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Water Movement and Conductivity Capacity in Unsaturated Conditions of Cultivated Soils

Abdelmonem Mohamed Ahmed AMER[1]
[1]Dept. of Soil Science, Faculty of Agriculture, Menoufia University, 32511Shebin EI-Kom, Egypt

***Corresponding Author**
E-mail:amer_abdel@hotmail.com

Abstract
The aim of this study is to propose equations to estimate water flow in cultivated clay soils. The water movement parameters were represented as unsaturated hydraulic conductivity $K(\theta)$[LT^{-1}], water diffusivity $D(\theta)$ [L^2T^{-1}] and intrinsic permeability, k [L^2] in plant-root zone. Two alluvial clay soils located at northern Nile Delta were used to apply the assumed equations. The soils were planted with cotton yield during 2014 season. The soil profiles were different in their salinity, clay % and source of irrigation water. The equations which assumed to predict soil water movement parameters considered only the matric potential as a driving force in capillary pores, and gravitational potential that is critical for the large, non-capillary pores. An equation for predicting a suggested parameter called conductivity potential or conductivity capacity of soil pores $Kp(\theta)$ [$M L^{-1}T^{-3}$] (erg. cm^{-3}.sec^{-1} or joule. m^{-3} sec^{-1}) was derived in vadose zone. Data of pore size distribution were obtained for the investigated soil profiles using water retention data. The calculated $K(\theta)$, $D(\theta)$ and k values were conformable to the common measured ranges, indicating the applicability of the proposed equations for predicting water movement parameters in cultivated clay soils.

Key words: unsaturated hydraulic conductivity; diffusivity; conductivity potential; soil pore classes; cultivated clay soils.

INTRODUCTION

The unsaturated condition of soil water is a major state in nature after irrigation process or rain fall. The effects of the unsaturated flow of water on minimizing the moisture gradients within the root zone are worthy of further investigation. The drainable and capillary pores are the main factors that affect water movement from a wet point to a dry one depending on moisture gradients. The vertical and lateral flow of water by gravitational forces occur through the large, non-capillary drainable soil pores, while redistribution and upward movement of water occur through capillary soil pores. The ability of pores to conduct water is controlled by soil pore volume, size, shape, type, continuity, and distribution in soil. Baver, et al. (1972) stated that the soil pore sizes could be classified into non-capillary pores, coarse capillary pores and fine capillary pores (FCP). The non-capillary pores represent the volume of the large pores or rapidly drainable pores (RDP), while the coarse capillary pores (CCP) represent the slowly drainable pores (SDP) and water holding pores (WHP). The pressure head that is corresponding to the cutoff between capillary and non-capillary pores could be specified as h=10 kPa (Marshall, 1956; Amer, 2009). Quantifying unsaturated water flow into soil pores requires knowledge of hydraulic conductivity $K(\theta)$ and soil water retention $h(\theta)$ (Dane and Topp, 2002). The techniques for measuring unsaturated hydraulic conductivity in situ are expensive and labor-intensive, and require extensive replication to characterize the spatial variability of $K(\theta)$ in the field. It would be advantageous to estimate unsaturated conductivity function from the retention curve without the need for any further measurements.

The objective of this work was to propose equations to predict unsaturated hydraulic conductivity, $K(\theta)$, intrinsic permeability, k, diffusivity, $D(\theta)$ and conductivity potential (conductivity capacity), $Kp(\theta)$ of capillary and non-capillary pores at different pressure heads of soil. The assumed equations were based on water retention function $h(\theta)$ for agricultural-alluvial clay (saline and non-saline) soils cultivated with cotton yield in the Nile Delta.

***Pore size classes*:**

The relation between equivalent (cylindrical) pore size radius (r) and pressure head (h) in length unit [L] or water potential (ψ) [$M L T^{-2}$] where $\Psi=\rho_w gh$, can be estimated using the capillary equation (Hillel, 1980):

$$h = \frac{2\gamma \cos\alpha}{gr\rho_w} \quad \text{-----------} \ (1a)$$

$$\psi = \frac{2\gamma \cos\alpha}{r} \quad \text{-----------} \ (1b)$$

where, γ is surface tension between water and air (at 20ºC = 0.0727 kg s^{-2}), cos α is assumed to be 1 for the wet surface, g is acceleration due to gravity (9.8 m s^{-2}), and ρ_w is density of water (998 kg m^{-3} at 20ºC). Pore size classes were determined from soil water retention curves (Stakeman, 1996) by applying equation (1). The equivalent pressure (h) ranges of Ψ = 0-10, 10-33, 10-1500, 33-1500, and > 1500 kPa, are roughly corresponding to the diameters of rapid draining pores (*RDP*), slowly draining pores (*SDP*), coarse capillary pores (*CCP*), water holding pores (*WHP*) (or the available water), and fine capillary pores (*FCP*). Pore classes (Fig.1) can be combined into total draining pores (*TDP*= 0-33 kPa) and total water-storage pores (*WSP* > 33 kPa).

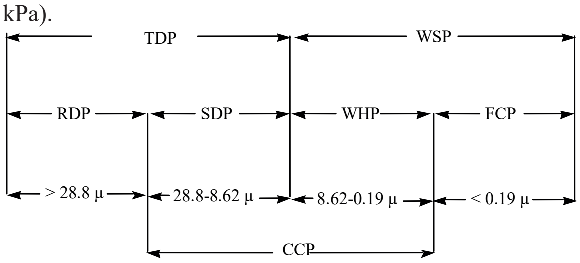

Figure1. Pore size classes and diameters.

Using Eq.1, the cutoff equivalents r for h of Ψ = 10, 33, and 1500 kPa are 14.47, 4.36, and 0.099 μm respectively. The ratio of air to water in soil or drainable pores to capillary pores = $(\theta_{>4.36\mu m}) / (\theta_{<14.47\mu m})$ and the *AWR*, available water ratio = $(\theta_{0.099\text{-}4.36\mu m}) / (\theta_{<14.47\mu m})$.

Hydraulic conductivity as related to pore's radius and water content:

If soil pores are modeled by strait, cylindrical capillary pores, the Poiseuille's equation for water flow (discharge), q [$L^3 T^{-1}$] through one capillary tube could be applied:

$$q = \frac{\pi r^4}{8\eta} . \frac{\Delta\psi}{\Delta L} . \quad \text{-----------} \ (2)$$

or $$q = \frac{\pi \rho_w g r^4}{8\eta} . \frac{\Delta h}{\Delta L} . \quad \text{-----} \ (3)$$

where, $\frac{\Delta\psi}{\Delta L}$ total hydraulic gradient; $\Delta\psi$, pressure forces (dyne.cm^{-2}) acting on distance (ΔL) of moisture range ($\Delta\theta$), and Δh is pressure head in terms [L].

The terms $\frac{\pi r^4}{8\eta}$ or $\frac{\pi \rho_w g r^4}{8\eta}$ represents the hydraulic conductivity through the capillary pores tube as compared with Darcy's law.

For number n of homogeneous pores, the total hydraulic conductivity, $K(\theta)$ into n soil pores varies to the fourth power of pore radius and is inversely proportional to viscosity η (Amer, 2016):

$$K(\theta) = \frac{n \pi \rho_w g r^4}{8\eta} \quad \text{------------} \ (4)$$

where η is water viscosity (0.001 kg m^{-1} s^{-1} at 20ºC). The number (n) of pores can be calculated as:

$$n = \frac{\Delta\theta}{\pi r^2} ,$$

where, $\Delta\theta$ is the volume fraction of pores occupied by water and πr^2 is the cross-sectional area of one equivalent cylindrical pores. Then $K(\theta)$ [L T^{-1}] in Eq.4 becomes:

$$K(\theta) = \frac{\rho_w g r^2 \Delta\theta}{8\eta} . \quad \text{------------} \ (5)$$

$\Delta\theta$ can be expressed as a ratio of soil bulk volume (m^3.m^{-3}) as in Eq.5 (Amer, et al. 2009), or of total volume pores ($\Delta\theta/\theta s$) as in the next equation:

$$K(\theta) = \frac{\rho_w g r^2 \Delta\theta}{8\eta\theta_s} . \quad \text{----------} \ (6)$$

where θ_s is saturated water content.

Water flow is directed from high hydraulic pressure head to low hydraulic pressure head in soil. On the directions of x, y, and z among long tortuous pathways of different pore sizes, the $K(\theta)$ is differ by orders of magnitude due to very small changes in soil porosity and in water potential as well as in saturation degree (θ_i/θ_s). Then K(θ) values for any pore size class will be reduced by about 200 fold (Sudnetcyn, 1979), and then Eq.6 at certain water content θi becomes:

$$K(\theta)_i = \frac{\rho_w g r^2}{8\eta T} \frac{\Delta\theta_i}{\theta_s} \quad \text{---------} \ (7)$$

where T = tortuous pathways factor (T=200) and $\Delta\theta_i$ is soil moisture content at certain pore size class (i).

It was found that in narrow capillaries, the flux is smaller than that which is predicted by Poiseuille's equation for viscous flow (Ravina and Zaslavsky, 1968). So, the Eq.7 should be adjusted by adding a matching factor (= K_s / K_c) or ratio of measured saturated K_S to that calculated (K_c) at $\Delta\theta$ <1 kPa for $r \geq 0.15$ mm, especially for large, non-capillary pores. Thus, $K_c = \sum_{Wa}^{RDP} K(\theta)$,where W_a is an immobile soil adsorbed water capacity.

Then Eq.7 becomes:

$$K(\theta)_i = \frac{K_S}{K_C} \frac{\rho_w g r^2}{8\eta T} \frac{\Delta\theta_i}{\theta_s} \quad \text{---------} \ (8)$$

The pore radius was taken as the largest for the class because the data was cumulated starting at the dry end and the largest radius of the smaller class is the smallest boundary for the next larger class. The K cutoff r was matched with the $\Delta\theta$ class. The larger classes cumulated the $K(\theta)$ from the smaller classes. The <10 kPa class (RDP) was calculated as the mean of the 0.1-10 kPa class.

***Water flow and intrinsic permeability*:**

The contribution of each water filled pore class or moisture range ($\Delta\theta$) between radius r and r +Δr to water flow (or discharge) (q) can be calculated as:

$$q = \frac{\pi \rho_w g r^4}{8\eta} \int_r^{r+\Delta r} f(r) dr . \frac{dh}{dL} \quad \text{--------} \ (9)$$

where, $\int_r^{r+\Delta r} f(r) dr = \Delta\theta$ and $f(r)$ is pore size distribution function with radii between r and ($r + \Delta r$). By applying the function $\int_r^{r+\Delta r} f(r) dr = \Delta\theta$ for pore radii (from r_{Wa} to r_{RDP}) to the Equations 3 and 9, the water flow or discharge rate (q) [L^3T^{-1}] can be calculated at saturation degree $\Delta\theta/\theta_s$ as:

$$q = \frac{\pi r^2 \rho_w g r^2 \sum_{Wa}^{RDP} \frac{\Delta\theta}{\theta_S}}{8\eta T} \frac{\Delta h}{\Delta L} \quad \text{----------- (10)}$$

where, the gradient, $\Delta h / \Delta L$ was set to 1, and the cross-sectional area, πr^2 was for the largest r of the class.

The value of hydraulic conductivity $K(\theta)$ is recognized as it depends on the nature of the medium (k) and the physical properties of the perfuse water ($\rho_w g/\eta$). The term intrinsic permeability, k was proposed for use in a quantitative functio $r^2 \int_r^{r+\Delta r} f(r)dr/8$ sense as the property of a porous medium alone and independent of the water, assuming the water does not alter the porous medium. So, taking $K(\theta) = k.\ \rho_w g/\eta$ in consideration, the intrinsic permeability (k) can be calculated using the following relation:

$$k = \frac{r^2 \sum_{Wa}^{RDP} \frac{\Delta\theta_i}{\theta_S}}{8T} \quad \text{----------- (11)}$$

However, k is related to pore size distribution in soils on a way similar to $K(\theta)$, similar cutoff values and ranges, where the smaller ranges are cumulated.

***Water diffusivity and conductivity potential of soil pores*:**

Under most field conditions, water moves to plant roots predominantly at intermediate water contents usually well below saturation but still above air dryness. Soil water diffusivity, $D(\theta)$ $[L^2T^{-1}]$ can be determined at these intermediate water content using the next derived equations. $D(\theta)$ is defined as the ratio of the hydraulic conductivity $K(\theta)$ to the specific water capacity ($d\theta/dh$) which is considered as the slope of soil moisture retention curve at any particular water content θ:

$D(\theta) = K(\theta)/(d\theta_i/dh)$ or $D(\theta) = K(\theta)\ dh/\ d\theta_i$ --------- (12)

Incorporation Eq.7 to Eq.12, the diffusivity is:

$$D(\theta) = \frac{\rho_w g r^2}{8\eta T} \cdot \frac{\Delta h}{\theta_S} \quad \text{--------- (13)}$$

Combining Eq.7 with the capillary rise equation (1) and at $\alpha = 0$, one obtains:

$$K(\theta)_i = \frac{\gamma\ r}{4\eta T\theta_S}\left(\frac{\Delta\theta_i}{\Delta h}\right) \quad \text{---------- (14)}$$

where $\Delta\theta/\Delta h$ represents inverse the slope of the soil moisture retention curve ($dh/d\theta_i$) at any segment that correspond to pore size class (i).

From Eqs.12 and 13:

$$D(\theta)_i = \frac{\gamma\ r_i}{4\eta T\theta_S} \quad \text{---------- (15)}$$

The state of soil water is often described in energy relations. The hydraulic head pressure is the work to move pure water (Logsdon, 2003). The amount of work that required to moves a unit quantity of soil volumetric water into a pore class per unit time [$erg.cm^{-3}.sec^{-1}$ or joule $m^{-3}\ sec^{-1}$] can be recognized as a conductivity capacity or conductivity potential, $Kp(\theta)$. Multiple the right term in the Eq.14 by $\rho_w g$, the $Kp(\theta)$ can be estimated as:

$$K_P(\theta)_i = \frac{\gamma\rho_w g r}{4\eta T\theta_S} \cdot \frac{\Delta\theta_i}{\Delta h} \quad \text{---------- (16)}$$

MATERIALS AND METHODS

Two soil profiles I and II different in their salinity were used to develop the concepts of the study. The profiles I and II are non-saline and saline heavy clay soils (~60-67% clay) located at El-Hamoul (Kafr El-Sheikh, north of the Nile Delta). The soils under investigation were planted with cotton during 2014 season and irrigated with fresh water which has been taken from Terra canal (Nile river water) and drainage water (from Gharbia drain) respectively. The chemical analysis of irrigation waters was; EC = 0.43-0.56 and 1.57-1.68 dS/m and SAR = 0.91-2.36 and 4.54-5.63 in average for canal and drain waters respectively. Undisturbed soil samples were collected in steel rings and were used to determine bulk density, soil water retention curve, $h(\theta)$ with pressure heads up to 100 kPa, and saturated hydraulic conductivity by falling head method (Klute,1972). For all sites, disturbed samples were air-dried, gently crushed, sieved through a 2mm sieve, and were used to determine the $h(\theta)$ at higher pressure heads, water adsorption capacity (Wa), OM%, $CaCO_3$, salinity (EC), and sodium adsorption ratio (SAR).

Moisture adsorption capacity (Wa) is considered an immobile water content, hence, the Wa was subtracted from $\Delta\theta$ of the >1500 kPa class. Amer, (2009) used the water vapour adsorption isotherm method with applying BET equation to estimate Wa, where Wa is equal to three layers of adsorbed water (films):

$Wa = Wm + 2Wme$ ---------- (17)

where, Wm is the mono-adsorbed layer of water vapor on soil particles, and Wme is the external mono-adsorbed layer of water vapor. Soil samples of I and II profiles were taken at plantation (P) and at harvest (H) of cotton crop. Standard physical and chemical

Table 1. Some physical and chemical properties of the studied soils

Soil profile & Site	Depth cm	pH	EC dS/ m	SAR*	ρb g.cm^{-3}	OM%	$CaCo_3$%	Particle size distribution			K_S cm/h	Wa $m^3.m^{-3}$
								Sand %	Silt %	Clay%		
I. El-Hamoul (non-saline)	0 - 30	7.53	2.72	7.39	1.14	1.53	2.60	15.90	23.87	60.23	0.305	0.1242
	30-60	7.67	3.07	9.50	1.22	0.66	3.06	12.30	24.13	63.57	0.243	0.1359
	60-90	7.54	3.48	10.84	1.15	0.45	0.97	10.34	23.90	65.76	0.224	0.1257
II. El-Hamoul (saline)	0 - 30	7.73	5.35	13.52	1.19	2.23	3.36	16.40	21.18	62.42	0.274	0.1270
	30-60	7.73	8.32	14.92	1.18	0.35	1.60	12.86	20.22	66.92	0.256	0.1424
	60-90	7.67	7.25	15.70	1.20	0.11	1.40	18.55	16.30	65.15	0.249	0.1246

analyses of the soil profiles are presented in Table (1) according to Sparks et al., (1996) and Dane and Topp, (2002). The SAR was calculated as

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{++} + Mg^{++}}{2}}}.$$

The suggested equations, 7, 8, 10, 11, 15 and 16 have been applied to determine K (hydraulic conductivity), Ks/Kc (matching factor), *q* water flow rate, *k* (intrinsic permeability), D (diffusivity) and potential of conductivity, *Kp(θ)* for each soil site.

RESULTS AND DISCUSSION

***Pore size distribution*:**

The most alluvial soils in the Nile Delta have considerable swelling, particularly the area of the studied soil profiles, whereas high clay, swelling and high salinity of the soils contribute to the steeper slope in both wet-end and dry-end of water retention *h(θ)* function (or curves) of the clay soils of northern Nile Delta (Amer, et al. 2009). Data in Tables 2 and3 based on *h(θ)* function, show the capillary and non-capillary pore size classes and distribution in the studied soil profiles. The larger volume of pores corresponding to the pressure heads 0-33 kPa was found in the surface depth (0-30cm) of El-Hamoul soil profiles (I and II), indicating that the water storage pores were the minimum for this depth. The Δθ of *drainable pores TDP / volume pores TVP* ratio, was the maximum in the surface depth of soil profile I, (*TDP*/*TVP*= 0.311). The values of pore volume in the sub-surfaces 30-60 and 60-90 cm of the the profiles were higher in the saline profile II than in the non-saline one. Amer (2001) showed that the values of storage water were different according to the distribution of pore sizes within the soil profile depth. The calculated *AWR* (=WHP/WSP) was larger for the depths of 0 – 30 cm and 60 – 90 cm of soil profile (II) than for the same depths of the profile I. This may due to the influence of salinity in the profile II. Trends with depth were inconsistent among the soils. The overall trends were in agreement with those obtained by El-Sharkawy (1994).

Table2. Pore size distribution as a fraction of total bulk volume for El-Hamoul soil profiles I &II (at planting cotton).

Soil profile & Location	Soil depth (cm)	RDP <10 kPa $m^3\ m^{-3}$	SDP 10-33kPa $m^3\ m^{-3}$	TDP <33kPa $m^3\ m^{-3}$	WHP 33-1500 $m^3\ m^{-3}$	CCP 10-1500 $m^3\ m^{-3}$	FCP >1500 $m^3\ m^{-3}$	TVP $m^3\ m^{-3}$	TDP/ TVP	AWR
I El-Hamoul (non-saline)	0-30	0.0823	0.1215	0.2038	0.2215	0.3430	0.2292	0.6545	0.3114	0.387
	30-60	0.0687	0.0867	0.1554	0.2544	0.3411	0.2510	0.6608	0.2352	0.426
	60-90	0.0517	0.0926	0.1443	0.2886	0.3812	0.2321	0.665	0.217	0.289
II El-Hamoul (saline)	0-30	0.0710	0.1107	0.0821	0.2504	0.3611	0.2344	0.5669	0.1448	0.420
	30-60	0.0687	0.1032	0.1719	0.2411	0.3443	0.2629	0.6759	0.2543	0.397
	60-90	0.0700	0.0969	0.1669	0.2570	0.3539	0.2301	0.654	0.2552	0.440

Table3. Pore size distribution as a fraction of total bulk volume for El-Hamoul cultivated soil profiles (I & II) (at cotton harvest).

Soil profile & Location	Soil depth (cm)	RDP <10 kPa $m^3\ m^{-3}$	SDP 10-33kPa $m^3\ m^{-3}$	TDP <33kPa $m^3\ m^{-3}$	WHP 33-1500 $m^3\ m^{-3}$	CCP 10-1500 $m^3\ m^{-3}$	FCP >1500 $m^3\ m^{-3}$	TVP $m^3\ m^{-3}$	K_S cm/h	W_a $m^3.m^{-3}$
I El-Hamoul (non-saline)	0-30	0.0549	0.1281	0.1830	0.2314	0.3595	0.2398	0.6542	0.420	0.1299
	30-60	0.0689	0.1122	0.1970	0.2587	0.3868	0.2392	0.6949	0.322	0.1296
	60-90	0.0504	0.1000	0.1504	0.2734	0.3734	0.2410	0.6648	0.264	0.1305
II El-Hamoul (saline)	0-30	0.0639	0.1196	0.1835	0.2436	0.3632	0.2248	0.6519	0.336	0.1218
	30-60	0.0483	0.0865	0.1348	0.2399	0.3264	0.2477	0.6224	0.214	0.1342
	60-90	0.0352	0.0953	0.1305	0.2594	0.3547	0.2354	0.6253	0.202	0.1275

Saturated hydraulic conductivity:

Table3 shows that the saturated hydraulic conductivity, K_S was low for the saline clay soil at El-Hamoul (profile II), but variability was likely very high. This is consistent with the results of Khan and Afzal (1989). They showed that *K* was positively correlated with pores of 1 to 33 kPa and was adversely affected by high electrical conductivity and *SAR*. Regarding the impact of cultivation on hydraulic conductivity, Table 3 shows that the values of K_s of subsurface layers (30-60cm) and (60-90cm) decreased at cotton crop harvest in saline profile II, but increased in all depths of non-saline profile I. This behavior may be refers to the leaching fraction which is resulted from the increase of salinity and ESP in subsurface layers of profile II.

Unsaturated hydraulic conductivity and diffusivity:

Data in Table4 shows the values of unsaturated hydraulic conductivity and diffusivity $D(\theta)$ as calculated by the assumed equations 7, 8 and 13 at different soil pore size classes for the surface depths of cultivated clay soil (profiles I). Numerically, $K(\theta)$ and $D(\theta)$ values at WHP, SDP, and RDP classes were higher in the surface soil depth at harvest than at planting for saline soil (profile II). This is due to the salt leaching during irrigation and cultivation practices

Table 4. *K(q)* cm/sec, *k* cm^2, *D(q)* cm^2/sec and *Kp(q)* erg. $cm^{-3}\ sec^{-1}$ for the surface depth (0-30cm) of El-Hamoul soil profile I at cotton planting (P) and at harvest (H).

Pore class	y kPa	P					H				
		q_i%	*k* cm^2	K(q) cm/s	Ks/Kc].K(q) cm/s	D(q)& *Kp (q)*	q_i%	*k* cm^2	K(q) cm/s	Ks/Kc].K(q) cm/s	D(q)& *Kp(q)*
FCP	1500	22.92	$4.16*10^{-17}$	$4.08*10^{-12}$	$5.58*10^{-13}$	$2.11*10^{-12}$ *$4.02*10^{-9}$*	23.98	$4.22*10^{-17}$	$4.13*10^{-12}$	$5.33*10^{-13}$	$2.53*10^{-12}$ *$4.05*10^{-9}$*
	100	40.47	$1.44*10^{-13}$	$1.41*10^{-8}$	$1.92*10^{-9}$	$3.85*10^{-9}$ *$3.66*10^{-7}$*	41.80	$1.64*10^{-13}$	$1.61*10^{-8}$	$2.07*10^{-9}$	$4.32*10^{-9}$ *$3.36*10^{-7}$*
	66	41.86	$1.59*10^{-13}$	$1.56*10^{-8}$	$2.13*10^{-9}$	$1.02*10^{-8}$ *$1.53*10^{-5}$*	43.03	$1.79*10^{-13}$	$1.76*10^{-8}$	$2.27*10^{-9}$	$2.49*10^{-8}$ *$1.89*10^{-6}$*
	50	43.22	$1.80*10^{-13}$	$1.76*10^{-8}$	$2.40*10^{-9}$	$7.46*10^{-8}$ *$1.76*10^{-5}$*	45.92	$2.41*10^{-13}$	$2.36*10^{-8}$	$3.04*10^{-9}$	$1.92*10^{-7}$ *$1.46*10^{-5}$*
WHP	33	45.07	$2.08*10^{-13}$	$2.04*10^{-8}$	$2.78*10^{-9}$	$2.24*10^{-7}$ *$1.99*10^{-5}$*	47.12	$2.70*10^{-13}$	$2.64*10^{-8}$	$3.41*10^{-9}$	$3.11*10^{-7}$ *$2.36*10^{-5}$*
SDP	10	57.22	$1.68*10^{-11}$	$1.65*10^{-6}$	$2.25*10^{-7}$	$4.65*10^{-6}$ *$1.62*10^{-3}$*	59.93	$2.55*10^{-11}$	$2.50*10^{-6}$	$3.23*10^{-7}$	$6.18*10^{-6}$ *$4.69*10^{-4}$*
	5	59.12	$1.97*10^{-11}$	$1.93*10^{-6}$	$2.63*10^{-7}$	$1.24*10^{-5}$ *$1.90*10^{-3}$*	61.96	$3.10*10^{-11}$	$3.04*10^{-6}$	$3.92*10^{-7}$	$1.58*10^{-5}$ *$1.20*10^{-3}$*
RDP	0.1	65.45	$3.17*10^{-10}$	$3.10*10^{-5}$	$4.22*10^{-7}$	$4.96*10^{-5}$ *$3.04*10^{-2}$*	65.42	$4.60*10^{-11}$	$4.50*10^{-6}$	$5.81*10^{-7}$	$3.65*10^{-5}$ *$2.77*10^{-3}$*

As expected the values of $K(\theta)$ remain smaller in capillary pores with gradually increasing from FCP up to RDP by increasing water content. The values were ($1.67x10^{-7}$-$3.76x10^{-12}$), ($2.75x10^{-4}$-$2.04x10^{-8}$), ($1.98x10^{-3}$-$1.72x10^{-6}$), and ($3.76x10^{-3}$-$3.11x10^{-5}$) $cm.min^{-1}$ for FCP, WHP, SDP, and RDP respectively for all the studied soils. Multiplying the values by the matching factor (K_s/K_c) resulted in numerical values a couple orders of magnitude smaller, but the trends were similar (Figure2). The values of water diffusivity $D(\theta)$ were higher than those of $K(\theta)$ for all pore size classes. However, the $D(\theta)$ values decrease much less rapidly than the hydraulic conductivity as soil dries. The calculated values of $K(\theta)$ and $D(\theta)$ seem to be lying in the acceptable ranges of measured $K(\theta)$ and $D(\theta)$ for the clay soils as mentioned by Marshall and Holmes, 1979. However, it is evident that the unsaturated hydraulic conductivity equations can be applied for fine-textured soil and incorporated flow reduction in dry soil due to the absorbed water, as well as enhanced flow through large pores in the wet soil.

Intrinsic permeability and conductivity potential:

Data in Table4 showed that the values of the intrinsic permeability, *k* as calculated by Eq.11 were numerically lower in FCP (dry condition) than in RDP (saturated condition).

At comparison, the *k* values were higher at FCP and WHP in cultivated saline soil (profile II) than non-saline profile I. The intermediate values were similar across the soils. The same trend will be expected for water flow (discharge rate) or flux *q* as it is calculated by Eq.10. Overall, the used equations in calculating *K(θ), D(θ), q*, and *k* had similar results to what would be expected. The data appears useful and applicable for high clay soils that are usually ignored in PTF equations and testing. The conductivity potential or capacity $Kp(\theta)$ may represent the discharge or flux potential, whereas the flux is defined as the volume of water flowing through a unit cross-sectional area per unit time t. The values of $Kp(\theta)$ were calculated by Eq.16 for the surface depth of soil profiles I and II.

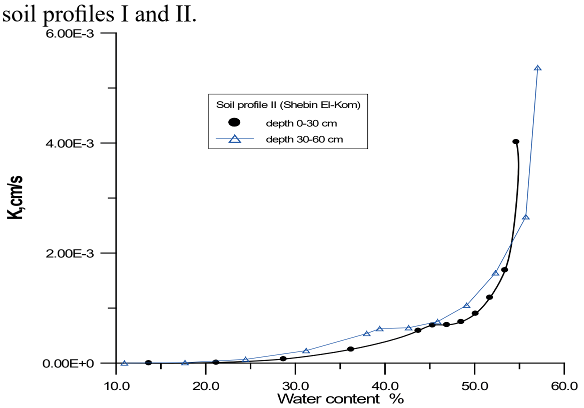

Fig.2. Hydraulic conductivity into capillary and drainable pores of non-saline soil (profile I) as calculated by Eq.7.

The results were found to be ranged from 10^{-9} in dry soil to 10^{-2} erg.cm^{-3}.sec^{-1} in saturated soil. Obviously, an increase in $Kp(\theta)$ occurs with increasing pore sizes, water content and hydraulic conductivity. Whatever, $Kp(\theta)$ values were higher than those for the hydraulic conductivity, diffusivity and intrinsic permeability, indicating the influence of water retention, tortuous pathways and soil pore sizes on water transfer through soil pores in plant root zone.

CONCLUSIONS

Equations were proposed to predict the hydraulic conductivity $K(\theta)$, conductivity potential $Kp(\theta)$ of soil pores in erg.cm^{-3}.sec^{-1}or joul.m^{-3}.sec^{-1} and diffusivity $D(\theta)$ in unsaturated clay soils. The Poiseuille's equation for average velocity of water through capillary tube was the start point for driving the equations. However, the equations were based on water retention function, $h(\theta)$ and on soil pore size, where the data of pore size distribution were obtained for non-cultivated and cotton-cultivated clay soils (saline and non-saline) using water retention $h(\theta)$ data. By applying the assumed equations, the values of $K(\theta)$, $D(\theta)$, $Kp(\theta)$ and intrinsic permeability k were calculated for each pore size class before and after cultivation The reduction of immobile adsorbed water from water flow gives an advantage to apply the assumed equations of $K(\theta)$, $D(\theta)$, $Kp(\theta)$ and k for clay soils which have considerable adsorbed water. The values of hydraulic conductivity and other water movement parameters were influenced by water content (θ) in capillary and non-capillary pore sizes. The predicted values of $K(\theta)$, $D(\theta)$ and k into water-filled pores of the studied soils were in the acceptable ranges of measured values.

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