Misr J. Ag. Eng., 31 (3): 799 - 816 IRRIGATION AND DRAINAGE

HYDRAULIC CONDUCTIVITY AND DIFFUSIVITY AS CALCULATED FOR WATER FILLED PORES IN CULTIVATED CLAY SOILS

**Abdelmonem M. Amer[1], William DeTar[2]
and Amal F. El-Sharkawy[3]**

ABSTRACT:

The aim of this study was to propose equations to estimate unsaturated hydraulic conductivity, $K(\theta)[LT^{-1}]$,, water diffusivity, $D(\theta)$ $[L^2T^{-1}]$, intrinsic permeability, k $[L^2]$ and water flow, ,$q[L^3T^{-1}]$ in plant-root zone. Also an equation for predicting so called potential conductivity of soil water filled pores $Kp(\theta)$ $[M L^{-1}T^{-3}]$ (erg. cm^{-3}.sec^{-1} or joule. m^{-3} sec^{-1}) was derived for each pore size class. Three alluvial clay soils located at middle and northern Nile Delta were used to apply the assumed equations. The first soil was uncultivated and the other two soils were cultivated with cotton yield during 2009 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. 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 agricultural clay soils.

Key words:: hydraulic conductivity;; intrinsic permeability; 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

---

1- Soil Science Dept., Faculty of Agriculture, Menoufia University, 32511Shebin EI-Kom, Egypt. *E-mail:* amer_abdel@hotmail.com
2- 17053 Shafter Avenue, Shafter, CA 93263, USA.
3-Agricultural Engineering Institute, Ministry of Agriculture, Dokki, Giza, Egypt

to a dry one depending on moisture gradients. The vertical downward 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, and Gander. (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 corresponds 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 (or 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 and uncultivated 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 $\Psi=\rho wgh$, can be estimated using the capillary equation (Hillel, 1980):

$$h = \frac{2\gamma \cos\alpha}{g r \rho_w} \qquad (1)$$

$$\text{or } \Psi = \frac{2\gamma \cos\alpha}{r} \qquad (2)$$

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 (9.8m s^{-2}), and ρw is density of water (998 kg m^{-3} at 20ºC). Pore size classes (Fig.1)

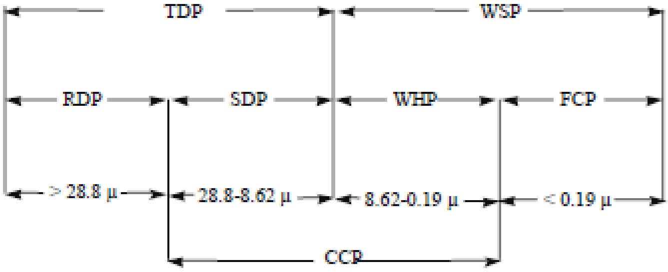

Figure1. Pore size classes and diameters.

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 can be combined into total draining pores (*TDP*= 0-33 kPa) and total water-storage pores (*WSP* > 33 kPa). 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 = $(\theta_{0.099-4.36\mu m}) / (\theta_{<14.47\mu m})$.

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:

$$Q = \frac{\pi r^4}{8\eta} \cdot \frac{\Delta\psi}{\Delta L} \qquad (3)$$

$$Or Q = \frac{\pi \rho_w g r^4}{8\eta} \cdot \frac{\Delta h}{\Delta L} \qquad (4)$$

where ($\Delta\psi$ / ΔL or Δh/ ΔL) is 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 unit [L]. The term ($\pi \rho_w g r$ / 8η) represents the discharge rate per unit time (q) [L^3 T^{-1}] at unit hydraulic gradient through the capillary pores tube .For number n of homogeneous pores, the q into n soil pores varies to the fourth power of pore radius and is inversely proportional to viscosity η:

$$q = \frac{\pi \rho_w g r^4}{8\eta} \qquad (5)$$

where η is water viscosity (0.001 kg m^{-1} s^{-1}at 20ºC).As the number (n) of pores can be calculated as: $n = (\Delta\theta / \pi r^2)$, where, $\Delta\theta$ is the volume fraction of pores occupied by water that can expressed as a ratio of total volume pores ($\Delta\theta/\theta s$), and πr^2 is the cross-sectional area of one equivalent cylindrical pores, then the q represents the total hydraulic conductivity, $K(\theta)$ [L T^{-1}] if compared with Darcy's law as follows (Amer, et al., 2009):

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

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 $K(\theta)$ values for any pore size class will be reduced by about 200 fold (Sudnitsyn, 1979), and then Eq.6 at certain water content θ_i becomes:

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

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 (or at $r \geq 0.15$ mm), especially for large, non-capillary pores.Thus $, K_c = \sum_{Wa}^{RDP} K(\theta)$,where Wa is an immobile soil adsorbed water capacity. Then Eq.7 becomes:

$$K(\theta)_i = \frac{K_s}{K_c}\,\frac{\rho_w g r^2}{8\,\eta\,T}\cdot\frac{\Delta\theta_i}{\theta_s} \qquad (8)$$

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 $r + \Delta r$ 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 rate (or discharge rate) (q) [L^3T^{-1}] can be calculated at a 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 function $r^2 \int_{r}^{r+\Delta r} f(r)dr$ /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:

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

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

***Water diffusivity and potential conductivity 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:

$$D(\theta) = K(\theta)/(d\theta_i/dh) \quad \text{or} \quad D(\theta) = K(\theta)\, dh/\, d\theta_i \text{ --------- } (12)$$

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

$$D(\theta) = \frac{\rho_w g r^2}{8\,\eta\, T} \cdot \frac{\Delta h}{\Theta_s} \qquad (13)$$

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

$$K(\theta)_i = \frac{\gamma\, r}{4\eta T\theta_s} \left(\frac{\Delta\theta_i}{\Delta h} \right) \qquad (14)$$

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 14:

$$D(\theta)_i = \frac{\gamma r_i}{4\eta T\theta_s} \qquad (15)$$

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 potential conductivity, $Kp(\theta)$ or conductivity capacity. Multiple the right term in the Eq.14 by $\rho w\ g$, the $K_p(\theta)_i$ can be estimated as:

$$K_p(\theta)_i = \frac{\gamma\rho_w g r}{4\eta T\theta_s} \cdot \frac{\Delta\theta_i}{\Delta h} \qquad (16)$$

MATERIALS AND METHODS

Three soils profiles different levels in their salinity and clay%, were used to develop the concepts of the study. The profile I is non-saline uncultivated alluvial soil (40-45%clay) located at Shebin El-Kom area (middle of the Nile Delta). The profiles II and III are non-saline and saline heavy clay soils (~60-67% clay) located at El-Hamoul (Kafr El-Sheikh, north of the Nile Delta). Physical and chemical analyses of the soil samples of the three soil profiles were done (Table1) (Sparks., 1996; Dane and Topp, 2002).

The soils II and III were planted with cotton during 2009 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).

Table (1) :Physical and chemical properties of the studied clay soils.

Soil profile&Site	**Depth Cm**	**pH**	**Ec ds/m**	**SAR**	**ρb g.cm^{-3}**	**OM %**	**CaCo3 %**	**Particles size distribution**			**Ks cm/h**	***Wa* m^3,m^{-3}**
								Sand%	**Silt%**	**Clay%**		
I.Sheben El-kom	0-30	7.45	1.90	3.79	1.30	1.19	1.80	23.39	35.28	41.33	1.280	0.1108
	30-60	7.59	1.60	4.73	1.38	0.56	1.55	23.60	34.75	41.65	1.391	0.1137
	60-90	7.60	2.00	9.90	1.35	0.10	0.62	22.14	33.89	43.97	1.204	0.1228
II.El-Hamoul	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
III.El-Hamoul	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

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%, CaCO3, salinity (EC) and sodium adsorption ratio (*SAR*). The SAR was calculated as

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

The 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 it was found that *Wa* is equal to three layers of adsorbed water (films):

$$Wa = Wm + 2Wme \text{ ---------- } (17)$$

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 II and III profiles were taken at planting time (P) and at harvest time (H) of cotton crop.

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

RESULTSAND DISCUSSION

Pore size distribution:

The most alluvial soils in the Nile Delta have considerable swelling, particularly the area of soil profiles II and III, 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 $h(\theta)$ function (or curves such as in fig.2) of the studied clay soils (Amer, et al. 2009). Data in Tables(2) and(3) based on $h(\theta)$ 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 II and III and in the subsurface depth of soil profile I, indicating that the water storage pores were the minimum for these depths. The Δθ ratio of the *drainable pores TDP to the total volume pores TVP*, was the maximum in the surface depth of soil profile II, (*TDP*/*TVP*= 0.311) while the lowest Δθ ratio was found in the surface depth of Shebin soil profile I. The values of pore volume in the sub surfaces 30-60 and 60-90 cm of the three profiles were in the ascending; III> I >II. 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 Shebin soil profile (I) than for El-Hamoul clay soils (II & III). This may due to clay content% and larger volume of water filled capillary pores in Shebin soil (profile I). Trends with depth were inconsistent among the soils. The overall trends were in agreement with those obtained by El-Sharkawy (1994).

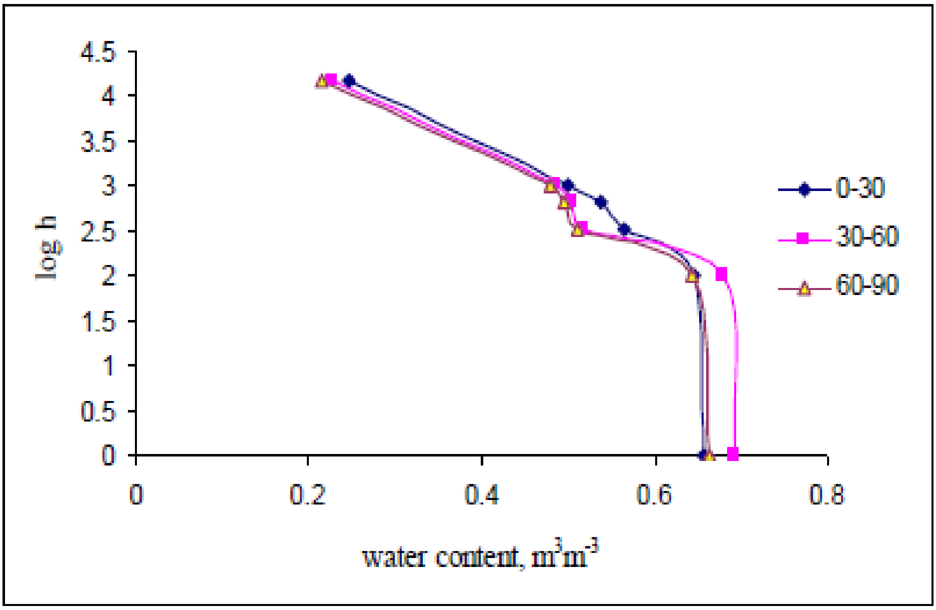

Fig.2. Soil moisture retention curves of Shebin El-Kom clay soil (profile1).

Table (2) : Pore size distribution as fraction of total bulk volume for Shebin soil profile I (non-cultivated) and El-Hamoul soil profile II& III(at planting cotton).

Soil profile & location	Soil depth Cm	RDP <10 kPa $m^3 m^{-3}$	SDP 10-33 kpa m^3m^{-3}	TDP < 33kPa $m^3 m^{-3}$	WHP 33-1500 $m^3 m^{-3}$	CCP 10-1500 $m m^{-3}$	FCP >1500 m^3m^{-3}	TVP m^3m^{-3}	TDP/ TVP	AWR
I.Sheben El-kom	0-30	0.0125	0.0810	0.0935	0.3168	0.3978	0.2474	0.6577	0.1421	0.491
	30-60	0.0133	0.1630	0.1763	0.2890	0.4520	0.2278	0.6931	0.2540	0.425
	60-90	0.0200	0.1328	0.1528	0.2954	0.4282	0.2146	0.6628	0.2305	0.459
II.El-Hamoul	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	0.6650	0.2170	0.289
III.El-Hamoul	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	0.6540	0.2552	0.440

Table (3) : Pore size distribution as a fraction of total bulk volume for El-Hamoul Cultivated soil profiles (II& III)(at cotton harvest).

Soil profile& Location	Soil depth Cm	RDP <10kpa $m^3 m^{-3}$	SDP 10-33 kPa $m^3 m^{-3}$	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 $m^3 m^{-3}$	Ks cm/h	Wa $m^3 m^{-3}$
II.El-Hamoul	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
III.El-Hamoul	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:*

Table (1) shows the saturated hydraulic conductivity, K_s values at cotton planting. The values were low particularly for the subsurface depths of clay soil at El-Hamoul (profiles II and III). This is consistent with the results of Khan and Afzal (1989). They showed that K_s was

positively correlated with pores sizes 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 time in saline soil profile III, but increased in all depths of non-saline profile II. This behaviour may be refers to the leaching fraction which is resulted from the increase of salinity, SAR and ESP in subsurface layers of profile III.

Unsaturated hydraulic conductivity and diffusivity:

Data in Tables (4) and (5) show the values of unsaturated hydraulic conductivity $K(\theta)$ and diffusivity $D(\theta)$ calculated by the assumed equations 7, 8 and 13. The calculations for different soil pore size classes and moisture retentions of the surface depths of cultivated non-saline and saline clay soils (profiles II and III), showed that the $K(\theta)$ and $D(\theta)$ values for WHP, SDP, and RDP classes were higher in the surface soil depth at harvest than at planting, in particular for saline soil (profile III). This is due to the salt leaching during irrigation and cultivation practices. On the other hand, the $K(\theta)$ values were higher in the subsurface depth (0-30 cm) of Shebin soil (profile I) for all pore size classes. Fig. 3 shows the relationship between $K(\theta)$ and water content (θ%) in surface and subsurface depths of soil profile I (Shebin El-Kom)

whereas, $K(\theta)$ values among the negative hydraulic head pressure were higher than that in the other two profiles due to the relatively low salinity and clay content. A high increase in $K(\theta)$ with moisture ranges ($\Delta\theta$) of SDP and RDP classes in uncultivated Shebin soil (profile I) was

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

Pore class	**Ψ kPa**	**P**						**H**					
		θ %	**K cm ^{2}**	**K(θ) cm/s**	**K(θ)* (Ks/Kc) *cm* /s**	**D(θ) *cm ^{2}/s***	**Kp erg. cm $^{-3}$ .s $^{-1}$**	**θ %**	**K cm ^{2}**	**K(θ) cm/s**	**K(θ)* (Ks/Kc) cm/s**	**D(θ) *cm ^{2}/s***	**Kp erg. cm $^{-3}$ .s $^{-1}$**
FC P	1500	22.92	4.16x 10^{-17}	4.08x 10^{-12}	5.58x 10^{-13}	2.11x 10^{-12}	4.02x 10^{-9}	23.98	4.22x 10^{-17}	4.13x 10^{-12}	5.33x 10^{-13}	2.53x 10^{-12}	4.05x 10^{-9}
	100	40.47	1.44x 10^{-13}	1.41x 10^{-8}	1.92x 10^{-9}	3.85x 10^{-9}	3.66x 10^{-7}	41.80	1.64x 10^{-13}	1.61x 10^{-8}	2.07x 10^{-9}	4.32x 10^{-9}	3.36x 10^{-7}
	66	41.86	1.59x 10^{-13}	1.56x 10^{-8}	2.13x 10^{-9}	1.02x 10^{-8}	1.53x 10^{-5}	43.03	1.79x 10^{-13}	1.76x 10^{-8}	2.27x 10^{-9}	2.49x 10^{-8}	1.89x 10^{-6}
	50	43.22	1.80x 10^{-13}	1.76x 10^{-8}	2.40x 10^{-9}	7.46x 10^{-8}	1.76x 10^{-5}	45.92	2.41x 10^{-13}	2.36x 10^{-8}	3.04x 10^{-9}	1.92x 10^{-7}	1.46x 10^{-5}
WH P	33	45.07	2.08x 10^{-13}	2.04x 10^{-8}	2.78x 10^{-9}	2.24x 10^{-7}	1.99x 10^{-5}	47.12	2,70x 10^{-13}	2.64x 10^{-8}	3.41 x 10^{-9}	3.11 x 10^{-7}	2.36 x 10^{-5}
SD P	10	57.22	1.68x 10^{-11}	1.65x 10^{-6}	2.25x 10^{-7}	4.65x 10^{-6}	1.99x 10^{-5}	59.93	2.55x 10^{-11}	2.50x 10^{-6}	3.23x 10^{-7}	6.18x 10^{-6}	4.69x 10^{-4}
	5	59.12	1.97x 10^{-11}	1.93x 10^{-6}	2.63x 10^{-7}	1.24x 10^{-5}	1.90x 10^{-3}	61.96	3.10x 10^{-11}	3.04x 10^{-6}	3.92x 10^{-7}	1.58x 10^{-5}	1.20x 10^{-3}
RDP	0.1	65.45	3.17x 10^{-10}	3.10x 10^{-5}	4.22x 10^{-7}	4.96x 10^{-5}	3.04x 10^{-2}	65.42	4.60x 10^{-11}	4.50x 10^{-6}	5.81x 10^{-7}	3.65x 10^{-5}	2.77x 10^{-3}

Table(5): K(θ) cm/sec, k cm ^{2} D(θ) cm ^{2} /sec and Kp(θ) erg cm $^{-3}$ sec $^{-1}$ for the surface depth (0- 30) of El-Hamoul soil profile III at cotton planting (P) and a harvest(H) .

Pore class	*Ψ* kPa	*P*						*H*					
		θ %	*K* *cm* ^{2}	*K(θ)* *cm/s*	*K(θ)** *Ks/Kc* *cm/s*	*D(θ)* *cm* ^{2} */s*	**Kp erg. cm $^{-3}$ .s $^{-1}$**	*θ %*	*K* *cm* ^{2}	*K(θ)* *cm/s*	*K(θ** *Ks/Kc* *cm/s*	*D(θ)* *cm* ^{2} */s*	**Kp erg. cm $^{-3}$ .s $^{-1}$**
FCP	1500	23.44	4.33x 10^{-17}	4.25x 10^{-12}	3.31x 10^{-13}	2.18x 10^{-12}	4.17x 10^{-8}	22.48	3.84x 10^{-18}	3.76x 10^{-12}	3.69x 10^{-13}	1.97x 10^{-12}	3.68x 10^{-9}
	100	44.07	2.40x 10^{-13}	2.36x 10^{-8}	1.84x 10^{-9}	2.12x 10^{-8}	2.32x 10^{-7}	41.72	1.93x 10^{-13}	1.90x 10^{-8}	1.86x 10^{-9}	4.68x 10^{-9}	1.86x 10^{-7}
	66	45.59	2.69x 10^{-13}	2.64x 10^{-8}	2.06x 10^{-9}	3.42x 10^{-8}	2.59x 10^{-5}	42.74	2.09x 10^{-13}	2.05x 10^{-8}	2.01x 10^{-9}	2.16x 10^{-8}	2.01x 10^{-5}
	50	46.77	2.94x 10^{-13}	2.89x 10^{-8}	2.25x 10^{-9}	1.02x 10^{-7}	2.86x 10^{-5}	43.82	2.28x 10^{-13}	2.24x 10^{-8}	2.19x 10^{-9}	7.65x 10^{-8}	2.19x 10^{-5}
WHP	33	48.48	3.48x 10^{-13}	3.41x 10^{-8}	2.66x 10^{-9}	2.67x 10^{-7}	3.33x 10^{-5}	46.84	3.41x 10^{-13}	3.34x 10^{-8}	3.27x 10^{-9}	3.52x 10^{-7}	3.27x 10^{-5}
SDP	10	59.55	1.76x 10^{-11}	1.73x 10^{-6}	1.35x 10^{-7}	4.94x 10^{-6}	1.69x 10^{-3}	58.80	2.15x 10^{-11}	2.11x 10^{-6}	2.07x 10^{-7}	5.64x 10^{-6}	2.06x 10^{-3}
	5	61.22	2.08x 10^{-11}	2.04x 10^{-6}	1.59x 10^{-7}	1.21x 10^{-5}	1.99x 10^{-3}	60.68	2.49x 10^{-11}	2.54x 10^{-6}	2.49x 10^{-7}	1.41x 10^{-5}	2.49x 10^{-3}
RDP	0.1	66.65	4.98x 10^{-11}	4.88x 10^{-6}	3.81x 10^{-7}	4.37x 10^{-5}	4.79x 10^{-3}	65.19	4.83x 10^{-10}	4.74x 10^{-5}	4.64x 10^{-7}	4.08x 10^{-5}	4.65x 10^{-2}

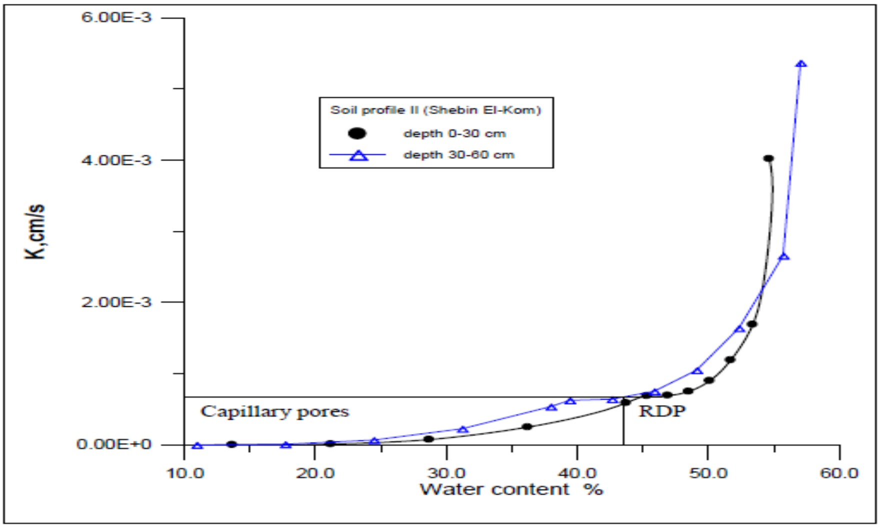

Figure3. $K(\theta)$ curves as calculated for Shebin El-Kom clay soil (profile I).

observed. As expected the values of $K(\theta)$ remain smaller in capillary pores and gradually increased with gradually increasing from FCP up to RDP by increasing water content. The values were ($1.67\text{x}10^{-7}$-$3.76\text{x}10^{-12}$), ($2.75\text{x}10^{-4}$-$2.04\text{x}10^{-8}$), ($1.98\text{x}10^{-3}$-$1.72\text{x}10^{-6}$), and($3.76\text{x}10^{-3}$-$3.11\text{x}10^{-5}$) 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. The values of water diffusivity $D(\theta)$ were higher than those of $K(\theta)$ for all pore size classes. However, the D(θ) 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).

Also, Amer, et al (2009) compared the calculated $K(\theta)$ using Eq.6 in the form $K(\theta)=\frac{K_S}{K_C}\frac{\rho_w g r^2 \Delta\theta}{8\eta}$ with experimental measured $K(\theta)$ for six silt loam soils and showed that the RMSE was 1.04 for log-transformed h and was reduced to 0.65 if the wet end pointed were omitted. However, it is evident that the modified equations (7 & 8) of the unsaturated hydraulic conductivity can be applied for fine textured soil and incorporated flow reduction in dry soil due to absorbed water, as well as enhanced flow through large pores in the wet soil.

***Intrinsic permeability and potential hydraulic conductivity*:**

Data in Tables(4) and(5) 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). On the other hand, the *k* values for FCP and WHP in cultivated saline soil (profile III) were higher than those for non-saline profile II. The intermediate values were similar across the soils. The same trend is 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 potential hydraulic conductivity *Kp*(θ) may represents the capacity of soil pores to transfer of water content. Thus *Kp*(θ) is defined as an energy required to move the discharge unit through a unit cross-sectional area per unit time (t). The values of *Kp*(θ) were calculated by Eq.16 (Tables 4 & 5) for the surface depth of soil profiles II and III. The results 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*(θ) occurs with increasing pore sizes, water content and hydraulic conductivity. Numerically, *Kp*(θ) 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*(θ), potential conductivity *Kp*(θ) of soil pores in $erg.cm^{-3}.sec^{-1}$or $joul.m^{-3}.sec^{-1}$ and diffusivity *D*(θ) 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*(θ) 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*(θ) data. By applying the assumed equations, the values of *K*(θ), *D*(θ), *Kp*(θ) 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.

REFERENCES:

Amer A.M.,(2001). Drainable and water-filled pores as related to water storage and conductivity in agricultural soils of the Nile Delta. Proc.28thSILCongress,4-10.February,ManashUniv Melbourne, Australia.-Verh. Internat. Verein. Limnol. 2002: 28(4), p.1912-1919, Stuttgart, Germany.

Amer A.M., (2009) .Moisture adsorption capacity and surface area as deduced from vapour pressure isotherms in relation to hygroscopic water of soils. Biologia 64 (3), 516-521.

Amer A.M., Logsdon S.D.and Davis D.,(2009). Prediction of hydraulic conductivity in unsaturated soils. Soil Sci., 174 (9), 508- 515.

Amer A.M.,(2012) .Water flow and conductivity into capillary and non-capillary pores o soils. Soil Sci. and Plant Nutrition, 12(1) 99-112.

Baver L.D.and Gardner W.R.,(1972). Soil physics. 4th ed. John Wiley & Sons, New York,498pp.

Dane, J.H., Topp G.C. (Eds.),(2002) .Methods of soil analysis, Part 4 Physical methods. SSSA, Madison, WI. 1692 pp.

El-Sharkawy A.F.,(1994) .Study of water imbibition in soil agricultural soils. M.Sc. Thesis, Faculty of Agriculture, Menoufia University, Shebin El-Kom, Egypt.

Hillel D., (1980). Fundamentals of soil physics. Academic Press, New York. 413 pp.

Khan G.S.and Afzal T.,(1989). Hydrualic characteristics of some important soil series of Pakistan. pp. 222-237. -Ahmed M. (Ed.) Soil physics in stress environments. Proceed. .Inter. Symp. on Soil Physics in Stress Environments, 22-26th January, Islamabad Pakistan.

Klute A.(1972). The determination of hydraulic conductivity and diffusivity of unsaturated soil. Soil Sci. 113 (4), 264-276.

Logsdon S.D.(2003). Soil water energy concepts. Encyclopedia Water Science, Marce Dekker, Inc. NY.

Marshall T.J.(1956). Relation between water and soil. Technical Communication No.50,Commonwealth Bureau of Soils, Farenham . Royal, Bucks, England.

Marshall T. J., Holmes J.W.(1979). Soil physicsCambridge Univ. Press. London.

Ravina I. and Zaslavsky D.,(1968). Non-linear electro-kinetiphenomena I: review of literature. Soil Sci., 106 (1), 60-66.

Sudnitsyn E.E.(1979). Soil water movement and wate r requirements of crops. Moscow Univ. Ezdat, Moscow.

Sparks D.L.(Ed.),(1996). Methods of soil analysis, Part 3,Chemical methods. ASA, SSSA, Madison, WI.

Stakeman W.P.(1966). Determination of pore size by the air Bubbly pressure method .Proceedings of UNESCO Symposium on Water in the Unsaturated Zone:366-372.

الملخص العربى

حساب التوصيل الهيدروليكى والانتشارية للمسام المملوه بالماء فى الاراضى الطينية المزروعة

١- عبد المنعم محمدعامر ٢- وليم ديتر ٣ – أمال فتوح الشرقاوى

تهدف هذه الدراسة الى استنتاج معادلات للتوصيل الهيدروليكى الغير مشبع($K(\theta)$, (LT^{-1} وانتشارية المياه (L^2T^{-1}) $D(\theta)$ والنفاذية $K(L^2)$ وتدفق المياه ($q(L^3T^{-1}$ فى منطقة جذور النبات .كما تم اشتقاق معادله للتنبؤ بالتوصيل الهيدروليكى المحتمل للتربة لكى تملأ كل المسام بالماء لتحقيق هذا الهدف تم تطبيق هذه المعادلات فى ثلاث قطاعات من التربة الطينية فى وسط وشمال الدلتا .وهذه القطاعات تختلف فى درجة الملوحة ,ونسبة الطين , ومصدر مياه الرى .

والقطاع الاول (وسط الدلتا) غير مزروع, أما القطاعان الاخران (فى شمال الدلتا) فتم دراستها بعد زراعة محصول القطن موسم ٢٠٠٩ . وأعتبرت المعادلات المفروضة فى هذا البحث للتنبؤ بعوامل حركة الماء الارضى أن الجهد الشعرى هو القوة الدافعة فى المسام الشعرية فقط ,وجهد الجاذبية الارضية و هو القوة الدافعة فى المسام كبيرة الحجم والمسام الغير شعرية . أظهرت النتائج تطابق قيم التوصيل الهيدروليكى الغير مشبع $K(\theta)$ والانشاريه($D(\theta$ والنفادية k المحسوبة والفعلية. وبناء على دلك فأن هذه المعادلات يمكن تطبيقها للتنبؤ بمتغيرات حركة المياه فى التربة الطينية .

١- استاذ بكلية الزراعة جامعة المنوفية ٢- الولايات التحدة الامريكية ٣- معهد الهندسة الزراعية