EFFECT OF EVAPORATION AND ROOT WATER UPTAKE ON THE DESIGN OF SUBSURFACE DRAINAGE SYSTEMS IN ARID REGIONS[1]

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ABSTRACT

In spite of the considerable effect of the evaporation and root water uptake on the water table drawdown, they still do not explicitly be taken into account in the traditional design equations. Therefore, the effect of the evaporation and root water uptake on the water table drawdown and consequently on the lateral drain spacing had to be predicted. To achieve that, a coupled finite element model for water and heat flow was exploited. The coupled finite element model introduces the numerical solution for the governing differential equations of the water and heat flow in variably saturated porous media under the unsteady state conditions. Four case studies were applied on four different soil types cultivated with maize crop. The applied soil types were clay, clay loam, sandy clay loam, and loamy sand. It was achieved that, taking the evaporation and root water uptake into consideration in the design process, wider lateral drain spacing is required. The predicted lateral drain spacing results in more economical lateral drain spacing with corresponding saving varies between 22.4% to 50% according to soil type.

Keywords: Evaporation, root water uptake, Design, Drainage, Model

1 INTRODUCTION

Evaporation plays an important role in lowering the water table in the soil profile (Philip et al, 1957). The evaporation depends on meteorological conditions, soil characteristics and depth of water table (Hammad, 1962). The ambient temperature is the main meteorological factor that affects the water flow through the soil as a porous medium. Therefore, coupling the water and the heat flow in the soil is important to study the water flow in the porous media under thermal effects. It helps in a more accurate prediction of the water table drawdown and consequently on a more accurate prediction of the lateral drain spacing. In addition, Root water uptake is an important factor that affects the water table drawdown (Van Bakel, 1981) due to the extracted water by plant roots. It is usually added as a sink term for the water flow models.

Many of the researchers described the importance of considering the effect of the evaporation into account in the design process of the subsurface drainage systems. Pandey and Gupta (1990), Nikam, et al. (1992), Hathoot et, al (1993), and Hathoot (2002) concluded that, taking the evaporation into consideration in the design process increases drain spacing by 25%, 9-18%, more than 60%, and more than 50% respectively. However, they did not take the effect of the temperature distribution through the soil on varying the soil hydraulic properties. On the other hand, Most of the models proposed to deal with the coupled water and heat flow in porous media as Collin et al, (2001) and Mendes et al. (2002) did not study the effect of evaporation on the design of subsurface drainage systems.

A coupled mathematical model is exploited to study the water and heat flow in porous media. The coupled model consists of two sub-models, which are coupled by few coupling terms.

The model is spatially discretized by Galerkin finite element method and temporally discretized by the finite difference method (Abdel-Fattah, 2003).

Several computational experiments were carried out for the sake of the verification based on actual and experimental field data and the results of a constructed experimental physical model. Then four design case studies were applied for different soil types to evaluate the effect of evaporation and root water uptake on the technical design criteria in Egypt. The results revealed that taking both factors into consideration in the design process lowers the water table and wider lateral drain spacing is required.

Therefore, The objective of this paper is studying the effect of considering the evaporation from the soil surface and root water uptake on the water table drawdown and consequently on the design of subsurface drainage systems.

2 DESIGN CRITERIA IN EGYPT

The design of the drainage systems is usually based on criteria that are derived from steady or unsteady state equations. The applied design criteria in Egypt are classified into agricultural and technical design criteria as described in Amer and de Ridder (1989).

2.1 Agricultural criteria

An average depth of the water table midway between tile drains might be at 1.0 m to guarantee favorable soil-water conditions for the deep rooting plants.

An average drainage rate of 1.0 mm/day to permit sufficient leaching and maintain soil salinity below the critical levels for crop production.

2.2 Technical criteria

A designed discharge rate for the determination of lateral drain varies from 1.0 to 1.5 mm/d, however for collector drainpipe capacity is 4.0 mm/day for rice areas and 3.0 mm/day for non-rice areas, including a safety factor of 33% the collector drains to take into account sedimentation and irregularities in the alignment.

An average drain depth is of 1.40 - 1.50 m for lateral drains and 2.50 m for collector drains. The criteria of the lateral drain spacing changes from 20m minimum spacing to 60 m maximum spacing depending on the soil type.

3 MATHEMATICAL MODEL

A coupled mathematical model is exploited to simulate the water flow through porous media under thermal effects. The coupled mathematical model consists of two sub-models that simulate two dimensional water and heat flow in porous media under the unsteady state conditions. The two sub-models are coupled by few coupling terms. The governing flow equation of the water flow sub-model is based on the modified form of the Richards' equation. Considering two-dimensional isothermal Darcian flow of water in a variably saturated porous media. However, The governing flow equation of the heat flow sub-model is based on the Sophocleous equation. Considering the movement of heat in the porous media due to conduction as well as convection by flowing water (Abdel-

Fattah, 2003). To study the effect of the heat flow on the water flow in the soil as a porous medium. The coupling of the two sub-models was essential. The two sub-models are coupled by two coupling terms that are unsaturated hydraulic conductivity (K) and Darcian fluid flux density (q) as shown in equations (1,2) (Abdel-Fattah, 2003).

The governing flow equation of the water flow sub-model is based on the modified form of the Richards' equation. Considering two-dimensional isothermal Darcian flow of water in a saturated-unsaturated porous media and assuming that the air phase plays an insignificant role in the liquid flow process the equation is given by the following form (Simunek and van Genuchten, 1994):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^{A}\frac{\partial h}{\partial x_j} + K_{iz}^{A}\right)\right] - S(h,t) \qquad (1)$$

Where, q is the volumetric water content [L^3L^{-3}], h is the pressure head [L], S is a sink term, represents the volume of water removed per unit time from a unit volume of soil due to plant root uptake [t^{-1}], x_i (i = 1, 2) are the spatial coordinates [L], t is time [t], K_{ij}^A are components of a dimensionless anisotropy tensor K^A, and K is the unsaturated hydraulic conductivity [Lt^{-1}].

However, the heat transport equation considers the movement of heat through the porous media by conduction as well as convection by flowing water.

Neglecting the effects of water vapor diffusion, two dimensional heat flow can be described as follows:

$$C(\theta)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i}\left[\lambda_{ij}(\theta)\frac{\partial T}{\partial x_j}\right] - C_w q_i \frac{\partial T}{\partial x_i} \qquad (2)$$

Where l_{ij}(q) is the apparent thermal conductivity of the soil [M/lt^{3} ^{o}C] e.g. [$W/m^{o}C$] and C(q) and C_W are the volumetric heat capacities [M/Lt^2 ^{o}C] [e.g. $J/m^{3o}C$] of the porous medium and the liquid phase respectively (Simunek and van Genuchten, 1994). The first term on the right-hand side of equation (2) represents heat flow due to conduction and the second term accounts for heat being transported by flowing water. We do not consider the transfer of latent heat by vapor movement.

Furthermore, due to high non-linearity of the governing differential equations of the sub-models, they had to be solved numerically. Therefore, the numerical solution for the coupled mathematical model is proposed following the Galerkin finite element method (Abdel-Fattah, 2003). In which the two partial differential equations are transformed into a set of ordinary differential equations. Furthermore, the achieved ordinary differential equations are transformed into a set of algebraic equations by using the backward implicit finite difference method. The proposed numerical solution had been verified to achieve the certainty of the proposed solution and an acceptable error norm had been achieved.

Chain-2D code is a computer software, which has been built by USSL (U.S. Salinity Laboratory) to simulate two-dimensional water flow, heat transport and multiple solutes transport in variably saturated porous media, Simunek and van Genuchten (1994). The CHAIN-2D is used to facilitate the proposed numerical solutions of the coupled mathematical model, the calculation processes and getting the final results.

4 PARAMETERS CALCULATION

4.1 Unsaturated hydraulic conductivity calculation

Van Genuchten (1980), used statistical pore size distribution model of Mualem (1976) to obtain a predictive equation for unsaturated hydraulic conductivity function. The K function is given by the following form:

$$K = \begin{cases} K_s K_r(h) & h < 0 \\ K_s & h \geq 0 \end{cases} \qquad (3)$$

Where

$$K_r = S_e^{1/2}\left[1 - (1 - S_e^{1/m})^m\right]^2 \qquad (4)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad (5)$$

Where, K is the unsaturated hydraulic conductivity; [L/t], K_S is the saturated hydraulic conductivity; [L/t], K_r is the relative hydraulic conductivity; [L/t], m= (n-1)/n, n is an empirical shape factor in soil water retention function, q= volumetric water content; [l^3l^{-3}], q_S= saturated water content; [l^3l^{-3}], q_r= residual water content [l^3l^{-3}].

4.2 Analytical soil moisture retention q(h)

The proposed analytical function of q(h) as follows (Van Genuchten, 1980):

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha h|^n)^{\frac{n-1}{n}}} \qquad (6)$$

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Where, q_S is the saturated water content [l l], q_r is the residual water content [l l], and a [L] and n [-] are empirical shape factors. Those parameters are predicted from the laboratory analysis. q(h) is calculated to simulate the laboratory obtained pF curves through the numerical solutions.

4.3 Thermal conductivity coefficient calculation

The apparent thermal conductivity l_{ij} of the porous media in case of the presence of the liquid flow is calculated as shown in the following equation (Simunek and van Genuchten, 1994):

$$\lambda_{ij}(\theta) = \lambda_T C_w |q| \delta_{ij} + (\lambda_L - \lambda_T) C_w \frac{q_j q_i}{|q|} + \lambda_0(\theta) \delta_{ij} \qquad (7)$$

Where, |q| is the absolute value of the Darcian fluid flux density [L/t], C_W is the volumetric heat capacity of the fluid phase [M/lt$^{2\ oC}$], d_{ij} is the Kronecker delta function, l_L and l_T are the longitudinal, transverse thermal dispersivities [L] and $l_0(q)$ is the apparent thermal conductivity of the porous media in absence of flow respectively. $l_0(q)$ is described by the following equation, Chung and Horton, (1987).

$$\lambda_0(\theta) = b_1 + b_2\theta_w + b_3\theta_w^{0.5} \qquad (8)$$

Where, b_1, b_2 and b_3 are empirical parameters of thermal properties dependent upon soil type. The values of b_1,b_2 and b_3 are listed in table 1, as given in Chung and Horton, (1987).

Table 1 Soil thermal properties

Soil Type	b_1 [ML/t$^{3\ oC}$]	b_2 [ML/t$^{3\ oC}$]	B_3 [ML/t$^{3\ oC}$]	C_n [M/Lt$^{2\ 0}$C]	C_0 [M/Lt$^{2\ oC}$]	C_w [M/Lt$^{2\ oC}$]
Clay	-1.27E+16	-6.2E+16	1.63E+17	1.43E+14	1.87E+14	3.12E+14
Loam	1.57E+16	2.54E+16	9.89E+16	1.43E+14	1.87E+14	3.12E+14
Sand	1.47E+16	-1.55E17	3.17E+17	1.43E+14	1.87E+14	3.12E+14

4.4 Volumetric heat capacity calculation

The volumetric heat capacity C(q) of the heat transport model is calculated according to the described equation (Simunek and van Genuchten, 1994):

$$C(q)=C_n q_n+C_o q_o+C_w q+C_g a_v \qquad (9)$$

Where C_n, C_o, C_g and C_W are volumetric heat capacity [M/lt$^{2\ oC}$] of, solid phase, organic matter, liquid phase and gas phase respectively. However, q_n, q_o, q_g and q are the volumetric fraction [$l^3 l^{-3}$] of solid phase, organic matter, liquid phase and gas phase respectively. a_v is the volumetric air content [$l^3 l^{-3}$]. The values of C_n, C_o, C_g and C_W are listed in table 5.1 according to Chung and Horton (1987).

4.5 Potential evapo-transpiration rate

The potential evapo-transpiration values for the cultivated lands are calculated by multiplying the potential evapo-transpiration rate for bare soil by crop coefficient (Jensen, 1983). The crop coefficient differs according to the cultivated crop type. It was taken for the late season of the cultivated crop as the most period of evapo-transpiration. The calculated values are used in calculating the potential transpiration rate to be used in the numerical solutions.

4.6 Potential evaporation rate

The potential evaporation rate values are collected as average monthly readings of the evaporation pan of Zankalon Pilot Area (ZPA). The calculated average monthly value is multiplied by a correction factor to simulate the reading of cultivated media (Jensen, 1983).

4.7 Potential transpiration rate

The monthly potential transpiration rate is calculated as the result of subtracting the average monthly potential evaporation rate from the average monthly potential evapo-transpiration rate (Jensen, 1983).

4.8 Actual evaporation rate

In case of wet soil, actual soil evaporation is determined by the atmospheric demand and equals potential soil evaporation rate. When the soil becomes drier, the soil hydraulic conductivity decreases that reduce the potential soil evaporation to a lower actual evaporation rate. Actual evaporation rate E_A(t) is calculated by Darcy's law (Van Dam, 2000).

$$K(h)\left(\frac{\partial h}{\partial x_i} + 1\right) = q = E_A(t) \qquad (10)$$

Where, K(h) is the unsaturated hydraulic conductivity [L/t], h is the pressure head [L], q is the flux [L/t] and E_A(t) actual evaporation rate [L/t].

4.9 4.9 Actual root water uptake

The actual root water uptake rate is assumed to be uniformly distributed over two dimensional rectangular domain. It is calculated by the following equation, (Simunek and Van Genuchten, 1999):

$$S(h,x,z) = a_r(h,x,z) b(x,z) L_t T_p \qquad (11)$$

Where, S(h,x,z) is the actual root water uptake distribution, T_p is the potential transpiration rate [L/t], b(x,z) is normalized water uptake distribution [L], L_t is the width [L] of the soil surface and a_r is water stress response function [-]. $a_r(h)$ is function of soil water pressure head ($0 \le a_r \le 1$) as shown in Fig. (1). In which, that water uptake is assumed to be zero close to saturation (i.e., wetter than some arbitrary point, h_1). For $h < h_4$ (the wilting point pressure head), water uptake is also assumed to be zero. Water uptake is considered optimal between pressure heads h_2 and h_3, whereas for pressure head between h_3 and h_4 (or h_1 and h_2), water uptake decreases (or increases) linearly with h.

4.10 Adjustments of the hydraulic conductivity surrounding the simulated drain

The tile drain is simulated in the finite element model as a single node, therefore the hydraulic conductivity around this node has to be adjusted. Adjustment of the hydraulic conductivity, K, for the neighboring elements of the node that simulates the drain, correspond to the change in the electric resistance as follows (Simunek and Van Genuchten, 1999):

$$K_{drain} = K_s C_d \qquad (12)$$

Where K_{drain} is the adjusted conductivity [L/t], K_s is the saturated hydraulic conductivity and C_d is the resistance adjustment factor (correction factor). C_d is determined from ratio of the effective diameter, d_{eff} [L], of the drain to the side length, D_L [L] of the square formed by finite elements surrounding the drain node. The effective drain diameter, d_{eff}, calculated from the number and size of small opening in the drain tube (Mohammad and Skaggs, 1983).

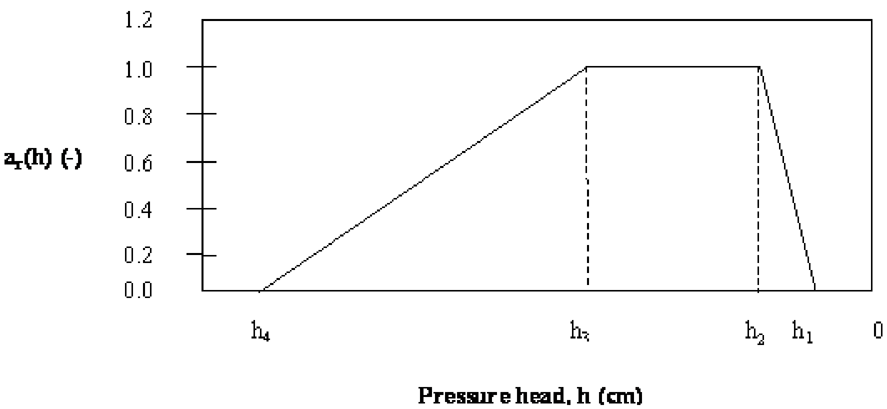

Figure 1 Schematic of the plant water stress response function, ar(h), as used by Simunek and Van Genuchten (1999)

5 RESULTS AND DISCUSSION

Four application case studies were applied for different soil types. The chosen soil types are representative to the main Egyptian soils. These soil textures are clay, clay loam, sandy clay loam and loamy sand. The soil textures and the soil hydraulic properties are obtained from El-Tony (1982) as shown in tables 2 and 3.

The soil thermal properties for the four chosen soils are given in Abdel-Fattah (2003), and listed in table 4. Herein, the thermal properties for the partially loamy texture soils are assumed to be equal to the thermal properties for the loam soil described in table 1.
The listed values of soil hydraulic properties and soil thermal properties are used as input data for the four applied case studies.

Table 2 The texture of the soils used in the application case studies

Soil NO.	O. M. %	CaCo3	Coarse Sand %	Fine Sand %	Silt %	Clay %	Texture
1	1.56	5.57	1.25	7.05	22	62.37	Clay
2	1.04	3.73	1.1	41.7	20	32.3	Clay Loam
3	2.06	1.44	2.4	50.75	14.82	28.5	Sandy Clay Loam
4	6.0	1.23	28.45	52.10	6.99	10.51	Loamy Sand

Table 3 The hydraulic properties for the soils used in the application case studies

Soil Type	K_s [cm/d]	q_s [L^3/L^3]	q_r [L^3/L^3]	a [1/cm]	n [-]
Clay	7.2	0.5592	0.2484	0.0098	1.6
Clay Loam	48	0.517	0.151	0.15	1.34
Sandy clay loam	77	0.494	0.16	0.02	1.3
Loamy sand	188	0.404	0.081	0.015	2.0

Table 4 The thermal properties for the soils used in the application case studies

Soil Type	b_1 [$ML/T^3\ ^0C$]	b_2 [$ML/T^3\ ^0C$]	b_3 [$ML/T^3\ ^0C$]	C_n [$M/LT^2\ ^0C$]	C_0 [$M/LT^2\ ^0C$]	C_w [$M/LT^2\ ^0C$]
Clay	-1.27E+16	-6.2E+16	1.63E+17	1.43E+14	1.87E+14	3.12E+14
Clay Loam	1.57E+16	2.54E+16	9.89E+16	1.43E+14	1.87E+14	3.12E+14
Sandy clay loam	1.57E+16	2.54E+16	9.89E+16	1.43E+14	1.87E+14	3.12E+14
Loamy sand	1.47E+16	-1.55E17	3.17E+17	1.43E+14	1.87E+14	3.12E+14

The atmospheric input data for the application case studies are the potential evaporation rate, E(t), the potential transpiration rate and the temperature degrees. The values of E(t) are calculated as the average monthly potential evaporation for 5 years (1992-1997) from Zankalon pilot area (ZPA) meteorological station of DRI. The $T_p(t)$, average potential transpiration rate, is calculated as a subtraction of E(t) from average monthly value of the potential evapo-transpiration rate calculated for 17 years period (1980-1997) (Moursy, 1998). T(t) is calculated as an average monthly temperature degrees for 5 years (1993 to 1997) collected from ZPA meteorological station. The values of the atmospheric data are listed in table 5.

Table 5 The atmospheric input data for the application case studies

	1^{st} day	2^{nd} day	3^{rd} day	4^{th} day	5^{th} day
E [cm/d]	0.593	0.593	0.593	0.593	0.593
T_p[cm/d]	0.3	0.3	0.3	0.3	0.3
T [^oC]	33	33	33	33	33

The typical domain that simulates a cross-section of real field domain is shown in Fig. (2). The typical domain extends horizontally between two lateral drains with different spacing and extends vertically from soil surface to the impermeable layer is going to be used for the next four case studies.

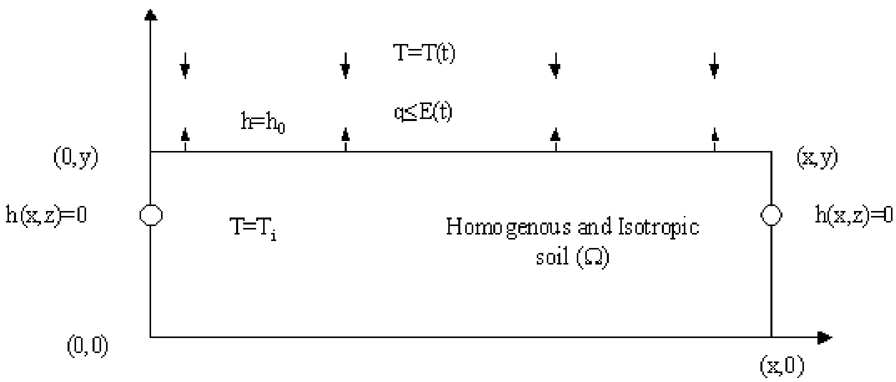

Figure 2 *Typical domain of the applied case studies with the applied initial and boundary conditions*

5.1 Case Study 1: Studying the effect of evaporation, root water uptake on the design for a clay soil considering heat transport

Two-dimensional unsteady water flow through homogeneous and isotropic clay soil under thermal effects is considered to study the effect of the evaporation and root water uptake on the design criteria of the clay soil in the summer season as a worst case of design process. The purpose for the study is to predict the optimum lateral drain spacing to satisfy the applied design criteria in Egypt. According to the Egyptian design criteria, lateral drain spacing for clay soil is considered to be equal to 20 m. It was assumed that the domain of the case study is cultivated with maize (corn) crop of a 40 cm uniformly effective root depth, Doorenbos and Pruilt (1977). Herein, the numerical coupled model is going to be used to predict the pressure head midway between drains above the drain level to be correlated to the proposed value of the pressure head, 40 cm, according to the present applied criteria in Egypt.
The texture of the considered clay soil is given in table 2 , the soil hydraulic properties are given in table 3 and the soil thermal properties are listed in table 4.
The domain of this case study has a rectangular shape as shown in Fig. (2) with a horizontal and vertical dimensions of 20 m and 6.4 m respectively. The depth of impermeable layer assumed to be equal 5.0 m below the drain level, (Abdel-Fattah, 2003).

5.1.1 Initial and Boundary conditions

The initial and boundary conditions for the 1^{st} case study as shown in Fig. (2) are as follows.

5.1.1.1 The initial conditions

$h(x,z,t) = h_0(x,z,t_0) = 0$ at soil surface for initial time $t_0=0$

$T(x, z,t) = T_i(x,z,t_0) = 20\ ^0C$ for initial time $t_0=0$

5.1.1.2 The boundary conditions

h(x,z,t) = h(x,z,t) =0 at drain node through the time period of the problem.
for t=1 to 5 days of summer season;
(x,z) equal (0,5.0) and (20.0,5.0) in meter for the left and right drain respectively.

T(x,z,t) = T(x,z,t) for t=1 to 5 days; (13)
(x,z)= (0,6.4), (0.4,6.4), (0.8,6.4), ….., (20.0,6.4);

$$K(\frac{\partial h}{\partial x_i}+1)=q\leq E(t)$$ for t=1 to 5 days. (14)

Where, T_i is the initial soil temperature, h_0 is the initial pressure head linearly distributed with the domain depth, h [L] is the pressure head function of x, z and t, K is the unsaturated hydraulic conductivity, q is the water flux, E(t) is the potential evaporation rate function of time, $T_p(t)$ average potential transpiration rate function of time and T(t) is the time dependent temperature degree. The value of the saturated hydraulic conductivity, K_s, is 7.2 cm/d as shown in table 3. The values of E(t), $T_p(t)$ and T(t) for clay soil are listed in table 5.

The pressure head midway between lateral drains along time cycle is calculated using the proposed model. It is noticed that the calculated value of the pressure head at the end of the case study period equals to 36.15 cm, which is less than the proposed value of 40 cm above the drain level midway between the lateral drains based on the applied design criteria. It proves that considering the evaporation and root water uptake in the design process leads to increase of water table depth than the required depth (1.0m) according to the agricultural criteria of Egypt. In addition, the 20m lateral drain spacing applied in Egyptian clay soils have to be checked and recalculated.

Therefore, to achieve the design criteria (40 cm pressure head above the drain level) under the effect of the evaporation and root water uptake, another run is applied for the same case study with the same input data. However, the drain spacing is assumed to be equal 30 m. Herein, the domain extends from (0,0) to (30.0,6.4) however; the dimension of the left and right tile drains will be (0,5.0) and (30.0,5.0) respectively.

It is found that the calculated pressure head midway between lateral drains along the 2^{nd} run time period equals 39.98@40.0cm, which almost coincides with the required pressure head. It indicates that 30m drain spacing is the optimum spacing for the applied clay soil that satisfies the required criteria.

5.2 Case Study 2: Studying the effect of evaporation, root water uptake on the design for a clay loam soil considering heat transport

Two-dimensional unsteady water flow through homogeneous and isotropic clay loam soil under thermal effects is applied to study the effect of the evaporation and root water uptake on the design criteria of the clay loam soil for the summer season. The purpose for this case study is to predict the optimum lateral drain spacing for the clay loam soil to satisfy the applied design criteria in Egypt.

Based on the described design criteria, lateral drain spacing for clay loam soil is considered to be equal 40 m. Maize (corn) crop with a 40 cm uniformly effective root depth is considered (Doorenbos and Pruilt, 1977). The numerical coupled model is going to be used to predict the pressure head midway between drains above the drain level to be correlated with the proposed value of the pressure head (40 cm) above the drain level, according to the present applied criteria in Egypt.

The texture of the considered clay loam soil is given in table 2. The soil hydraulic properties are given in table 3. The soil thermal properties are given in table 4.

The domain has a rectangular shape as shown in Fig. (2) with a horizontal dimension of 40.0 m and vertical dimension of 6.40 m assuming that the depth of impermeable layer equals 5.0 m below the drain level (Abdel-Fattah, 2003).

5.2.1 Initial and Boundary conditions

The initial and boundary conditions for the 2^{nd} case study as shown in Fig. (2) are follows:

5.2.1.1 The initial conditions

$h(x,z,t) = h_0(x,z,t_0) = 0$ at soil surface for initial time $t_0=0$ (15)

$T(x,z,t) = T_i(x,z,t_0) = 20\ ^0C$ for initial time $t_0=0$ (16)

5.2.1.2 The boundary conditions

$h(x,z,t) = h(x,z,t) = 0$ at drain position through the time period of the problem.
for t=1 to 5 days, of summer season;
(x,y) equal (0,5.0) and (40.0,5.0) in meter for the left and right drain respectively.

$T(x,z,t) = T(x,z,t)$ for t=1 to 5 days; (17)
(x,z)= (0,6.4), (0.4,6.4), (0.8,6.4), ….., (40.0,6.4)

$$K(\frac{\partial h}{\partial x_i}+1)=q\leq E(t)$$ for t=1 to 5 days. (18)

Where, T_i is the initial soil temperature, h_0 is the initial pressure head linearly distributed with the domain depth, h [L] is the pressure head function of x, z and t, K is the unsaturated hydraulic conductivity, q is the water flux, E(t) is the potential evaporation rate function of time, $T_p(t)$ average potential transpiration rate function of time and T(t) is the time dependent temperature degree. The value of the saturated hydraulic conductivity, K_s, is 48 cm/d as shown in table 3. The values of E(t), $T_p(t)$ and T(t) for clay soil are listed in table 5.

According to the proposed model, the pressure head midway between lateral drains along time cycle is calculated. The calculated pressure head value is 30.44 cm, which is less than the proposed value of 40.0 cm above the drain level midway between the lateral drains based on the applied design criteria. This indicates that considering both evaporation and root water uptake in the design process leads to more lowering of the water table than the required depth (100 cm) according to the agricultural criteria of Egypt. In addition, the 40 m drain spacing applied in the Egyptian clay loam soils have to be checked and recalculated.

Therefore to achieve the design criteria (40 cm pressure head above the drain level) in case of taking the effect of the evaporation and root water uptake into consideration, another run is applied for the same case study. The input data is the same, however the drain spacing equals 60m. Therefore, the domain extends from (0,0) to (60.0,6.4) however, the dimension of the left and right tile drains will be (0,5.0) and (60.0,5.0) respectively.

The pressure head midway between laterals along 2^{nd} run time period is calculated. It is noticed that the calculated pressure head midway between lateral drains (40.0 cm) coincides with the required pressure head. It indicates that the 60m drain spacing is the optimum spacing that can satisfy the required criteria for clay loam soil. The daily temperature distribution through the clay loam soil domain is also calculated along the 2^{nd} run time period according to the proposed model.

5.3 Case Study 3: Studying the effect of evaporation, root water uptake on the design for a sandy clay loam soil considering heat transport

This case study is applied to simulate two-dimensional unsteady water flow through homogeneous and isotropic sandy clay loam soil under thermal effects. It is considered to study the effect of the evaporation and root water uptake on the design criteria of the sandy clay loam soil in the summer season. Then, predicting the optimum lateral drain spacing to satisfy the applied design criteria in Egypt.

According to the described criteria, lateral drain spacing for sandy clay loam soil is considered to be equal 50 cm. Maize (corn) crop with a 40 cm uniformly effective root depth is considered, (Doorenbos and Pruilt, 1977). The numerical coupled model is going to be used to predict the pressure head midway between drains above the drain level to be correlated with the proposed value of the pressure head 40 cm according to the present applied criteria in Egypt.

The texture of the considered sandy clay loam soil is given in table 2. The soil hydraulic properties are given in table 3. The soil thermal properties are listed in table 4.

The domain of the 3rd case study has the same rectangular shape shown in Fig. (2) with a horizontal dimension of 50.0 m and vertical dimension of 6.40 cm assuming that the depth of impermeable layer equals 5.0 m below the drain level.

5.3.1 Initial and Boundary conditions

The initial and boundary conditions for the 3rd case study as shown in Fig. (2) are as follows:

5.3.1.1 The initial conditions

$h(x,z,t) = h_0(x,z,t_0) = 0$ at soil surface for initial time $t_0=0$ (19)

$T(x,z,t) = T_i(x,z,t_0) = 20\ ^0C$ for initial time $t_0=0$ (20)

5.3.1.2 The boundary conditions

$h(x,z,t) = h(x,z,t) = 0$ at drain position through the time period of the problem. (21)
for t=1 to 5 days, of summer season;
(x,z) equal (0,5.0) and (50.0,5.0) in meter for the left and right drain respectively.

$T(x,z,t) = T(x,z,t)$ for t=1 to 5 days; (22)
(x,z)= (0,6.4), (0.4,6.4), (0.8,6.4), ….., (50.0,6.4)

$$K\left(\frac{\partial h}{\partial x_i} + 1\right) = q \leq E(t)$$ for t=1 to 5 days. (23)

Where, T_i is the initial soil temperature, h_0 is the initial pressure head linearly distributed with the domain depth, h [L] is the pressure head function of x, z and t, K is the unsaturated hydraulic conductivity, q is the water flux, E(t) is the potential evaporation rate function of time, $T_p(t)$ average potential transpiration rate function of time and T(t) is the time dependent temperature degree. The value of the saturated hydraulic conductivity, K_s, is 77 cm/d as shown in table 3. The values of E(t), $T_p(t)$ and T(t) for sandy clay loam soil are listed in table 5.

The pressure head midway between lateral drains along the case study time period is calculated according to the proposed model. It is noticed that the calculated pressure head value equals 32.97 cm, which is less than the proposed value of 40.0 cm above the drain level midway between the lateral drains based on the applied design criteria. This indicates that the evaporation and root water uptake in the design process leads to lower the water table than the required depth, (100 cm), according to the agricultural criteria of Egypt. In addition, the 50 m lateral drain spacing applied in is Egyptian sandy clay loam soil have to be checked and recalculated.

Therefore to achieve the design criteria (40 cm pressure head above the drain level) considering the effect of the evaporation and root water uptake, another run is applied for the same case study with the same input data. It is assumed that the drain spacing equals a 60 m. In this case, the domain dimension will be (0,0) to (60.0,6.40) however, the dimension of the left and right tile drains will be (0,5.0) and (60.0,5.0) respectively.

The recalculated pressure head midway between laterals along the 2nd run time period is 37.66 cm. It is noticed that the calculated pressure head midway between lateral drains still do not satisfy the required water table depth.

A 3rd run was applied with 66 m drain spacing of the same input data. In this case, the domain dimension will be (0,0) to (66.0,6.40) however, the dimension of the left and right tile drains will be (0,5.0) and (66.0,5.0) respectively. In this run the predicted pressure head had a value of 39.89 cm, which is nearly equals the proposed value of the design criteria.

As the predicted pressure head midway the lateral drains almost coincides with the required criteria pressure head, the 66 m tile drain spacing is considered the optimum drain spacing that can satisfy the required criteria for the sandy clay loam soil.

5.4 Case Study 4: Studying the effect of evaporation, root water uptake on the design for a loamy sand soil considering heat transport

In this case study, two-dimensional unsteady water flow through homogeneous and isotropic loamy sand soil under thermal effects is simulated. It is simulated to study the effect of the evaporation and root water uptake on the design criteria on loamy sand soil for the summer season. The purpose for this case study is to predict the optimum lateral drain spacing that satisfies the applied design criteria in Egypt.

Based on the described criteria, lateral drain spacing for loamy sand soil is considered to be equal 60 m. Maize (corn) crop of a 40 cm uniformly effective root depth is considered (Doorenbos and Pruilt, 1977). The numerical coupled model is going to be used to predict the pressure head midway between drains above the drain level to be correlated with the proposed value of the pressure head (40 cm) above the drain level, according to the present applied criteria in Egypt.

The texture of the considered loamy sand soil is given in table 2. The soil hydraulic properties are given in table 3 and the soil thermal properties are given in table 4.

The domain of this case study has a rectangular shape as shown in Fig. (2) with a horizontal dimension of 60.0 m and vertical dimension of 6.40 m assuming that the depth of impermeable layer equals 5.0 m below the drain level, (Abdel-Fattah, 2003).

5.4.1 Initial and Boundary conditions

The initial and boundary conditions for the 4^{th} case study are shown in Fig. (2) are as follows.

5.4.1.1 The initial conditions

$h(x,z,t) = h_0(x,z,t_0) = 0$ at soil surface for initial time $t_0=0$ (24)

$T(x,z,t) = T_i(x,z,t_0) = 20\ ^oC$ for initial time $t_0=0$ (25)

5.4.1.2 The boundary conditions

$h(x,z,t) = h(x,z,t) = 0$ at drain position through the time period of the problem. (26)
for t=1 to 5 days of summer season;
(x,y) equal (0,5.0) and (60.0,5.0) in meter for the left and right drain respectively.

$T(x,z,t) = T(x,z,t)$ for t=1 to 5 days; (27)
(x,z)= (0,6.40), (0.4,6.4), (0.8,6.4), ….., (60.0,6.4)

$$K\left(\frac{\partial h}{\partial x_i}+1\right) = q \le E(t)$$
for t=1 to 5 days. (28)

Where, T_i is the initial soil temperature, h_0 is the initial pressure head linearly distributed with the domain depth, h [L] is the pressure head function of x, z and t, K is the unsaturated hydraulic conductivity, q is the water flux, E(t) is the potential evaporation rate function of time, $T_p(t)$ average potential transpiration rate function of time and T(t) is the time dependent temperature degree. The value of the saturated hydraulic conductivity, K_s, is 188 cm/d as shown in table 3. The values of E(t), $T_p(t)$ and T(t) for loamy sand soil are listed in table 5.
The pressure head midway between lateral drains along the case study time period is calculated based on the proposed model. It is noticed that the calculated pressure head value equals 33.2 cm and is less than the proposed value of 40 cm above the drain level midway between the lateral drains based on the applied design criteria. This indicates that considering the evaporation and the root water uptake in the design process leads to lowering the water table than the required depth, (100 cm), according to the agricultural criteria of Egypt. In addition, the 60m drain spacing applied in is Egyptian loamy sand soil has to be checked and recalculated.

Therefore, to achieve the design criteria (40 cm pressure head above the drain level) taking the effect of evaporation and root water uptake into consideration, another run is applied for the same case study. It has the same input data however, the drain spacing is assumed to be equals 70 m. In this case, the domain dimension will be (0,0) to (70.0,6.40) however, the dimension of the left and right tile drains will be (0,5.0) and (70.0,5.0) respectively.

It is noticed that the calculated pressure head midway between lateral drains (38.25 cm) still do not satisfy the required criterion. Therefore, a 3^{rd} run is applied with 73.5 m, drain spacing of a same input data. In this case, the domain dimension will be (0,0) to (73.5,6.4) however, the dimension of the left and right tile drains will be (0,5.0) and (73.5,5.0) respectively. In this run the predicted pressure head had a value of 39.99 cm, which is almost equals the proposed value of the agricultural criteria.

As the predicted pressure head midway the lateral coincides with the required criteria pressure head, then the 73.5m tile drain spacing that can satisfy the required criteria for loamy sand soil.

The relations between the predicted pressure head and tile drains spacing are drawn for the four soil types as shown in the Figs. (3, 4, 5 and 6). From the analysis of these figures, it is recognized that considering the evaporation and root water uptake into the design process requires a wider spacing than the recommended in the design criteria of Egypt for the chosen soil types. The variation in the lateral drains spacing and the corresponding pressure head midway between lateral drains is shown in table 6. It indicates that taking evaporation and root water uptake into consideration in the design process has a significant effect on lowering the water table and consequently wider lateral drain spacing is required.
Accordingly, the percentage of saving in the drain spacing is calculated and listed in table 6. It shows that applying the predicted spacing offers a more economic subsurface drainage system than the present applied system according the recommended criteria of Egypt.

Table 6 The percentage of saving in lateral drain spacing in case of applying modified lateral drain spacing

Variables	Clay	Clay Loam	Sandy Clay Loam	Loamy Sand
Standard p. head [cm]	40.0	40.0	40.0	40.0
Criteria spacing [m] Opposite p. head [cm]	20 36.15	40 30.4	50 32.97	60 33.2
Modified spacing [m] Opposite p. head [cm]	30 39.98	60 40	66 39.89	73.5 39.98
% Save in spacing [m]	50%	50%	30%	22.4%

5.5 Heat transport correlation

The heat distribution through the four soils versus space and time are shown in Figs. (7 and 8). In Fig. (7), the heat distribution through the four soil types used in the application is drawn versus depth of the domain below the soil surface at the 5^{th} day of the case study. It is noticed that the temperature degree of the soil decreases with the increase of depth of the soil for the four applied soils. It is obvious that the heat transport rate through the clay soil is slower than the other types relative to the domain depth, however the rate through the loamy sand soil is the highest one among the others.

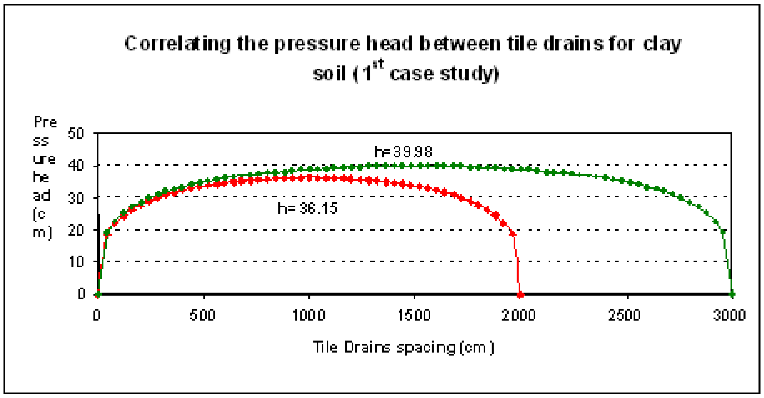

Figure 3 The pressure heads outputs for the 1st and 2nd run of the 1st case study

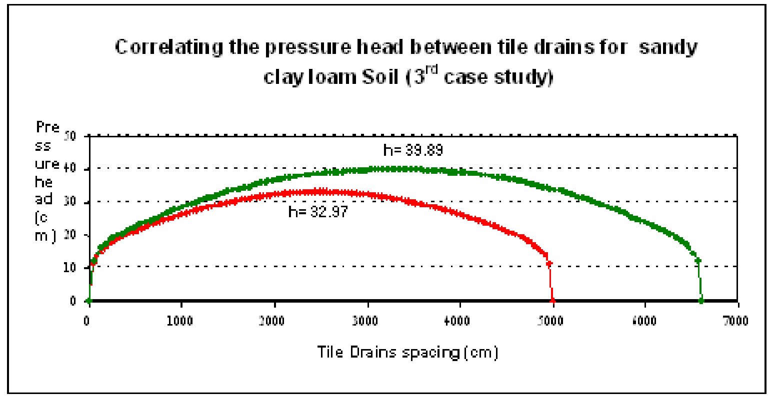

Figure 5 The pressure heads outputs for the 1st and 3rd run of the 3st case study

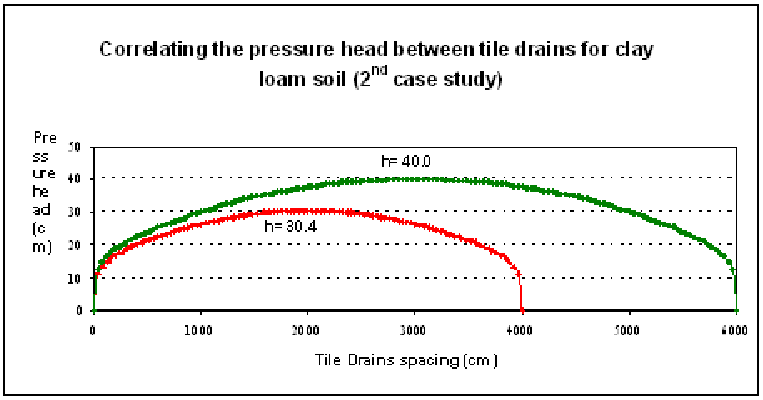

Figure 4 The pressure heads outputs for the 1st and 2nd run of the 2st case study

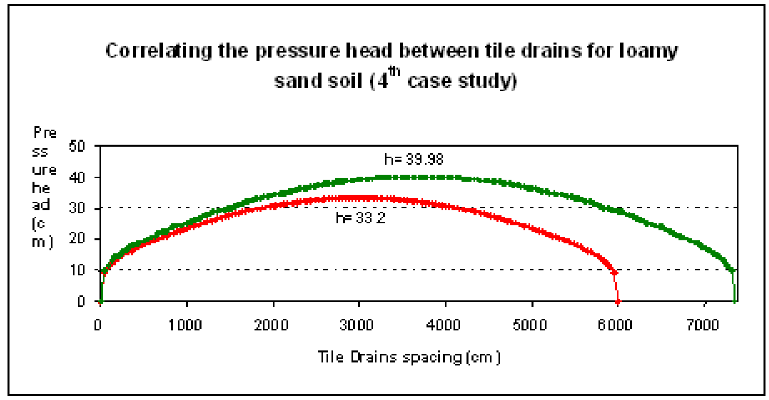

Figure 6 The pressure heads outputs for the 1st and 3rd run of the 4th case study

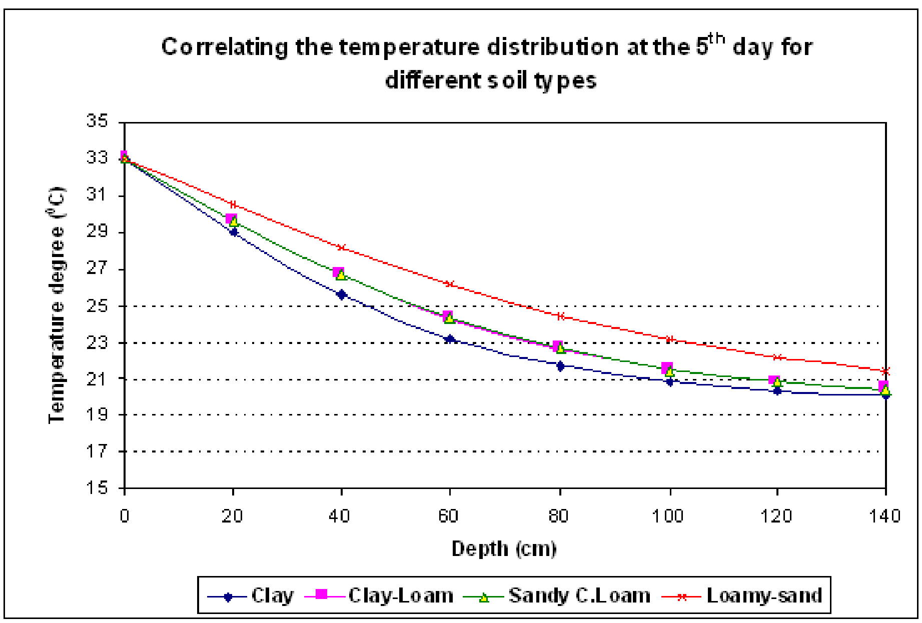

Figure (7) Comparison between temperature distribution versus depth for the different soil types

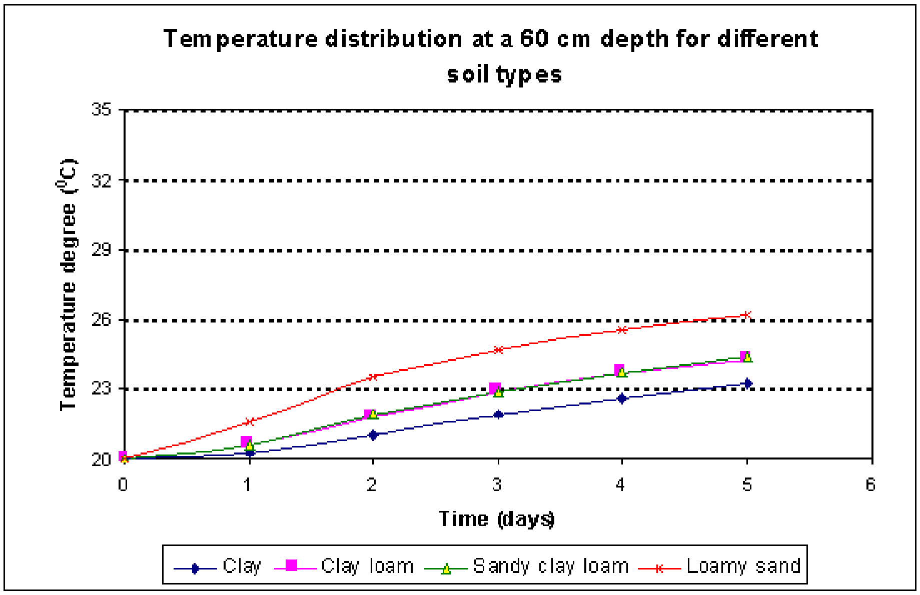

Figure (8) Comparison between temperature distribution versus time for the different applied soil types

The temperature distribution function of time at 60cm depth for the four applied soil types is shown in Fig. (8). It is noticed that, the temperature increases with time for the four applied soil types. It was recognized that, the increase of the temperature degrees is higher, in case of loamy sand soil, than other soil types, however the temperature values of the clay soil is the lowest one.

6 CONCLUSION

Evaporation from soil surface and is one of the variables that affect the water table drawdown. In spite of its considerable effect on lowering the water table, it is not explicitly considered in drainage design equations commonly used for drain spacing calculation. In addition, water uptake by plant roots is also an effective parameter that leads to increase the water table depth due to the exhausted amount of water. Therefore, studying the effect of incorporating evaporation, root water uptake into the design of subsurface drainage systems is important. It is achieved through studying the effect of heat flow on the water flow through porous media under unsteady state condition.

The results it can be concluded that, considering the evaporation and root water uptake into design process satisfy better actual field conditions. In which, wider lateral drain spacing for the applied soils in the case studies is required than the recommended according to the design criteria of Egypt. The modified lateral drains spacing for the clay, clay loam, sandy clay loam and loamy sand would be 30, 60, 66 and 73.5 m respectively. This will result in drain spacing saving of 50%, 50%, 30% and 22.4%.

In addition, the heat transport through porous media changes with time and space relatively with soil type. Herein, the heat transport rate in clay soil is slower than in clay loam and sandy clay loam soil than in loamy sand soil.

7 REFERENCES

Abdel-Fattah, M., (2003). Effect of evaporation on the design criteria of subsurface drainage system in arid and semi arid regions. Faculty of Engineering, Zagazig University, Egypt.

Amer M. H. and de Ridder, N. A., 1989. Land Drainage in Egypt. Drainage Research Institute, DRI, Cario, Egypt.

Chung S. and Horton R., 1987. Soil heat and water flow with a partial surface mulch. Water Resources Research, Vol. 23, No. 12, Pp. 2175-2186, December.

Collin, F. Li, Radu, X. L., J. P. and Charlier, R., 2001. Thermo-hydro-mechanical coupling in clay barriers. Engineering Geology 2032, pp. 1-15.

Doorenbos J. and Pruilt W. O., 1977. Guidelines for predicting crop water requirements. FAO, Food and Agriculture Organization of the United Nations, Irrigation and Drainage Paper. No.24.

El-Tony, M. A., 1982. The effect of the physical and chemical properties of south delta soils on their moisture characteristics. Ph.D Thesis in Soil Science. Faculty of Agriculture. Ain Shams University.

Hammad, H. Y., 1962. Depth and spacing of tile drain systems. Journal of Irrigation and Drainage Division, ASCE, Vol. 88, No. IR1, Proc. Paper 3084, March, pp. 15-34.

Hathoot, H. Y., 2002. Pipe-drainage spacing design considering subsurface evaporation. Alexandria Engineering Journal Vol. 41, No. 2, pp. 307-312, Faculty of Engineering, Alexandria University, Egypt.

Hathoot, H. Y., Al-Amoud, A. I., Mohammad, F. S. and Abo-Ghobar H. M. 1993. Design criteria of drain tube systems in the central region of Saudi Arabia. Journal of King Saud University, Vol. 5, Eng. Sci. (2), pp. 155-312, Riyadh.

Jensen, M. E., 1983. Design and operation of farm irrigation systems. American Society of Agricultural Engineers (ASAE), Chapter 6, pp. 189-232.

Mendes, N., Philippi, P. C. and Lamberts, R., 2002. A new mathematical method to solve highly coupled equations of heat mass transfer in porous media. International Journal of Heat and Mass Transfer 45, pp 509-518.

Mohammad, F. S., and Skaggs, R. W., 1983. Drain tube opening effects on drain on drain inflow, J. Irrig. and Drain. Div., Water Resources Research, 12(3), pp. 513-522.

Nikam, P. J., Chauhan, S. K., Gupta S. K. and Sewa Ram, 1992. Water table behaviour in drained lands: effect of evapotranspiration from the water table. Agricultural-Water-Management, Vol. 20, No. 4, Pp. 313-328; 18 ref.

Pandey, R. S. and Gupta, S. K., 1990. Drainage Design equation with simultaneous evaporation from soil surface. International Commission of Irrigation and Drainage (ICID) Bulletin, Vol. 39, No. 1.

Philip J. R., and de Vries D. A., 1957. Moisture movement in porous materials under temperature gradients, Eos Trans. AGU, Vol. 38, No. 2, pp. 222-232.

Simunek J. Van Genuchten M. Th., 1994. The CHAIN-2D code for simulating two dimensional movement of water, heat and multiple solutes in variably-saturated porous media. Version 1.1, Research Report No. 136. U. S. Salinity Laboratory, USDA, Agricultural Research Center, Riverside, California, USA.

Simunek J. Van Genuchten M. Th., 1999. The Hydrus-2D code for simulating two dimensional movement of water, heat and multiple solutes in variably-saturated media.

Version 2, U. S. Salinity Laboratory, USDA, Agricultural Research Center, Riverside, California, USA.
Van Bakel, P. J. T., 1981. Unsaturated zone and evapo-transpiration. Technical Bulletin (new series), Institute for Land and Water Management Research (ICW), Wageningen, the Netherlands, pp. 38-58.
Van Dam, J. C., 2000. Field scale water flow and solute transport. SWAP model concepts, parameter estimation and case studies. Ph.D thesis, Wageningen University, the Netherlands.
Van Genuchten M. Th., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Soc.Am. J. 44:pp. 892-898.

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[1] Paper No 010. Presented at the 9th International Drainage Workshop, September 10 – 13, 2003, Utrecht, The Netherlands.

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