WATER RETENTION OF MAJOR SOIL SERIES OF THAILAND

Suntaree Yingjajaval and Kumut Sangkhasila
Department of Soil Science
Kasetsart University
Kamphaeng Saen 73140, Thailand

ABSTRACT

Water retention functions were compiled for sixty major soil series from 4 regions (Western Central Plain, North, upper Northeast and South) of Thailand, 10 series of which are highland, 18 are upland and 32 are lowland soils. Samples were taken from 3 depths, representing soil layers of 0-0.1, 0.1-0.3 and 0.3-0.6 m from soil surface. Water retention, $\Theta(h)$, saturation hydraulic conductivity, K_{sat}, texture, densities and porosity of each layer of soil were determined. Water contents at various matric potentials of $\leq$ -0.005 MPa show good relationships with texture. The van Genuchten's equation of $(\Theta-\Theta_r)/(\Theta_m-\Theta_r) = [1+\alpha^n h^n]^{-m}$, where Θ_m, Θ_r, α, m and n, with $m=1-1/n$ are parameters to be determined, was curve fitted to the retention data. The parameter n-1, which reflects the pore size distribution, is distinctly different among soils of the four regions. Soils of the NE region have the highest average n-1 value of 0.561, while the others range from 0.136 to 0.197, with the overall average value of 0.249. This parameter is found inversely related to the soil textural index in the square root form of $\sqrt{n-1} = a + b/\sqrt{TI}$. Averaged over the whole profile, K_{sat} for highland soils has the logarithmic mean value of 17.74 mm hr^{-1}, 5.71 for upland soils and 0.293 mm hr^{-1} for the lowland soils. It is proposed in this study that the upper limit of available water capacity (AWC) for the majority of the tropical soils of Thailand is set at the matric potential of -0.005 MPa. The resulting AWC of the soils ranges from 0.032 to 0.365 m^3 m^{-3} with the overall average of 0.17 m^3 m^{-3}. Significantly, water content at saturation and K_{sat} show no relationship with soil texture. These soil properties should be determined directly.

1. INTRODUCTION

As soil physics is a relatively new field in Thailand, the study of physical properties pertaining soil water availability is mostly incomplete. This study provides a set of database on water retention functions for 60 major soil series of the country which can be used for simulation of water movement in the soil and for water management planning.

2. MATERIALS AND METHODS

2.1 Soil Sampling

Soils were sampled from four regions of Thailand, i.e. the Western Central Plain (Mae Klong Basin), the North, the upper Northeast and the South. Altogether, 60 soil series from 63 sites were collected as representatives of the above four regions, based on their extent of occurrence and land use. Of the 60 soil series, 10 are highland soils, 18 upland and 32 lowland soils. Sampling was taken in 3 layers down to 0.6 m deep, representing layers of 0-0.1 m, 0.1-0.3 m and 0.3-0.6 m. Both soil cores (in PVC core of I.D. = 0.052 m and 0.06 m high) and disturbed soil sample were collected. Soil cores were used for water retention measurement in the matric potential range of 0 to -0.033 MPa. At lower potentials down to -1.5 MPa, sieved soil (through 2 mm sieve) was used. Soil analysis followed essentially the standard methods (Black, 1965; Klute, 1980). The particle size distribution adopts the USDA classification system: 2000-50 μm for sand separate, 50-2 μm for silt and <2 μm for clay separates. The texture of soil is expressed in terms of textural index, which according to Sillanpaa (1982) is as follows:

$$TI = 0.1(\%sand) + 0.3(\%silt) + 1.0(\%clay) \tag{1}$$

2.2 Data Analysis

The water retention function is described by van Genuchten's equation (van Genuchten, 1980) as

$$Se = (\Theta-\Theta_r)/(\Theta_m-\Theta_r) = [1/\{1+(\alpha h)^n\}]^m \tag{2}$$

where Se is the effective saturation, Θ_m and Θ_r are the maximum and residual water contents, α, n and m are parameters to be determined, with $m=1-1/n$. The matric potential, h, has the unit of cPa (cm of water). The van Genuchten's equation was chosen over Brooks and Corey's (Brooks and Corey, 1964) as it can cover the whole range of $h(\Theta)$ from saturation to -1.5 MPa, which makes it convenient to determine its derivatives. The differential water capacity is the derivatives of the soil water retention function, $C_\Theta = d\Theta/d|h|$ (Hillel, 1980). With water retention function following the van Genuchten's form, the differential water capacity is described as

$$C_\Theta = d\Theta/d|h| = -(\Theta_m-\Theta_r)(\alpha^n mn)\{1+(\alpha h)^n\}^{-(m+1)}\,h^{(n-1)} \tag{3}$$

When C_Θ is plotted as a function of matric potential (h), it shows a general configuration of a skewed bell shape. The peak of the C_Θ function will be at the matric potential of

$$h \text{ at } C_{\Theta,max} = (m^{1/n})/\alpha \tag{4}$$

The data were analyzed for all layers, but are presented here as the average value of the 0.6 m profile. The value of each layer was weighed by its thickness. For all the data, except the saturation hydraulic conductivity, the average value is $X_Z = (\Sigma x_i z_i)/\Sigma z_i$. As it is the soil resistance of each layer which lies in series, the average saturation hydraulic conductivity is $K_Z = (\Sigma z_i)/(\Sigma z_i/K_i)$; X_Z and K_Z are the average values for the root zone of Z = 0.6 m; x_i and K_i are the soil properties measured for each layer of thickness z_i.

3. RESULTS AND DISCUSSIONS

The listings of soil series, their taxonomy, particle size distribution, dry bulk density and total porosity are shown in Table 1. The samples, considering all layers, cover a wide range of very coarse to very fine texture (Figure 1). Soils of the Northeast region have coarser texture, while those of the Central Plain consist mostly of fine textural soils. Each soil type comprises soils of such a wide range of texture that its texture can not be generalized. The lowland soils under paddy production are not necessarily of fine texture.

3.1 Retention Function

The retention functions are shown by their parameters according to Eq.(2) in Table 2, together with the maximum value of the differential water capacity and its corresponding matric potential. The general shape of the water retention and the water capacity functions are shown for 4 selected textural classes in Figure 2a. Soil series in the same textural class with relatively equal magnitude of textural index are presented together in order to make comparison of the water release patterns among the lowland, upland and highland soils. From the figures, van Genuchten's equation seems to describe the retention function quite satisfactorily. The worst fit is data points at saturation, which occurs in soils that lose water easily when the matric potential drops from saturation. The fitting can be improved by having more measurement points in the matric potential range of 0 to -0.005 MPa, especially in the coarse textural soils.

The differential water capacity functions as in Figure 2b show that the difference in the pattern of water release from soil matrix takes place only in the wet range from 0 to -0.02 MPa. When the matric potential drops to and below -0.02 MPa, the amount of water released per unit drop in matric potential is almost zero. This indicates that although water in the dry range of -0.02 MPa to -1.5 MPa (the lower limit of available water capacity) is still considered as available to plant, its relative degree of availability becomes very much lower than water in the wet range of saturation to -0.02 MPa. In other words, this means that in the matric potential range of saturation to -0.02 MPa, a large amount of water can be extracted from the soil before causing a drop in matric potential, whereas in the potential range of -0.02 to -1.5 MPa, a small amount of water lost from the soil can cause a big drop in potential. Another interesting point is that among soils of similar texture, the paddy soils show a distinct pattern of differential water capacity function. All of the water capacity function of the paddy soils had a bell shape form, although some may not be readily apparent in the figures due to the scale used. In these soils, when the matric potential drops from saturation, water is not immediately released, but held up by surface tension, until a certain level of tension is reached then water flows out from the soil. This may be due to surface tension of water in the small pores which controls the release of water in the interconnected big pores. The surface tension effect is minimal or almost absent in the upland and highland soils, where water is released as soon as the matric potential drops below saturation. That the surface tension effect is imminent in paddy soils may be due to particle size stratification caused by puddling process.

The retention function parameter, n-1, is shown to be equivalent to the pore size distribution index in Brooks and Corey's equation, while the $1/\alpha$ value is the bubbling potential (van Genuchten, 1980). The $1/\alpha$ value is not found to be in good correlation with texture, but the parameter n-1 in a transformed value is fairly well correlated with the value of textural index. The linear relationship of $\sqrt{(n-1)}$ vs $1/\sqrt{TI}$ is shown in Figure 3. The range of the value n-1 is more than 0.5 for sandy soils, and decreases gradually to values of 0.2-0.1 for finer texture soils. Pak Chong soil series is a peculiar soil in the sense that it contains high amount of clay separates (mostly iron oxides) with exceptionally good structure. So with TI of around 83, the soil has the mean n-1 value of 0.5, which is more a value for coarse texture soils. The range of n-1 values in this study agrees very well with the values of pore size distribution index of US soils reported by Rawls *et al.* (1982).

The water contents at various matric potentials are shown to be a logarithmic function of textural index in the form of $\Theta = a + b\mathrm{Ln}(TI)$, with the coefficients listed in Table 3. The correlation coefficient values show increasing better fit for water contents at decreasing potential. This is expected as water content at high potential is a function of structure, while at low potential a function of texture. Water contents of matric potentials of -0.005 MPa and lower are fairly well correlated with texture. Only water content at saturation is poorly related to textural index, although the correlation coefficient is still statistically significant. This is clearly shown in Figure 4.

3.2 Available Water Capacity (AWC)

Considering the pattern of differential water capacity and the magnitude of the saturation hydraulic conductivity to be discussed later on, it is recommended that the upper limit of AWC be set at water content of matric potential of -0.005 MPa, while the lower limit be at the conventional potential of -1.5 MPa. The water content at these two limits are shown as function of textural index in Figure 5. Setting the upper limit at -0.005 MPa may not be suitable for certain heavy textural soils, such as Bl, Rb, Sb and Lp, as water content at this matric potential has degree of saturation greater than 0.90, which can cause aeration problem. However, water content of these soils decreases only slightly from matric potentials of -0.005 MPa to -0.033 MPa. So even though the upper limits in these soils are closer to water contents at -0.01 to -0.033 MPa, the magnitudes of the water content will not differ much.

The values of AWC which is the water content difference between the two limits are shown as a function of textural index in Figure 6. It is clear from the figure that the value of AWC is not related to texture, although the two limits are. This is also shown by almost identical slope values of the linear relationships of water content to the logarithmic of textural index of the two limits. The resulting average value of AWC for the 0.6 m profile of all soils is 0.17 $m^3\ m^{-3}$.

3.3 Saturation Hydraulic Conductivity (K_{sat})

The values of K_{sat} for the 0.6 m profile are shown in Table 2. Their logarithmic values are plotted as a function of soil texture in Figure 7, which clearly shows that K_{sat} can not be predicted from the texture. The interesting point is that the K_{sat} value of one of the soil layers can be two to three orders of magnitude less than the upper or the underlying layers, with no apparent association with its texture, porosity, density or pore size. In particular, the coarse texture soils of the Northeast can have the K_{sat} value of one layer many folds less than those of other layers. This limiting layer can reduce the overall K_{sat} of the 0.6 m profile tremendously. This is pointed out in the earlier report (Akratanakul, 1985) as the underlying explanation why the coarse textural soils of the Northeast region of Thailand can be used for paddy production and support the vegetation exceeding the level indicated by their texture. Combining the information on the reduced overall values of K_{sat}, available data on the hydraulic conductivity functions ($K(\Theta)$) of a coarse and a medium to fine texture soils (Akratanakul, 1985; Yingjajaval and Sangkhasila, 1990) and the pattern of water uptake in plant which was shown to be very high in the day of irrigation and dropped quickly once the easily available water had been extracted (Konyang, 1989), it is concluded that the water content at -0.005 MPa has high level of differential water capacity, while the loss by deep drainage with respect to rate of plant uptake may be discerned. So for major soil series of Thailand, the water content at -0.005 MPa is recommended as the upper limit of available water capacity.

In this study, the hydraulic conductivity functions have not been determined. However, the hydraulic conductivity can be predicted by using the retention function parameter (m value) and K_{sat} value (Burdine, 1953; Mualem, 1976).

4. CONCLUSIONS

The arithmetic means of soil parameters TI, n-1, AWC and the logarithmic mean of K_{sat} are summarized in Table 4 according to soil type and the sampling region. For soil water retention function, water contents show good correlation with texture, except at saturation. The parameter n-1 can also be estimated from texture but not the α value. Then AWC and K_{sat} are also not functions of texture. Therefore, for estimation of soil hydraulic properties, the water content at saturation and K_{sat} should be measured directly. The calculation of differential water capacity provides insight into the release pattern of water from soil matrix. The result shows that water is readily available in the range of saturation to matric potential of -0.02 MPa. Water at lower potentials, though is still regarded as available to plant, is difficult to extract. For water management planning aiming at high yield, water should be maintained in the soil so that its matric potential should not drop below -0.02 MPa. The overall average of available water capacity of all major soil series of Thailand is 0.17 $m^3\ m^{-3}$.

REFERENCES

1. Akratanakul, S. (1985) Hydraulic properties of major Northeast soils. p.189-201. Proceeding on the First KKU-USAID International Seminar on Soil, Water and Crop Management Systems for Rainfed Agriculture in Northeast Thailand. Khon Kaen University, Khon Kaen.

2. Black, C.A. (1965) Methods of Soil Analysis. Part I. Agronomy Monograph No.9. Am. Soc. of Agron., Madison, Wisconsin.

3. Brooks, R.H. and A.T. Corey. (1964) Hydraulic properties of porous media. Hydrology Paper No.3, Colorado State University, Fort Collins, Colorado.

4. Burdine, N.T. (1953) Relative permeability calculations from pore-size distribution data. Petr. Trans. Am. Inst. Mining Metall. Eng. 198:71-77.

5. Hillel, D. (1980) Fundamentals of Soil Physics. Academic Press, New York.

6. Klute, A. (1986) Methods of Soil Analysis. Part I. Physical and Mineralogical Methods. 2nd Edition. Agronomy Monograph No.9. Am. Soc. of Agron., Madison, Wisconsin.

7. Konyang, A. (1989) Water Movement Across Plant Bed and Water Use of Chinese Cabbage. Ph.D. dissertation. Kasetsart University, Bangkok. (In Thai with English Abstract)

8. Mualem, Y. (1976) A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res. 12:513-522.

9. Rawls, W.J.; D.L. Brakensiek and K.E. Saxton. (1982) Estimation of soil water properties. Transaction of ASAE 25(5):1316-1320, 1328.

10. Sillanpaa, M. (1982) Micronutrients and the Nutrient Status of Soils : A Global Study. FAO Soils Bull. No. 48, United Nations, Rome.

11. van Genuchten, M. Th. (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soil. Soil Sci. Amer. J. 44:892-898.

12. Yingjajaval, S. and K. Sangkhasila (1990) The upper limit of available water for Kamphaeng Saen soil series. (In Thai with English Abstract, submitted for publication)

Table 1 General soil descriptions and basic properties

Region		Soil Series	Soil Taxonomy	% Sand	% Clay	TI	Bulk Density $(m^3 m^{-3})$	Total Porosity
C	Bk	Bangkok	Typic Tropaquepts	1.68	78.63	84.71	1.18	0.4569
C	Bl	Bang Len	Typic Haplaquolls	11.67	70.12	76.75	1.22	0.4544
C	Bn	Bang Khen	Typic Tropaquepts	4.37	77.99	83.72	1.45	0.3547
C	Dn	Damnoen Saduak	Typic Haplaquolls	5.95	71.76	79.04	1.23	0.4335
C	Ks-1	Kamphaeng Saen	Typic Haplustalfs	19.91	46.30	58.43	1.32	0.4474
C	Kyo	Khao Yoi	Aeric Tropaqualfs	49.64	37.06	46.01	1.78	0.2766
C	Nn	Nakhon Phanom	Aeric Plinthic Paleaquults	13.88	56.07	66.47	1.56	0.3491
C	Np	Nakhon Pathom	Aeric Tropaqualfs	6.90	59.83	70.50	1.36	0.4282
C	Pth	Pak Tho	Aeric Plinthic Paleaquults	57.49	26.99	37.39	1.67	0.3391
C	Rb	Ratchaburi	Aeric Tropaquepts	4.64	74.23	81.03	1.35	0.4198
C	Sb	Saraburi	Aeric Tropaquepts	20.23	55.04	64.48	1.36	0.4363
C	Se	Sena	Sulfic Tropaquepts	2.39	75.13	82.11	1.43	0.3752
C	Sm	Samut Prakan	Typic Tropaquepts	3.18	74.45	81.48	0.85	0.5856
C	Tm	Tha Muang	Typic Ustifluvents	67.66	21.78	31.71	1.31	0.4798
N	Ce	Chiang Saen	Orthoxic Palehumults	15.48	53.97	64.68	1.13	0.5763
N	Cr	Chiang Rai	Plinthic Paleaquults	30.00	28.75	44.12	1.58	0.4052
N	Hd-1	Hang Dong	Typic Tropaqualfs	24.65	18.89	38.29	1.66	0.3565
N	Hd-2	Hang Dong	Typic Tropaqualfs	23.04	34.06	49.23	1.43	0.4424
N	Ks-2	Kamphaeng Saen	Typic Haplustalfs	1.76	10.35	36.89	1.25	0.5205
N	Lp	Lampang	Typic Tropaqualfs	20.49	10.22	33.06	1.55	0.4051
N	Ms	Mae Sai	Aeric Tropaqualfs	3.13	60.77	71.91	1.37	0.4732
N	Mt	Mae Taeng	Typic Paleustults	54.81	15.74	30.06	1.46	0.4425
N	Na	Nan	Aeric Tropaqualfs	5.82	30.78	50.38	1.42	0.4523
N	Ph	Phan	Typic Tropaqualfs	11.47	20.38	41.97	1.54	0.4085
N	Sai	San Sai	Typic Tropaqualfs	74.30	8.09	20.80	1.67	0.3606
N	Sir	Si Satchanalai	Ultic Haplustalfs	5.32	20.71	43.43	1.35	0.4811
N	Sp	San Pa Tong	Oxic Paleustults	76.17	4.01	17.58	1.67	0.3719
N	Tp	That Phanom	Ultic Haplustalfs	55.84	10.12	25.92	1.46	0.4424
N	Utt	Uttaradit	Aeric Tropaqualfs	15.18	15.45	37.77	1.41	0.4577
NE	Ki	Kula Ronghai	Typic Natraqualfs	71.83	16.67	27.30	1.61	0.3280
NE	Kt	Korat	Oxic Paleustults	79.33	7.83	19.62	1.52	0.3743
NE	Ng	Nam Phong	Ustoxic Quartzipsamments	90.00	2.67	13.87	1.48	0.4667
NE	Pc	Pak Chong	Oxic Paleustults	5.67	77.67	83.23	1.08	0.4419
NE	Pm	Phimai	Vertic Tropaquepts	53.83	27.67	38.60	1.55	0.3522
NE	Re	Roi Et	Aeric Paleaquults	73.00	7.67	20.77	1.61	0.3254
NE	Rn	Renu	Aeric Plinthic Paleaquults	80.17	6.67	18.63	1.47	0.4362
NE	Suk	Satuk	Oxic Paleustults	76.67	10.17	21.78	1.46	0.3908
NE	Ub	Ubon	Aquic Quartzipsamments	79.00	3.17	16.42	1.50	0.3830
NE	Ud	Udon	Typic Tropaquepts	81.17	5.00	17.27	1.70	0.3224
NE	Ud,cl	Udon, clay	Typic Tropaquepts	37.33	27.00	41.43	1.58	0.2505
NE	Wn	Warin	Oxic Paleustults	37.67	31.00	44.17	1.34	0.3908
NE	Yt	Yasothon	Oxic Paleustults	66.67	17.83	29.15	1.38	0.4184
S	Ak	Ao Luk	Rhodic Paleudults	7.17	73.17	79.78	1.11	0.5759
S	Ba	Bangnara	Typic Paleaquults	22.33	36.17	50.85	1.65	0.3897
S	Bc	Bacho	Typic Quartzipsamments	88.25	4.17	15.27	1.62	0.3913
S	Bh	Ban Thon	Typic Tropohumods	96.50	0.08	10.76	1.46	0.4634
S	Cp	Chumphon	Typic Paleudults	72.83	3.25	17.71	1.66	0.3604
S	Fd	Fang Daeng	Rhodic Paleudults	68.33	10.17	23.45	1.49	0.4271
S	Kh	Kohong	Typic Paleudults	67.50	13.17	25.72	1.63	0.3776
S	Kl	Klaeng	Typic Plinthaquults	25.67	30.50	46.22	1.32	0.4600
S	Klt	Khlong Teng	Dystropeptic Tropudults	40.00	26.00	40.20	1.34	0.4383
S	Km	Khlong Thom	Typic Paleudults	66.17	13.83	26.45	1.45	0.4503
S	Ko	Kokkiean	Typic Paleaquults	67.17	17.83	29.05	1.80	0.2748
S	Koi	Khok Kloi	Orthoxic Tropudults	51.00	29.17	40.22	1.37	0.4709
S	Lgu	La-ngu	Typic Tropaqualfs	55.83	19.50	32.48	1.08	0.5668
S	Ll	Lamphu La	Typic Paleudults	12.50	43.50	57.95	1.13	0.5475
S	Ntm	Na Tham	Oxic Plinthudults	75.17	11.67	23.13	1.43	0.4365
S	Pga	Phang-nga	Typic Paleudults	51.83	37.17	45.65	1.29	0.4894
S	Ran	Ranot	Typic Tropaqualfs	21.83	37.83	52.12	1.50	0.3949
S	Sd	Sadao	Oxic Dystropepts	77.50	9.00	20.80	1.47	0.4388
S	Ta	Tak Bai	Typic Tropaquepts	4.50	40.17	57.22	1.44	0.4435
S	Tan,v	Thanyaburi variant	Sulfic Tropaquepts	23.17	35.17	49.98	1.60	0.3937
S	Te	Tha Sae	Typic Paleudults	55.00	22.67	34.87	1.49	0.4211

Table 2 Parameters of retention function according to van Genuchten's equation, available water capacity, saturation hydraulic conductivity and water content at saturation

Type/ Region		Soil Series	Θ_r $(m^3\ m^{-3})$	Θ_m $(m^3\ m^{-3})$	α (cPa)	n	m	r^2	h at $C_{\Theta,max}$ (cPa)	$C_{\Theta,max}$ $(m^3\ m^{-3}\ cPa^{-1})$	AWC $(m^3\ m^{-3})$	K_{sat} $(mm\ hr^{-1})$	Θ_{sat} $(m^3\ m^{-3})$
L	C	Bk	0.00000	0.69098	0.02578	1.11907	0.10640	0.9594	5.23837	0.00149	0.2821	0.0037	0.7054
L	C	Bl	0.00000	0.57886	0.00203	1.23152	0.18800	0.9919	126.79670	0.00016	0.2956	0.0234	0.5985
L	C	Bn	0.00000	0.64692	0.16298	1.08100	0.07493	0.9644	0.55827	0.00651	0.2008	1.8511	0.6487
L	C	Kyo	0.03427	0.46040	0.18345	1.11168	0.10046	0.9818	0.68982	0.00624	0.1750	0.0472	0.4605
L	C	Nn	0.11274	0.42703	0.09261	1.09132	0.08368	0.9468	1.11201	0.00198	0.1238	1.0391	0.4275
L	C	Np	0.06950	0.47974	0.09875	1.07521	0.06995	0.9673	0.85320	0.00235	0.1249	0.0116	0.4811
L	C	Pth	0.00000	0.56145	0.05927	1.22800	0.18567	0.9975	4.28227	0.00454	0.2940	22.8254	0.5623
L	C	Rb	0.00000	0.47846	0.01087	1.09336	0.08539	0.9654	9.69202	0.00036	0.1637	2.9835	0.4924
L	C	Sb	0.00000	0.43278	0.01101	1.10250	0.09297	0.9768	10.53104	0.00036	0.1598	1.2677	0.4424
L	C	Se	0.07271	0.60993	0.43904	1.07023	0.06562	0.9539	0.17872	0.01295	0.1542	0.0195	0.6104
L	C	Sm	0.00000	0.66486	0.00315	1.23687	0.19151	0.9785	83.43385	0.00029	0.3504	0.0810	0.7001
U	C	Dn	0.00000	0.65548	0.00927	1.15411	0.13353	0.9693	18.84803	0.00062	0.3053	0.1822	0.6851
U	C	Ks-1	0.10452	0.54548	0.53375	1.11201	0.10073	0.9787	0.23780	0.01882	0.1563	4.5605	0.5457
U	C	Tm	0.00000	0.39629	0.12886	1.19869	0.16576	0.9927	1.73272	0.00630	0.1886	4.0560	0.3963
H	N	Ce	0.00000	0.50082	0.21010	1.07353	0.06849	0.9498	0.39172	0.00600	0.1480	270.8153	0.5016
H	N	Mt	0.04791	0.37147	0.28300	1.12403	0.11034	0.9914	0.49727	0.00793	0.1140	9.6558	0.3717
L	N	Cr	0.00000	0.29875	0.00192	1.20552	0.17048	0.9544	120.05039	0.00007	0.1434	0.2575	0.3203
L	N	Hd-1	0.06502	0.32533	0.18771	1.08266	0.07635	0.9012	0.49501	0.00307	0.1032	0.0444	0.3257
L	N	Hd-2	0.00131	0.39681	0.11188	1.07525	0.06998	0.9095	0.75349	0.00257	0.1497	3.8048	0.3976
L	N	Lp	0.00000	0.31146	0.00033	1.34890	0.25866	0.8466	1112.01331	0.00002	0.1622	1.5570	0.3518
L	N	Ms	0.00000	0.48862	0.25136	1.04807	0.04587	0.8905	0.21017	0.00489	0.1043	0.0096	0.4898
L	N	Na	0.00000	0.54277	0.13706	1.08351	0.07707	0.8848	0.68515	0.00471	0.1971	2.2274	0.5449
L	N	Ph	0.00000	0.36922	0.00239	1.21822	0.17913	0.9437	101.98844	0.00012	0.1754	0.0776	0.4110
L	N	Sai	0.00000	0.26451	0.06527	1.27074	0.21306	0.9748	4.53786	0.00266	0.1386	13.5679	0.2657
L	N	Ut	0.14361	0.38523	0.32812	1.06561	0.06157	0.8298	0.22278	0.00411	0.0849	0.0095	0.3855
U	N	Ks-2	0.11136	0.41206	0.34276	1.12479	0.11095	0.9517	0.41310	0.00897	0.1259	2.0929	0.4123
U	N	Sir	0.16605	0.39661	0.75565	1.09506	0.08681	0.8545	0.14203	0.01224	0.0881	9.2333	0.3968
U	N	Sp	0.00000	0.27685	0.06189	1.33654	0.25180	0.9919	5.75769	0.00308	0.1390	5.9430	0.2775
U	N	Tp	0.07621	0.32194	0.29330	1.23378	0.18948	0.9559	0.88541	0.01000	0.1174	2.9110	0.3219
H	NE	Pc	0.24533	0.49553	0.07726	1.54227	0.35161	0.9845	6.57219	0.00483	0.1145	3.7350	0.4955
H	NE	Yt	0.06109	0.41948	0.04626	1.44498	0.30795	0.9992	9.56743	0.00361	0.2109	10.7939	0.4193
L	NE	Ki	0.04480	0.37050	0.02007	1.32799	0.24698	0.9977	17.38278	0.00115	0.2349	0.4420	0.3696
L	NE	Pm	0.13600	0.50565	0.06038	1.34658	0.25738	0.9940	6.04483	0.00409	0.2135	0.1186	0.5057
L	NE	Re	0.03946	0.43113	0.03932	1.49950	0.33311	0.9920	12.21818	0.00364	0.2391	5.7572	0.4305
L	NE	Rn	0.03633	0.43460	0.01845	1.83116	0.45390	0.9965	35.21015	0.00248	0.2788	6.8750	0.4377
L	NE	Ub	0.02831	0.40862	0.02536	1.72485	0.42024	0.9946	23.85443	0.00295	0.2363	3.3349	0.4103
L	NE	Ud	0.02219	0.36578	0.01407	1.69677	0.41064	0.9991	42.06302	0.00144	0.2788	0.6252	0.3657
L	NE	Ud,cl	0.04481	0.50614	0.92849	1.10916	0.09842	0.9890	0.13317	0.03357	0.1496	0.0158	0.5063
U	NE	Kt	0.04111	0.34388	0.02478	1.71161	0.41575	0.9989	24.16608	0.00227	0.2118	0.0147	0.3432
U	NE	Ng	0.02329	0.34003	0.02298	2.15562	0.53610	0.9984	32.58703	0.00311	0.2045	12.4794	0.3393
U	NE	Suk	0.03692	0.33708	0.06349	1.49363	0.33049	0.9968	7.50527	0.00446	0.1428	20.5819	0.3373
U	NE	Wn	0.13789	0.37995	0.02576	1.40598	0.28875	0.9301	16.04553	0.00128	0.1852	3.6519	0.3775
H	S	Ak	0.00000	0.53750	20.78061	1.05066	0.04822	0.9943	0.00269	0.46534	0.0842	135.9772	0.5375
H	S	Cp	0.00000	0.55713	0.29041	1.35034	0.25945	0.9980	1.26782	0.02987	0.1737	8.5146	0.5572
H	S	Fd	0.05376	0.55971	0.62705	1.29938	0.23040	0.9977	0.51531	0.05248	0.1345	29.6089	0.5598
H	S	Pga	0.15574	0.52808	3.07031	1.17348	0.14783	0.9901	0.06387	0.12762	0.0810	92.1795	0.5283
H	S	Sd	0.04468	0.54664	2.30047	1.23677	0.19144	0.9976	0.11420	0.16171	0.1112	11.5647	0.5468
H	S	Te	0.08448	0.54161	1.32687	1.20369	0.16922	0.9956	0.17226	0.07619	0.1195	0.8036	0.5418
L	S	Ba	0.27021	0.64942	30.88098	1.14344	0.12545	0.9810	0.00527	1.13340	0.0490	2.5320	0.6495
L	S	Kl	0.13445	0.60695	4.94921	1.13048	0.11542	0.9679	0.02992	0.21054	0.1217	0.5785	0.6073
L	S	Ko	0.00000	0.58313	0.55515	1.14388	0.12578	0.9935	0.29408	0.03140	0.1945	0.1857	0.5833
L	S	Lgu	0.17442	0.61658	2.78244	1.18272	0.15449	0.9880	0.07409	0.14271	0.1202	0.1156	0.6168
L	S	Ran	0.16221	0.62245	2.00228	1.15742	0.13601	0.9716	0.08910	0.09568	0.1440	0.0297	0.6228
L	S	Ta	0.00000	0.66712	0.31607	1.09937	0.09039	0.9775	0.35537	0.01534	0.2260	0.0085	0.6677
L	S	Tan,v	0.00000	0.64474	0.01858	1.24628	0.19761	0.9812	14.65290	0.00173	0.3652	7.7270	0.6572
U	S	Bc	0.02642	0.54264	5.01160	1.26059	0.20672	0.9991	0.05714	0.38794	0.0890	112.8893	0.5427
U	S	Bh	0.00000	0.49737	293.79745	1.24535	0.19701	0.9991	0.00092	20.99108	0.0320	466.4964	0.4973
U	S	Kh	0.02402	0.53679	1.79306	1.21002	0.17357	0.9975	0.13118	0.11809	0.1315	3.6211	0.5370
U	S	Klt	0.08778	0.58244	0.75932	1.19088	0.16028	0.9943	0.28308	0.04499	0.1570	10.2818	0.5827
U	S	Km	0.03106	0.58487	1.53906	1.27353	0.21478	0.9970	0.19418	0.13228	0.1210	12.9276	0.5850
U	S	Koi	0.18989	0.53678	138.00479	1.20023	0.16683	0.9886	0.00163	5.93859	0.0418	17.6577	0.5368
U	S	Ll	0.00000	0.51016	0.18292	1.09525	0.08697	0.9671	0.58794	0.00656	0.1620	5.8264	0.5112
U	S	Ntm	0.05053	0.53584	0.71307	1.23434	0.18985	0.9975	0.36498	0.04810	0.1440	5.8686	0.5360

Table 3 Coefficients of linear correlation of water contents at selected matric potentials of logarithmic value of textural index: $\Theta = a + b\mathrm{Ln}(TI)$

Matric Potential (MPa)	Coefficients a ($m^3 m^{-3}$)	b	Correlation Coefficient, r
0 (saturation)	0.19664	0.082057	0.367 **
-0.005	-0.25617	0.164204	0.720 **
-0.01	-0.33927	0.181904	0.782 **
-0.02	-0.44645	0.204637	0.854 **
-0.033	-0.49392	0.212566	0.870 **
-1.00	-0.55167	0.221655	0.925 **
-1.5	-0.42626	0.163233	0.926 **

** statistically difference at 0.01 level

Table 4 Mean values of soil parameters, averaged for soil types (L=lowland, U=upland, H=highland) and soils in each region

a. Textural Index

	C	N	NE	S	mean
L	70.42	43.60	25.77	45.42	48.84
U	56.39	30.95	24.86	29.96	33.27
H	-	47.37	56.19	37.04	42.94
mean	67.42	40.41	30.17	37.14	43.21

b. Parameter n-1

	C	N	NE	S	mean
L	0.131	0.155	0.505	0.158	0.220
U	0.155	0.198	0.692	0.214	0.302
H	-	0.099	0.494	0.219	0.250
mean	0.136	0.159	0.561	0.197	0.249

c. AWC ($m^3 m^{-3}$)

	C	N	NE	S	mean
L	0.2113	0.1399	0.2330	0.1744	0.1892
U	0.2167	0.1176	0.1861	0.1098	0.1444
H	-	0.1310	0.1627	0.1173	0.1291
mean	0.2125	0.1327	0.2077	0.1335	0.1662

d. K_{sat} ($mm\ hr^{-1}$)

	C	N	NE	S	log mean
L	0.191	0.290	0.681	0.250	0.293
U	1.499	4.276	1.926	18.754	5.710
H	-	51.137	6.349	17.565	17.745
log mean	0.297	1.185	1.322	4.365	1.377

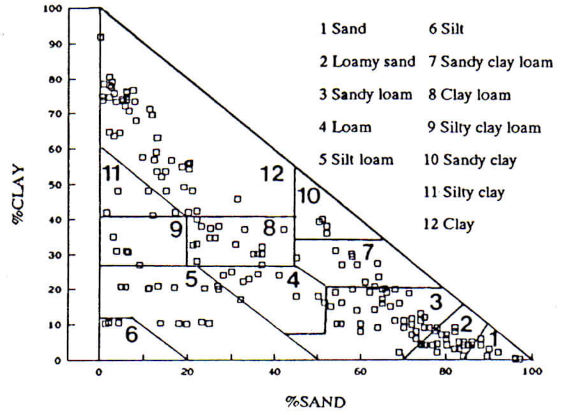


Figure 1 Particle-size distribution of soil samples included in this study, showing data of all layers for a total of 189 points

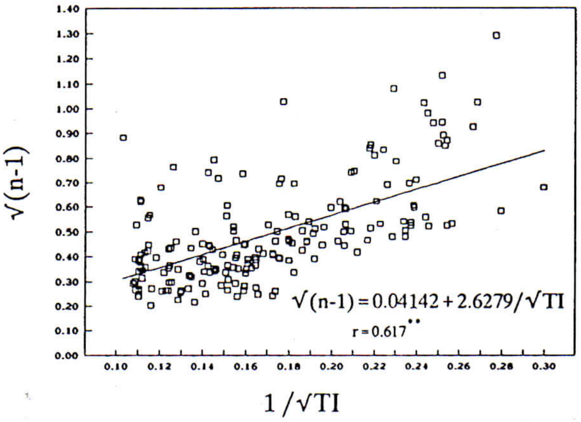


Figure 3 Parameter n-1 as a function of textural index for all soil samples

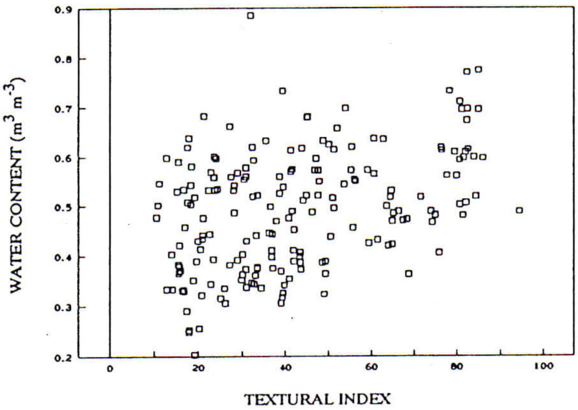


Figure 4 Water content at saturation as a function of textural index

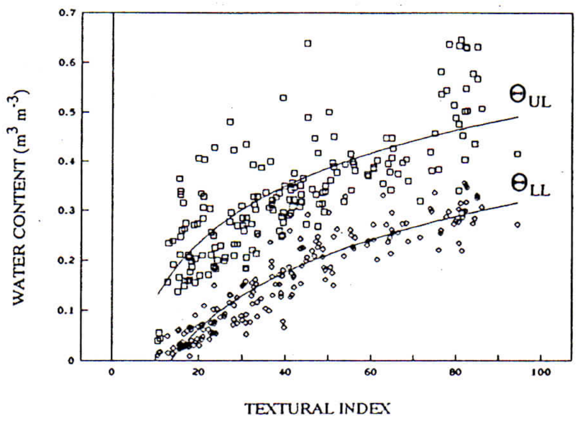


Figure 5 Water contents at upper (h=-0.005 MPa) and lower limits (h=-1.5 MPa) as a function of textural index

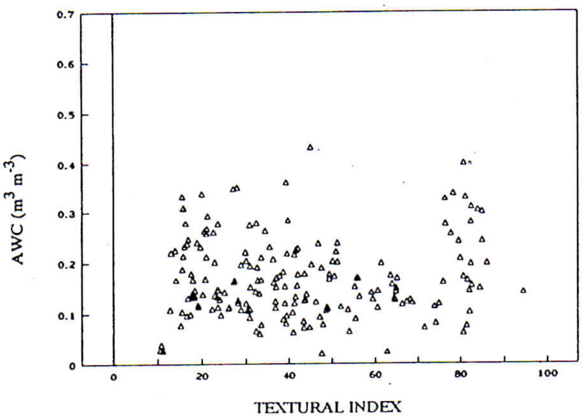


Figure 6 Available water capacity as a function of textural index

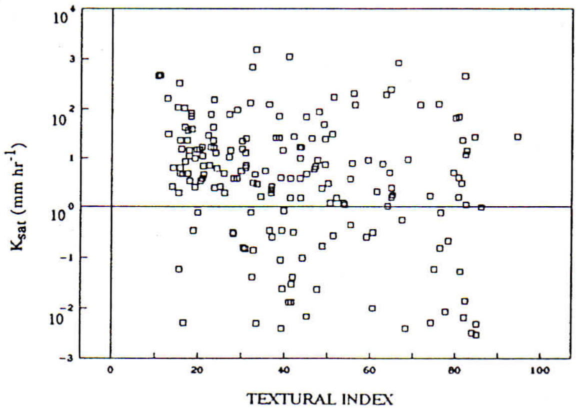
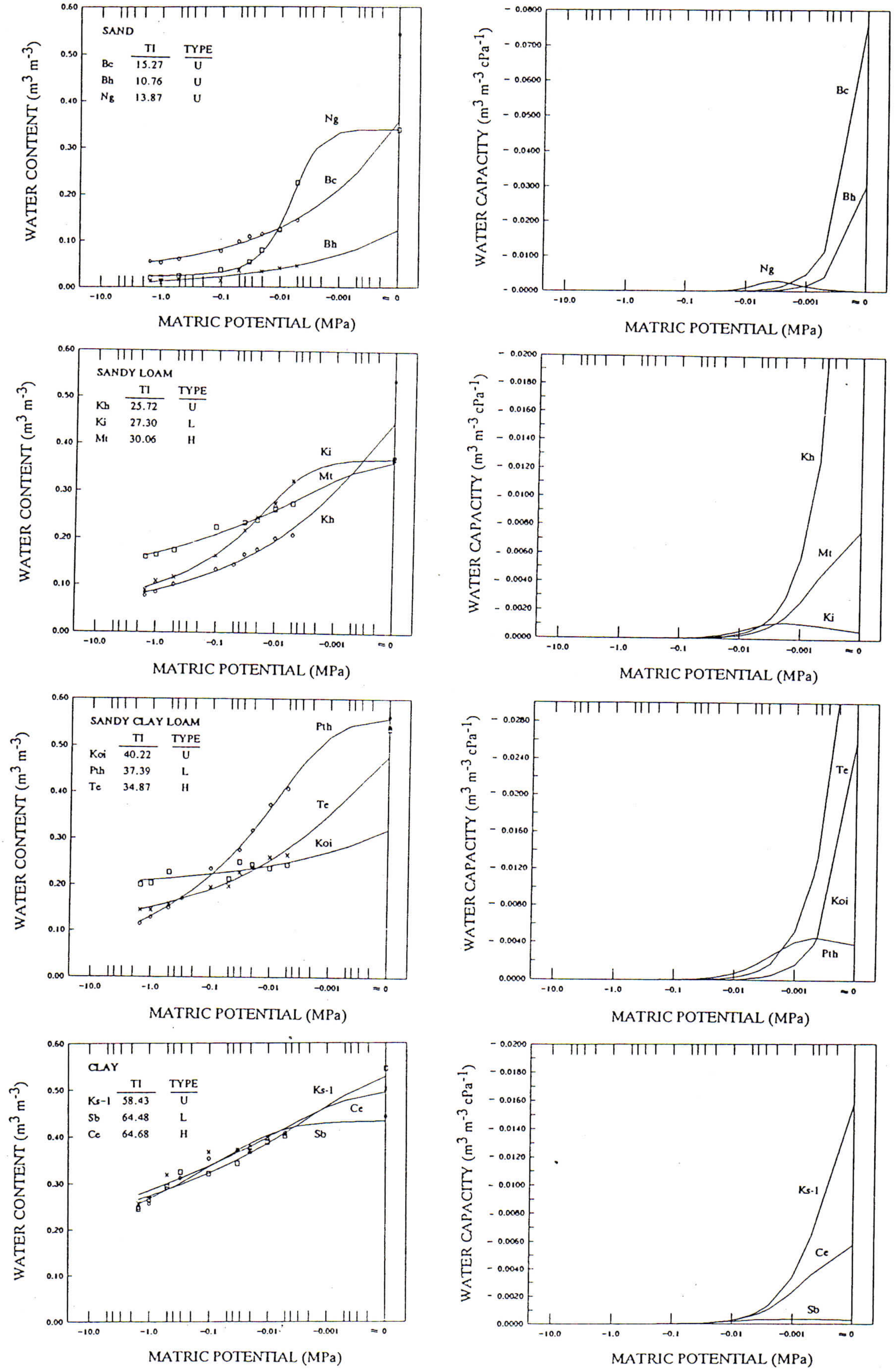


Figure 7 Saturation hydraulic conductivity as a function of textural index



(a) (b)

Figure 2 Examples of (a) soil water retention and (b) differential water capacity. Each figure shows 3 soil series of similar texture representing highland, lowland and upland soils (except the only 3 sandy soils which are all uplands soils)