SOIL HYDRAULIC PROPERTIES OF A CHROMIC LUVISOL IN KATUMANI, KENYA †

[PROPIEDADES HIDRÁULICAS DEL SUELO DE UN LUVISOL CRÓMICO EN KATUMANI, KENIA]

Caleb W. Mbayaki * and George N. Karuku

Department of Land Resource Management and Agricultural Technology, University of Nairobi, P.O. Box 29053-00625, Kangemi, Nairobi-Kenya. Email: *calebwangira@gmail.com.*
**Corresponding author*

SUMMARY

Background: Soil hydraulic parameters in non-saturated conditions are crucial for explaining soil water dynamics in the field. It is therefore necessary to understand the link between soil water potential and hydraulic conductivity in the soil in order to estimate plant available water and hence simulate its movement within the soils. However, measurement of such hydraulic properties in the field and laboratory is somehow difficult, laborious and costly. **Objective**: To determine soil hydraulic properties of Ferro-chromic Luvisols in Katumani using the RETC code based on pedo-transfer functions; % sand, silt, clay and soil bulk density. **Methodology:** Undisturbed soil samples were collected from a profile pit at 0-15, 16-30, 31-45 and 46-60 cm depths using core rings for bulk densities and texture determination. Soil water retention curves and saturated hydraulic conductivities (Ksat) were estimated for all the samples using standard suction apparatus and the constant head method, respectively. The air entry suction (α) and pore size distribution (n) were generated using the RETC code. **Results:** The permanent wilting point and field capacity were at 0.081, 0.102, 0.107 and 0.121 and 0.188, 0.225, 0.241, 0.262 m^3m^{-3} H_2O, whilst its soil water diffusivity ranged from a low of 6.39, 6.94, 9.03 to a high of 12.5 cm^2min^{-1} in the 0-15, 16-30, 31-45 and 46-60 cm depth, respectively. Ksat values from RETC code ranged from 29 - 48 cm day^{-1}, while the total and readily available water within the soil profile were 330.4 and 214.7 mm H_2O, respectively. **Implication:** The air entry value (α) and pore size distribution (n) implied an almost even distribution from the top and subsequent horizons. The soils ‘field capacity was achieved at pF 2.0 whilst PWP was arbitrary indicated at pF 4.2 reducing the time it takes to calculate irrigation cycles based on the amount of water available to the crops. **Conclusion:** The data indicates that pedo-transfer functions; especially high bulk densities negatively impact on soil hydraulics conductivity.
Key words: Pedotransfer functions; RETC code; Van Genuchten parameters; field capacity; permanent wilting point.

RESUMEN

Antecedentes: Los parámetros hidráulicos del suelo en condiciones no saturadas son cruciales para explicar la dinámica del agua del suelo en el campo. Por lo tanto, es necesario comprender el vínculo entre el potencial hídrico del suelo y la conductividad hidráulica en el suelo para estimar el agua disponible para las plantas y, por lo tanto, simular su movimiento dentro de los suelos. Sin embargo, la medición de tales propiedades hidráulicas en el campo y en el laboratorio es algo difícil, laboriosa y costosa. **Objetivo:** Determinar las propiedades hidráulicas del suelo de los luvisoles ferrocrómicos en Katumani utilizando el código RETC basado en las funciones de pedotransferencia de; % arena, limo, arcilla y densidad aparente del suelo. **Metodología:** Se recogieron muestras de suelo no perturbadas de un pozo de perfil a 0-15, 16-30, 31-45 y 46-60 cm de profundidad utilizando anillos de núcleo para determinar las densidades aparentes y la textura. Se estimaron las curvas de retención de agua del suelo y las conductividades hidráulicas saturadas (Ksat) para todas las muestras utilizando un aparato de succión estándar y un método de cabeza constante, respectivamente. La succión de entrada de aire (α) y la distribución del tamaño de poro (n) se generaron utilizando el código RETC. **Resultados:** El punto de marchitez permanente y la capacidad de campo del suelo estuvieron en 0.081, 0.102, 0.107 y 0.121 y 0.188, 0.225, 0.241, 0.262 $m^{-3}m^{-3}$ H_2O, mientras que la difusividad del agua del suelo varió de un mínimo de 6.39, 6.94, 9.03 a un máximo de 12.5 cm^2/min en los 0-15, 16-30, 31-45 y 46-60 cm de profundidad, respectivamente. Los valores de Ksat del código RETC oscilaron entre 29 y 48 cm $día^{-1}$, mientras que el agua total y fácilmente disponible dentro del perfil del suelo fue de 330.4 y 214.7 mm H_2O, respectivamente. **Implicaciones:** El valor de entrada de aire (α) y la distribución del tamaño de poro (n) implicaron

† *Submitted January 15, 2022 – Accepted May 14, 2022.*

ISSN: 1870-0462.

una distribución casi uniforme desde la parte superior y los horizontes subsiguientes. La capacidad de campo de los suelos se alcanzó en pF 2.0 mientras que PWP se indicó arbitrariamente en pF 4.2 reduciendo el tiempo que se tarda en calcular los ciclos de riego en función de la cantidad de agua disponible para los cultivos. **Conclusión:** Los datos indican que las funciones de pedo-transferencia; las densidades aparentes especialmente altas tienen un impacto negativo en la conductividad hidráulica del suelo.
Palabras clave: funciones de pedotransferencia; código RETC; parámetros de Van Genuchten; capacidad de campo; punto de marchitamiento permanente.

INTRODUCTION

Soil is a non-renewable natural resource which supports activities such as soil-plant-water movements and other productivities in land use (Giddens, 2009; Schoonover and Crim, 2015). Ferro-chromic Luvisols are the most prevalent soil types within eastern Kenya, characterized by a base saturation determined by NH_4OAc at pH 7.0 >50 per cent, posing a low to moderate fertility. Luvisols have an argillic horizon due to translocation of clay from the surface to a depth of accumulation, within 100cm from the surface (Miedema *et al*., 1999). Most Luvisols in the arid and semi-arid lands (ASALS) of eastern Kenya, form a strong surface sealing that cause low rates of infiltration paving way for high runoff, hence eroding the topsoil (Muchena and Gachene, 1988). Studies by Karuku and Mochoge (2016) on various forms of nitrogen in luvisols from Katumani indicated the existence of a low amino acid-N (23.1-30.8% of total N) and low organic matter content.

Luvisols are suitable for crop production, though prolonged cultivation without proper management practices tends to change some of its physical properties, leading to compaction, reduced permeability as well as interfering with the soil-plant water continuum (Karuma *et al*., 2014; Kahlon and Khurana, 2017). In most agricultural landscapes, soil compaction is a major challenge hindering crop production; as it negatively impacts on the available soil water, air permeability (pore size), bulk density, porosity and inhibits root penetration and thus the soil-plant water relation (Hakl *et al*., 2007; Nawaz *et al*., 2013).

Water retention characteristics are fundamental in solving problems related to crop water needs and quantifying the response of hydrologic systems to climate change (Vorosmarty *et al*., 1989; Dolph *et al*., 1992). Soil water movements are mainly dependent on pedo-transfer functions of the texture, organic matter content and bulk density (Hillel, 1998; Karuku, 2011; Karuku *et al*., 2012). Hillel (1982) indicated that particle-size distribution affects soil water content at matric soil water potential < 100 kPa, whereas Klute (1986) documented that the influence of soil organic matter on soil water retention characteristics was due to its hydrophilic nature and position in the soil structure, which are important pedo-transfer functions.

Measurement of soil water characteristic curves (SWCCs) has proven to be time consuming and expensive (Benson *et al*., 2014; Peranić *et al*., 2018, Karuku, 2011; Karuku *et al*., 2012). Thus, alternative methods to estimate the SWCC have been sought (Aubertin *et al*., 2003; Chin *et al*., 2010; Anlauf, 2014). Empirical functional relationships based on the particle size distribution and other pedo-transfer functions (PTFs), are the most commonly used methods in estimating the SWCC (Van Genuchten *et al*. 1992). To estimate the soil moisture curve, a variety of mathematical models have been presented (Tyler and Wheat craft, 1992). Generally, the model curve is more successful since one can estimate the sigmoid shape of moisture; as seen in the Van Genuchten model (1980). Retention Curve program (RETC) is a computer program used for analyzing soil water retention and hydraulic conductivity functions of unsaturated soils (Van Genuchten *et al*., 1991) and utilizes the least squares optimization approach to estimate the hydraulic conductivity and unknown model parameters from observed retention data.

Soil and water are two fundamental resources in the agricultural environment. The potential response of soil water properties is a key indicator of the impact of agricultural management on the movement of water and chemicals through the soil. Unfortunately, soil water characteristics are difficult to measure in the field, hence methods are needed to relate easily measured soil physical properties to soil water retention characteristics the use of the RETC code. In Kenya, there is relatively little documentation on soil hydraulic properties as impacted by both physical and chemical aspects of the soils. Henceforth, this will create a novel framework for revitalizing sustainable food production in the arid and semiarid areas of Eastern Kenya.

MATERIALS AND METHODS

Study site description

The study was conducted at the Kenya Agricultural and Livestock Research Organisation, Katumani in Machakos County, Kenya (Figure 1) and lies under agro-ecological zone IV (Jaetzold *et al*., 2006) and at an altitude of 1624m asl. The center is located at latitudes -1.5819° S and longitude 37.2450° E as per the Military Grid Reference System coordinates. The site experiences a bimodal rainfall distribution; with the long rains from March to May and the short rains from November to mid-December. The mean daily maximum and minimum temperatures are 24.7 and 13.7 ºC, respectively with a mean annual rainfall of 450-600 mm (Jaetzold *et al*., 2006). The average wind speed varies from 7-11km hr^{-1}. The predominant soil types are derived from a pre-Cambrian basement system rock mainly composed of quartz felspatic gneiss parent material poor in ferro-magnesiurn minerals, and are classified as Ferro-chromic Luvisol in the FAO- UNESCO System (Mbuvi and Van de Weg, 1975). The soils exhibit a sandy clay loam texture with a saturated hydraulic conductivity ranging from 0.91- 1.98 mhr^{-1} (Gicheru and Ita, 1987; Deckers *et al*., 2010; Mwendia *et al*., 2017). Total available water (TAW) ranges between 10-50 mm m^{-1}. The area is suitable for sweet potato (*Ipomoea batatas L.*), maize (*Zea mays*) Katumani variety, beans (*Phaseolus vulgaris*), pigeon peas (*Cajanus cajan*) and mangoes (*Mangifera indica*).

Data collection

Using core rings, undisturbed soil samples were obtained from different horizon depths of 0-15, 16-30, 31-45, and 46-60 cm in a profile pit dug in the field (Green *et al*., 1986). The samples were used to determine the soil water content (SWC), dry bulk density ($_{\rho}b$), total porosity and total soil water potential. Saturated hydraulic conductivity, Ksat was determined using the constant head method as described by Reynolds and Elrick (2002). Soil water retention was determination with ceramic pressure plates at pF 0.0, 2, 2.5, 3.7 and 4.2 as described by Schofield (1935).

Soil physical properties were determined as follows: soil texture analysis done using the hydrometer method described by Huluka and Miller (2014); the particle size distribution was further classified as sand, silt clay according to USDA. The constant head method was also used in the laboratory to determine Ksat (Ibrahim, 2016).

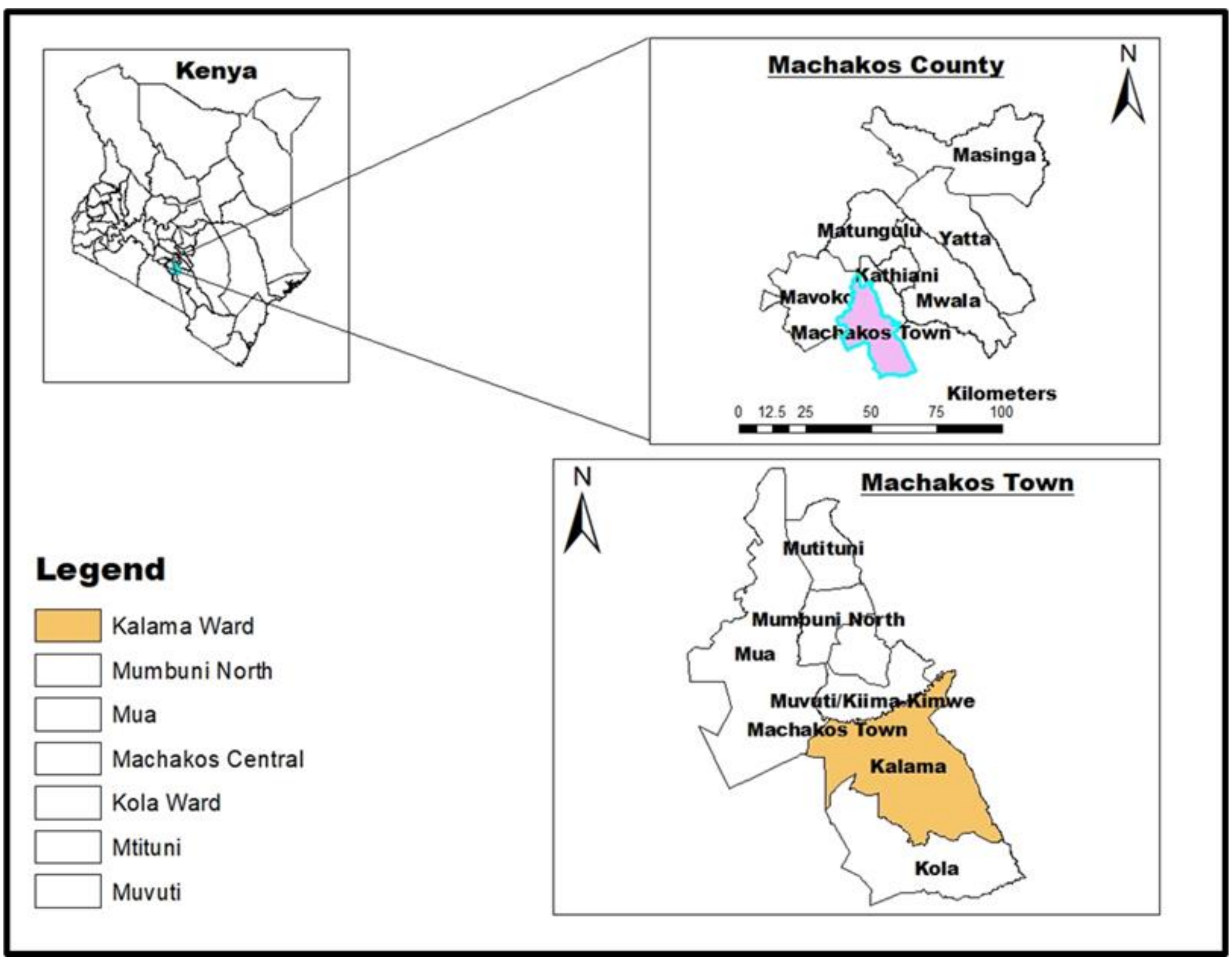

Figure 1. Study Area: Map of Kenya (top left) extract of Machakos county (top right) and Machakos town sub-county insert Kalama ward (below). Source: Generated from ARC-GIS.

Soil water computations

Soil wetness from gravimetric method was computed using the core rings as the ratio of the amount of water in the soil sample to the dry weight of the soil, after drying in an oven at 105 °C for 24 hours Eqn 1, 2 and 3;

$$\% \boldsymbol{GSMC} = \frac{\boldsymbol{Mw - Md}}{\boldsymbol{Md}} \boldsymbol{x}\ \mathbf{100} \qquad (1)$$

Where: Mw = Weight of fresh wet soil Md= weight of oven-dry soil

$$\textbf{Volumetric soil water} = \textbf{Gravimetric soil moisture} \times \textbf{bulk density} \qquad (2)$$

$$\textbf{Water storage in a horizon (mm)} = \frac{\textbf{volumetric soil water} \times \textbf{soil depth}}{\mathbf{10}} \qquad (3)$$

The capacity of soil to retain water and avail it to crops after rainfall was computed as total available water (TAW). It is a measure of the quantity of water a crop extracts from its rooting zone; Eqn 4;

$$\boldsymbol{TAW} = \mathbf{1000}(\boldsymbol{\theta FC} - \mathbf{0.5}\boldsymbol{\theta PWP})\boldsymbol{Zr}(\boldsymbol{mm}) \qquad (4)$$

Where; TAW as the quantity of water in the root zone; **Zr** representing the rooting depth; θ FC; field capacity; θ PWP permanent wilting point (m^3m^{-3}).

Modelling soil water retention using the RETC Code

The retention curve model (RETC) is a computerized program used in determining soil hydraulic conductivities and water retention functions of unsaturated soils characteristic of field conditions (Van Genuchten *et al*., 1991; Wessolek *et al*., 1994). The model can be used in predicting the soil moisture characteristic curve of any given soil given the pedo-transfer functions (PTFs). This model incorporates three predictors PTFs: i) soil textural classes, ii) sand, silt, and clay percentages (SSC) and iii) % Sand, silt, clay and soil bulk density. It uses a non-linear least square analyses to estimate the unknown model parameters from the observed retention and diffusion data by incorporating the van Genuchten model (Schaap and Leij, 2000). The soil water retention curve (SWRC), Mualem–Van Genuchten 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); Karuku (2011) and Karuku *et al*. (2012) was followed. The Van Genuchten (1980) equation (Eqn.5) was fitted on a set of discreet points determined in the laboratory using the Leven Marquardt algorithm (Marquardt, 1963) for fitting the SWRC (Van Genuchten al., 1991) Eqn 5:

$$\boldsymbol{\theta}(\boldsymbol{\psi}) = \boldsymbol{\theta}_{\boldsymbol{r}} + \frac{\boldsymbol{\theta}_{\boldsymbol{s}} - \boldsymbol{\theta}_{\boldsymbol{r}}}{(\mathbf{1}+)(\boldsymbol{\alpha}|\boldsymbol{\varphi}|)^{\boldsymbol{n}})^{\mathbf{1}-\mathbf{1}/\boldsymbol{n}}} \qquad (5)$$

RESULTS AND DISCUSSIONS

Soil physical characteristics

Table 1 show the sites soil physical properties observed throughout the soil profile.

Sand and silt fractions, constitute only the skeletal activity of a soil, while clay fraction performs an additional role in soil water relations (Mojid *et al*., 2009). Consequently, most soil properties, such as the hydro-chemical and electrical properties, are described by the clay fraction of a soil. Bulk density, porosity, hydraulic conductivity and textural classes of a ferro chromic Luvisol in Katumani are listed in Table 1.

The bulk density decreased down the profile as the soils were highly compacted in the upper horizons (0-15 cm) (Table 1). The high bulk density in top layers may have formed due to compaction caused by previous shallow ploughing or which created a hard pan and also due human traffic and raindrop impact. A hard pan is a cemented or compacted and often clayey layer in soil that is impenetrable by roots (Costantini, 2021). Under such conditions, soil pores are compressed from large to intermediate, thereby

Table 1. Soil physical properties of the studied soil.

Depth	*Pb* (g/cm3)	Porosity %	Sand %	Silt %	Clay %	Ksat	Textural class
0-15	1.5301	42.26	68	15	17	21.72	Sandy loam
15-30	1.4689	44.57	64	13	23	54.86	Sandy clay loam
30-45	1.3831	47.81	60	15	25	31.94	Sandy clay loam
45-60	1.3025	50.85	60	11	29	47.47	Sandy clay loam
Average	1.4211	46.37	63	14	24	40	Sandy clay loam

Key: Pb- Bulk density, Ksat- Saturated hydraulic conductivity impeding root penetration, water infiltration, drainage and air exchange, ensuing less plant growth thus lower yields, especially during drought (Karuku *et al*., 2012; Karuku and Mochoge, 2016). The detrimental effects of increased bulk density may be coupled with decreased porosity, and thus altering the soil's water retention and hydraulic conductivity, which in turn affect the infiltration ability of the soil and its plant-available water storage capacity (Zhang *et al*., 2006). Similarly, Mwendwa *et al*. (2020) working on nitisols in Kabete reported a decrease in Ksat values with increased bulk density. The effects of traffic on soil hydraulic properties have been presented by Miller *et al*. (2002) indicating that the soil-water characteristic curves (SWCCs) being more sensitive to changes in compaction than changes in water content when compaction occurred. Similar studies by Zhou *et al*. (2004) identifies soil structure (and aggregation), initial water content, void ratio, type of soil, mineralogy, and compaction method also have potentially significant effects on features of the SWCC. However, the compaction levels in this study did not affect the textural pores, though significantly changed the structural pores, which form the main functional environment for plant roots. Most of the soils within the Kenyan semi-arid areas are mainly formed on gravelly sand materials and some from weathered rock materials derived from limestones and many contain loess (Pye,1995 and 2015; Wright, 2001; Mutuku *et al*., 2021). These may have resulted due to the slow rates of weathering, aggravated by lack of water and hence their clay contents are usually relatively low (Hewitt *et al*., 2021). Bulk densities range from high to very high whereas the total available water capacities range from low to very high, depending on the gravel contents of the soils and the amount of finer interstitial fill (Flint and Flint, 2002; Phalempin *et al*., 2021). However, with irrigation these soils can be used for productive agriculture.

According to the USDA soil texture classification system, the soil at the site was sandy clay loam (Table 1). Nevertheless, the percentage sand decreased as clay increased down the profile through illuviation process. Soil texture influences other soil physical properties such as structure, moisture availability, soil erodibility, root penetration, and fertility, as well as the physico-chemical components of the soil (Karuma *et al*., 2014). Producing crops under sandy soil is a promising solution to address hunger especially in developing countries (Ismail and Ozawa, 2007). However, the major issue associated with such a textural class is water deficiency (DeBano, 1981). In the same way, the upper horizon (0-15cm) of the soil has large interconnected pores and propensity to adjust to the degree of saturation at a rapid rate as values of suction increase, thus having a low available water capacity which affects crop production.

Soil water retention

Figure 2 and 3 presents the soil water characteristic curve for a Chromic Luvisol in Katumani.

The SWCC is critical in agricultural, ecological, and environmental soil research as it emphasizes the hydro-physical link between soil water content and energy state (Cornelis *et al*., 2001). It provides the optimal amount of moisture that can be retained in soil

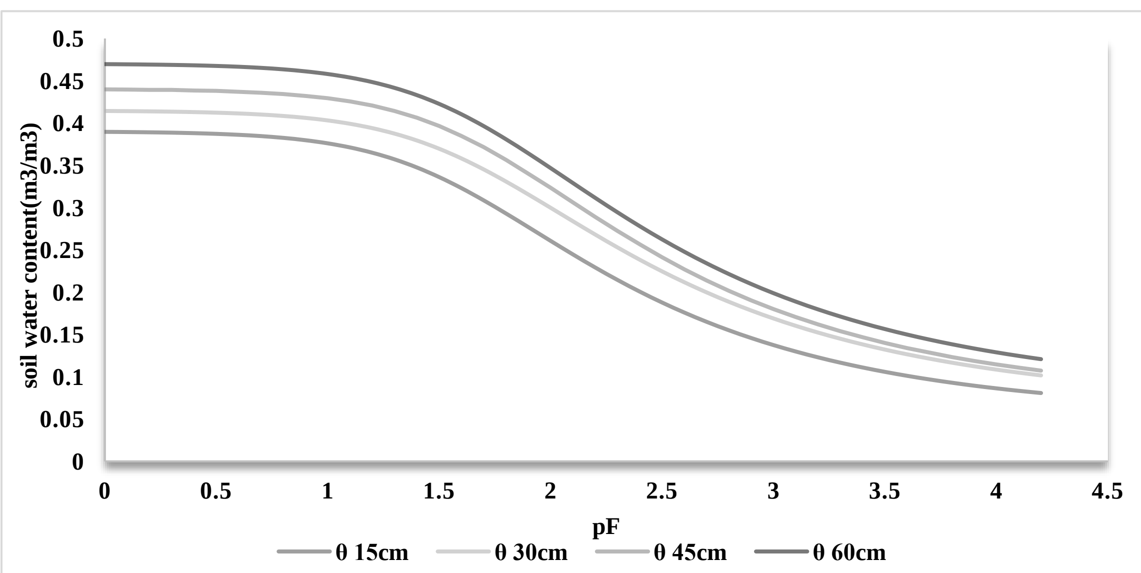

Figure 2. Soil water retention curve for a Chromic Luvisol in Katumani.

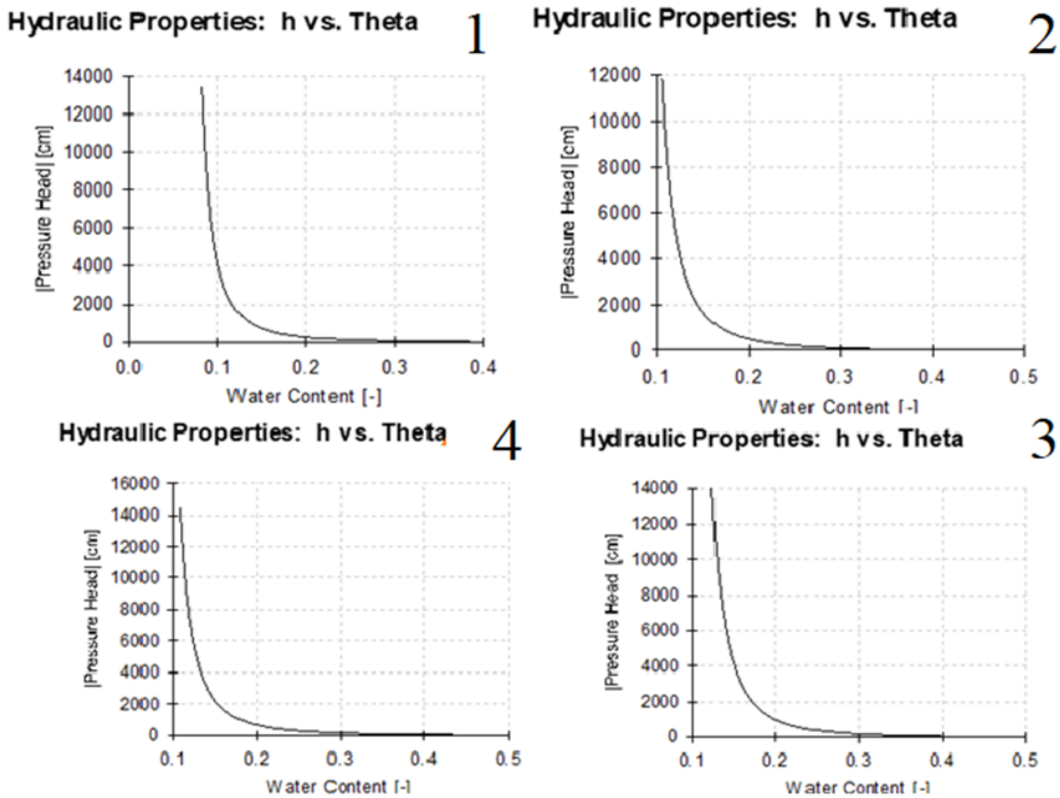

Figure 3. Predicted soil moisture characteristic curves for a chromic Luvisol in Katumani from the RETC model. Key: 1(0-15cm); 2(15-30cm); 3(30-45cm) and 4(45-60cm depth).

and the degree of dryness to which plants can reduce the moisture content through uptake and transpiration process and to avail moisture to plants under a particular matric (Richards and Weaver, 1944). Its slope represents the amount of moisture stored in unsaturated soils, which can be represented as gravimetric water content, volumetric water content potential, or saturation degree (Tian, 2014).

The studied soil attained field capacity (FC) at pF 2.0. Readily available water (RAW) ranged from pF 3.0 and 4.0 (Figure 2). The soil had a greater portion of water release at pF 1.5 (water content near saturation), and decreased as it approached pF 3.0, though some moisture was still retained in the soil pores signifying the dry and wet range of moisture in the soil. In such clay textured soils, the gradual reduction in soil water content with increased matric suction may be attributed to the pore size distribution and adsorptive forces holding the water (Barbour, 1998; Or *et al*., 2002). As the soil dries up, it becomes more difficult for the plant to extract water from it. At FC, plants draw water at maximum rate. As water content drops below FC, plants use draw less of its water, thus acting as an early warning system, and hence facilitating agricultural production. The quantity of soil water accessible for absorption by plants is determined by the difference in soil water content between FC and the PWP. Researchers are therefore able to calculate the necessary irrigation frequency based on the plant's accessible water and the pace at which this water is drained/transpired by crops. Besides irrigation scheduling, this information can be valuable in crop growth modelling and yield prediction as well as construction of sand dams in the study region.

The 0-15 cm depth attained a PWP at lower water contents of 0.081 compared to the deeper horizons with PWP at 0.102, 0.107 and 0.121 m^3m^{-3} for 0-15, 16-30, 31-45 and 46-60 cm depth, respectively (Figure 3). Similarly, the soil water content reduced as the suction increased from FC to a pressure head of approximately 15,000cm. The 0-15cm depth had the narrowest curve among all the depths, probably because of the high bulk density and thus poising low available water extractible by the plant roots (Shang and Li, 2019). On the hand, the 45-60cm depth had the highest water retention and this could be due to the increased clay percentage within the depth (Table 1). It could be further observed that a higher clay content culminated to high water retention at any given matric potential (Figure 4). This distinctive variation in SWCC in different depths may be ascribed to the differences in hydro-physical soil properties such as the bulk density, macro and micro porosity, pore size distribution, water storage, infiltration rate and hydraulic conductivity) (Yeom, 2017; Bahmani, 2019; Shojaee *et al*., 2019).

SWCC's fitting parameters

Table 2 presents the van Genuchten parameters obtained using the RETC water equation model. *a* controls the point of inflection on the SWCC and bears a relation to the air entry value (AEV) of the soil whereas the *n* indicates approximately the pore size distribution of soils and hence controls the rate of desaturation (or absorption) as soon as the air entry is completed. The air entry suction (α) and pore size distribution (n) (van Genuchten soil parameters) for the horizons ranged from 0.0272 to 0.0218 and 1.3896 to 1.4247, respectively, and were higher in the top 0-15cm.

AEV indicates the matric suction from which air begins to enter into the soil's largest voids (Corey, 1977) voids as water empties. In unsaturated soils, the air entry suction mainly influences the seepage and the soil shear strength (Lin *et al*., 2021). The observed air decreased down the profile as presented in Table 2 though uniform. Down the profile, the pores are micro, not macro due to high clay content and these tends to hold more water and less air. An increase in clayey content influenced the soil water holding capacity and consequently soil plant water relations, resulting in an increase in pore size distribution in the lower horizons. On the other hand, the n values in this case were relatively uniform (Table 2), indicating more uniformity in the distribution of pores unlike those of Karuku *et al*. (2012) in Nitisols which has a higher clay percentage than the case of Luvisols. Conversely, these parameters are dependent on the type of soil, size of voids and the depth of ground water table which determines the matric suction governing the difference between Nitisols and Luvisols. In chemically active soils like clay, pore fluid (water) chemistry and mineral composition are influencing parameters as well (Scelsi *et al*., 2021).

The total available water (TAW) increased down the profile ranging from lows of 16 mm to highs of 85 mm reflecting a change in soil texture and structure (Wang and Liu, 2013). The top 0-15cm exhibited a low TAW (16.1 mm) (Table 3), which might be ascribed to the high bulk density caused by compaction, that reduced the large soil pores to intermediate and therefore reducing the available water. Muya *et al*. (2011) reported a TAW of approximately 20-35 mm within the 0–30cm depth of Salic Luvisols in Northern Kenya citing compaction as the major. The observed cumulative TAW within the 0.6m profile depth was 198.2 mm. This is lower since the amount of water needed for major crops grown within the study area are; 488.1 mm sweet potato (Mbayaki and Kinama, 2022), maize, beans and mangoes 696.8 mm. 554.9 mm and 1307.8 mm, respectively (Onyancha *et al*., 2017). As a consequence, this opens up the door to adopting optimal irrigation schedules for sustainable crop production, boosting crop water uptake, and thereby improving the economic use of water in ASALs.

Table 2. Saturated and residual soil water content and air entry suction of the study area.

Depth (cm)	θr ($m^3 m^{-3}$)	θsc($m^3 m^{-3}$)	α (cm^{-1})	n (-)	Ks (cm day^{-1})
0-15	0.0553	0.3902	0.0272	1.4247	31.16
15-30	0.0662	0.4148	0.023	1.3896	28.94
30-45	0.0711	0.4403	0.0208	1.4008	33.98
45-60	0.0791	0.4702	0.0218	1.3826	47.78

Key: θs saturated soil water content m^3m^{-3}; θr residual soil water content m^3m^{-3} and α indicating the inverse of the air entry suction; Ks: saturated hydraulic conductivity.

Table 3. Soil water content at saturation (θs), field capacity (θfc), permanent wilting point (θpwp) and total available water.

Depth	θs (m^3m^{-3})	θfc (m^3m^{-3})	θpwp (m^3m^{-3})	S (mm)	FC (mm)	PWP (mm)	TAW (mm)
15cm	0.390	0.188	0.081	58.44	28.16	12.12	16.05
30cm	0.414	0.225	0.102	124.29	67.38	30.48	36.90
45cm	0.440	0.241	0.107	197.93	108.56	48.26	60.30
60cm	0.470	0.262	0.121	281.79	157.45	72.49	84.96

θs; saturated soil water content, θfc; field capacity; θ PWP permanent wilting point; FC cumulative water storage at field capacity; PWP cumulative storage of water at wilting point; TAW, total available water.

In crop production, the rate of evaporation from the soil is mainly determined by water-transmitting properties of the soil (Rijtema, 1969; Balba, 2018) and also the source of the water per the water table depth, plus the energy-latent heat of evaporation. This implies that; the actual evaporation rate is determined either by external evaporativity or by the soils own ability to deliver water; whichever is less (hence the limiting factor). When the soil water potential at the soil surface is low, the evaporation rate is then driven by external conditions which may be linked to reference evaporativity of the given site. On the other hand, when the soil water potential at the soil surface increases, the evaporation approaches a limiting value regardless of how high external evaporativity may be (Nelson, 2001). Thus, results obtained in the site show low water content within the upper horizon and thus minimal transpirable water available in the soil. This implies that water loss will mainly be driven by crop transpiration and thus affect its production and resultant yield. Hence, such results imply that the evaporation from the soil increases with the increase of the moisture content and the rate of diffusivity.

Soil water diffusivity

Interaction of solid, liquid and air phases within the soil determines the movement of water in unsaturated soils and thus, the saturated hydraulic conductivity value cannot be effectively used to define water flow alone. Flow and solute transport determination under non-saturated conditions is important in order to improve the usage efficiency of water resources and to protect ground water from contamination and depletion. Therefore, the term soil water diffusivity is introduced since all constant parameters such as water potential, permeability, strength etc. of saturated soil become a function in unsaturated soil. Diffusivity in soil is a crucial as it aids in predicting the movement of water and solute within the vadose zone and expressed as a function of its volumetric water content (θ) (Merdun and Quisenberry, 2005; Kassaye *et al.*, 2021).

The predicted rate of diffusivity increased down the profile ranging from a low of 6.39, 6.94, 9.03 to and a high of 12.5 cm^2min^{-1} depth, respectively (Figure 4). It could be noted that the rate of diffusivity among the four depths was lowest in the 0-15cm depth. This could be linked to the high bulk density observed in the studied soil. Soil compaction process increases soil bulk density and decreases total pore space; as a result, water-related soil properties are significantly altered. As the level of compaction increases, the volume of soil macropores decreased to intermediate resulting to variability of air and water permeability. A low soil bulk

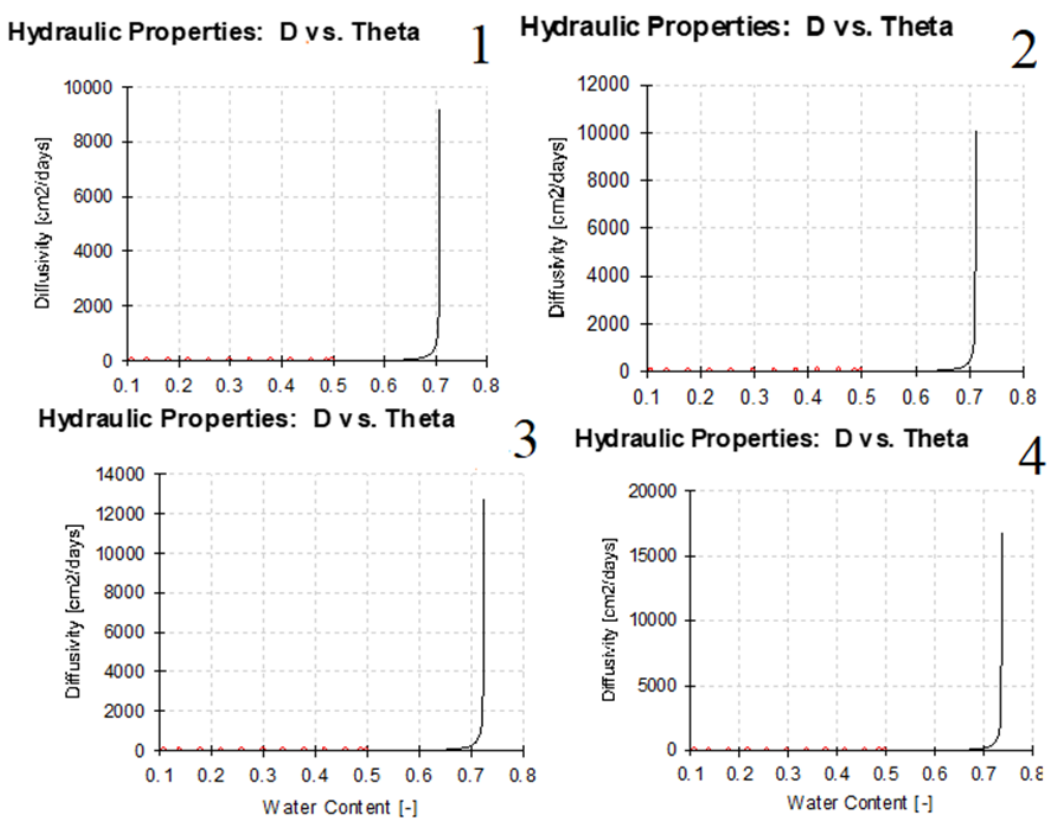

Figure 4. Predicted soil water diffusivity vs relative water content for a chromic Luvisols in Katumani based on the RETC model. Key: 1(0-15cm); 2(15-30cm); 3(30-45cm) and 4(45-60cm depth).

density coupled with a higher clay content are assumed to be positively correlated with soil hydraulic properties and thus results in increased soil porosity in the subsequent depths (Dingman, 2015; Landl *et al*., 2021). Hence, the profile with the highest porosity is usually characterised with a higher soil water diffusivity, and therefore an increase in the diffusivity at a given water content may be attributed to an increase its hydraulic conductivity as observed in Table 1. Henceforth, this study establishes that soil water diffusivity is a function of water content.

CONCLUSION

Soil hydraulic characteristics are significant for defining and forecasting water and electrolyte transport in soils, which are relevant to many agronomic, engineering, and environmental fields of study. Physico hydraulic state of the soil influences the soil plant water relationship, water flow, diffusivity and air permeability. Henceforth, models used to predict soil hydraulic conductivity have space for development in terms of dataset size and soil types, and should thus incorporate quantity of organic carbon and other hydraulic conductivity-controlling characteristics. The findings of this study will aid in predicting water movements in soils for most rainfed and irrigated crop production especially in ASALs.

Acknowledgement
The authors acknowledge University of Nairobi Soil Science Laboratory staff, Mr. J.M. Kimotho and Mr. Ferdinand Anyika and Boniface Muliro from the Biosystem engineering department for their technical support.

Funding statement. This work was fully funded by Mr. and Mrs. Wechuli Mbayaki and family.

Conflict of interest. The authors confirm that there are no known conflicts of interest associated with this publication.

Compliance with ethical standards. No human participants or animals were used in the studies undertaken in this article by any of the authors

Data availability. All the data is present in this paper.

Author contribution (CRediT). Caleb W. Mbayaki – conceptualization, data curation, formal analysis, funding acquisition, methodology, Investigation, Project administration, visualization, resources, software, writing original draft, **George N. Karuku** – Supervision, validation, writing – review & editing.

REFERENCES

Anlauf, R., 2014. Using the EXCEL solver function to estimate the van Genuchten parameters from measured pF/water content values. Retrieved July, 4, p.2017.

Aubertin, M., Mbonimpa, M., Bussière, B. and Chapuis, R.P., 2003. A model to predict the water retention curve from basic geotechnical properties. *Canadian Geotechnical Journal*, 40(6), pp. 1104-1122 https://doi.org/10.1139/t03-054.

Bahmani, O., 2019. Evaluation of the short-term effect of tillage practices on soil hydro-physical properties. *Polish Journal of Soil Science*, *52*(1), p. 43.

Balba, A.M., 2018. Management of problem soils in arid ecosystems. *CRC Press* https://doi.org/10.1201/9780203748411.

Barbour, S.L., 1998. Nineteenth Canadian Geotechnical Colloquium: The soil-water characteristic curve: a historical perspective. *Canadian Geotechnical Journal*, 35(5), pp. 873-894 https://doi.org/10.1139/t98-040.

Benson, C.H., Chiang, I., Chalermyanont, T. and Sawangsuriya, A., 2014. Estimating van Genuchten parameters α and n for clean sands from particle size distribution data. *In From Soil Behavior Fundamentals to Innovations in Geotechnical Engineering:* Honoring Roy E. Olson. pp. 410-427.

Chin, K.B., Leong, E.C. and Rahardjo, H., 2010. A simplified method to estimate the soil-water characteristic curve. Canadian Geotechnical Journal, 47(12), pp. 1382-1400 https://doi.org/10.1139/T10-033.

Cornelis, W.M., Ronsyn, J., Van Meirvenne, M. and Hartmann, R., 2001. Evaluation of pedotransfer functions for predicting the soil moisture retention curve. Soil Science Society of America Journal, 65(3), pp. 638-648 https://doi.org/10.2136/sssaj2001.653638x.

Costantini, E.A., 2021. Considering Cloddiness When Estimating Rooting Capacity and Soil Fertility. *In Biology and Life Sciences Forum*, 3(1), p. 29) https://doi.org/10.3390/IECAG2021-09669.

DeBano, L.F., 1981. Water repellent soils: a state-of-the-art (Vol. 46). US Department of Agriculture, *Forest Service, Pacific Southwest Forest and Range Experiment Station* https://doi.org/10.1111/ejss.13188.

Dingman, S.L., 2015. Physical hydrology. *Waveland press.*

Dolph, J., Marks, D. and King, G.A., 1992. Sensitivity of the regional water balance in the Columbia River Basin to climate variability: *Application of a spatially distributed water balance model. In Watershed management* (pp. 233-265). Springer, New York, NY. https://doi.org/10.1007/978-1-4612-4382-3_8.

Flint, A.L. and Flint, L.E., 2002. 2.2 Particle Density. *Methods of soil analysis: Part 4 physical methods*, 5, pp. 229-240.

Gicheru, P.T. and Ita, B.N., 1987. Detailed soil survey of the Katumani National Dryland Farming Research Station Farms (Machakos District). *Republic of Kenya, Ministry of Agriculture, National Agricultural Laboratories, Kenya Soil Survey.*

Giddens, A., 2009. Politics of climate change.

Green, R.E., Ahuja, L.R. and Chong, S.K., 1986. Hydraulic conductivity, diffusivity, and sorptivity of unsaturated soils: Field methods. *Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods*, *5*, pp. 771-798 https://doi.org/10.2136/sssabookser5.1.2ed.c30.

Hakl, J., Šantrùèek, J., Fuksa, P. and Krajíc, L., 2010. The use of indirect methods for the prediction of lucerne quality in the first cut under the conditions of Central Europe. *Czech Journal of Animal Science*, 55(6), pp. 258-265 https://doi.org/10.17221/86/2009-CJAS.

Han, F.X. and Singer, A., 2007. Arid zone soils: Nature and properties. In *Biogeochemistry of trace elements in arid environments* (pp. 3-44). Springer, Dordrecht https://doi.org/10.1007/978-1-4020-6024-3_1.

Hewitt, A.E., Balks, M.R. and Lowe, D.J., 2021. Semiarid Soils. *In The Soils of Aotearoa New Zealand*, Springer, Cham. pp. 231-247. https://doi.org/10.1007/978-3-030-64763-6_15.

Hillel, D., 1998. Environmental soil physics: Fundamentals, applications, and environmental considerations. *Elsevier*.

Huluka, G. and Miller, R., 2014. Particle size determination by hydrometer method. *Southern Cooperative Series Bulletin*, *419*, pp. 180-184.

Ismail, S.M. and Ozawa, K., 2007. Improvement of crop yield, soil moisture distribution and water use efficiency in sandy soils by clay application. *Applied Clay Science*, 37(1-2), pp. 81-89 https://doi.org/10.1016/j.clay.2006.12.005.

Jaetzold, R., Schmidt, H., Hornetz, B. and Shisanya, C., 2006. Farm management handbook of Kenya Vol. II–Natural Conditions and Farm Management Information–2nd Edition part c; East Kenya Subpart C1 Eastern Province. *Ministry of Agriculture, Nairobi, Kenya*.

Jong, E.D., Acton, D.F. and Stonehouse, H.B., 1990. Estimating the Atterberg limits of southern Saskatchewan soils from texture and carbon contents. *Canadian Journal of Soil Science*, *70*(4), pp. 543-554 https://doi.org/10.4141/cjss90-057.

Kahlon, M.S. and Khurana, K., 2017. Effect of land management practices on physical properties of soil and water productivity in wheat-maize system of North West India. *Applied Ecology and Environmental Research*, 15(4), pp. 1-13 http://dx.doi.org/10.15666/aeer/1504_001013.

Karuku, G.N. and Mochoge, B.O., 2016. Nitrogen forms in three Kenyan soils Nitisols, Luvisols and Ferralsols. *International Journal for Innovation Edcution and Research*, 4(10), pp. 17-30.

Karuku, G.N., 2011. Effects of crop residue management practices on soil moisture conservation and validation of cropwat model for predicting water use requirements for tomato crop in Kabete, Kenya. *Doctoral dissertation, University of Nairobi, Kenya*.

Karuku, G.N., Gachene, C.K.K., Karanja, N., Cornelis, W., Verplancke, H. and Kironchi, G., 2012. Soil hydraulic properties of a Nitisol in Kabete, Kenya. *Tropical and Subtropical Agroecosystems*, 15, pp. 595-609 https://www.revista.ccba.uady.mx/ojs/index.php/TSA/article/view/1024.

Karuma, A., Mtakwa, P., Amuri, N., Gachene, C.K. and Gicheru, P., 2014. Tillage effects on selected soil physical properties in a maize-bean intercropping system in Mwala District, Kenya. *International Scholarly Research Notices*, 2014 http://dx.doi.org/10.1155/2014/497205.

Karuma, A.N., Gachene, K., Charles, K., Msanya, B.M., Mtakwa, P.W., Amuri, N. and Gicheru, P.T., 2014. Soil morphology, physico-chemical properties and classification of typical soils of Mwala District, Kenya http://www.suaire.sua.ac.tz/handle/123456789/750.

Kassaye, K.T., Boulange, J., Saito, H. and Watanabe, H., 2021. Soil water content and soil temperature modeling in a vadose zone of Andosol under temperate monsoon climate. *Geoderma*, 384, p. 114797 https://doi.org/10.1016/j.geoderma.2020.114797.

Lal, R. and Shukla, M.K., 2004. Principles of soil physics. *CRC Press*

Landl, M., Phalempin, M., Schlüter, S., Vetterlein, D., Vanderborght, J., Kroener, E., and Schnepf, A. 2021. Modeling the Impact of Rhizosphere Bulk Density and Mucilage Gradients on Root Water Uptake. *Frontiers in Agronomy*, 3, 6 https://doi.org/10.3389/fagro.2021.622367.

Marquardt, D. W. 1963. An algorithm for least-squares estimation of nonlinear parameters. *Journal of the society for Industrial and Applied Mathematics*, 11(2), 431-441 https://doi.org/10.1137/0111030.

Mbayaki, C.W. and Kinama, J.M., 2022. More Crop Per Drop: The Magic of Sweet Potato (*Ipomoea Batatas L*). *Tropical and Subtropical Agroecosystems*, *25*, p. #018. https://www.revista.ccba.uady.mx/ojs/index.php/TSA/article/view/3834

Merdun, H., and Quisenberry, V. L. 2005. Simulation of water and solute transport with MACRO model in Cecil loamy sand soil. *Soil Research*, 42(8), 939-951 https://doi.org/10.1071/SR03126.

Miedema, R., Koulechova, I. N., and Gerasimova, M. I. 1999. Soil formation in Greyzems in Moscow district: micromorphology, chemistry, clay mineralogy and particle size distribution. *Catena*, 34(3-4), 315-347 https://doi.org/10.1016/S0341-8162(98)00105-2.

Miller, C. J., Yesiller, N., Yaldo, K., and Merayyan, S. 2002. Impact of soil type and compaction conditions on soil water characteristic. *Journal of Geotechnical and Geoenvironmental Engineering*, 128(9), 733-742 https://doi/abs/10.1061/(ASCE)1090-0241(2002)128:9(733).

MM Ibrahim, J.A., 2016. Comparison of Methods for saturated hydraulic conductivity determination: field, laboratory and empirical measurements. *British Journal of Applied Science & Technology*, *15*(3). https://doi:10.9734/BJAST/2016/24413.

Mojid, M. A., Mustafa, S. M. T., and Wyseure, G. C. L., 2009. Growth, yield and water use efficiency of wheat in silt loam-amended loamy sand. *Journal of the Bangladesh Agricultural University*, 7(2), 403-410 https://doi/:10.3329/jbau.v7i2.4753.

Muchena, F. N., and Gachene, C. K. K., 1988. Soils of the highland and mountainous areas of Kenya with special emphasis on agricultural soils. *Mountain Research and Development*, 183-191. https://doi.org/10.2307/3673446.

Mutuku, E. A., Vanlauwe, B., Roobroeck, D., Boeckx, P., and Cornelis, W. M. 2021. Visual soil examination and evaluation in the sub-humid and semi-arid regions of Kenya. *Soil and Tillage Research*, 213, 105135. https://doi.org/10.1016/j.still.2021.105135.

Muya, E. M., Obanyi, S., Ngutu, M., Sijali, I. V., Okoti, M., Maingi, P. M., and Bulle, H. 2011. The physical and chemical characteristics of soils of Northern Kenya Aridlands: Opportunity for sustainable agricultural production. *Journal of Soil Science and Environmental Management*, 2(1), 1-8. https://doi.org/10.5897/JSSEM.9000077

Mwendwa, S. M., Mbuvi, J. P., Kironchi, G., and Gachene, C. K. 2020. A Geopedological Approach to Soil Classification to Characterize Soils of Upper Kabete Campus Field, University of Nairobi, Kenya. *Tropical and Subtropical Agroecosystems*, 23(2).

Nawaz, M. F., Bourrie, G., and Trolard, F. 2013. Soil compaction impact and modelling. A review. *Agronomy for sustainable development*, 33(2), 291-309. https://doi.org/10.1007/s13593-011-0071-8.

Nelson Jr, R. M. (2001). Water relations of forest fuels. In Forest fires (pp. 79-149). *Academic Press*. https://doi.org/10.1016/B978-012386660-8/50006-4.

Onyancha, D.M., Gachene, C.K.K. and Kironchi, G., 2017. FAO-CROPWAT model-based estimation of the crop water requirement of major crops in Mwala, Machakos County. *Research Journal's Journal of Ecology*, *4*(2).

Or, D., Wraith, J. M., and Warrick, A. W. 2002. Soil water content and water potential relationships. *Soil physics companion*, 1, pp. 49-84.

Peranić, J., Arbanas, Ž., Cuomo, S., and Maček, M. 2018. Soil-water characteristic curve of residual soil from a flysch rock mass. *Geofluids*, 2018. https://doi.org/10.1155/2018/6297819.

Phalempin, M., Lippold, E., Vetterlein, D., and Schlüter, S. 2021. Soil texture and structure heterogeneity predominantly governs bulk density gradients around roots. *Vadose Zone Journal*, 20(5), pp. e20147. https://doi.org/10.1002/vzj2.20147.

Pires, L.F., Bacchi, O.O. and Reichardt, K., 2007. Assessment of soil structure repair due to wetting and drying cycles through 2D tomographic image analysis. *Soil and Tillage Research*, *94*(2), pp. 537-545. https://doi.org/10.1016/j.still.2006.10.008.

Pye, K. (1995). The nature, origin and accumulation of loess. *Quaternary Science Reviews*, 14(7-8), 653-667. https://doi.org/10.1016/0277-3791(95)00047-X.

Reynolds, W., Elrick, D., Youngs, E., Amoozegar, A., Booltink, H., and Bouma, J. 2002. 3.4 Saturated and field-saturated water flow parameters. *Methods of soil analysis*, Part, 4, pp. 797-801.

Richards, L. A., and Weaver, L. R. 1944. Moisture retention by some irrigated soils as related to soil moisture tension. *Journal of Agricultural Research*, 69(6), pp. 215-235.

Rijtema, P. E. (1969). Soil moisture forecasting (No. 513). *ICW.*

Scelsi, G., Abed, A. A., Della Vecchia, G., Musso, G., and Sołowski, W. T. 2021. Modelling the behaviour of unsaturated non-active clays in saline environment. *Engineering Geology*, 295, pp. 106441. https://doi.org/10.1016/j.enggeo.2021.106441.

Schaap, M. G., and Leij, F. J. 2000. Improved prediction of unsaturated hydraulic conductivity with the Mualem-van Genuchten model. *Soil Science Society of America Journal*, 64(3), pp. 843-851. https://doi.org/10.2136/sssaj2000.643843x.

Schofield, R. K. 1935. The pF of water in soil. In Trans. of the Third International Congress on Soil Science, 2, *Plenary Session Papers*, 30 July-7 August, 1935 Oxford, UK. pp. 37-48.

Schoonover, J. E., and Crim, J. F. 2015. An introduction to soil concepts and the role of soils in watershed management. *Journal of Contemporary Water Research and Education*, 154(1), pp. 21-47. https://doi.org/10.1111/j.1936-704X.2015.03186.x.

Shang, L. and Li, D., 2019. Comparison of different approaches for estimating soil water characteristic curves from saturation to oven dryness. *Journal of Hydrology*, *577*, p. 123971 https://doi.org/10.1016/j.jhydrol.2019.123971.

Shojaee, A., Khalilimoghaddam, B. and Moradi, F., 2019. Short-Term Effect of Tillage Methods, Residue Levels, and Forward Speeds on Soil-Water Characteristic Curve (SWCC): A Case Study on the Eastern Soils of Karun River, Khuzestan Province, *Iran. Desert*, *24*(2), pp. 307-318. https://dx.doi.org/10.22059/jdesert.2019.76387.

Shwetha, P., and Varija, K. 2015. Soil water retention curve from saturated hydraulic conductivity for sandy loam and loamy sand textured soils. *Aquatic Procedia*, 4, pp. 1142-1149. https://doi.org/10.1016/j.aqpro.2015.02.145.

Thompson, A.M., Paul, A.C. and Balster, N.J., 2008. Physical and hydraulic properties of engineered soil media for bioretention basins. *Transactions of the Asabe*, *51*(2), pp. 499-514. https://doi:10.13031/2013.24391.

Tyler, S.W. and Wheatcraft, S.W., 1992. Fractal scaling of soil particle-size distributions: Analysis and limitations. *Soil Science Society of America Journal*, *56*(2), pp. 362-369. https://doi.org/10.2136/sssaj1992.03615995005600020005x

Van de Weg, R.F. and Mbuvi, J.P., 1975. *Soils of the Kindaruma area (Quarter degree sheet 136)* (No. R1). Ministry of Agriculture, University of Nairobi, Kenya,

Van Genuchten, M. T., Leij, F. J., and Lund, L. J. 1992. Indirect methods for estimating the hydraulic properties of unsaturated soils. Proccedings of the Intenational Workshop on Indirect methods for estimating the hydraulic properties of unsaturated soils. Riverside, CA. https://www.pc-progress.com/Documents/RVGenugten/1992_vG_Leij_Lund_Indirect_methods_UCR.pdf

Van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil science society of America journal*, *44*(5), pp. 892-898. https://doi.org/10.2136/sssaj1980.03615995004400050002x.

Van Genuchten, M.V., Leij, F.J. and Yates, S.R., 1991. The RETC code for quantifying the hydraulic functions of unsaturated soils. Riverside, CA. https://www.pc-progress.com/Documents/programs/retc.pdf

aVörösmarty, C. J., Moore III, B., Grace, A. L., Gildea, M. P., Melillo, J. M., Peterson, B. J., and Steudler, P. A. 1989. Continental scale models of water balance and fluvial transport: An application to South America. *Global* *biogeochemical cycles,* 3(3), pp. 241-265. https://doi.org/10.1029/GB003i003p00241.

Wang, Y. and Liu, Z., 2013. Vertical distribution and influencing factors of soil water content within 21-m profile on the Chinese Loess Plateau. *Geoderma*, *193*, pp. 300-310. https://doi.org/10.1016/j.geoderma.2012.10.011.

Witkowska-Walczak, B. 2003. Hydro-physical characteristics and evaporation of Haplic Luvisol and Mollic Gleysol aggregates. *International Agrophysics*, 17(3), pp. 137-141. http://www.international-agrophysics.org/Hydrophysical-characteristics-and-evaporation-of-Haplic-Luvisol-and-Mollic-Gleysol,106739,0,2.html

Wright, J. 2001. Making loess-sized quartz silt: data from laboratory simulations and implications for sediment transport pathways and the formation of 'desert'loess deposits associated with the Sahara. *Quaternary International*, 76, pp. 7-19. https://doi.org/10.1016/S1040-6182(00)00085-9.

Yeom, S., 2017. Influence of soil characteristics on structural soil crust development. *Drexel University*.

Zhang, H. B., Luo, Y. M., Wong, M. H., Zhao, Q. G., and Zhang, G. L. 2006. Distributions and concentrations of PAHs in Hong Kong soils. *Environmental pollution,* 141(1), pp. 107-114. https://doi.org/10.1016/j.envpol.2005.08.031.

Zhou, J., and Jian-Lin, Y. U. 2005. Influences affecting the soil-water characteristic curve. *Journal of Zhejiang University-Science* A, 6(8), pp. 797-804. https://doi.org/10.1631/jzus.2005.A0797.