SOIL HYDRAULIC PROPERTIES OF A NITISOL IN KABETE, KENYA

[PROPIEDADES HIDRAULICASL DEL UN NITISOL EN KABETE, KENYA]

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SUMMARY

Water relations are among the most important physical phenomena that affect the use of soils for agricultural, ecological, environmental, and engineering purposes. To formulate soil-water relationships, soil hydraulic properties are required as essential inputs. The most important hydraulic properties are the soil-water retention curve and the hydraulic conductivity. The objective of this study was to determine the soil hydraulic properties of a Nitisol, at Kabete Campus Field Station. Use of an internal drainage procedure to characterize the hydraulic properties and soil and water retention curves allowed for the establishment of the moisture and matric potential at field capacity and permanent wilting point. The Bt_2 (84 -115) and Bt_3 (115 - 143 cm) had the highest clay contents of 619 compared to Ap, AB and Bt_1 horizons. The PWP was attained at soil moisture contents of 0.223, 0.284, 0277, 0.307 and 0.314 m^3m^{-3} in the Ap, AB, Bt_1, Bt_2, and Bt_3 horizons, respectively. Horizontal saturated hydraulic conductivity (K_{sat}) was high at 6.0 cm hr^{-1} in Ap horizon and decreased to 0.4 cm hr^{-1} in the subsurface horizon (Bt_3). K_{sat} in the vertical direction was higher than horizontal and ranged from 8.3 cm hr^{-1} in surface layer to 0.6 cm hr^{-1} in Bt_3 horizon, with exception of Bt_1 and Bt_2 where horizontal K_{sat} was greater than vertical. The Ap horizon also had the highest crop extractable water. Though the AB and Bt_1 had the same water content at low matric suction, the variation was very wide as the SWRC approached saturation point. Bt_1 and Bt_2 also had similar water contents at suction range of – 7kPa after which Bt_1, tended towards Bt_3. Bt_3 had the narrowest range of crop extractable water and thus was attributed to texture. The Bt_3 retained the most amount of water at 0.314 m^3m^{-3} concluding that θ_{PWP} increased with depth. The total available water capacity between FC and PWP in the profile was 79.2 mm m^{-1}. The study observed that the field capacity, crop available water contents and hydraulic conductivities were influenced positively by soil organic matter. The Van Genuchten parameters of air entry value (α) and pore size distribution (n) indicated that pore size distribution was not even in the AP and AB horizons. The field capacity was attained at higher matric potential at -5kPa for Bt_1 while Bt_2 and AP, AB, Bt_2 and Bt_3 was at -10kPa.The functional relationship, $K(\theta) = a\theta^b$ that deals with water redistribution as a result of soil hydraulic properties and evaporative demand of the atmosphere was highly correlated to soil moisture content and texture with R^2 values > 0.85.

Key words: Soil water retention; hydraulic conductivity; water content; field capacity; permanent wilting point; Van Genuchten parameters

RESUMEN

Las relaciones del agua son entre los fenómenos físicos que afectan el uso del suelo para propósitos agrícolas, ecológicos, ambientales y de ingeniería. Para formulas las relaciones agua-suelo, se requieren como datos esenciales las propiedades hidráulicas del suelo. Las propiedades hidráulicas más importantes del suelo son la curva de retención de agua y la conductividad hidráulica. El objetivo de este estudio fue determinar las propiedades hidráulicas del suelo Nitisol en la estación del campus Kabete. Se usó un procedimiento de drenaje interno para caracterizar las propiedades hidráulicas y las curvas de retención del suelo y agua que permitieron el establecimiento de la humedad y el potencial matrico en capacidad de campo y punto de marchitez permanente. El Bt_2 (84 - 115) y Bt_3 (115 - 143 cm) tuvieron los más altos contenidos de arcilla de 619 comparados con los horizontes Ap, AB y Bt_1. El PWP fue alcanzado con un humedad del suelo de 0.223, 0.284, 0277, 0.307 y 0.314 m^3m^{-3} en los horizontes Ap, AB, Bt_1, Bt_2, y Bt_3 respectivamente. La conductividad saturada horizontal (K_{sat}) fue mayor en 6.0 cm hr^{-1} en Ap horizontal y disminuyo a 0.4 cm hr^{-1} en la subsuperficie horizontal (Bt_3)). K_{sat} en dirección

vertical fue más alta que la horizontal en un rango de 8.3 cm hr^{-1} en la capa superficial a 0.6 cm hr^{-1} en el horizonte Bt$_3$ con excepción de Bt$_1$ y Bt$_2$ donde Bt$_1$ tuvo el mismo contenido de agua en la succión matricial baja, la variación fue muy amplia en la SWC, el cual fue cercano al punto de saturación Bt$_1$ y Bt$_2$ tuvieron también contenidos rangos de succión de agua similares de – 7kPa después del cual Bt$_1$, tendió hacía Bt$_3$. Bt$_3$ tuvo el más estrecho rango de agua extraíble de un cultivo y sin embargo fue atribuido a la textura. La Bt$_3$ retuvo la mayor cantidad de agua en 0.314 m^{3}m^{-3}concluyendo que la θ_{PWP} incrementó con la profundidad. La capacidad total de agua disponible entre FC y PWP en el perfil fue 79.2 mm m^{-1}. En el estudio se observó la capacidad de campo, contenido y disponibilidad de agua y conductividad del suelo

fueron influenciados positivamente por la materia orgánica del suelo. Los parámetros de Van Genuchten para entrada de aire (α) y distribución de tamaño de poro (n) indicaron que la distribución de tamaño de poro no estuvo incluso en los horizontes AP y AB h. AB, Bt$_2$ y Bt$_3$ fueron de -10kPa .La relación funcional $K(\theta) = a\theta^b$ que de acuerdo con la redistribución como resultado de las propiedades hidraulicas del suelo y la demanda evaporativa de la atmosfera fue altamente correlacionada con el contenido de humedad del suelo y la textura con valores de R^2>0.85

Palabras clave: Retención de agua del suelo; conductividad hidráulica; contenido de agua; capacidad de campo; punto de marchitez permanente; parámetros de Van Genuchten.

INTRODUCTION

Knowledge of soil hydraulic properties is important for describing and predicting movements of water and solutes through soils, which may be related to many agronomic, engineering, and environmental fields of research. Key soil hydraulic properties include saturated hydraulic conductivity (K_s), unsaturated hydraulic conductivity function – $K(\psi)$, K(θ) or K(ϑ), where ψ is water potential, θ is volumetric water content and ϑ is water volume ratio – and the soil moisture retention curve. Over the years many direct methods have been developed for measuring soil hydraulic properties in the field, for example the internal drainage method (Hillel et al., 1972; Libardi et al., 1980), the zero plane flux method (Richards et al., 1956) and the Guelph permeameter method (Reynolds and Elrick, 1985), and in the laboratory, e.g. the hot-air method (Arya et al., 1975), the out-flow method (Gardner, 1956) and the constant head method (Klute and Dirksen, 1986).

On sandy loam and silt loam soils, water retention curves generated using data obtained by the undisturbed soil core and field internal drainage methods agree well, but give saturated conductivity values that are up to three times higher than those obtained using the Guelph permeameter (Paige and Hillel, 1993). In addition, both the soil water retention curves and hydraulic conductivity values obtained on a sandy loam soil using various measuring techniques differ considerably (Mallants et al., 1997). Hence, no single method has been developed that performs well in a wide range of circumstances and for all soil types. Most direct methods require restrictive initial and boundary conditions, which make measurements time consuming, range restrictive and expensive.

Other investigators, therefore, have sought to derive soil hydraulic properties from moisture retention curves of undisturbed soil cores measured in the laboratory (Brooks and Corey, 1964; Mualem, 1976; van Genuchten, 1980; Kosugi, 1999).

Various indirect methods have also been used including predicting hydraulic properties from more easily measured soil properties, such as texture, bulk density or organic matter content, using pedo-transfer functions (PTFs), and the inverse modelling techniques have provided a good review of these functions (Wosten et al., 2001). Since PTFs predict missing characteristics from already available basic soil data, they have the clear advantages of being relatively inexpensive, easy to derive and convenient to use. However, for application at a specific point, prediction by a PTF might be inadequate and in such cases, direct measurement is the only option.

Various types of organic materials have been found to have similar effects on soil physical properties (Barzegar et al., 2002), and almost all studies indicate that application of organic materials improves soil properties (Celik et al., 2004; Mando et al., 2005). However, reported effects of manure additions on soils' hydraulic properties, such as water retention and saturated hydraulic conductivity, are inconsistent. Unger and Stewart (1974) reported that water contents at low tensions (< 150 kPa) were significantly higher for manure-treated soils than for untreated soils, but they found no significant difference at 1500 kPa tension. Sommerfeldt and Chang (1987) found that manure amendment significantly (P ≤ 0.05) increased soil water retention (at 0-5 and 10-15 cm depths) compared with the control across the whole tension range between 0 and 1500 kPa (Miller et al., 2002). Obi and Ebo (1995)

found that poultry manure significantly increased water retention at tensions between 0 and 33 kPa, but decreased it at tensions between 33 and 1500 kPa. In contrast, Schjonning et al. (1994) reported that soil water retention (tension range: 0.6 to 1500 kPa) was not significantly affected by inputs of either organic or inorganic fertilizer compared with unfertilized controls.

A number of authors have found that saturated hydraulic conductivity in tested soils significantly increased following applications of diverse kinds of organic matter, including poultry manure (Mbagwu, 1992; Obi and Ebo, 1995), cattle manure (Schjonning et al., 2002) and compost (Gonzalez and Cooperland, 2002). Conversely, others have found the saturated hydraulic conductivity to be unaffected by applied manure (Shirani et al., 2002; Arriaga and Lowery, 2003). However, Miller et al. (2002) detected differences in the saturated conductivity responses between manure and control treatments during observations over two years. Normally unsaturated conditions prevail in the field and consequently this is of importance for both dryland and irrigated land management. Surface mulching or no tillage can increase infiltration rates by increasing the abundance of biopores or macropore connectivity (Green et al., 2003). The soil water retention curve is changed at the wet end of the scale because the abundance of large pores increases in the absence of tillage (Hamblin and Tennant, 1981; Mapa et al., 1986). Furthermore, organic surface mulching also increase soil organic matter contents (Tebrugge and During, 1999), and in some respects surface mulching has similar effects to the addition of organic manure on soil properties. Nevertheless, the changes in total porosity and bulk density induced by these treatments differ (Haynes and Naidu, 1998; Tebrugge and During, 1999).

In Kenya very little information is available on soil hydraulic properties in the literature or the best way to fit the limited data in a model in order to evaluate how they are affected by both physical and chemical characteristics of the soils. The objective of this study was therefore to determine how some of these soil physical and chemical properties affect the soil hydraulic properties of a Nitisol in Kenya. These soils are of high agricultural value as most of the export crops such as tea and coffee are grown in these soils.

MATERIALS AND METHODS

Study area

The study was carried out at Kabete Campus Field Station, University of Nairobi. The Field Station farm lies 1°15[l] S and 36° 44[l] E and is at an altitude of 1940 m. The site is representative, in terms of soils and climate, of large areas of the Central Kenya highlands. The geology of the area is composed of the Nairobi Trachyte of the Tertiary age. The soils are well-drained, very deep (> 180 cm), dark red to dark reddish brown, friable clay (Gachene, 1989). The soil is classified as a humic Nitisol (FAO, 1990, WRB, 2006). There is no surface sealing or crusting and the profile has clay cutans throughout the B-horizon (Gachene, 1999). The groundwater is more than 30 m deep and runoff is negligible in the research plots. Slope gradient is relatively flat. According to the Kenya Soil Survey agro climatic zonation methodology (Sombroek et al., 1982), the climate of the study area can be characterized as semi-humid. The ratio of annual average rainfall to annual potential evaporation, r/Eo is 58%. The site experiences a bimodal rainfall distribution with long rains in Mid March – May and the short rains in mid October – December. The mean annual rainfall is 1006 mm. The land is cultivated for horticultural crops such as kales (*Brassica oleracea*), tomatoes (*Lycopersicon esculentum*), cabbage (*Brassica oleracea*), carrots, (*Daucus carota*), onions (*Allium fistulosum*), fruit trees such as avocadoes (*Persea americana*) and coffee (*Coffea Arabica*) as cash crops.

Soil characterization

Soil sampling was conducted on land that had freshly been ploughed. Plant litter on the surface was gently removed before soil sampling. Soil samples were collected from six locations for each horizon in the profile and were mixed to form composite samples. Organic carbon was determined following Walkley and Black (1934) as described by Nelson and Sommers (1996). Soil pH-H_2O and pH-$CaCl_2$ was determined with a pH meter in a 1:2.5 ratio extract. Electrical conductivity (ECe) was measured on a 1:2.5 ratio extract with an EC meter. Cation Exchange Capacity (CEC) was by leaching with ammonium acetate followed by steam distillation (micro Kjedhal), and then by titration. Exchangeable Ca and Mg in the NH_4 leachate were determined using Atomic Adsorption Spectroscopy (AAS) while K was determined by flame photometry using flame photometer. Total N was determined by Kjeldhal method as described by Bremner (1996).
The Atterberg limits were measured as described by Mcbride (2002). Liquid limit was determined with Casagrande apparatus. Bulk density was measured as described by Grossman and Reinsch (2002). Soil texture was by hydrometer as described by Glendon and Doni (2002). Particle density was determined by liquid displacement referred to as the pycnometer method and described by Flint and Lorraine (2002). From the bulk and particle density values obtained, porosity f was calculated in accordance with Flint and

Lorraine (2002). Infiltration was determined using the double ring infiltrometer (Reynolds et al., 2002). The PWP was taken as -1500 kPa which is the lower limit of available water (Nemes et al. 2008) while the FC for individual soil layers was measured using the internal drainage procedure. Soil moisture content was determined by gravimetric method as described by Topp and Free (2002). Saturated hydraulic conductivity, K_{sat} was determined using the constant head soil core method in accordance with Reynolds and Elrick (2002). The soil water retention curve (SWRC) was fitted by measuring soil water content at six matric potentials using undisturbed soil samples. For pressure potentials of 0.1, 1 kPa, 20 kPa, 32 kPa, 100 kPa, 500 kPa and 1500 kPa, pressure chambers were used. The procedure described by Cornelis et al. (2005) was followed. The Van Genuchten (1980) equation was fitted on a set of discreet points determined in the laboratory using the Leven-Marquardt algorithm (Marquardt, 1963) for fitting the SWRC.

RESULTS AND DISCUSSIONS
Chemical and physical soil properties

The soil chemical characteristics of the study area are presented in Table 1 while the physical properties are shown in Table 2. The clay content ranged from 49% in Ap horizon to 62% in Bt_2 and Bt_3 horizons (Table 2). The soils were well-developed with an argillic B-horizon and the sand and silt contents were low (<30%) and decreased down the soil profile as clay increased. Soil texture is known to affect soil water content and hydraulic conductivity, K (h)(Hillel, 1980; 2004).

The ρ_b ranged from 1.0 to 1.1 Mg m^{-3} (Table 2) in the 0-26 cm and the 115-143 cm layers, respectively. The tendency of ρ_b to increase with depth is as a result of cultivation on surface horizons and decline in organic carbon content with depth (Table 1). Chakraborty et al. (2010) reported that bulk density was significantly

lowered (1.51 Mg m^{-3}) with manure application, corresponding to maximum SOC content (6.8 g kg^{-1}). Generally, the soil in the study exhibited low bulk densities indicating low resistance to root penetration. Actual average particle density (ρ_s) for soil in this study was found to be 2.71 Mg m^{-3}.

This value is higher than the much quoted value of 2.65 Mg m^{-3}. Phiri (2002) reported similar values of 2.72 Mg m^{-3}at Msekera, Zambia. Well drained and aerated nature of the soils in the research site are a result of high pore volume (porosity) ranging from 57 to 65% at Bt_3 (lowest value) and Ap (highest value) depths, respectively. With decline in organic matter followed by an increment in clay content with depth, the number of macropores could have decreased. Iverson et al. (2000) quoted porosity values of between 30 and 70%. The soils were relatively fine textured and fall within the quoted values.

The steady state infiltration (I_L) observed of 13.4 cm hr^{-1}and the time taken (tL) to attain of 2 hours and 18 minutes (Fig.2) suggested a rapid infiltration rate of the soil. Reynolds et al. (2002) reported that steady infiltration is about twice the value of saturated hydraulic conductivity (Ks). This supports findings in this study where average Ks was about 7.15 cm hr^{-1} against infiltration rate of 13.4 cm hr^{-1}. The high infiltration rate observed in a Nitisol with high clay content was attributed to well developed soil aggregates and dominance of macropores in the upper 50 cm of the profile. The latter is due to high level of macro fauna activity especially termites. The infiltration rate suggests that the soil drained easily without causing waterlogging and at the same time retained some water, so as not to completely desiccate the soil through transport of water to the surface for evaporation purposes.

Table 1. Soil chemical properties of the research site.

Horizon depth (cm)	C %	CEC cmol (+) kg^{-1}	Mg cmol (+) kg^{-1}	Ca cmol (+) kg^{-1}	N %	pH H$_2$O (1:2.5)	pH KCl (1:2.5)	ECe dS m^{-1}
Ap 0-26	2.84	30.25	2.50	15.80	0.66	6.20	4.60	0.20
AB 26-47	2.62	33.38	3.34	12.90	0.36	6.30	4.70	0.14
Bt$_1$ 47-84	1.63	28.88	2.75	10.05	0.25	6.90	5.20	0.10
Bt$_2$ 84-115	1.02	33.13	2.72	9.75	0.22	7.10	5.60	0.10
Bt$_3$ 115-143+	0.53	37.25	3.96	6.65	0.16	7.20	5.60	0.10

Table 2. Soil physical properties of the research site.

Horizon cm	K_s (H) cm hr^{-1}	K_s (V) cm hr^{-1}	ρb Mg m^{-3}	Porosity %	Sand g kg^{-1}	Clay g kg^{-1}	Silt g kg^{-1}	Soil type
Ap 0-26	6.00 (M)	8.30 (MR)	1.00	65	291	489	220	Clay
AB 26-47	4.20 (M)	4.50 (M)	1.02	62	281	559	160	Clay
Bt$_1$ 47-84	2.70 (M)	2.40 (M)	1.07	60	271	569	160	Clay
Bt$_2$ 84-115	1.60 (MS)	0.50 (MS)	1.08	60	211	619	170	Clay
Bt$_3$ 115-143	0.40 (S)	0.60 (MS)	1.10	57	231	619	150	Clay

Note: $\rho s = 2.71$ Mg m^{-3} for all depths.   H: Horizontal. V: Vertical direction
K_s ratings: MR moderately rapid. M moderate, MS moderately slow, S slow
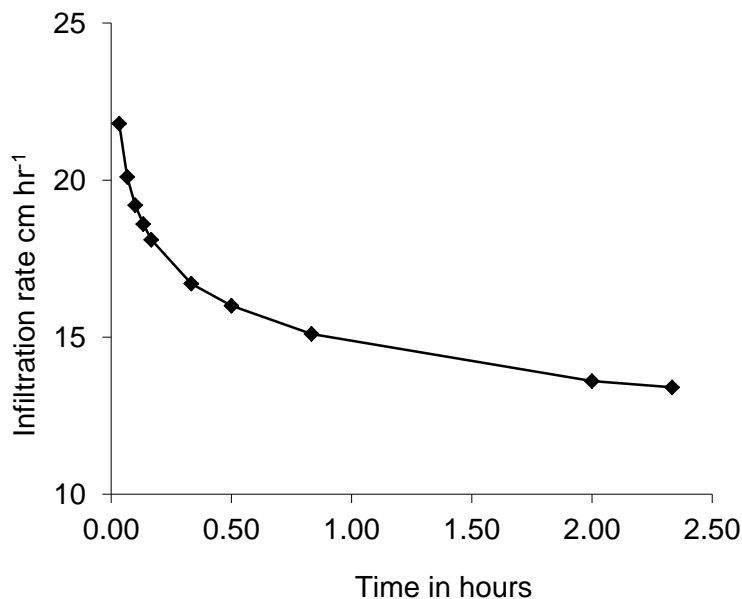
Figure 2. Infiltration rate (cm hr^{-1})

Atterberg limits

The Atterberg limits are presented in Table 3. The plastic limit was generally uniform at all depths at 39% on average. In contrast with the liquid limit, the amount of clay content had no significant effect on the plastic limit meaning that as the soil dried, the soil micro-pores tended to hold similar amounts of water, and this influenced soil plasticity. Plastic limit depends on soil and clay type, and also its location just like in liquid limits. Bell (2000) gave plastic limit values of 22 to 26 for red clays, 36 for Kenya black clays and 73% for the Kenyan Andosols. The values

obtained in the study fell between 37 and 41% in AB and Bt$_3$, respectively and were within these ranges. The liquid or higher plastic limit increased with depth from 47 in Ap to 64% in Bt$_3$. The range differed with depth probably due to the increased clay content with depth. The ranges given by Geological Society for Engineering of America are between 28 and 48 for red clays, and 75 and 132% for black clays. In Kenya, liquid limit values for black clay are 103% (Bell, 2000). Yongshan et al. (2002) observed Atterberg limits in amorphous clay-size materials in less weathered volcanic soils rich in silica of 65-135 for liquid limit, 30 to 40 for plastic limit, and 9-25 for

plastic index and concluded that plasticity and shrink-swell potential increased with increasing the content of amorphous clay-size materials in the soil. The values obtained were within those in the study area.

The increase in plastic index with depth from 7 to 23% in Ap and Bt$_3$ horizons, respectively, suggests that it is influenced by the clay content of the soil. Hillel (1998) reported that the plastic index not only depended on the clay content but also on the nature of the clay present, (swelling or non-swelling type), as well as on adsorbed cations, organic matter content and on pre-treatment of the sample. Kaolinite is the dominant clay mineral of these soils with small quantities of quartz (Van Ranst, 2005) both of which are non-expanding clays. This could be the reason of the high plastic index observed at higher clay contents compared to the 2:1 type of clay minerals (e.g. montmorillonite) that attains high plastic index at lower clay contents (Hillel, 1998). The general increase in adsorbed cations with depth (Table1) could have contributed positively to the plastic index deeper down into the profile. Just like for liquid limit, the sticky limit increased with increase in clay content ranging from 51 to 67% in the Ap and Bt$_3$ horizons, respectively.

Table 3 Atterberg limits.

Horizon Depth (cm)	Liquid Limit %	Sticky limit %	Plastic Limit	Plastic Index %
Ap 0-26	47	51	40	7
AB 26-47	50	58	37	13
Bt$_1$ 47-84	52	58	38	14
Bt$_2$ 84-115	49	57	41	8
Bt$_3$ 115-143+	64	67	41	23

The speed at which the sticky limit was attained indicated that clay content had strong influence on soil stickiness. High clay content retained more water that in turn contributed to the stickiness of the soil. The lower the clay content as was the case in the upper horizons, the more water was lost easily through drainage as soil pores were larger leading to lower water retention.

Table 4 shows percentage of dispersed and natural clays, and flocculation indices of various horizons. Dispersed clays increased with profile depth (except Bt$_1$) while natural clays were low at the top (Ap) and bottom (Bt$_2$ and Bt$_3$), but high in the mid (AB and Bt$_1$) horizons. Generally, natural clays were similar throughout the profile at an average of 19%. Stability of aggregates depended on cementing agents of soil

organic matter (SOM) and the water films that bound them (Daraghmeh et al., 2007; 2009). Flocculation index is mass wetness value at which soil suspension is transformed from a liquid to semi-liquid state with an appreciable increase in viscosity (Hillel, 1980). Flocculation index increased with depth and ranged from 54% in Bt$_1$ to 71% in Bt$_2$ and Bt$_3$. Values were high at 71% in Ap, Bt$_2$ and Bt$_3$ horizons, and low in the mid horizons following the same trend as natural clays.

The high values observed in the upper horizon could be due to higher organic matter, while high clay content in lower horizons contributed to high flocculation. Both SOM and clay bind particles together. The high flocculation index in the upper layers (Ap) could also be due to high content of divalent cations such as Ca and Mg that reduces the double layer allowing particles to flock together. X-ray diffraction analysis showed kaolinite had low crystallinity due to Fe substituting for Al in the lattice (Van Ranst, 2005). This Fe probably played a major role in binding the clay plates together. This was observed down the soil profile as the amount of divalent cations increased resulting in reduced swelling pressure and increased stability of plate condensation (Table 1). Chakraborty et al. (2010) observed that better aggregation was found with application of 100% NPK + farmyard manure, where the macro-aggregates were greater than 50% of total soil mass. They concluded that aggregation indices were positively and significantly correlated with soil organic carbon (SOC) in 8- 4 mm aggregates and that most of the effects were pronounced in 0-15 cm layer as observed in this study.

Table 4. Structural Stability – Flocculation Index

Horizon Depth (cm)	Dispersed Clay %	Natural Clay %	Flocculation Index (%)
Ap	58	17	70.7
AB	60	20	66.7
Bt$_1$	46	21	54.4
Bt$_2$	63	18	71.4
Bt$_3$	63	18	71.4

Hydraulic properties of a Nitisol

Horizontal saturated hydraulic conductivity (K_{sat}) was high at 6.0 cm hr^{-1} in Ap horizon and decreased to 0.4 cm hr^{-1} in the subsurface horizon (Bt$_3$) (Table 2). K_{sat} in the vertical direction was higher than horizontal values that ranged from 8.3 cm hr^{-1} in surface layer to 0.6 cm hr^{-1} in Bt$_3$ horizon, with exception of Bt$_1$ and Bt$_2$ where horizontal K_{sat} was greater than vertical. This could have been a result of faunal activities that had created tunnels in the soil layer. Decrease in K_{sat} with depth is associated with decrease in organic matter and an increase in clay content (Table 2). The compaction of soil reduced macro- to intermediate pores while the number of micropores remained constant leading to a lower hydraulic conductivity. Nwokocha et al. (2007) in southern Nigeria, observed mean values of between 32.7 and 56.9 cm hr^{-1} in the sub and topsoil layers of a loamy sandy soil, respectively. In the US Department of Agriculture Classification Scheme, K_{sat} values for clay soils of 0.46 cm hr^{-1} have been quoted (Leij et al., 1996; Clapp and Horneberg, 1978) which would agree with those obtained in this study.

Soil water retention (SWR) and internal drainage procedure

The relationship between water content, θ, and the soil water potential, ψ is shown in Figure 3 after fitting closed-form analytical expressions containing several parameters to discrete (θ, ψ) data sets, which were obtained through laboratory experiment. The shapes of water retention curves are characterized by several models and in this case the Mualem–van Genuchten model (Mualem, 1976; Van Genuchten, 1980) was used.

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha|\psi|)^n]^{1-1/n}}$$

Where, θ (φ) is the water retention curve [L^{3}L^{-3}]; ψ | is suction pressure ([L^{-1}] or cm of water); θ_s saturated water content [L^{3}L^{-3}]; θ_r residual water content [L^{3}L^{-3}]; α is related to the inverse of the air entry suction, $\alpha > 0$ ([L^{-1}], or cm^{-1}); and, n is a measure of the pore-size distribution, $n > 1$ (dimensionless).

The surface horizon (Ap) attained a permanent wilting point (PWP) at lower water contents of 0.223 m^{3}m^{-3} compared to the deeper horizons with PWP at 0.284, 0.277, 0.307 and 0.314 m^{3}m^{-3} for the AB, Bt$_1$, Bt$_2$, Bt$_3$ horizons, respectively. The soil water content drastically reduced as the suction was increased from field capacity (FC) to -1500 kPa. The Ap horizon had the most gradual curve, possibly because of the high organic matter content. This gave a wide range of crop extractable water between FC and permanent wilting point (PWP). AB and Bt$_1$ had almost same water content at low matric potentials, and the variation was very wide as the curves approached saturation. Bt$_1$ and Bt$_2$ were similar at the low suction range up to -7 kPa at which Bt$_2$ held its water at almost similar matric potential and tended towards Bt$_3$. The Bt$_1$ curve however was gradual. Bt$_3$ had the shortest range of extractable water between FC and PWP, a fact attributable to soil texture. As clay content increased, water was held at high tension and only very little was readily available for crop uptake. However, Bt$_3$ that retained the highest amount of water in the high suction range was equal to AB at -50 kPa. AB continued to lose water gradually as suction increased unlike Bt$_3$. The θ_{PWP} increased with depth a reflection of the high number of micropores as clay content increased leading to high suction. Greater clay content resulted in greater water retention at any given matric potential (Figure 2). The curves obtained were characteristic for the different soil layers as influenced by soil properties such as the pedotranfer functions (texture, organic matter content and bulk density among others) that estimate distinct soil water retention curve (SWRC) data pairs.

The most widely adopted and best-performing PTFs enabled, however, to directly predict the parameters of some closed-form analytical expressions (Cornelis et al., 2001). The SWRC predicts the soil water storage, water supply to the plants (field capacity) and soil aggregate stability. Due to the hysteretic effect of water filling and draining of the pores, different wetting and drying curves may be distinguished. At matric potentials close to zero, the soil was close to saturation, and water was held in the soil primarily by capillary forces. As θ decreased, binding of the water became stronger, and at small potentials (more negative, approaching wilting point) water was strongly bound in the smallest of pores, at contact points between grains and as films bound by adsorptive forces around particles in all horizons. However, the high water content in AP horizon at low suction could be due to the high organic matter present, meaning structure plays a major role in water retention at this point. As suction is increased, the Ap lost most of the water while the lower horizons Bt horizons held more water at wilting point implying that structure was no longer the major player as texture became the more influential factor. The lower horizons Bt$_2$ and Bt$_3$ had 130 and 60 g kg^{-1} more clay compared to the upper Ap and AB horizons, respectively indicating an increase in soil micro-aggregates down the soil profile leading to large number of micro-pores that tend to reduce the hydraulic conductivity (Rengasamy and Murti, 1978). The water holding capacity of any soil is due to the porosity and the nature of the bonding in the soil.

Chakraborty et al. (2010) observed that field capacity moisture content, plant-available water content, and saturated hydraulic conductivity were significantly higher in manure plots and that transmission and storage pores were more abundant in manure-treated plots a fact that was observed in the current study where organic matter content was high (Table1) in topsoil. All these parameters had an effect on the soil water retention curves.

Table 5 shows the saturation (θs) and residual (θr) soil water contents, inverse air entry suction (α) and pore size distribution (n) (van Genuchten soil parameters) for different soil horizons. The resulting soil moisture retention curves showed that the soil horizons were relatively homogeneous. However, there were large differences in the slope of the soil water retention curves; the parameters α and n ranged from 0.019 to 0.277 and 1.412 to 1.922, respectively and were highest in the middle and low at the top and bottom soil horizons. These findings indicate that the pore size distribution was not even especially in the AP and AB horizons where most water was lost between suctions of 1 and 100 kPa. Pore size distribution was more even in the Bt_3 horizon compared to Ap, AB and Bt_1 horizons due to the difference in their structure and texture. The Bt_2 and Bt_3 had higher clay content of 619 g kg^{-1} compared to Ap, AB and Bt_1 with 489, 559 and 569 g kg^{-1}, respectively. Zhang (2005) observed similar findings in the loess plateau of China. Hodnet and Tomasella (2002) observed that for the more clayey textural classes, the value of α was higher for tropical soils, implying more large pores and well structured soils.
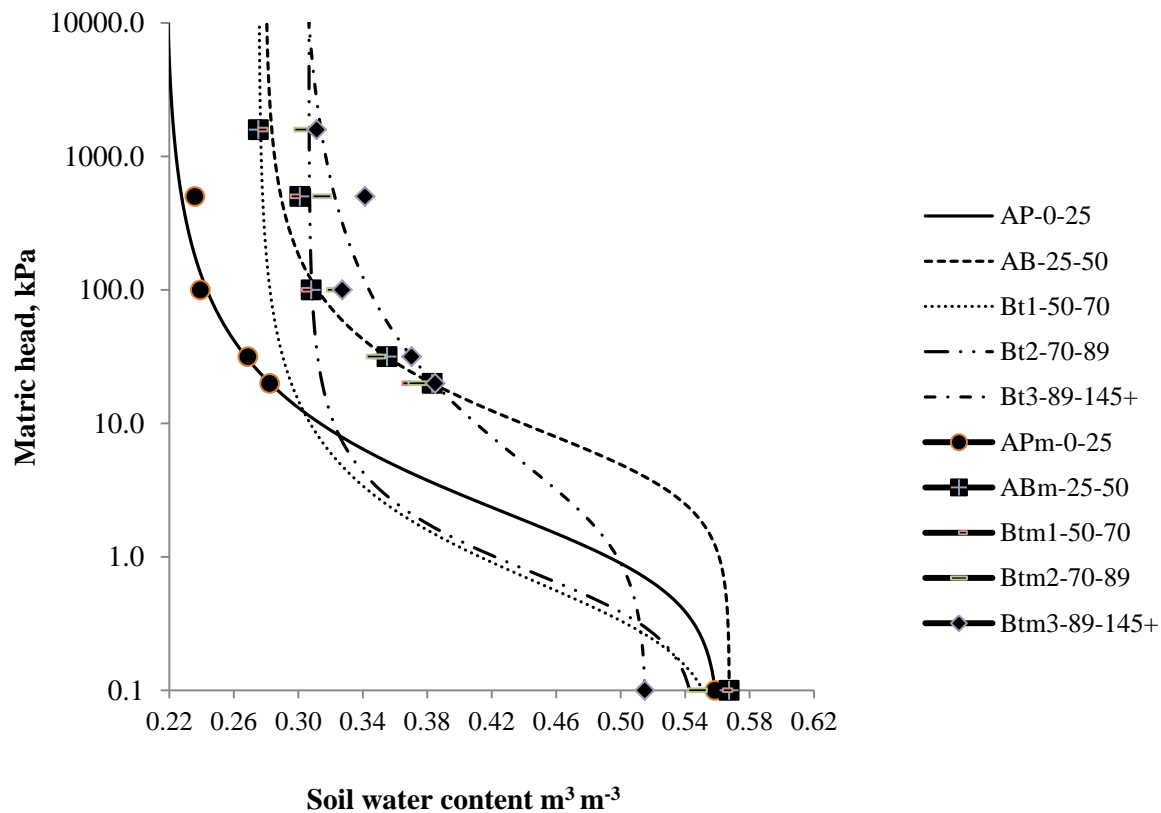

Figure. 2 Soil water retention curves for the study area.
§The measured values are indicated as Apm, ABm, Bt1m, Bt2m and Bt3m in the legend while the other values are fitted using Van Genuchten model.

Table 5. Saturation (θs) and residual (θr) soil water content ($m^3 m^{-3}$), inverse air entry suction (α) (cm^{-1}) and pore size distribution (n) parameters in the study area.

Horizon	Depth (cm)	θs (m^3 m^{-3})	θr (m^3 m^{-3})	α (cm^{-1})	n (-)
Ap	0-26	0.5639	0.21728	0.090	1.574
AB	26-47	0.56745	0.27937	0.019	1.743
Bt_1	47-84	0.56371	0.27549	0.277	1.663
Bt_2	84-115	0.54768	0.30660	0.196	1.922
Bt_3	115-145+	0.51587	0.30005	0.047	1.413

Water content at matric potential of -1500 kPa (which corresponded well in this case to residual water content, θr) was higher in the lower horizons leading to more water retention. All soil horizons had a gradual SWRC but PWP at -15000 kPa was achieved at a lower moisture level in the upper layers giving them higher water content. The lower soil horizons on the other hand (Bt_2 and Bt_3) achieved PWP at higher moisture content values leading to low available water capacities (AWC) as the range defining AWC between PWP and field capacities decreased. This was probably due to the increased clay content down the soil profile that may have increased the number of micropores that in turn held the water tightly at higher matric potentials. The PWP were reached at equally higher moisture contents in the lower horizons. These findings are consistent with expectations, since the amount of water retained at low matric tensions (0-100 kPa) depends on capillarity and pore size distribution, both of which are strongly affected by structure at low suctions. At high suctions (100 - 1500 kPa) water retention is more influenced by soil texture and specific area (Hillel, 2004; Zhang, 2005).

Soil moisture content and the readily available water between -80 to -150 kPa are shown in Table 6. Field capacity was established when drainage attained steady state, i.e. when water content became constant with time at a given depth. The Ap horizon had the lowest water content values of 0.314 $m^3 m^{-3}$ at field capacity compared with 0.439 and 0.410 $m^3 m^{-3}$ of AB and Bt_3 soil horizons, respectively. The AB horizon had the highest moisture at field capacity compared to all the other depths. Bt_3 had the least soil moisture content values of 0.515 at saturation (θs) followed by Bt_2 at 0.548 $m^3 m^{-3}$. Saturation soil moisture content was 0.558 for Ap (15 and 30 cm), 0.567 for AB (30-45 cm) and 0.563 m^3 m^{-3} for Bt_1 (at 45 and 60 cm depths). Using the soil water retention curves (Fig.3), the matric potential at FC was calculated as -10 kPa. The Bt_1 and Bt_2 horizons (45-60, and 75 -90 cm depths, respectively) attained field capacity at -5 kPa and had 0.326, and 0.337 $m^3 m^{-3}$ water, respectively. The matric potential at which field capacity was

attained in different depth is very high compared to the commonly used values in the tropics and subtropics. For the tropics and subtropics, significant evaporation losses in addition to drainage losses can take place during 24 to 48 hour period following wetting and for a medium textured soils, a pF moisture content corresponding to – 0.33bar (-33kpa, - 330cm or pF 2.5) is commonly used, if for some reasons, FC in the field cannot be determined (Hillel, 2004). However, the values are similar to those cited for the United Kingdom of -5kPa (0.05bar) and the Netherlands where they use -10kpa (0-1bar) values for field capacity (Hillel, 2004).

Both the total available water content (TAM) and readily available water (RAM) were highest in AB horizon ranging from 50.55 and 38.3 mm, respectively and this reflected a combination of both the soil texture and structure while high amounts in Bt_1 was as a result of texture. The Ap horizon had 2.84 % OC and this could have led to higher water retention. AB horizon also had high soil organic carbon (an indicator of SOM) of 2.62 % and retained the most water. This could have been as a result of a combination of high SOM and higher clay content of 559 compared to that of AP of 489 g kg^{-1}. Differences in RAM can be attributed mainly to the observed differences in texture and OC. The total available water capacity between FC and PWP in the profile was 79.2 mm m^{-1}. However, the readily available water capacity for crops such as tomatoes at critical stages of growth is between 61.2 and 67.3 mm m^{-1}. These are high value horticultural crops mostly grown in these soils for income generation especially for small holder farmers with limited plots of land. The greater the clay and soil organic matter content, the higher the volume of water retained.

Functional relationship, K (θ)

K(θ) relations are needed in the calculation of drainage fluxes in the soil water balance. Figure 3 shows the values of the coefficients a and b (in the form K(θ) = $a\theta^b$) and corresponding R^2 values in the

hydraulic conductivity relationship. The high R^2 values, above 85%, indicated a high correlation between hydraulic conductivity and soil moisture contents. The Ap (15 and 30 cm), Bt_1 (60 and 75 cm) and Bt_2 (90 cm) had similar R^2 values that were slightly lower compared to AB (45 cm) and Bt_3 (105 and 120 cm depths) suggesting the high TAM in these horizons was probably due to the soil texture and structure. As soil water increased, the hydraulic conductivity increased in a linear relationship and the equations were typical of those obtained by Gardener. Gardner's (1958) equation was fitted to the observed pairs giving the relationship $K(\theta) = a\theta^b$. Siyagi et al. (1983) reported that $K(\theta)$ was highly dependent on soil water content and texture and that a decrease in water and clay content led to its decrease. This phenomenon was observed in this study.

CONCLUSIONS

It can be concluded that field capacity, water, crop available water contents and hydraulic conductivities were high in Ap horizons as a result of high SOM compared to the lower horizons. The Van Genuchten parameters were highest in the mid horizons leading to the conclusion that pore size distribution was not even in the Ap and AB horizons where most water was lost between matric suctions of -1 and -100 kPa.

The field capacity was attained at higher matric potential of -5kPa for Bt_1 and Bt_2. The functional relationship that deals with water redistribution as a result of soil hydraulic properties and evaporative demand of the atmosphere was highly correlated to soil moisture content and texture with R^2 values > 0.85.

Knowledge of soil hydraulic properties is important for describing and predicting movements of water and solutes through soils, which may be related to many agronomic, engineering, and environmental fields of research. As soil profile evolve into a differentiated sequence of horizons, the resulting hydrological changes can be both measured and quantified by relating K_{sat} to textural properties and bulk density. The results are significant for interpretation of changing runoff processes and slope stability. Hydraulic properties of soil may give an indication of the physical disintegration of aggregates as a response to externally imposed disruptive forces of soil or physico-chemical dispersion and swelling of soil clays (intrinsic behaviour). The numerical modelling of soil moisture and related hydraulic properties have practical significance to improve the management of water capture and retention and development of water-saving agriculture.

Table 6. Soil moisture at field capacity (θFC), permanent wilting point (θPWP), matric potential and readily available moisture (RAM).

Depth (cm)	θFC (m^3m^{-3})	FC kPa	θPWP (m^3m^{-3})	S_{PWP}, (mm)	S_{FC}, (mm)	TAM, (mm)	-80 to -150kPa θ_{Cr} (m^3m^{-3})	RAM(mm) (p)
15	0.314	10.0	0.223	33.45	47.10	13.65	0.2469-0.2372	10.1-11.5
30	0.314	10.0	0.223	66.90	94.20	27.30	0.2469-0.2372	20.1-23.0
45	0.439	10.0	0.284	109.50	160.05	50.55	0.3179-03025	38.3-43.5
60	0.326	5.0	0.277	151.05	208.95	57.90	0.2836-0.2806	44.7-50.3
75	0.326	5.0	0.277	192.60	257.85	65.25	0.2836-0.2806	51.0-61.4
90	0.336	5.0	0.307	238.65	308.25	69.60	0.3089-0.3078	55.1-57.1
105	0.410	10.0	0.314	285.75	369.75	84.00	0.3483-0.3363	64.3-72.4
120	0.410	10.0	0.314	332.85	431.25	98.40	0.3483-0.3363	73.6-83.5

θFC field capacity; θPWP permanent wilting point, FC kPa, matric potential at field capacity; S_{FC} cumulative storage at field capacity; s_{pwp} cumulative storage at PWP; TAM, total cumulative available water capacity between FC and PWP; RAM (p) Cumulative fraction of readily available water (between FC and θ_{Cr} for tomato)
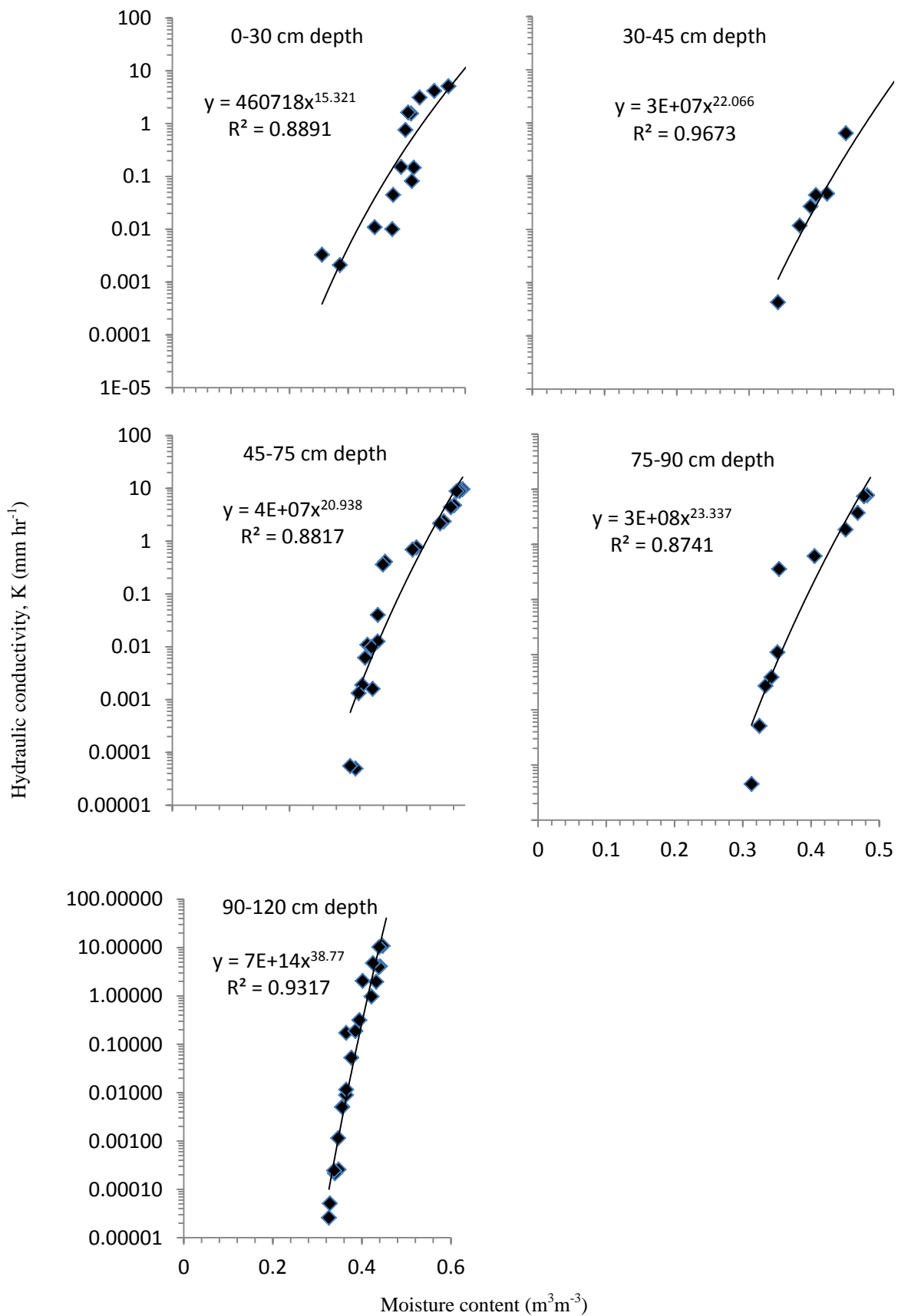
Figure 3. $K(\theta) = a\theta^b$ relationship between hydraulic conductivity and soil water content

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