Clay	OC	BD	Si+C	-1	-5	-8	-10	-30	-60	-100	-300	-1500
0-10	49.48	12.02	38.50	0.87	1.31	50.52	0.388	0.346	0.312	0.294	0.266	0.251	0.248	0.233	0.191
15-25	48.32	10.56	41.12	0.64	1.38	51.68	0.380	0.339	0.315	0.297	0.271	0.255	0.247	0.235	0.156
25-35	48.54	10.84	40.62	0.61	1.35	51.46	0.415	0.331	0.307	0.287	0.256	0.232	0.220	0.215	0.185
35-45	47.64	11.26	41.10	0.47	1.38	52.36	0.418	0.353	0.318	0.296	0.257	0.234	0.223	0.216	0.191
45-55	47.06	11.76	41.18	0.41	1.38	52.94	0.408	0.359	0.328	0.297	0.258	0.239	0.230	0.216	0.195
55-65	46.00	11.56	42.44	0.43	1.37	54.00	0.425	0.364	0.334	0.303	0.264	0.244	0.236	0.224	0.202
65-75	44.90	12.18	42.92	0.36	1.41	55.10	0.441	0.376	0.340	0.312	0.274	0.251	0.240	0.233	0.212
75-85	44.62	12.12	43.26	0.36	1.35	55.38	0.451	0.379	0.347	0.319	0.279	0.257	0.247	0.234	0.221
85-95	46.04	11.88	42.08	0.38	1.36	53.96	0.424	0.363	0.332	0.301	0.264	0.242	0.233	0.223	0.202
95-105	46.68	11.90	41.42	0.31	1.49	53.32	0.415	0.362	0.332	0.300	0.262	0.241	0.230	0.218	0.198
105-115	45.96	12.54	41.50	0.27	1.39	54.04	0.434	0.364	0.338	0.306	0.267	0.244	0.236	0.229	0.203
115-125	45.80	11.66	42.54	0.25	1.35	54.20	0.435	0.365	0.340	0.309	0.270	0.247	0.237	0.232	0.211
125-135	46.88	11.46	41.66	0.23	1.40	53.12	0.410	0.361	0.332	0.297	0.260	0.240	0.230	0.218	0.198
							GP2								
0-10	3.00	31.00	66.00	1.96	1.14	97.00	0.521	0.510	0.507	0.504	0.483	0.470	0.460	0.435	0.333
10-20	3.40	28.20	68.40	1.55	1.10	96.60	0.590	0.571	0.553	0.550	0.518	0.497	0.487	0.469	0.333
20-30	3.60	27.84	68.56	1.51	1.13	96.40	0.588	0.569	0.551	0.548	0.516	0.497	0.485	0.467	0.332
30-40	4.10	26.64	69.26	1.50	1.10	95.90	0.585	0.563	0.547	0.543	0.513	0.496	0.481	0.464	0.331
40-50	3.86	26.12	70.02	1.45	1.10	96.14	0.586	0.566	0.549	0.544	0.514	0.496	0.483	0.466	0.332
50-60	3.88	25.54	70.58	1.52	1.13	96.12	0.586	0.565	0.549	0.545	0.514	0.496	0.483	0.466	0.332
60-70	4.46	25.72	69.82	1.52	1.15	95.54	0.583	0.560	0.544	0.539	0.509	0.495	0.478	0.462	0.330
70-80	6.32	23.68	70.00	1.30	1.08	93.68	0.572	0.543	0.530	0.522	0.509	0.492	0.461	0.442	0.327

Appendix 2.2. Continued…

Depth	Sand	Silt	Clay	OC	BD	Si+C	-1	-5	-8	-10	-30	-60	-100	-300	-1500
80-90	5.70	23.68	70.62	1.24	1.02	94.30	0.575	0.549	0.535	0.527	0.499	0.493	0.467	0.455	0.328
90-100	6.42	23.04	70.54	1.27	1.15	93.58	0.572	0.543	0.529	0.522	0.493	0.489	0.460	0.401	0.326
100-110	6.48	24.80	68.72	1.18	1.15	93.52	0.571	0.541	0.530	0.521	0.492	0.480	0.459	0.422	0.326
110-120	6.12	23.56	70.32	1.14	1.10	93.88	0.573	0.544	0.532	0.524	0.496	0.477	0.463	0.431	0.327
120-130	5.42	24.26	70.32	1.15	1.02	94.58	0.577	0.551	0.537	0.530	0.501	0.494	0.469	0.430	0.329
BEP1															
0-10a	5.86	30.16	63.98	1.64	0.98	94.14	0.552	0.484	0.480	0.471	0.451	0.442	0.430	0.369	0.295
15-25	5.00	26.78	68.22	1.33	0.98	95.00	0.560	0.479	0.473	0.468	0.454	0.442	0.431	0.373	0.310
25-35	5.24	23.28	71.48	1.23	0.99	94.76	0.578	0.547	0.543	0.533	0.520	0.503	0.489	0.416	0.343
35-45	5.14	23.08	71.78	1.21	1.00	94.86	0.578	0.547	0.544	0.534	0.520	0.504	0.489	0.416	0.343
45-55	6.30	22.68	71.02	1.14	1.03	93.70	0.577	0.538	0.532	0.526	0.511	0.496	0.483	0.415	0.342
55-65	5.96	23.20	70.84	1.13	1.03	94.04	0.577	0.541	0.536	0.528	0.514	0.499	0.485	0.415	0.342
65-75	6.44	23.46	70.10	1.21	1.08	93.56	0.577	0.536	0.530	0.524	0.509	0.495	0.482	0.415	0.342
80-90	10.30	21.10	68.60	0.99	1.02	89.70	0.594	0.519	0.510	0.501	0.493	0.486	0.470	0.402	0.334
90-100	10.22	22.62	67.16	0.85	1.06	89.78	0.594	0.521	0.511	0.502	0.494	0.488	0.472	0.403	0.335
100-110	12.22	19.84	67.94	0.66	1.09	87.83	0.594	0.502	0.497	0.487	0.467	0.454	0.438	0.377	0.315
110-120	12.36	22.26	65.38	0.57	1.03	87.64	0.594	0.501	0.495	0.486	0.465	0.450	0.434	0.374	0.313
120-130	8.94	21.56	69.50	0.63	1.11	91.06	0.575	0.518	0.506	0.500	0.490	0.479	0.468	0.413	0.339
BEP2															
0-10	4.48	28.56	66.96	1.73	1.10	95.52	0.506	0.485	0.474	0.443	0.425	0.417	0.403	0.355	0.290
10-20	3.02	24.04	72.94	1.30	1.09	96.98	0.504	0.483	0.476	0.446	0.425	0.418	0.405	0.374	0.306
20-30	2.72	22.10	75.18	1.26	1.09	97.28	0.597	0.556	0.535	0.523	0.490	0.451	0.428	0.406	0.320
35-45	3.28	20.14	76.58	1.16	1.08	96.72	0.586	0.551	0.530	0.517	0.482	0.448	0.424	0.400	0.317
45-55	4.38	19.88	75.74	1.01	1.10	95.62	0.567	0.542	0.523	0.506	0.465	0.442	0.416	0.390	0.311

Appendix 2.2. Continued…

Depth	Sand	Silt	Clay	OC	BD	Si+C	-1	-5	-8	-10	-30	-60	-100	-300	-1500
55-65	4.26	18.78	76.96	0.99	1.12	95.74	0.569	0.542	0.523	0.507	0.467	0.442	0.418	0.391	0.312
65-75	3.66	18.04	78.30	0.89	1.15	96.34	0.580	0.547	0.527	0.513	0.476	0.446	0.422	0.397	0.315
75-85	4.64	19.06	76.30	0.84	1.05	95.36	0.563	0.540	0.521	0.503	0.462	0.441	0.415	0.388	0.310
85-95	4.64	18.34	77.02	0.77	1.09	95.36	0.563	0.540	0.521	0.504	0.462	0.441	0.415	0.388	0.310
95-105	4.52	18.28	77.20	0.69	1.10	95.48	0.565	0.541	0.522	0.504	0.464	0.441	0.416	0.388	0.311
CJP1															
0-10	13.94	46.62	39.44	2.02	0.90	86.06	0.540	0.497	0.486	0.475	0.464	0.431	0.417	0.356	0.294
10-20	10.58	42.74	46.68	1.31	1.00	89.42	0.548	0.503	0.492	0.483	0.469	0.450	0.422	0.359	0.287
25-35	11.46	38.12	50.42	0.97	1.01	88.54	0.586	0.518	0.513	0.504	0.476	0.468	0.448	0.361	0.303
35-45	10.08	35.36	54.56	0.65	1.10	89.92	0.590	0.516	0.506	0.491	0.479	0.475	0.463	0.393	0.328
45-55	13.06	34.06	52.88	0.50	1.09	87.05	0.588	0.516	0.505	0.486	0.467	0.463	0.448	0.389	0.323
55-65	14.70	29.34	55.96	0.50	1.08	85.30	0.586	0.515	0.505	0.484	0.461	0.456	0.440	0.387	0.320
65-75	13.32	30.12	56.56	0.32	1.04	86.68	0.587	0.516	0.505	0.486	0.466	0.462	0.446	0.389	0.322
CJP2															
10-20	25.50	40.82	33.68	2.09	0.88	74.50	0.511	0.423	0.423	0.417	0.399	0.384	0.380	0.332	0.265
25-35	22.44	44.64	32.92	1.86	0.96	77.56	0.514	0.391	0.380	0.375	0.342	0.320	0.306	0.289	0.233
40-50	25.90	43.86	30.24	0.96	1.12	74.10	0.547	0.436	0.417	0.412	0.373	0.353	0.339	0.299	0.245
50-60	32.56	43.12	24.32	0.51	1.19	67.44	0.514	0.425	0.402	0.399	0.366	0.350	0.342	0.283	0.206
60-70	27.24	45.54	27.22	0.62	1.29	72.76	0.514	0.399	0.391	0.388	0.362	0.348	0.338	0.307	0.250
70-80	32.38	42.80	24.82	0.54	1.28	67.62	0.478	0.382	0.370	0.363	0.337	0.322	0.311	0.268	0.207
CJP3															
0-10	15.74	46.96	37.30	1.80	1.08	84.26	0.537	0.445	0.433	0.427	0.411	0.393	0.386	0.338	0.278
10-20	11.08	48.38	40.54	2.04	1.14	88.92	0.533	0.472	0.468	0.460	0.442	0.422	0.410	0.360	0.300
20-30	11.28	48.76	39.96	1.89	1.11	88.72	0.544	0.506	0.494	0.480	0.464	0.436	0.433	0.398	0.306

Appendix 2.2. Continued…

Depth	Sand	Silt	Clay	OC	BD	Si+C	-1	-5	-8	-10	-30	-60	-100	-300	-1500
30-40	14.86	47.24	37.90	1.16	1.21	85.14	0.543	0.521	0.512	0.504	0.488	0.468	0.458	0.392	0.327
40-50	14.12	48.52	37.36	1.03	1.19	85.88	0.550	0.450	0.438	0.430	0.413	0.399	0.380	0.338	0.335
50-60	17.02	45.10	37.88	0.87	1.19	82.98	0.551	0.492	0.478	0.462	0.421	0.402	0.380	0.340	0.290
							CJP4								
0-10	4.28	29.88	65.84	1.30	1.08	95.72	0.554	0.541	0.532	0.519	0.505	0.493	0.482	0.447	0.324
10-20	4.68	30.42	64.90	0.77	1.12	95.32	0.599	0.575	0.561	0.555	0.538	0.521	0.510	0.407	0.343
25-35	6.00	26.44	67.56	0.52	1.02	94.00	0.599	0.565	0.552	0.548	0.535	0.528	0.504	0.415	0.337
35-45	7.42	29.44	63.14	0.39	0.99	92.58	0.594	0.553	0.543	0.540	0.531	0.524	0.498	0.392	0.331
45-55	6.26	27.22	66.52	0.43	1.04	93.74	0.596	0.563	0.551	0.547	0.534	0.527	0.503	0.414	0.336
55-65	4.06	22.54	73.40	0.51	1.04	95.94	0.599	0.581	0.565	0.558	0.540	0.533	0.512	0.405	0.346
65-75	5.12	22.28	72.60	0.50	0.98	94.88	0.599	0.572	0.558	0.552	0.537	0.530	0.508	0.421	0.341
75-85	4.18	21.06	74.76	0.44	1.05	95.82	0.598	0.580	0.565	0.557	0.539	0.532	0.512	0.432	0.345
85-95	4.80	20.10	75.10	0.37	0.98	95.20	0.599	0.574	0.560	0.554	0.538	0.531	0.509	0.432	0.342
							CJP5								
0-10	4.80	28.20	67.00	1.09	1.07	95.20	0.554	0.487	0.477	0.466	0.460	0.443	0.428	0.398	0.304
10-20	5.92	24.50	69.58	0.93	1.07	94.08	0.577	0.495	0.482	0.479	0.469	0.456	0.449	0.410	0.338
20-30	5.18	22.96	71.86	0.87	1.11	94.82	0.577	0.518	0.510	0.507	0.490	0.479	0.469	0.426	0.355
30-40	4.98	23.44	71.58	0.85	1.12	95.02	0.577	0.525	0.522	0.517	0.499	0.487	0.479	0.433	0.359
40-50	4.82	24.06	71.12	0.79	1.15	95.18	0.577	0.530	0.528	0.521	0.501	0.490	0.480	0.436	0.363
50-60	6.12	23.06	70.82	0.87	1.13	93.88	0.576	0.492	0.479	0.470	0.467	0.454	0.447	0.408	0.335
60-70	5.84	23.86	70.30	0.96	1.13	94.16	0.576	0.502	0.488	0.481	0.476	0.462	0.453	0.413	0.340
70-80	5.34	24.98	69.68	0.99	1.17	94.66	0.577	0.516	0.509	0.505	0.489	0.476	0.467	0.423	0.351
80-90	6.12	26.60	67.28	1.07	1.08	93.88	0.576	0.494	0.478	0.472	0.467	0.454	0.447	0.407	0.333

Appendix 2.2. Continued…

Depth	Sand	Silt	Clay	OC	BD	Si+C	-1	-5	-8	-10	-30	-60	-100	-300	-1500
90-100	6.52	27.56	65.92	1.07	1.01	93.48	0.576	0.480	0.461	0.459	0.455	0.440	0.433	0.397	0.325
							HP1								
0-10	11.36	38.60	50.04	1.77	1.06	88.64	0.548	0.460	0.453	0.443	0.419	0.405	0.394	0.371	0.302
10-20	4.24	35.44	60.32	1.45	1.12	95.76	0.522	0.457	0.452	0.442	0.420	0.405	0.394	0.353	0.292
20-30	3.88	34.98	61.14	1.43	1.08	96.12	0.547	0.477	0.472	0.452	0.434	0.420	0.407	0.367	0.293
30-40	3.70	33.64	62.66	1.43	1.08	96.30	0.549	0.500	0.482	0.464	0.445	0.424	0.406	0.390	0.307
40-50	3.58	32.68	63.74	1.20	1.05	96.42	0.587	0.527	0.525	0.488	0.473	0.458	0.443	0.400	0.340
50-60	3.48	30.38	66.14	1.03	0.99	96.52	0.594	0.538	0.535	0.498	0.483	0.466	0.448	0.403	0.345
60-70	3.48	26.76	69.76	0.98	1.09	96.52	0.593	0.539	0.536	0.499	0.483	0.465	0.448	0.403	0.345
70-80	3.44	31.06	65.50	0.89	1.02	96.56	0.596	0.543	0.538	0.502	0.487	0.468	0.450	0.404	0.347
80-90	3.26	31.48	65.26	0.83	1.04	96.74	0.599	0.564	0.556	0.522	0.507	0.483	0.461	0.410	0.355
90-100	3.62	31.70	64.68	0.75	1.08	96.38	0.585	0.524	0.522	0.484	0.470	0.454	0.440	0.399	0.338
							HP2								
0-10	75.94	9.68	14.38	0.59	1.52	24.06	0.323	0.247	0.229	0.218	0.180	0.161	0.148	0.119	0.087
10-20	71.66	10.92	17.42	0.54	1.51	28.34	0.334	0.264	0.243	0.233	0.196	0.175	0.160	0.131	0.073
20-30	73.54	9.54	16.92	0.59	1.47	26.46	0.345	0.260	0.238	0.225	0.195	0.179	0.171	0.144	0.086
30-40	66.00	9.60	24.40	0.50	1.30	34.00	0.425	0.310	0.282	0.255	0.214	0.203	0.195	0.151	0.117
40-50	60.82	11.12	28.06	0.39	1.35	39.18	0.444	0.332	0.306	0.277	0.228	0.220	0.211	0.172	0.145
55-65	63.14	9.78	27.08	0.17	1.39	36.86	0.433	0.324	0.297	0.269	0.221	0.210	0.202	0.161	0.130
65-75	68.04	8.26	23.70	0.10	1.37	31.96	0.415	0.303	0.276	0.246	0.206	0.195	0.187	0.142	0.106
							KP								
0-10	9.00	39.20	51.80	2.21	1.06	91.00	0.553	0.523	0.512	0.503	0.484	0.467	0.454	0.433	0.337
15-25	8.64	36.10	55.26	1.98	1.09	91.36	0.565	0.531	0.525	0.508	0.492	0.475	0.463	0.434	0.306

Appendix 2.2. Continued…

Depth	Sand	Silt	Clay	OC	BD	Si+C	-1	-5	-8	-10	-30	-60	-100	-300	-1500
30-40	8.64	36.22	55.14	1.89	1.06	91.36	0.570	0.543	0.539	0.525	0.510	0.493	0.481	0.456	0.297
40-50	7.88	34.24	57.88	1.46	1.06	92.12	0.584	0.564	0.560	0.556	0.538	0.520	0.508	0.405	0.297
50-60	9.10	26.62	64.28	1.16	1.05	90.90	0.566	0.545	0.543	0.541	0.522	0.506	0.495	0.401	0.281
60-70	9.02	27.38	63.60	0.92	1.04	90.98	0.576	0.546	0.542	0.528	0.511	0.496	0.487	0.397	0.313
							LP1								
0-10	49.50	25.40	25.10	1.27	1.31	50.50	0.427	0.346	0.335	0.314	0.286	0.274	0.262	0.233	0.199
10-20	45.26	25.60	29.14	1.09	1.29	54.74	0.445	0.360	0.351	0.331	0.306	0.295	0.285	0.269	0.206
20-30	40.00	26.46	33.54	1.30	1.28	60.00	0.445	0.371	0.362	0.352	0.317	0.306	0.295	0.274	0.237
30-40	38.68	25.64	35.68	1.31	1.34	61.32	0.446	0.379	0.373	0.347	0.325	0.309	0.295	0.286	0.240
40-50	39.70	18.32	41.98	0.84	1.33	60.30	0.447	0.377	0.357	0.349	0.325	0.287	0.280	0.251	0.213
50-60	27.14	20.06	52.80	0.82	1.24	72.86	0.508	0.454	0.445	0.440	0.425	0.412	0.403	0.336	0.287
60-70	20.50	21.54	57.96	0.75	1.21	79.50	0.545	0.494	0.484	0.474	0.452	0.439	0.430	0.370	0.308
75-85	16.50	26.24	57.26	0.55	1.22	83.50	0.541	0.538	0.524	0.508	0.480	0.463	0.451	0.395	0.331
85-95	14.66	25.14	60.20	0.52	1.13	85.34	0.563	0.496	0.486	0.475	0.452	0.439	0.429	0.380	0.322
95-105	13.98	26.44	59.58	0.47	1.15	86.02	0.565	0.537	0.524	0.503	0.468	0.464	0.451	0.418	0.319
							KE								
0-10	40.40	26.66	32.94	0.87	1.25	59.60	0.479	0.379	0.361	0.342	0.299	0.283	0.273	0.254	0.183
10-20	26.04	26.42	47.54	0.83	1.20	73.96	0.500	0.389	0.370	0.351	0.318	0.315	0.305	0.255	0.202
20-30	35.14	18.60	46.26	0.73	1.22	64.86	0.452	0.383	0.374	0.359	0.338	0.319	0.307	0.270	0.220
30-40	40.58	18.22	41.20	0.49	1.50	59.42	0.495	0.442	0.433	0.418	0.382	0.357	0.347	0.319	0.205
40-50	39.88	16.48	43.64	0.40	1.34	60.12	0.447	0.373	0.358	0.344	0.321	0.277	0.268	0.245	0.214
50-60	50.18	14.00	35.82	0.38	1.35	49.82	0.466	0.383	0.360	0.334	0.295	0.271	0.257	0.248	0.188
60-70	50.12	14.36	35.52	0.36	1.34	49.88	0.481	0.390	0.374	0.354	0.305	0.289	0.280	0.254	0.200

Appendix 2.2. Continued…

							AD								
Depth	Sand	Silt	Clay	OC	BD	Si+C	-1	-5	-8	-10	-30	-60	-100	-300	-1500
0-10	38.36	20.46	41.18	0.81	1.32	61.64	0.436	0.388	0.384	0.363	0.338	0.324	0.313	0.298	0.194
10-20	34.76	20.02	45.22	0.89	1.20	65.24	0.480	0.402	0.393	0.381	0.362	0.350	0.339	0.307	0.227
20-30	34.30	21.16	44.54	1.01	1.23	65.70	0.440	0.393	0.384	0.367	0.348	0.333	0.322	0.304	0.204
35-45	45.74	18.18	36.08	0.83	1.18	54.26	0.418	0.346	0.340	0.320	0.300	0.288	0.278	0.259	0.225
45-55	32.42	20.94	46.64	0.58	1.34	67.58	0.453	0.389	0.384	0.363	0.340	0.331	0.327	0.292	0.224
55-65	34.98	19.44	45.58	0.76	1.38	65.02	0.451	0.381	0.377	0.363	0.337	0.333	0.323	0.275	0.221
65-75	36.96	19.54	43.50	0.77	1.42	63.04	0.448	0.381	0.364	0.357	0.332	0.325	0.290	0.258	0.218
75-85	40.22	21.12	38.66	0.65	1.37	59.78	0.446	0.396	0.389	0.375	0.352	0.334	0.322	0.290	0.247
85-95	42.16	19.68	38.16	0.66	1.40	57.84	0.423	0.353	0.348	0.327	0.305	0.293	0.283	0.267	0.245
95-105	31.86	22.18	45.96	0.91	1.38	68.14	0.457	0.390	0.380	0.363	0.350	0.346	0.333	0.300	0.226
							DP								
20-30	78.54	13.52	7.94	0.42	1.47	21.46	0.362	0.285	0.260	0.253	0.180	0.149	0.129	0.099	0.052
35-45	83.90	10.26	5.84	0.21	1.43	16.10	0.354	0.262	0.234	0.180	0.134	0.106	0.077	0.063	0.022
45-55	54.22	30.14	15.64	0.26	1.22	45.78	0.440	0.382	0.367	0.333	0.266	0.234	0.206	0.172	0.094
55-65	63.82	21.16	15.02	0.63	1.20	36.18	0.488	0.435	0.422	0.393	0.317	0.290	0.260	0.200	0.075
65-75	61.08	23.84	15.08	0.33	1.11	38.92	0.490	0.399	0.371	0.317	0.223	0.209	0.162	0.128	0.080
							AUVP1								
0-10	9.92	32.68	57.40	1.39	0.89	90.08	0.540	0.475	0.464	0.450	0.431	0.414	0.397	0.352	0.265
10-20	9.26	32.52	58.22	1.11	1.09	90.71	0.520	0.454	0.444	0.439	0.394	0.382	0.370	0.352	0.257
20-30	10.14	30.12	59.74	1.31	1.04	89.86	0.590	0.522	0.511	0.503	0.489	0.467	0.454	0.404	0.320
30-40	8.90	32.14	58.96	1.18	1.13	91.10	0.535	0.461	0.453	0.444	0.400	0.389	0.378	0.360	0.269
45-55	7.44	33.16	59.40	1.32	1.17	92.56	0.589	0.491	0.488	0.459	0.440	0.426	0.415	0.393	0.352

Appendix 2.2. Continued…

Depth	Sand	Silt	Clay	OC	BD	Si+C	-1	-5	-8	-10	-30	-60	-100	-300	-1500
55-65	7.62	31.86	60.52	1.15	1.09	92.38	0.593	0.488	0.484	0.458	0.433	0.420	0.411	0.390	0.343
65-75	7.92	29.20	62.88	0.97	1.14	92.08	0.587	0.481	0.478	0.454	0.426	0.413	0.403	0.382	0.317
75-85	8.00	27.40	64.60	0.85	1.16	92.00	0.580	0.480	0.476	0.454	0.424	0.412	0.401	0.381	0.313
85-95	8.48	26.72	64.80	0.80	1.11	91.52	0.557	0.470	0.464	0.447	0.430	0.399	0.388	0.369	0.278
95-105	8.48	24.52	67.00	0.81	1.20	91.52	0.557	0.470	0.464	0.448	0.410	0.399	0.388	0.369	0.285
105-115	8.82	23.70	67.48	0.81	1.18	91.18	0.540	0.463	0.456	0.444	0.412	0.392	0.381	0.362	0.267
115-125	8.84	21.90	69.26	0.77	1.25	91.16	0.541	0.462	0.455	0.444	0.423	0.391	0.380	0.362	0.269
							AURP2								
0-10	52.50	20.06	27.44	1.63	1.18	47.50	0.448	0.328	0.315	0.303	0.277	0.262	0.253	0.231	0.172
10-20	53.60	18.98	27.42	1.60	1.43	46.40	0.406	0.319	0.302	0.293	0.267	0.253	0.244	0.230	0.167
20-30	40.64	20.14	39.22	1.41	1.28	59.36	0.422	0.329	0.317	0.304	0.276	0.261	0.255	0.246	0.217
30-40	23.64	19.18	57.18	1.30	1.15	76.36	0.511	0.440	0.428	0.406	0.380	0.365	0.322	0.303	0.242
							AUAP3								
0-10	75.08	13.56	11.36	0.96	1.34	24.92	0.382	0.299	0.270	0.265	0.231	0.213	0.202	0.173	0.100
10-20	74.24	11.90	13.86	0.40	1.50	25.76	0.347	0.268	0.248	0.239	0.196	0.174	0.153	0.138	0.086
20-30	74.16	11.32	14.52	0.28	1.54	25.84	0.353	0.261	0.238	0.217	0.175	0.194	0.164	0.116	0.063
							AUCP4								
0-10	36.88	27.10	36.02	1.83	1.27	63.12	0.467	0.383	0.376	0.362	0.341	0.330	0.320	0.306	0.244
10-20	30.26	23.32	46.42	1.31	1.28	69.74	0.438	0.369	0.364	0.350	0.331	0.322	0.312	0.293	0.254
20-30	27.84	21.36	50.80	1.19	1.24	72.16	0.477	0.414	0.402	0.398	0.368	0.355	0.348	0.327	0.275
30-40	27.40	18.90	53.70	1.08	1.16	72.60	0.493	0.419	0.407	0.400	0.375	0.364	0.360	0.336	0.280
40-50	24.62	18.48	56.90	1.03	1.21	75.38	0.526	0.461	0.446	0.437	0.417	0.403	0.396	0.379	0.315
50-60	26.96	17.20	55.84	0.82	1.11	73.04	0.511	0.449	0.436	0.426	0.402	0.391	0.380	0.361	0.288

Appendix 2.2. Continued…

Depth	Sand	Silt	Clay	OC	BD	Si+C	-1	-5	-8	-10	-30	-60	-100	-300	-1500
0-10	23.66	25.82	50.52	1.16	1.22	76.34	0.473	0.409	0.396	0.376	0.345	0.331	0.317	0.246	0.204
10-20	23.02	20.08	56.90	0.79	1.21	76.98	0.475	0.406	0.389	0.372	0.337	0.323	0.311	0.252	0.201
25-35	23.50	15.14	61.36	0.59	1.22	76.50	0.504	0.424	0.407	0.392	0.361	0.339	0.302	0.247	0.210
40-50	17.92	17.92	64.16	0.63	1.24	82.08	0.498	0.406	0.386	0.368	0.324	0.310	0.298	0.251	0.227
50-60	20.90	18.38	60.72	0.68	1.23	79.10	0.512	0.425	0.409	0.392	0.374	0.360	0.311	0.259	0.214
60-70	18.26	17.68	64.06	0.65	1.13	81.74	0.485	0.374	0.344	0.319	0.278	0.262	0.250	0.213	0.190
70-80	20.34	21.92	57.74	0.74	1.14	79.66	0.519	0.425	0.410	0.392	0.380	0.363	0.344	0.261	0.215
80-90	14.12	24.00	61.88	0.86	1.26	85.88	0.512	0.421	0.399	0.374	0.331	0.317	0.303	0.265	0.215
90-100	22.34	18.92	58.74	0.67	1.23	77.66	0.507	0.424	0.407	0.392	0.366	0.344	0.298	0.252	0.212
							KO								
50-60	8.74	19.30	71.96	0.93	1.10	91.26	0.542	0.440	0.431	0.420	0.353	0.341	0.326	0.280	0.224
60-70	5.72	22.04	72.24	0.90	1.03	94.28	0.543	0.463	0.381	0.372	0.357	0.352	0.338	0.289	0.236
70-80	4.52	20.62	74.86	0.75	1.04	95.48	0.543	0.480	0.440	0.374	0.359	0.356	0.344	0.293	0.242
80-90	8.10	18.00	73.90	0.65	1.14	91.90	0.542	0.425	0.376	0.368	0.354	0.343	0.329	0.282	0.226
90-100	6.82	16.80	76.38	0.45	1.12	93.18	0.542	0.444	0.379	0.370	0.356	0.347	0.334	0.286	0.232
							BAP								
0-10	74.84	15.62	9.54	0.53	1.59	25.16	0.313	0.260	0.247	0.236	0.203	0.180	0.167	0.133	0.081
10-20	78.46	13.18	8.36	0.45	1.54	21.54	0.322	0.250	0.240	0.222	0.200	0.189	0.168	0.130	0.073
20-30	80.64	8.74	10.62	0.42	1.62	19.36	0.371	0.262	0.229	0.204	0.167	0.126	0.097	0.071	0.041
30-40	79.94	10.80	9.26	0.40	1.67	20.06	0.374	0.273	0.237	0.218	0.165	0.131	0.102	0.076	0.028
40-50	60.38	8.92	30.70	0.74	1.38	39.62	0.447	0.316	0.309	0.295	0.275	0.246	0.224	0.183	0.147
50-60	53.38	10.32	36.30	0.75	1.26	46.62	0.445	0.357	0.314	0.281	0.251	0.230	0.221	0.210	0.189
60-70	53.18	10.06	36.76	0.69	1.21	46.82	0.448	0.360	0.321	0.283	0.254	0.238	0.230	0.228	0.192

Appendix 2.2. Continued:...

Depth	Sand	Silt	Clay	OC	BD	Si+C	-1	-5	-8	-10	-30	-60	-100	-300	-1500
70-80	53.48	9.76	36.76	0.65	1.24	46.52	0.441	0.343	0.305	0.275	0.239	0.222	0.214	0.208	0.183
80-90	53.86	11.52	34.62	0.61	1.17	46.14	0.412	0.337	0.299	0.268	0.237	0.215	0.206	0.190	0.168
JKP1															
0-10	49.48	12.02	38.50	0.87	1.31	50.52	0.388	0.346	0.312	0.294	0.266	0.251	0.248	0.233	0.191
10-20	53.92	16.82	29.26	0.91	1.23	46.08	0.438	0.387	0.378	0.366	0.331	0.311	0.301	0.275	0.202
20-30	38.42	19.38	42.20	0.71	1.27	61.58	0.447	0.376	0.358	0.347	0.324	0.298	0.288	0.243	0.215
30-40	44.32	19.82	35.86	0.82	1.39	55.68	0.427	0.365	0.353	0.341	0.308	0.290	0.281	0.262	0.204
40-50	56.14	13.98	29.88	0.67	1.42	43.86	0.411	0.326	0.311	0.295	0.257	0.243	0.231	0.228	0.174
50-60	5.22	34.96	59.82	1.16	1.26	94.78	0.540	0.467	0.372	0.362	0.333	0.322	0.309	0.263	0.225
60-70	34.02	22.86	43.12	0.78	1.33	65.69	0.453	0.383	0.374	0.359	0.336	0.330	0.320	0.277	0.221
70-80	37.26	22.92	39.82	0.71	1.22	62.74	0.448	0.376	0.360	0.349	0.325	0.300	0.289	0.251	0.217
80-90	50.24	16.62	33.14	0.81	1.44	49.76	0.444	0.399	0.385	0.371	0.344	0.325	0.318	0.300	0.207
JCHP2															
0-10	13.04	44.58	42.38	1.44	1.06	86.96	0.501	0.441	0.431	0.427	0.392	0.376	0.364	0.301	0.253
10-20	8.72	39.42	51.86	1.47	1.17	91.28	0.508	0.474	0.466	0.455	0.437	0.422	0.412	0.351	0.288
30-40	6.24	35.02	58.74	0.99	1.11	93.76	0.564	0.501	0.493	0.482	0.463	0.448	0.435	0.394	0.329
40-50	6.98	34.12	58.90	0.95	1.20	93.02	0.551	0.475	0.470	0.463	0.437	0.419	0.409	0.373	0.314
50-60	7.28	38.04	54.68	0.91	1.20	92.72	0.542	0.475	0.469	0.462	0.435	0.418	0.408	0.371	0.311
60-70	8.36	31.36	60.28	1.01	1.26	91.64	0.527	0.468	0.459	0.446	0.416	0.398	0.388	0.351	0.305
70-80	7.48	31.28	61.24	0.86	1.21	92.52	0.532	0.468	0.460	0.456	0.422	0.403	0.390	0.353	0.305
80-90	6.90	29.96	63.14	0.82	1.25	93.10	0.555	0.494	0.491	0.479	0.456	0.437	0.424	0.376	0.315
90-100	6.32	29.76	63.92	0.72	1.16	93.68	0.557	0.498	0.491	0.482	0.457	0.438	0.429	0.387	0.326

Appendix 2.2. Continued…

JAP3

Depth	Sand	Silt	Clay	OC	BD	Si+C	-1	-5	-8	-10	-30	-60	-100	-300	-1500
0-10	7.14	42.88	49.98	1.76	1.11	92.86	0.531	0.467	0.460	0.452	0.419	0.399	0.389	0.313	0.271
10-20	5.86	36.14	58.00	1.60	1.08	94.14	0.503	0.427	0.419	0.408	0.385	0.369	0.363	0.325	0.277
25-35	4.62	32.68	62.70	1.45	1.21	95.38	0.545	0.476	0.467	0.455	0.431	0.413	0.404	0.357	0.303
35-45	4.80	31.10	64.10	1.43	1.23	95.20	0.542	0.474	0.464	0.452	0.427	0.406	0.400	0.348	0.295
45-55	4.68	32.56	62.76	1.24	1.27	95.32	0.544	0.476	0.466	0.454	0.430	0.411	0.403	0.354	0.300
55-65	4.46	31.80	63.74	1.21	1.23	95.54	0.547	0.479	0.469	0.457	0.435	0.419	0.408	0.366	0.310
65-75	4.28	31.06	64.66	1.31	1.21	95.72	0.550	0.483	0.472	0.460	0.439	0.426	0.413	0.378	0.318
75-85	4.36	27.98	67.66	1.36	1.21	95.64	0.549	0.481	0.471	0.458	0.437	0.422	0.411	0.372	0.314
85-95	4.52	26.86	68.62	1.23	1.21	95.48	0.546	0.478	0.469	0.456	0.434	0.416	0.407	0.362	0.307

Appendix 3.1. Results of evaluation of the PTFs in Table 3.2 (Complete data set)

Matric potential (KPa)	Silt plus clay equations				Clay content equations			Multiple linear regression equations		
	mMAE	mMBE	mRMSE	md	mMAE	mMBE	mRMSE	mMAE	mMBE	mRMSE
-1	0.022	-0.002	0.027	0.867	0.033	-0.002	0.040	0.020	-0.003	0.025
-5	0.028	-0.003	0.034	0.850	0.040	-0.003	0.047	0.028	-0.004	0.034
-8	0.028	-0.002	0.037	0.853	0.043	-0.004	0.052	0.029	0.003	0.036
-10	0.030	-0.002	0.038	0.860	0.045	-0.004	0.055	0.030	-0.002	0.038
-30	0.031	-0.002	0.040	0.859	0.046	-0.005	0.057	0.031	-0.004	0.040
-60	0.033	-0.003	0.041	0.859	0.047	-0.005	0.057	0.032	0.002	0.040
-100	0.034	-0.001	0.042	0.853	0.046	-0.004	0.057	0.031	-0.003	0.039
-300	0.031	-0.002	0.040	0.848	0.040	-0.004	0.051	0.027	-0.003	0.036
-1500	0.029	-0.001	0.036	0.838	0.038	-0.025	0.048	0.021	0.001	0.027

- For each evaluation index, m refers to the mean values at each matric potential. Units are cm^3 cm^{-3}.

Appendix 3.2. Results of evaluation of the PTFs in Table 3.5 (the complete data set for topsoils)

Matric potential (KPa)	Silt plus clay equations				Organic carbon equations			Clay content equations			Multiple regression equations		
	mMAE	mMBE	mRMSE	md	mMAE	mMBE	mRMSE	mMAE	mMBE	mRMSE	mMAE	mMBE	mRMSE
-1	0.021	-0.002	0.024	0.867	0.038	-0.002	0.046	0.033	-0.002	0.040	0.017	0.002	0.019
-5	0.018	-0.002	0.024	0.886	0.047	-0.004	0.056	0.034	-0.002	0.042	0.021	-0.001	0.027
-8	0.020	0.001	0.025	0.872	0.048	-0.004	0.058	0.035	-0.003	0.045	0.022	-0.003	0.028
-10	0.020	-0.001	0.026	0.866	0.047	-0.004	0.057	0.038	-0.003	0.047	0.023	-0.001	0.028
-30	0.023	-0.002	0.029	0.854	0.048	-0.005	0.061	0.040	-0.004	0.051	0.025	-0.003	0.031
-60	0.023	-0.002	0.028	0.852	0.050	-0.006	0.061	0.038	-0.004	0.048	0.024	0.003	0.030
-100	0.024	-0.002	0.029	0.850	0.049	-0.005	0.060	0.038	-0.003	0.048	0.023	0.002	0.029
-300	0.031	-0.001	0.036	0.765	0.046	-0.005	0.057	0.037	-0.003	0.047	0.022	0.003	0.031
-1500	0.025	-0.000	0.030	0.800	0.036	-0.004	0.046	0.031	-0.004	0.039	0.013	0.001	0.016

Appendix 3.3. Results of evaluation of the PTFs in Table 3.6 (PTFs based on the mean values of the relevant soil properties)

Matric potential (KPa)	Silt plus clay equations				Organic carbon equations			Clay content equations			Multiple regression equations		
	mMAE	mMBE	mRMSE	md	mMAE	mMBE	mRMSE	mMAE	mMBE	mRMSE	mMAE	mMBE	mRMSE
-1	0.010	0.000	0.012	0.975	0.025	-0.001	0.034	0.018	-0.001	0.025	0.008	0.001	0.009
-5	0.006	-0.001	0.008	0.845	0.034	-0.003	0.049	0.024	-0.001	0.029	0.010	-0.001	0.012
-8	0.007	0.001	0.009	0.843	0.036	-0.004	0.051	0.023	-0.002	0.030	0.009	-0.002	0.012
-10	0.008	0.001	0.009	0.842	0.036	-0.004	0.051	0.025	-0.002	0.032	0.010	-0.001	0.013
-30	0.011	0.001	0.013	0.829	0.038	-0.004	0.053	0.025	-0.002	0.034	0.011	0.003	0.013
-60	0.010	-0.001	0.012	0.838	0.038	-0.004	0.053	0.023	-0.002	0.031	0.010	0.000	0.013
-100	0.012	-0.000	0.014	0.837	0.037	-0.004	0.052	0.021	-0.001	0.030	0.010	0.003	0.012
-300	0.021	-0.000	0.023	0.702	0.034	-0.003	*0.046*	0.016	-0.001	0.025	0.006	0.002	0.007
-1500	0.023	0.000	0.024	0.774	0.031	-0.003	0.041	0.017	-0.001	0.024	0.002	0.000	0.002

Appendix 3.4. Results of evaluation of the PTFs in Table 3.9 (subsoils with Si:C ratios < 0.75)

Matric potential (KPa)	Silt plus clay equations				Clay content equations			Multiple regression equations		
	mMAE	mMBE	mRMSE	md	mMAE	mMBE	mRMSE	mMAE	mMBE	mRMSE
-1	0.019	-0.001	0.023	0.884	0.024	-0.001	0.030	0.015	0.004	0.020
-5	0.028	-0.003	0.033	0.795	0.030	-0.002	0.039	0.024	0.003	0.031
-8	0.030	-0.003	0.038	0.820	0.035	-0.003	0.045	0.028	-0.003	0.035
-10	0.032	-0.003	0.041	0.825	0.036	-0.003	0.048	0.028	0.004	0.038
-30	0.034	-0.004	0.044	0.811	0.040	-0.003	0.052	0.030	0.000	0.039
-60	0.036	-0.004	0.045	0.793	0.042	-0.003	0.053	0.031	0.003	0.040
-100	0.036	-0.004	0.045	0.795	0.043	-0.004	0.054	0.031	-0.003	0.040
-300	0.030	-0.003	0.040	0.832	0.037	-0.003	0.048	0.025	0.004	0.036
-1500	0.023	-0.001	0.030	0.807	0.028	-0.003	0.037	0.019	0.003	0.027

Appendix 3.5. Results of evaluation of the PTFs in Table 3.10

Matric	Silt plus clay equations				Clay content equations			Multiple regression equations		
potential (KPa)	mMAE	mMBE	mRMSE	md	mMAE	mMBE	mRMSE	mMAE	mMBE	mRMSE
-1	0.016	-0.001	0.019	0.925	0.022	-0.001	0.025	0.007	0.003	0.007
-5	0.008	-0.000	0.011	0.964	0.016	-0.001	0.016	0.007	0.002	0.008
-8	0.006	-0.000	0.008	0.982	0.014	-0.001	0.015	0.005	0.003	0.007
-10	0.006	-0.000	0.007	0.993	0.012	-0.001	0.014	0.005	0.004	0.007
-30	0.008	-0.000	0.008	0.994	0.010	0.000	0.013	0.003	-0.003	0.004
-60	0.008	-0.000	0.009	0.995	0.012	-0.001	0.015	0.004	0.003	0.005
-100	0.007	0.001	0.009	0.996	0.013	-0.001	0.015	0.004	0.001	0.005
-300	0.009	-0.001	0.013	0.990	0.011	-0.001	0.013	0.008	-0.001	0.009
-1500	0.011	-0.001	0.013	0.982	0.009	0.002	0.010	0.007	0.004	0.008

Appendix 3.6. Results of evaluation of the PTFs in Table 3.13

Matric	Silt plus clay equations				Clay content equations			Multiple regression equations		
potential (KPa)	mMAE	mMBE	mRMSE	md	mMAE	mMBE	mRMSE	mMAE	mMBE	mRMSE
-1	0.017	-0.001	0.024	0.775	0.017	0.000	0.022	0.026	-0.023	0.038
-5	0.028	-0.002	0.036	0.737	0.028	-0.000	0.034	0.033	-0.018	0.041
-8	0.031	-0.002	0.038	0.777	0.030	-0.000	0.036	0.033	-0.013	0.040
-10	0.027	-0.001	0.035	0.872	0.024	0.000	0.032	0.031	-0.017	0.040
-30	0.023	-0.002	0.031	0.907	0.024	0.000	0.029	0.033	-0.009	0.042
-60	0.022	-0.001	0.029	0.917	0.025	0.000	0.030	0.033	-0.001	0.040
-100	0.023	-0.004	0.030	0.944	0.028	0.000	0.034	0.032	0.001	0.041
-300	0.015	-0.001	0.021	0.977	0.024	-0.000	0.030	0.025	0.009	0.033
-1500	0.013	0.004	0.015	0.991	0.029	0.000	0.035	0.029	0.014	0.037

Appendix 3.7. Results of evaluation of the PTFs in Table 3.14

Matric	Silt plus clay equations				Clay content equations		
potential (KPa)	mMAE	mMBE	mRMSE	md	mMAE	mMBE	mRMSE
-1	0.015	-0.000	0.021	0.817	0.015	0.000	0.019
-5	0.028	-0.001	0.033	0.793	0.023	-0.000	0.028
-8	0.029	-0.001	0.035	0.797	0.023	-0.000	0.029
-10	0.024	-0.001	0.028	0.817	0.018	-0.000	0.022
-30	0.014	0.000	0.016	0.981	0.007	-0.001	0.007
-60	0.014	-0.000	0.017	0.970	0.007	-0.000	0.008
-100	0.010	-0.001	0.012	0.991	0.008	0.000	0.008
-300	0.004	-0.002	0.005	0.998	0.007	0.000	0.009
-1500	0.008	0.008	0.011	0.993	0.017	0.000	0.022

Appendix 4.1 Comparison of water contents estimated from the actual parameters of different water retention equations with the corresponding measured values for topsoils

	Van Genuchten				Brooks-Corey				Campbell				Hutson & Cass				Smith (1992)				Power function			
Class	MAE	RMSE	d	R^2	MAE	RMSE	d	R^2	MAE	RMSE	d	R^2	MAE	RMSE	d	R^2	MAE	RMSE	d	R^2	MAE	RMSE	d	R^2
20.01-30	0.006	0.008	1.000	0.989	0.006	0.008	1.000	0.988	0.006	0.008	1.000	0.988	0.014	0.017	1.00	0.985	0.006	0.008	1.000	0.988	0.006	0.008	1.000	0.987
40.01-50	0.014	0.015	0.998	0.953	0.005	0.008	0.999	0.987	0.011	0.013	0.998	0.963	0.012	0.015	0.998	0.964	0.010	0.011	0.999	0.972	0.011	0.013	0.998	0.963
50.01-60	0.008	0.009	0.998	0.979	0.036	0.040	0.985	0.992	0.005	0.007	0.999	0.988	0.006	0.008	0.999	0.985	0.005	0.006	0.999	0.990	0.005	0.007	0.999	0.988
60.01-70	0.011	0.012	0.967	0.958	0.008	0.010	0.967	0.969	0.008	0.010	0.968	0.968	0.012	0.014	0.936	0.969	0.008	0.010	0.968	0.969	0.008	0.010	0.968	0.969
70.01-80	0.011	0.013	0.985	0.970	0.007	0.009	0.992	0.985	0.008	0.010	0.991	0.983	0.011	0.013	0.985	0.978	0.008	0.010	0.991	0.983	0.008	0.010	0.991	0.982
80.01-90	0.011	0.012	1.000	0.969	0.015	0.021	0.998	0.901	0.015	0.021	0.998	0.901	0.014	0.016	0.999	0.973	0.010	0.013	0.999	0.964	0.011	0.013	0.999	0.961
90.01-100	0.013	0.014	1.000	0.956	0.016	0.019	0.999	0.910	0.016	0.019	0.999	0.910	0.018	0.020	0.999	0.956	0.013	0.015	0.999	0.945	0.013	0.017	0.999	0.934
Mean	0.010	0.012	0.992	0.968	0.013	0.017	0.991	0.962	0.010	0.013	0.993	0.957	0.012	0.015	0.988	0.973	0.009	0.011	0.994	0.973	0.009	0.011	0.994	0.969
s.e	0.001	0.001	0.005	0.005	0.004	0.005	0.005	0.015	0.001	0.002	0.004	0.012	0.001	0.001	0.009	0.004	0.001	0.001	0.004	0.006	0.001	0.001	0.004	0.007

Appendix 4.2 Comparison of water contents estimated from the actual parameters of different water retention equations with the corresponding measured values for subsoils with a Si:C ratio < 0.75

	Van Genuchten				Brooks-Corey				Campbell				Hutson & Cass				Smith (1992)				Power function			
Class	MAE	RMSE	d	R^2	MAE	RMSE	d	R2	MAE	RMSE	d	R^2	MAE	RMSE	d	R^2	MAE	RMSE	d	R^2	MAE	RMSE	d	R^2
30.01-40	0.010	0.012	1.000	0.981	0.005	0.006	1.000	0.994	0.007	0.009	1.000	0.990	0.006	0.008	1.000	0.993	0.006	0.008	1.000	0.993	0.007	0.009	1.000	0.990
40.01-50	0.006	0.007	1.000	0.990	0.006	0.007	1.000	0.990	0.008	0.010	0.999	0.981	0.007	0.009	0.999	0.986	0.006	0.007	1.000	0.990	0.008	0.010	0.999	0.981
50.01-60	0.004	0.005	1.000	0.994	0.004	0.005	1.000	0.995	0.009	0.010	0.999	0.987	0.009	0.010	0.999	0.982	0.052	0.056	0.985	0.992	0.009	0.010	0.999	0.979
60.01-70	0.008	0.009	0.995	0.981	0.005	0.006	0.997	0.991	0.005	0.006	0.997	0.991	0.007	0.008	0.996	0.992	0.007	0.009	0.996	0.990	0.005	0.006	0.997	0.991
70.01-80	0.008	0.009	0.998	0.984	0.016	0.025	0.988	0.867	0.016	0.025	0.988	0.867	0.010	0.011	0.997	0.985	0.021	0.025	0.967	0.980	0.007	0.009	0.998	0.984
80.01-90	0.010	0.012	0.999	0.973	0.019	0.027	0.997	0.864	0.019	0.027	0.997	0.864	0.013	0.015	0.999	0.976	0.023	0.028	0.996	0.968	0.009	0.012	0.999	0.972
90.01-100	0.011	0.012	1.000	0.970	0.016	0.021	1.000	0.906	0.016	0.021	0.999	0.906	0.015	0.017	0.999	0.974	0.011	0.013	1.000	0.965	0.011	0.014	1.000	0.959
Mean	0.008	0.009	0.999	0.982	0.010	0.014	0.997	0.944	0.012	0.015	0.997	0.941	0.010	0.011	0.999	0.984	0.018	0.021	0.992	0.983	0.008	0.010	0.999	0.979
s.e	0.001	0.001	0.001	0.003	0.002	0.004	0.002	0.024	0.002	0.003	0.002	0.022	0.001	0.001	0.001	0.003	0.006	0.007	0.005	0.004	0.001	0.001	0.000	0.004

Appendix 4.3 Comparison of water contents estimated from the actual parameters of different water retention equations with the corresponding measured values for subsoils with a Si:C ratio > 0.75

	Van Genuchten				Brooks-Corey				Campbell				Hutson & Cass				Smith (1992)				Power function			
Class	MAE	RMSE	d	R^2	MAE	RMSE	d	R^2	MAE	RMSE	d	R^2	MAE	RMSE	d	R^2	MAE	RMSE	d	R^2	MAE	RMSE	d	R^2
10.01-20	0.006	0.007	1.000	0.995	0.013	0.014	1.000	0.980	0.006	0.007	1.000	0.995	0.010	0.012	1.000	0.993	0.006	0.007	1.000	0.995	0.013	0.014	1.000	0.981
20.01-30	0.003	0.004	1.000	0.998	0.013	0.015	1.000	0.977	0.004	0.005	1.000	0.997	0.012	0.015	0.999	0.993	0.004	0.005	1.000	0.997	0.013	0.015	1.000	0.979
30.01-40	0.010	0.012	0.997	0.991	0.011	0.013	0.996	0.989	0.011	0.013	0.996	0.989	0.023	0.027	0.990	0.984	0.011	0.013	0.996	0.989	0.023	0.029	0.974	0.949
60.01-70	0.014	0.016	0.997	0.958	0.011	0.013	0.998	0.970	0.011	0.013	0.998	0.970	0.018	0.018	0.996	0.973	0.012	0.013	0.998	0.970	0.011	0.013	0.998	0.970
70.01-80	0.014	0.015	0.999	0.962	0.010	0.011	0.999	0.978	0.010	0.012	0.999	0.974	0.009	0.010	0.999	0.988	0.011	0.012	0.999	0.974	0.010	0.012	0.999	0.974
80.01-90	0.009	0.010	1.000	0.980	0.016	0.022	0.999	0.899	0.016	0.022	0.999	0.899	0.011	0.011	1.000	0.979	0.009	0.010	1.000	0.977	0.009	0.011	1.000	0.975
Mean	0.009	0.011	0.999	0.981	0.012	0.015	0.999	0.966	0.010	0.012	0.999	0.971	0.014	0.016	0.997	0.985	0.009	0.010	0.999	0.984	0.013	0.016	0.995	0.971
s.e.	0.002	0.002	0.001	0.007	0.001	0.002	0.001	0.014	0.002	0.002	0.001	0.015	0.002	0.003	0.002	0.003	0.001	0.001	0.001	0.005	0.002	0.003	0.004	0.005

Appendix 4.4 Comparison of water contents estimated from predicted parameters of water retention equations with the corresponding measured values for topsoils

	Van Genuchten						Hutson & Cass						Smith					
Class	MAE	RMSE	d	Slope	Inter	R^2	MAE	RMSE	d	Slope	Inter	R^2	MAE	RMSE	d	Slope	Inter	R^2
20.01-30	0.010	0.012	1.000	1.006	-0.011	0.987	0.014	0.016	1.000	0.962	0.020	0.985	0.012	0.017	0.999	1.138	0.042	0.985
40.01-50	0.057	0.060	0.956	1.384	-0.184	0.940	0.013	0.004	1.000	0.957	0.018	0.957	0.015	0.017	0.996	1.079	0.035	0.969
50.01-60	0.020	0.023	0.990	0.912	0.009	0.971	0.011	0.011	0.997	0.917	0.016	0.983	0.013	0.015	0.993	0.910	0.016	0.990
60.01-70	0.013	0.016	0.987	0.851	0.050	0.954	0.013	0.004	0.995	0.846	0.057	0.963	0.018	0.022	0.898	0.925	0.043	0.961
70.01-80	0.033	0.039	0.958	0.820	0.090	0.964	0.013	0.006	0.997	0.884	0.046	0.980	0.012	0.015	0.987	1.037	0.024	0.983
80.01-90	0.030	0.033	0.996	0.951	0.050	0.966	0.014	0.007	1.000	0.907	0.042	0.962	0.013	0.016	0.999	1.055	0.014	0.964
90.01-100	0.012	0.014	1.000	1.046	-0.018	0.954	0.021	0.012	1.000	0.842	0.060	0.940	0.011	0.017	0.999	1.094	0.049	0.947
Mean	0.025	0.028	0.984	0.996	-0.002	0.962	0.014	0.009	0.998	0.902	0.037	0.967	0.014	0.017	0.982	1.034	0.032	0.971
s.e	0.006	0.006	0.007	0.071	0.034	0.006	0.001	0.002	0.001	0.018	0.007	0.006	0.001	0.001	0.014	0.032	0.005	0.006

Appendix 4.5 Comparison of water contents estimated from predicted parameters of water retention equations with the corresponding measured values for subsoils with a Si:C ratio < 0.75

	Van Genuchten						Hutson & Cass						Smith					
Class	MAE	RMSE	d	Slope	Inter.	R^2	MAE	RMSE	d	Slope	Inter.	R^2	MAE	RMSE	d	Slope	Inter.	R^2
30.01-40	0.044	0.047	0.991	1.075	-0.066	0.968	0.011	0.015	0.999	1.155	-0.031	0.992	0.009	0.010	1.000	1.090	-0.024	0.993
40.01-50	0.063	0.065	0.985	1.201	0.016	0.983	0.016	0.019	0.998	0.958	0.028	0.987	0.016	0.020	0.997	0.872	0.052	0.989
50.01-60	0.017	0.020	0.995	0.779	0.065	0.989	0.024	0.026	0.988	0.969	-0.014	0.979	0.034	0.036	0.992	0.876	0.067	0.989
60.01-70	0.028	0.032	0.974	0.790	0.090	0.979	0.016	0.019	0.944	0.896	0.020	0.990	0.012	0.014	0.991	0.875	0.049	0.987
70.01-80	0.053	0.054	0.884	0.954	0.068	0.978	0.010	0.011	0.997	0.952	0.013	0.983	0.030	0.035	0.939	0.840	0.087	0.976
80.01-90	0.011	0.013	0.999	1.077	-0.031	0.972	0.012	0.017	0.999	0.934	0.039	0.970	0.016	0.018	0.999	1.031	0.000	0.972
90.01-100	0.024	0.032	0.998	1.367	-0.202	0.972	0.016	0.018	0.999	0.868	0.064	0.961	0.013	0.015	0.999	0.973	0.005	0.965
Mean	0.034	0.038	0.975	1.034	-0.008	0.977	0.015	0.018	0.989	0.962	0.017	0.980	0.018	0.021	0.988	0.937	0.034	0.982
s.e	0.007	0.007	0.016	0.081	0.039	0.003	0.002	0.002	0.008	0.035	0.012	0.004	0.004	0.004	0.008	0.036	0.015	0.004

Appendix 4.6 Comparison of water contents estimated from predicted parameters of water retention equations with the corresponding measured values for subsoils with a Si:C ratio > 0.75

	Van Genuchten						Hutson & Cass						Smith					
Class	MAE	RMSE	d	Slope	Inter.	R^2	MAE	RMSE	d	Slope	Inter.	R^2	MAE	RMSE	d	Slope	Inter.	R^2
10.01-20	0.025	0.026	0.999	0.994	-0.024	0.992	0.014	0.020	0.999	0.881	0.009	0.994	0.008	0.011	1.000	1.017	-0.011	0.995
20.01-30	0.009	0.010	1.000	0.977	-0.004	0.998	0.015	0.021	0.999	0.842	0.027	0.989	0.006	0.008	1.000	0.958	0.005	0.996
30.01-40	0.052	0.056	0.961	1.179	0.005	0.976	0.041	0.045	0.969	1.062	0.022	0.966	0.028	0.029	0.980	1.130	-0.013	0.989
60.01-70	0.025	0.031	0.983	0.816	0.081	0.954	0.023	0.029	0.993	0.826	0.045	0.966	0.018	0.019	0.996	0.861	0.049	0.962
70.01-80	0.025	0.028	0.994	0.828	0.078	0.953	0.018	0.024	0.997	0.857	0.039	0.973	0.013	0.014	0.999	0.912	0.036	0.974
80.01-90	0.014	0.018	1.000	0.939	0.040	0.976	0.010	0.013	1.000	0.960	0.024	0.973	0.010	0.016	1.000	1.155	-0.077	0.977
Mean	0.025	0.028	0.989	0.956	0.029	0.975	0.020	0.025	0.993	0.905	0.028	0.977	0.014	0.016	0.996	1.005	-0.002	0.982
s.e	0.006	0.006	0.006	0.054	0.018	0.008	0.004	0.004	0.005	0.037	0.005	0.005	0.003	0.003	0.003	0.048	0.018	0.005

Appendix 6.1 Quantitative measures of the performance of pedotransfer functions in Table 5.2.

h	Forms of silt plus clay content functions					
	Linear		Power		Exponential	
(KPa)	mMAE	mRMSE	mMAE	mRMSE	mMAE	mRMSE
-1	0.023	0.027	0.027	0.032	0.022	0.028
-10	0.031	0.039	0.033	0.041	0.032	0.041
-30	0.030	0.039	0.032	0.041	0.034	0.043
-60	0.030	0.039	0.032	0.041	0.035	0.043
-100	0.031	0.039	0.031	0.040	0.036	0.045
-300	0.027	0.036	0.027	0.036	0.036	0.045
-1500	0.022	0.029	0.023	0.029	0.030	0.038

Appendix 6.2 Quantitative measures of the performance of pedotransfer functions in Table 5.4.

h (KPa)	Forms of silt plus clay content functions						Multiple linear regression equations	
	Linear		Power		Exponential			
	mMAE	mRMSE	mMAE	mRMSE	mMAE	mRMSE	mMAE	mRMSE
-1	0.021	0.024	0.027	0.031	0.021	0.025	0.019	0.022
-10	0.024	0.032	0.024	0.032	0.032	0.039	0.023	0.031
-30	0.024	0.030	0.024	0.031	0.034	0.040	0.023	0.029
-60	0.023	0.028	0.022	0.029	0.034	0.040	0.022	0.028
-100	0.022	0.028	0.022	0.028	0.036	0.042	0.021	0.027
-300	0.026	0.032	0.024	0.032	0.042	0.048	0.026	0.032
-1500	0.019	0.023	0.019	0.023	0.031	0.037	0.018	0.022

Appendix 6.3 Quantitative measures of the performance of pedotransfer functions in Table 5.6.

h (KPa)	Forms of silt plus clay content functions					
	Linear		Power		Exponential	
	mMAE	mRMSE	mMAE	mRMSE	mMAE	mRMSE
-1	0.019	0.023	0.024	0.027	0.018	0.024
-10	0.031	0.040	0.034	0.042	0.032	0.042
-30	0.032	0.042	0.035	0.044	0.035	0.045
-60	0.034	0.043	0.035	0.044	0.036	0.046
-100	0.034	0.042	0.035	0.044	0.037	0.046
-300	0.028	0.039	0.028	0.039	0.035	0.045
-1500	0.022	0.029	0.022	0.029	0.027	0.036

Appendix 6.4 Quantitative measures of the performance of pedotransfer functions in Table 5.8.

	Forms of silt plus caly function				Multiple linear regression functions	
h (KPa)	Linear		Exponential			
	mMAE	mRMSE	mMAE	mRMSE	mMAE	mRMSE
-1	0.017	0.023	0.016	0.024	0.017	0.023
-10	0.027	0.034	0.028	0.036	0.027	0.034
-30	0.022	0.031	0.021	0.031	0.021	0.030
-60	0.023	0.031	0.021	0.031	0.020	0.028
-100	0.024	0.030	0.023	0.031	0.022	0.028
-300	0.018	0.023	0.020	0.025	0.015	0.020
-1500	0.024	0.029	0.021	0.025	0.020	0.024