Pertanika J. Sci. & Technol. 27 (1): 205 - 223 (2019)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Two-dimensional Modeling of Water Distribution under Capillary Wick Irrigation System

Rowshon Md Kamal[1]*, Hadi Hamaaziz Muhammed[1], Mohammad Abdul Mojid[2], Ruediger Anlauf[3] and Mohd Amin Mohd Soom[4]

[1]*Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia*
[2]*Department of Irrigation and Water Manageemnt, Faculty of Agricultural Engineering and Technology, Bangladesh Agricultural University, Mymensingh 2202, Bangladesh*
[3]*Faculty of Agricultural Sciences and Landscape Architecture, University of Applied Sciences, Osnabrück 49009, Germany*
[4]*Faculty of Sustainable Agriculture, Universiti Malaysia Sabah, 88400 Kota Kinabalu, Sabah, Malaysia*

ABSTRACT

Competition for limited available water for crop production is an ever-increasing issue for farmers due to increasing demand of irrigation water worldwide. Due to high energy cost in operating pressurized irrigation systems, energy-efficient low-pressure wick irrigation systems can play important roles for smallholder greenhouse crop production by ensuring higher water use efficiency than most traditional approaches. The objectives of this study were to investigate HYDRUS 2D-simulated water distribution patterns in soil and soilless growing media, and to evaluate water balance in these media under capillary wick irrigation system. To accomplish these objectives, eggplants (*Solanum melongena* L.) were grown in potted peatgro and sandy clay loam in a greenhouse experiment, water distribution was simulated by using HYDRUS 2D software package and compared with the measured values, and water uptake by the plant roots was determined for water balance calculation. The wetting pattern was found axially symmetric in both growing media (peatgro and soil) under the wick emitters. The simulated water distribution in both growing media revealed dependency of spatial extent of the wetted zone on water application period and hydraulic properties of the media. The mean absolute error (MAE) in water content over depth varied from 0.04 to 0.10 $m^3\ m^{-3}$ and

ARTICLE INFO

Article history:
Received: 04 July 2018
Accepted: 30 August 2018
Published: 24 January 2019

E-mail addresses:
rowshon@yahoo.com (Rowshon Md Kamal)
hadiazizm@gmail.com (Hadi Hamaaziz Muhammed)
ma_mojid@yahoo.com (Mohammad Abdul Mojid)
r.anlauf@hs-osnabrueck.de (Ruediger Anlauf)
mohd.amin@ums.edu.my (Mohd Amin Mohd Soom)
* Corresponding author

Current affiliation:
Hadi Hamaaziz Muhammed
Research Center, Sulaimani Polytechnic University, Sulaymaniyah 46001, KRG/Iraq

ISSN: 0128-7680
e-ISSN: 2231-8526

the root mean square error (RMSE) varied from 0.04 to 0.11 $m^3 m^{-3}$. Deviations between the measured and simulated water contents in the peatgro medium were larger over depth than over lateral distance. In contrast, the model criteria matched well for the sandy clay loam and provided MAE of 0.01 to 0.02 $m^3 m^{-3}$ and RMSE of 0.01 to 0.03 $m^3 m^{-3}$, indicating good agreement between the measured and simulated water contents.

Keywords: Numerical modeling, water balance, water distribution, Wick irrigation

INTRODUCTION

Global agriculture has changed dramatically over the last few decades, and the use of soilless cultures has expanded considerably (Raviv and Lieth 2007). Plant production in containers/pots is characterized as either soilless or soil-based medium; typically, the latter is found in usual practices. Currently, several crops are cultivated on different substrates such as peat, perlite, rockwool, coconut coir and scoria (Bougoul and Boulard, 2006; Naddaf et al., 2011). The soilless substrates are characterized by greater fluctuations in the key variables that affect conditions of crop growth. Compared to mineral soils, soilless media in containers, usually, have a smaller root zone, higher water holding capacity, higher percentage of available water, lower water tension and higher hydraulic conductivity (Schröder & Lieth, 2002). But, supplying too little or too much water results in decreasing plant productivity or, when extreme, can cause plant damage (Raviv and Lieth, 2007). Excessive water application can also cause runoff, causing soil erosion and nutrient loss. Consequently, growers often intend to optimize root-zone conditions for betterment of their crops by looking for new design and implementing systems that allow better control of the root-zone variables. They always look for a cost-effective water- and fertilizer-efficient irrigation system.

Three main types of irrigation system – overhead sprinklers, drippers and sub-irrigation – are commonly used to produce potted plants. The sub-irrigation system includes three irrigation methods: ebb and flow (Ebb) system, capillary mat system and capillary wick system (CWS) (Son et al., 2006). The CWS is often regarded as an efficient system for potted plants since it reduces costs of water and labor compared to conventional irrigation systems (Dole et al., 1994). It is a more efficient and environment-friendly system with minimum water and nutrient loss than other irrigation systems, and it augments water and nutrient uptakes by plants (In et al., 2003) with a resulting higher and good quality production. Additionally, being easy and cheap, the installation and operation of the method are inexpensive (Bainbridge, 2002). A few researchers have developed and tried the capillary wick irrigation system for potted plant production in greenhouses and nurseries in Japan and South Korea (Kwon et al., 1999). They reported avoiding excess water loss and obtaining uniformity in production as the important advantages of CWS. The ability of a capillary wick system in raising water was reported to be 10 to 20 cm (Lee et al., 2010;

Wesonga et al., 2014). The reported disadvantages of the system are that the wick materials become moldy causing development of biological activities in the water reservoirs over time that are likely to hamper water transport (Toth et al., 1988; Bainbridge, 2002) and build up of salt in the upper portion of the growing media when irrigation water is saline (Raviv and Lieth, 2007).

In order to design and manage a cost-effective and efficient capillary wick irrigation system, prior knowledge of the extent of wetted volume of root zone under wick emitters is essential. Furthermore, knowledge about vertical and horizontal distances to which water extends within growing media under a point source is vital in designing efficient micro-irrigation systems. Therefore, two- dimensional modeling is essential for determining the horizontal and vertical directions of water movement within soil profile (Naglic et al., 2012). Type of the wick material controls water absorption from the source/reservoir and distribution into the growing media. Although several studies (Assouline, 2002; Li et al., 2006; Shen and Hao, 2006; Huang and Han, 2011) analyzed relationships between dripper discharge and wetting pattern for drip irrigation, to our knowledge, no studies have yet investigated water distribution and wetting pattern in soils and soilless growing media under wick irrigation system because wetting pattern in growing media under wick irrigation requires accurately measured parameters using several equipment. Also, little is known about two-dimensional modeling of water movement through the root zone and root-water uptake for potted plants. In this study, we investigated two-dimensional water distribution in two growing media – sandy clay loam and peatgro – and their wetting patterns under wick irrigation system and evaluated water balance for the potted plants.

MATERIALS AND METHODS

Container Setup

The experiment was done in a non-controlled greenhouse at a cash-crop field, which is used for teaching and research under the Universiti Putra Malaysia (UPM). Two plastic containers, each of 40 cm diameter and 43 cm height, were used: one for peatgro medium and the other for field soil (sandy clay loam). Each container was located under a PVC pipe, which was connected to a bucket that served as a water source/reservoir (Figure 1). A constant water level was maintained inside the PVC pipe by controlling water entry into it by means of a float placed in the bucket. A 3-cm gravel layer was placed at the bottom of both containers and was covered with nylon net to facilitate drainage and prevent water-logging in the containers. A small hole was made at the base of each container to drain out excess water, if there is any. One container was filled with peatgro and the other with sandy clay loam, which was collected from a vegetable farm of the UPM near the experimental greenhouse. Two representative eggplants (*Solanum melongena* L.) of 8 weeks old were excavated from the vegetable farm and transplanted in the containers. When filling with the growing media, the containers were instrumented with ECH_2O-5TE data logger–capacitance sensors (Decagon Devices, Pullman, WA, USA) in order to measure water contents of the growing media. Three ECH_2O sensors were installed horizontally in each container, 5 cm away from the trunk of the plant and at 10, 20 and 30 cm depths from the surface of the growing media. Two additional ECH_2O sensors were installed, also horizontally, at 8 and 16 cm lateral distances from the trunk of the plant and at 10 cm depth. Horizontal position of the sensors in the containers enhanced their good contact with the growing media and minimized measurement error. The ECH_2O sensors were calibrated a priori for water content measurement in the two growing media against their gravimetric water contents at different bulk densities. The gravimetric water contents of peatgro were determined by drying the material in oven at $60^{o}C$ for 48 h following Cobos and Chambers (2010). Following Phogat et al. (2013b), the growing media in both containers with plants were saturated to remove air pockets and make the media settle. The plants were then irrigated manually for 10 days to enable them to adapt to the container environment. Three replicates of the growing media samples were collected in core samplers (5.2 cm diameter × 5 cm height) to determine (only) texture of the soil and bulk density of both media. Water content measurements in the containers with the ECH_2O sensors were initiated after 10 days of planting.

(a) (b)

Figure 1. Assembling of the watering system and container planted with eggplants in the growing media (peatgro and soil): (a) view of water control at inlet and (b) wick watering system

Wick Irrigation

Irrigation was applied to the plants in the containers with wick emitter (1 cm width × 25 cm length) having a discharge rate of 0.015 L h^{-1}. The emitter was located on a half-circle of the container surface and 5 cm away from the plant trunk (Figure 1). The quantity of water application was based on evapotranspiration (ET_c) of eggplants grown in greenhouse. In order to determine ET_c, the growing media in the containers were saturated and, afterwards, allowed to drain out excess water through the opening at the bottom for one hour. Each container with the plant was weighed with an analytical balance immediately after one hour drainage process and also 24 hours after the drainage process. The loss of weight of each container between the two measurements was ET_c, which was expressed in terms of depth over the surface of the growing media in the container. The measurement was repeated for five times during a two-week period. It should be noted that the crop was in the second stage of vegetative and growth period. The observed average ET_c was 5 mm day^{-1}. Irrigation was initiated on 1 September 2014 and terminated on 21 September 2014. Irrigation was applied continuously (24 hours a day) during the 21 days of simulation.

Theory of Numerical Modeling by HYDRUS 2D

Water movement in soil and peatgro medium under capillary wick irrigation system was simulated by employing HYDRUS 2D/3D simulation model of Šimůnek et al. (2012). This software package is capable of simulating two- and three-dimensional variably-saturated water flow, heat transport and transport of multiple solutes. It solves Richard's equation numerically by using finite element method for variably-saturated water flow and advection–dispersion equations for heat, water and solute transports. Additionally, the HYDRUS model allows users to specify water uptake by plant roots that influences spatial distribution of water and salinity of water during irrigation events. Assuming that the air phase does not play any important role in the flow process of water and also water flow due to thermal gradient is negligible, the two-dimensional governing flow equation is described by modifying Richard's equation (Celia et al., 1990) as

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial xi}\left[K\left(K_{ij}^{A}\frac{\partial h}{\partial xj} + K_{iz}^{A}\right)\right] - S(h, x, z) \quad (1)$$

where θ is volumetric water content (L^3L^{-3}), h is pressure head (L), x_i (i = 1, 2) is horizontal coordinate (L), z is vertical coordinate (positive upward), t is time (T), K_{ij}^A are components of a dimensionless anisotropy tensor K^A, K is unsaturated hydraulic conductivity (LT^{-1}) and $S(h, x, z)$ is a sink term that represents root-water uptake (T^{-1}).

HYDRUS 2D/3D code was used to solve Eq. (1) using finite element method on the basis of mass conservative iterative scheme. Water extraction, $S(h, x, z)$, was calculated based on Feddes' model (Feddes et al., 1978), which sets root-water uptake rates according to soil-water pressure head, h, at any point in the root zone. Feddes' model also defines the conditions in which transpiration is reduced below potential when soil cannot supply the amount of water required by crops under predominant climate conditions (Phogat et al., 2012). In addition, additive or multiplicative model can be used for implementing osmotic head reduction in HYDRUS code; the later model was considered for simulation in this study. Based on space and time, the actual local uncompensated root-water uptake was obtained by (Feddes et al., 1978; van Genuchten, 1987; Šimůnek and Hopmans, 2009)

$$S(h.h\phi, x, z, t) = \alpha(h, h\phi, x, z, t)b(x, z, t)S_p(x, z, t)$$
$$= \alpha(h, h\phi, x, z, t)b(x, z, t)L_t T_p(t) \quad (2)$$

where $S(h, h\varphi, x, z, t)$ is actual volume of water removed from a unit volume of soil per unit time ($L^3\ L^{-3}\ T^{-1}$), $S_p(x, z, t)$ is potential volume of water removed from a unit volume of soil per unit time ($L^3\ L^{-3}\ T^{-1}$), $\alpha(h, h\varphi, x, z, t)$ is a prescribed dimensionless stress response function ($0 \leq \alpha \leq 1$) of soil-water pressure head (h) and osmotic pressure head ($h\varphi$), $b(x, z, t)$ is a normalized root-density distribution function (L^{-3}), T_p is potential transpiration rate (LT^{-1}) and L_t is width [L] of the soil surface associated with the transpiration process. The actual transpiration rate, T_a (LT^{-1}), was then obtained by integrating Eq. (2) over the root domain Ω_R as

$$T_a(t) = Tp(t) \int_{\Omega R} \alpha(h, h\phi, x, z, t)b(x, z, t)d\Omega \quad (3)$$

The soil-water retention function and unsaturated hydraulic conductivity function were described by using van Genuchten–Mualem constitutive relationships (Mualem, 1976; van Genuchten, 1980) as

$$\theta(h) = \theta(r) + \frac{\theta s - \theta r}{[1+(\alpha h)^n]^m} \text{ for } h < 0$$
$$\theta(h) = \theta_s \text{ for } h \geq 0 \quad (4)$$

$$\mathrm{K(h)} = \mathrm{K_s}\, S_e^l\, [1 - (1 - S_e^{\frac{1}{m}})^m]^2 \quad (5)$$

where θ_r and θ_s denote residual and saturated water content, respectively ($L^3\ L^{-3}$), $m = (1 - 1/n)$, K_s is saturated hydraulic conductivity ($L\ T^{-1}$), α is inverse of the air-entry value (L^{-1}), n is a pore-size distribution index >1, l is a pore-connectivity parameter and S_e is effective saturation given by

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (6)$$

The governing water-flow and solute-transport equations in the HYDRUS package are solved using Galerkin finite element method applied to a network of triangular elements. The program interface allows users to manipulate time discretization and specification of boundary conditions.

Estimation of Hydraulic Properties of the Growing Media

Running the HYDRUS code requires assigning van-Genuchten parameters (θ_r, θ_s, α, n, l and K_s) to describe soil hydraulic functions (Eqns. (4) and (5)). Direct determination of these soil hydraulic parameters in the field or laboratory is time consuming and costly. So, they were estimated (Table 1) by using ROSETTA model (Schaap et al., 2001), which is a pedo-transfer function software and uses a neural network model to predict the hydraulic parameters from soil data. Soil particle size and bulk density, determined from the soil samples of planted container, were input to the ROSETTA model. The parameter l (Eq. (5)) was taken as 0.5 since this value was estimated for many soils by Mualem (1976). The ROSETTA model cannot, however, provide hydraulic parameters of soilless substrates. So, for peatgro, following Anlauf (2014), the hydraulic parameters were estimated from the measured pF/water-retention values by nonlinear least-square fit using EXCEL solver function.

Table 1
Hydraulic parameters of peatgro and sandy clay loam (Equations 4 and 5) used in model

Growing media	Saturated water content, θ_s (m^3 m^{-3})	Residual water content, θ_r (m^3 m^{-3})	Inverse air-entry value, α (cm^{-1})	Pore-size distribution index, n	Saturated hydraulic conductivity, K_s (cm day^1)	Pore-connectivity parameter, l (-)
Peatgro	0.68	0.0	0.027	2.26	5875.2	0.5
Sandy clay loam	0.39	0.1	0.059	1.48	31.44	0.5

Root Distribution and Water Uptake Parameters

Plant-root distribution influences soil water and salinity distributions in the root domain under micro-irrigation. Because of constrained root growth in a closed system, such as in a container, its distribution for container-grown plants differs substantially from field-grown plants. Phogat et al. (2013b) reported that in a closed system, roots developed more in vertical direction than in horizontal direction. Consequently, the root distribution for eggplants in the container was described by using the model of Vrugt et al. (2001), according to which the two-dimensional root-distribution function, $b(x, z)$, is defined in HYDRUS by

$$b(x,z) = \left(1 - \frac{z}{z_m}\right)\left(1 - \frac{r}{r_m}\right) e^{-\left(\frac{P_z}{Z_m}|Z^* - Z| + \frac{P_r}{r_m}|r^* - r|\right)} \tag{7}$$

where z is depth (L) in the soil/peatgro profile (x, z), z_m is maximum rooting depth (L) of the eggplants that was taken as the depth of container (40 cm), r is radial distance from the plant (L) and r_m is maximum rooting length in radial direction (L) that was taken equal to the radius of the container (20 cm). In Equation (7), p_z (-), z^* (L), p_r (-) and r^* (L) are all empirical parameters. When transferring the plants to the containers, both horizontal and vertical dimensions of the roots were measured following Phogat et al. (2013b). The parameters z^* and r^* represent, two-dimensionally, the zone of maximum root-water uptake. The value of z^* was taken as 17 cm and that of r^* was taken as 6 cm (Figure 2).

Figure 2. Root distribution of a transplanted eggplant in the potted growing media

Hanson et al. (2006) considered the values of p_z and p_r for tomato plant to be unity. The root system of tomato is considered mostly similar to that of eggplant and, consequently, p_z and p_r were set equal to one except for $r > r^*$ and $z > z^*$ when they became zero (Ramos et al., 2012). The effects of water stress reduction were considered from the model of Feddes et al. (1978). The assigned model parameters are given in Table 2; the values of the parameters were adopted from tomato to be used for eggplants following Selim et al. (2013).

Table 2
Recommended parameters of Feddes et al. (1978) model for evaluating the effects of water stress reduction

Growing media	Parameters of Feddes et al. (1978) model						
	p_o (cm)	p_{opt} (cm)	p_{2H} (cm)	p_{2L} (cm)	p_3 (cm)	r_{2H} (cm day^{-1})	r_{2L} (cm day^{-1})
Peatgro	–1	–2	–25	–50	–100	0.5	0.1
Sandy clay loam	–1	–2	–800	–1500	–8000	0.5	0.1

p_0: pressure head below which plant roots begin to extract water from the soil
p_{opt}: pressure head below which plant roots extract water at the maximum rate
p_{2H}: limiting pressure head below which plant roots are not able to extract water at the maximum rate at potential transpiration rate of 0.5 cm day^{-1}
p_{2L}: limiting pressure head at potential transpiration rate of 0.1 cm day^{-1}
p_3: pressure head below which plant roots stop uptaking water, which is usually taken at wilting point
r_{2H}: potential transpiration rate at which the limiting pressure head allows extracting water at the maximum rate
r_{2L}: potential transpiration rate at which the limiting pressure head allows extracting water at the minimum rate

Multiplicative models were employed to combine the effects of water and salinity stress on root-water uptake. The threshold model of Maas (1990) was used to describe the osmotic effects with a threshold EC_e of 2.5 dS m^{-1} to correspond to EC of the nutrient solution, and the decline per unit increase (slope) in EC_e beyond the threshold value was fixed at 5% following Ünlükara et al. (2010). Note that, in HYDRUS, the simulation model requires salinity of nutrient solution as input.

Flow Domain and Simulations

HYDRUS 2D/3D was employed to simulate transient axis-symmetrical two-dimensional movement of water and solute by assuming that a two-dimensional problem approximates a three-dimensional flow process. The simulation domain was represented by a 40-cm deep and 20-cm wide half of cylindrical cross section of the growing media. A 25-cm long wick was set 5 cm away from the plant trunk in the containers. The transport domain was discretized into 3321 nodes, which corresponded to 6400 structured triangular elements as illustrated in Figure 3. The observation nodes corresponded to the locations where the five ECH_2O sensors were installed (three sensors at 10, 20 and 30 cm depth, and two sensors at 10 cm depth and at 8 and 16 cm lateral distance from the plant trunk). Simulations were done for sandy clay loam and peatgro medium over a period of 21 days without interruption.

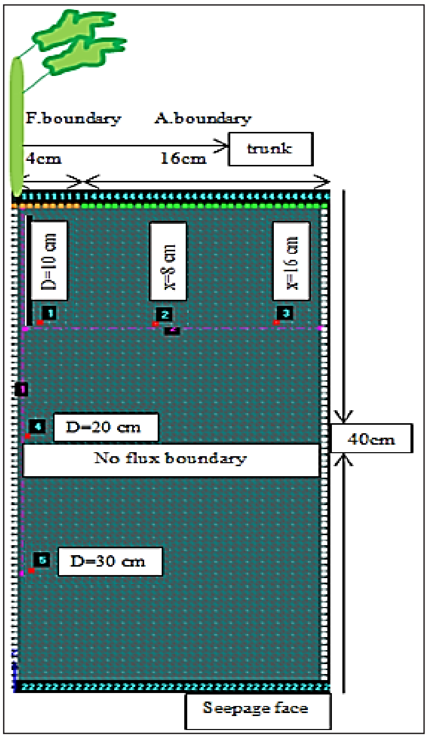

Figure 3. Axisymmetrical domain geometry of potted growing media with finite element discretization used in HYDRUS 2D simulations with observation nodes

Initial and Boundary Conditions

HYDRUS 2D/3D requires setting boundary conditions along the outer sides of the flow domain. The upper surface of the growing media was subject to atmospheric boundary condition with a constant flux of 6.96 cm day^{-1} (0.015 L h^{-1}) imposed by the wick emitter that resulted in a two-dimensional axis-symmetrical water flow. The boundary flux of half circle was set on 4 cm since the wetted diameter of the surface was 8 cm. The atmospheric boundary conditions were represented by actual evaporation (E_a = 0.3 cm day^{-1}) and actual transpiration (T_p = 0.2 cm day^{-1}). The vertical sides of the flow domain were no flow boundaries except for a 2-cm seepage face at the bottom boundary. The flux was determined by dividing wick discharge (370 cm^3 day^{-1}) by the area of wetted surface (50.24 cm^2). The discharge of the wick (q_e, ml day^{-1}) was quantified by

$$q_e = 32.85\, h_c{}^{-0.26} \qquad (8)$$

where h_c is capillary height of water (cm) in the wick. The initial soil-water distribution was based on the ECH_2O sensor-measured values that varied from 0.22 to 0.27 m^3 m^{-3} from top to the bottom of the container. The initial peatgro-water distribution varied from 0.20 to 0.30 m^3 m^{-3} from top to the bottom of the container.

Statistical criteria

The performance of the model was evaluated by comparing the measured and HYDRUS-2D-simulated water-content distributions at different positions of the soil and peatgro medium at different times. The quantitative measures of uncertainty, MAE and RMSE, were estimated by

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|Mi - Si| \qquad (9)$$

and

$$RMSE = \sqrt{1/N\sum_{i=1}^{N}(Mi - Si)^2} \qquad (10)$$

where M_i and S_i are the measured and simulated values of an output variable and N is the number of observations.

RESULTS AND DISCUSSION

Water Distribution and Wetting Pattern in the Growing Media

Tables 3−6 compare simulated water contents in the two growing media at different depths, lateral distances from the wick emitter and times with their measured water contents within the flow domain. The distribution of water in the two growing media reflects water availability for eggplants, and plays an important role in water flow through the root zone. Two statistical indicators, MAE and RMSE, evaluated the level of agreement between the simulated and measured water contents at 10, 20 and 30 cm depths, and at 8 and 16 cm lateral distances with 10 cm depth. The measured water contents matched the simulated values well, both spatially and temporally, for the soil, but the agreement between the measured and simulated water contents was fair for the peatgro medium.

Water contents in the peatgro at all depths increased gradually with time until 15th day of simulation, and then decreased gradually during the following five days as illustrated in Figure 4. The decrease in water content with depth in the later days was attributed, mainly, to reduced wick efficiency as demonstrated by the observed lower wick discharge (330 ml day^{-1}) in the last week of simulation than that (370 ml day^{-1}) at the beginning of

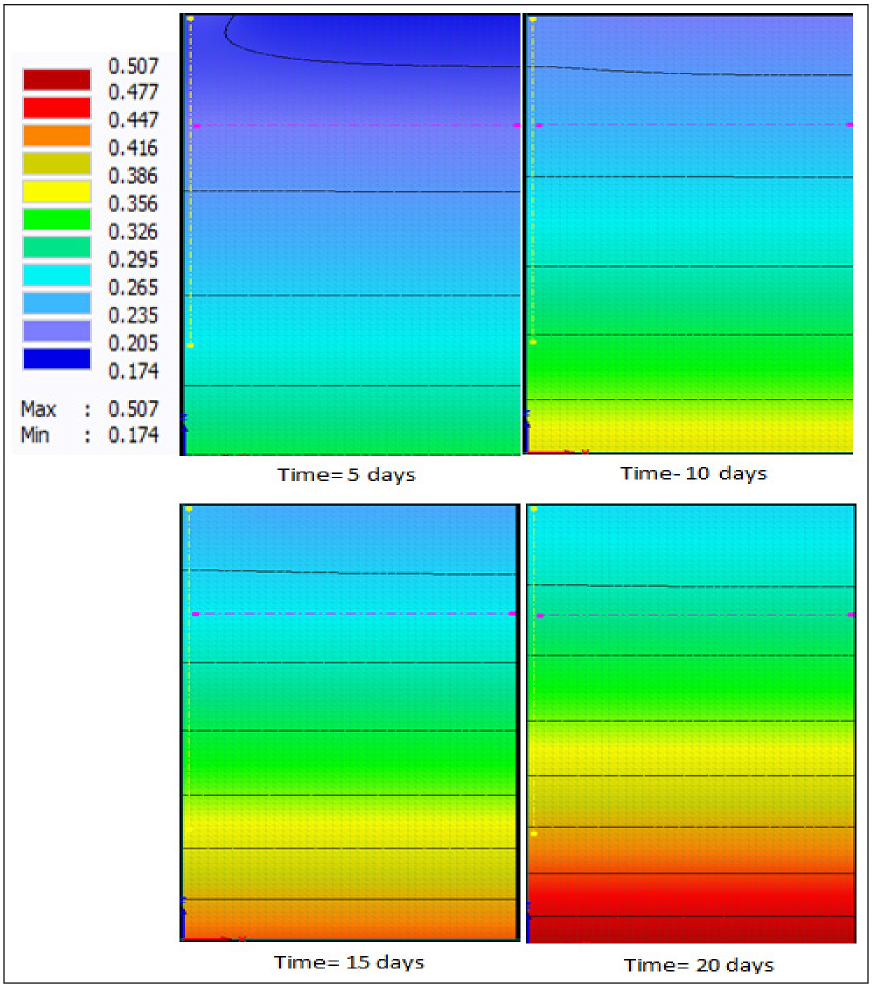

Figure 4. Distribution of simulated water content (m^3 m^{-3}) in the peatgro medium

the experiment. Deeper depths exhibited larger deviations in water content due to that the lower part of the peatgro medium was in contact with the outside air through the drainage opening. Consequently, some water of the medium was lost in the form of evaporation. In contrast, the simulated water content increased with increasing depth; this trend in water content appeared to be more realistic than the trend in the observed water contents. Unlike the deviations in water content over depth, the deviations over lateral distance were more consistent (Table 4). The mean absolute error, MAE, in water contents over depth varied from 0.04 to 0.10 $m^3 m^{-3}$ and the RMSE varied from 0.04 to 0.10 $m^3 m^{-3}$, indicating considerable deviations between the measured and simulated water contents. The deviations might possibly be related to model input parameters, model structure and, to some extent, measurement errors. The accuracy of simulations also depended on the estimated hydraulic parameters used in the modeling and, hence, they should closely represent the experimental media (Phogat et al., 2012).

Table 3
Comparison of measured (M) and simulated (S) peatgro-water contents ($m^3 m^{-3}$) at different times and depths along with the mean absolute error (MAE) and root-mean square error (RMSE) of the water contents

Depth in container (cm)	Time (days)									
	5		10		15		20		Statistical indicators	
	M	S	M	S	M	S	M	S	MAE	RMSE
10	0.27	0.22	0.27	0.25	0.31	0.28	0.27	0.31	0.04	0.04
20	0.26	0.25	0.27	0.29	0.32	0.32	0.25	0.36	0.04	0.06
30	0.23	0.28	0.24	0.33	0.29	0.38	0.25	0.42	0.10	0.11

Table 4
Comparison of measured (M) and simulated (S) peatgro-water contents ($m^3 m^{-3}$) at different times and distances from the emitter along with the mean absolute error (MAE) and root-mean square error (RMSE) of the water contents

Distance from emitter (cm)	Time (days)									
	5		10		15		20		Statistical indicators	
	M	S	M	S	M	S	M	S	MAE	RMSE
8	0.20	0.21	0.21	0.24	0.22	0.27	0.24	0.30	0.04	0.04
16	0.19	0.21	0.20	0.24	0.22	0.27	0.23	0.30	0.05	0.05

Similar to peatgro, the simulated water distribution in sandy clay loam was visually compared with the measured water distribution in Figure 5 for 10, 20 and 30 cm depths, and 8 and 16 cm lateral distances from the emitter with 10 cm depth. The water contents and statistical indicators are summarized in Tables 5 and 6. The small values of MAE (0.01 to 0.02 $m^3 m^{-3}$) and RMSE (0.01 to 0.03 $m^3 m^{-3}$) for water contents at different depths indicated good matching between the measured and simulated water contents. In case of lateral water distribution, the average MAE and RMSE, both of 0.025, also implied good performance of the model for predicting water contents. It is noted that water distribution

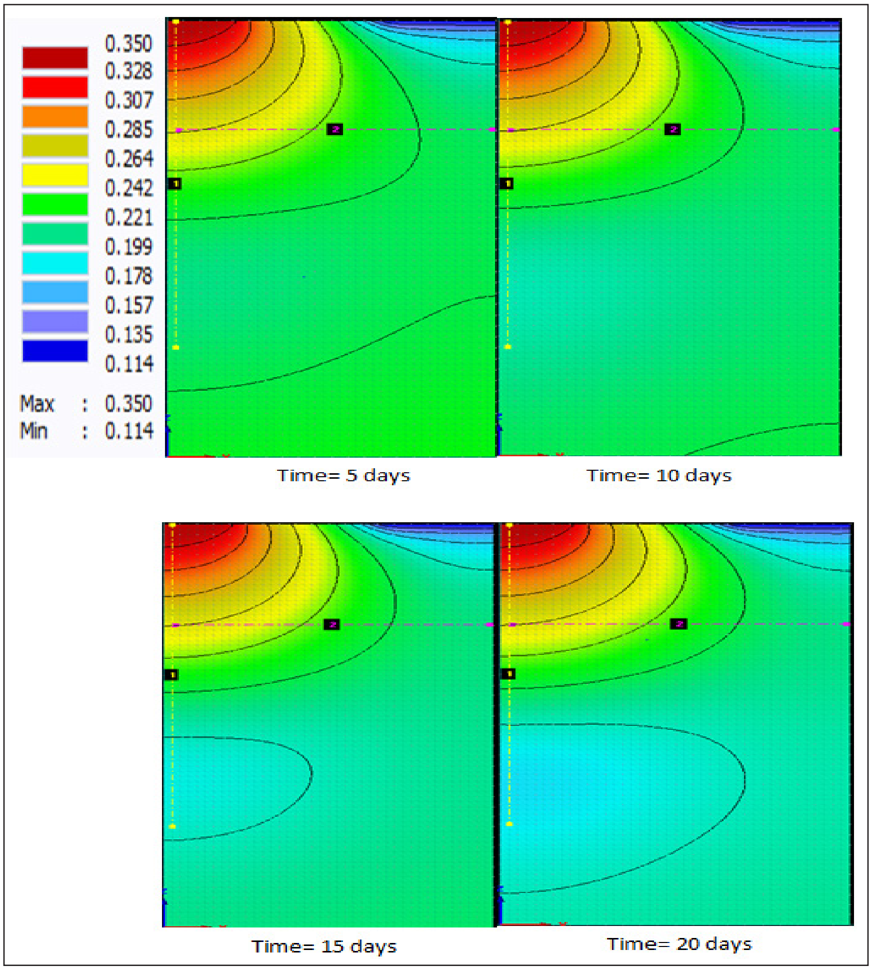

Figure 5. Distribution of simulated water content (m^3 m^{-3}) in sandy clay loam

Table 5
Comparison of measured (M) and simulated (S) soil-water contents (m^3 m^{-3}) at different times and depths along with the mean absolute error (MAE) and root-mean square error (RMSE) of the water contents

Depth in container (cm)	Time (days)									
	5		10		15		20		Statistical indicators	
	M	S	M	S	M	S	M	S	MAE	RMSE
10	0.25	0.26	0.23	0.26	0.25	0.26	0.22	0.26	0.02	0.03
20	0.24	0.23	0.21	0.23	0.20	0.22	0.21	0.22	0.02	0.02
30	0.23	0.21	0.21	0.20	0.19	0.19	0.17	0.18	0.01	0.01

Table 6
Comparison of measured (M) and simulated (S) soil water contents (m^3 m^{-3}) at different times and distances from the emitter along with the mean absolute error (MAE) and root-mean square error (RMSE) of the water contents

Distance from emitter (cm)	Time (days)									
	5		10		15		20		Statistical indicators	
	M	S	M	S	M	S	M	S	MAE	RMSE
8	0.22	0.20	0.20	0.17	0.17	0.14	0.14	0.12	0.03	0.03
16	0.20	0.18	0.17	0.14	0.14	0.12	0.13	0.12	0.02	0.02

over depth was different in sandy clay loam from that in the peatgro medium. Both the measured and simulated water contents in the soil decreased with increasing depth, showing that a balance between the wick discharge and crop evapotranspiration was established.

The comparison of water-content distributions in the two growing media revealed that the wetted volume and lateral movement of water were greater in peatgro than in sandy clay loam during the simulation period. Because of different hydraulic properties (residual and saturated water contents), the peatgro medium could uptake water again and redistribute it, thus increasing the wetted volume and length of lateral movement. The low discharge rate of emitter, on the other hand, allowed more water to move in the vertical direction than in the horizontal direction (Badr and Taalab, 2007). The close agreement between the measured and simulated water contents in the two growing media demonstrated that the HYDRUS 2D/3D software package can successfully predict water movement in different growing media-filled containers planted with eggplants. Phogat et al. (2012), Ramos et al. (2012) and Phogat et al. (2013a & b) also reported good performance of HYDRUS 2D/3D for predicting water movement in different soils.

Water Balance Components

The water balance is based on the law of mass conservation, based on which the change in water content (ΔS) in a given volume of a growing medium in a given period of time is equal to the difference between the amount of water added to the medium and the amount of water withdrawn from it. The water balance is thus expressed by (Phogat et al., 2013a)

$$\Delta S = I + R + ET - D \tag{11}$$

where I is irrigation, R is rainfall (not present in greenhouse experiment), ET is crop evapotranspiration and D is drainage, the dimensions of all components of Eq. (11) are in length. The simulated components of water balance over the 21-day experimental period are provided in Tables 7 and 8. The measured drainage was nil/zero during the experimental period. HYDRUS 2D/3D also simulated zero drainage during this period (Table 7). With a drip irrigation system, on the other hand, the amount of drainage could be up to 49% of the total water balance in a planted container (Phogat et al., 2013b). So, there is a clear advantage of the capillary wick system in saving irrigation water. Also, the simulated root-water uptake (actual transpiration, T_a) was 17.5% of the applied water in the potted peatgro medium against 52.7% of the applied water in sandy clay loam, implying a lower water uptake rate in coarse texture medium than in fine texture medium. Selim et al. (2013) also observed similar results; root-water uptake rate was lower in sand than in loamy sand. As depicted in Figure 6, root-water uptake rate varied from 1.4 to 1.6 mm day^{-1} for peatgro and 1.7 to 2.0 mm day^{-1} for sandy clay loam. The closely matched potential root-water uptake and actual root-water uptake (Table 8) under capillary wick irrigation indicated high irrigation efficiency of the wick system. In addition, the wick irrigation system can be controlled and adjusted to the water requirement of plants. Evaporation from the peatgro medium was 65.6% of the applied water (Table 7) that was considerably large compared to evaporation from sandy clay loam (47.3%). Argo (1998) reported a surface evaporation loss of 50% of applied water from the peatgro medium. The evaporation loss depends, mainly, on the component materials of the growing media in addition to the prevailing climatic conditions. Any fiber material in the growing medium adopts the role of capillary tube, and accelerates evaporation by transporting water to the medium surface (Argo, 1998). The simulated water balance in the two growing media under slightly, but sustained, deficit irrigation demonstrated that plant roots were forced to extract whatever water was applied and stored in the root zone.

Table 7
Simulated components of water balance of the source and sink after 21 days

Components		Peatgro medium		Sandy clay loam	
		(mm)	(%)	(mm)	(%)
Sources	Irrigation	105.0	66.2	105	82.0
	Soil-water depletion	53.7	33.8	23.0	18.0
Sinks	Actual root uptake	54.7	34.4	67.5	52.7
	Evaporation	104.3	65.6	60.5	47.3
	Drainage	0	0	0	0

Table 8
Simulated components of daily water balance under capillary wick irrigation

Components	Peatgro medium (mm day^{-1})	Sandy clay loam (mm day^{-1})
Potential root-water uptake	2	2
Actual root-water uptake	1.67	1.77
Evaporation	3	1.8
Drainage	0	0

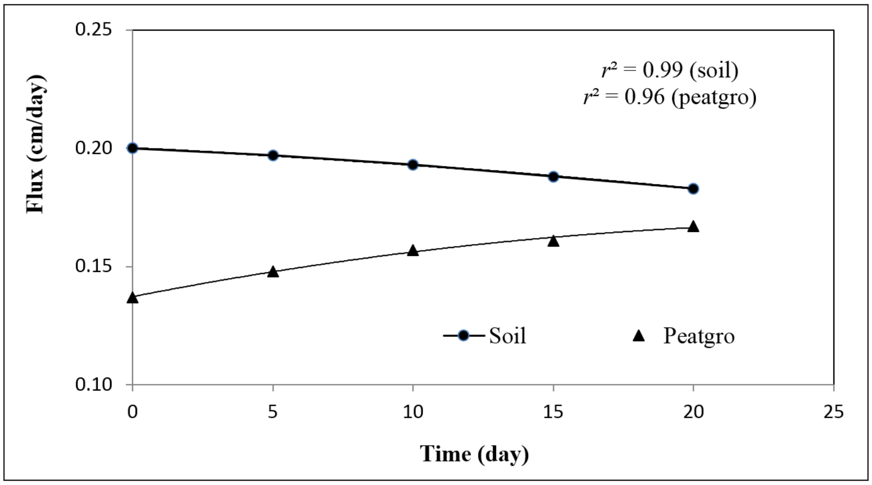

Figure 6. Simulated actual root-water uptake for sandy clay loam and peatgro medium

CONCLUSION

Water distribution pattern in the crop-growing media under wick emitters differed from traditional and modern watering methods in that the emitters' flow wetted the growing media in an axially symmetric pattern rather than in a one-dimensional pattern. This study combined HYDRUS 2D modeling with potted eggplant cultivation in two growing media and compared simulated and measured water contents as well as estimated root-water uptake under capillary wick irrigation system. Water application period and hydraulic properties of the growing media controlled spatial extent of the wetted zone in the media. Water movement below the emission point was more prominent in vertical direction than in horizontal direction. Consequently, for growing media with high infiltration capacity like peatgro, capillary wick irrigation is recommended from top of the media instead of within the media in order to retain water and fertilizer for a prolong time. The observed and simulated zero drainage over a 21-day experimental period demonstrated no water wastage in capillary wick irrigation system with high efficiency. Water-uptake efficiency was higher in sandy clay loam (finer medium) than in peatgro medium (coarser medium). The predicted water distribution agreed well with the observed values for both growing media with relatively small MAE and RMSE; however, the model performed better for sandy clay loam than for the peatgro medium. Although, the potential and actual root-water uptakes agreed well, the later (1.77 mm day^{-1}) was higher in sandy clay loam than in the peatgro medium (1.67 mm day^{-1}). The predicted surface evaporation over 21 days accounted for 65.6% of the applied water in peatgro medium against 47.3% in sandy clay loam. More experiments and modeling study over longer time period are needed to assess maximum lateral extent of water distribution, and water and nutrient uptake by potted plants under wick irrigation system.

ACKNOWLEDGMENTS

This research was supported by a grant of Universiti Putra Malaysia (UPM). The authors gratefully acknowledge the financial support from the Putra Grant No: 9411100 of UPM. They also acknowledge the supports rendered by the staffs of the Laboratory and Technology Park UPM (TPU) for providing technical supports in conducting the experiments.

REFERENCES

Assouline, S. (2002). The effects of micro-drip and conventional drip irrigation on water distribution and uptake. *Soil Science American Journal 66*(5), 1630-1636.

Anlauf, R. (2014). *Using the EXCEL solver function to estimate the van Genuchten parameters from measured pF/water content values*. Retrieved July 4, 2017, from http://www.al.hs-osnabrueck.de/anlauf.html

Argo, W. R. (1998). Root medium physical properties. *Horticulture Technology, 8*(4), 481-485.

Badr, M., & Taalab, A. (2007). Effect of drip irrigation and discharge rate on water and solute dynamics in sandy soil and tomato yield. *Australian Journal of Basic Applied Science, 1*(4), 545-552.

Bainbridge, D. A. (2002). Alternative irrigation systems for arid land restoration. *Ecological Restoration, 20*(1), 23-30.

Bougoul, S., & Boulard, T. (2006). Water dynamics in two rockwool slab growing substrates of contrasting densities. *Scientia Horticulturae, 107*(4), 399-404.

Cobos, D. R., & Chambers, C. (2010). *Calibrating ECH2O soil moisture sensors*. Decagon Devices, Application Note. Retrieved July 4, 2017, from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.559.4409&rep=rep1&type=pdf

Celia, M. A., Bouloutas, E. T., & Zarba, R. L. (1990). A general mass-conservative numerical solution for the unsaturated flow equation. *Water Resources Research, 26*(7), 1483-1496.

Dole, J. M., Cole, J. C., & von Broembsen, S. L. (1994). Growth of poinsettias, nutrient leaching, and water-use efficiency respond to irrigation methods. *Scientia Horticulturae, 29*(8), 858-864.

Feddes, R. A., Kowalik, P. J., & Zaradny, H. (1978). *Simulation of field water use and crop yield*. Wageningen: Centre for Agricultural Publishing and Documentation.

Hanson, B. R., Šimůnek, J., & Hopmans, J. W. (2006). Evaluation of urea–ammonium–nitrate fertigation with drip irrigation using numerical modeling. *Agricultural Water Management, 86*(1), 102-113.

Huang, Z. Y., Liu, R. X., & Han, L. B. (2011). Dynamics of water movement in subsurface soil of drip irrigation lawn. *Journal of Northwest Forestry University, 26*(5), 59-65.

So, S., Kang, H., Cho, K. H., & Lee, C. W. (2003). Production of cyclamen using capillary wick system: I. influence of wick material and root substrate composition. *Journal of Korean Flower Resources Society, 11*(2), 199-206.

Kwon, K. M., & Broschat, T. K. (1999). Differences in bedding plant growth and nitrate loss with a controlled-release fertilizer and two irrigation systems. *Horticuture Technology, 9*(2), 206-209.

Lee, C., So, I., Jeong, S., & Huh, M. (2010). Application of subirrigation using capillary wick system to pot production. *Journal of Agriculture and Life Science, 44*(3), 7-14.

Mingsi, L., Shaozhong, K., & Haiyan, S. (2006). Relationships between dripper discharge and soil wetting pattern for drip irrigation. *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE), 22*(4), 32-35.

Liu, Z., Li, P., Hu, Y., & Wang, J. (2015). Wetting patterns and water distributions in cultivation media under drip irrigation. *Computers and Electronics in Agriculture, 112*, 200-208.

Maas, E. (1990). Crop salt tolerance. In K. K. Tanji (Ed.), *Agricultural Salinity Assessment and Management* (pp. 262−304). New York: American Society of Civil Engineering.

Mualem, Y. (1976). A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research, 12*(3), 513-522.

Al Naddaf, O., Livieratos, I., Stamatakis, A., Tsirogiannis, I., Gizas, G., & Savvas, D. (2011). Hydraulic characteristics of composted pig manure, perlite, and mixtures of them, and their impact on cucumber grown on bags. *Scientia horticulturae, 129*(1), 135-141.

Naglič, B., Kechavarzi, C., & Pintar, M. (2012). Modelling of water distribution under drip irrigation systems. *Hmeljarski Bilten, 19*, 100-114.

Phogat, V., Skewes, M. A., Mahadevan, M., & Cox, J. W. (2013a). Evaluation of soil plant system response to pulsed drip irrigation of an almond tree under sustained stress conditions. *Agricultural Water Management, 118*, 1-11.

Phogat, V., Skewes, M., Cox, J. W., Alam, J., Grigson, G., & Šimůnek, J. (2013b). Evaluation of water movement and nitrate dynamics in a lysimeter planted with an orange tree. *Agricultural Water Management, 127*, 74-84.

Phogat, V., Mahadevan, M., Skewes, M., & Cox, J. W. (2012). Modelling soil water and salt dynamics under pulsed and continuous surface drip irrigation of almond and implications of system design. *Irrigation Science, 30*(4), 315-333.

Ramos, T., Šimůnek, J., Gonçalves, M., Martins, J., Prazeres, A., & Pereira, L. (2012). Two-dimensional modeling of water and nitrogen fate from sweet sorghum irrigated with fresh and blended saline waters. *Agricultural Water Management, 111*, 87-104.

Raviv, M., & Lieth, J. H. (2007). *Soilless culture: Theory and practice*. San Diego: Elsevier.

Schaap, M. G., Leij, F. J., & van Genuchten, M. T. (2001). Rosetta: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *Journal of Hydrology, 251*(3), 163−176.

Schröder, F., & Lieth, J. H. (2002). Irrigation control in hydroponics. D. Savvas & H. Passam (Eds.), *Hydroponic Production of Vegetables and Ornamentals* (pp. 263-298). Athens: Embryo Publication.

Shen, M. W., Hao, S., & Fei, L. (2006). Numerical simulation of the effect of irrigation method on soil water movement in greenhouse. *Journal of Zhejiang University, 32*(2), 186-190.

Selim, T., Berndtsson, R., & Persson, M. (2013). Simulation of soil water and salinity distribution under surface drip irrigation. *Irrigation and Drainage, 62*(3), 352-362.

Simunek, J., Van Genuchten, M. T., & Sejna, M. (2012). *The HYDRUS software package for simulating the two-and three-dimensional movement of water, heat, and multiple solutes in variably-saturated media* (Technical Manual Ver. 2). Retrieved July 4, 2017, from https://www.researchgate.net/profile/Jiri_Jirka_Simunek/publication/236901785_The_HYDRUS-2D_Software_Package_for_Simulating_Water_Flow_and_Solute_Transport_in_Two_Dimensional_Variably_Saturated_Media_Version_20/links/565dc02108aeafc2aac88886/The-HYDRUS-2D-Software-Package-for-Simulating-Water-Flow-and-Solute-Transport-in-Two-Dimensional-Variably-Saturated-Media-Version-20.pdf

Šimůnek, J., & Hopmans, J. W. (2009). Modeling compensated root water and nutrient uptake. *Ecological Modelling, 220*(4), 505-521.

Son, J., Oh, M., Lu, Y., Kim, K., & Giacomelli, G. (2006). Nutrient-flow wick culture system for potted plant production: System characteristics and plant growth. *Scientia Horticulturae, 107*(4), 392-398.

Toth, J., Nurthen, E., & Chan, K. (1988). A simple wick method for watering potted plants which maintains a chosen moisture regime. *Animal Production Science, 28*(6), 805-808.

Ünlükara, A., Kurunç, A., Kesmez, G. D., Yurtseven, E., & Suarez, D. L. (2010). Effects of salinity on eggplant (solanum melongena L.) growth and evapotranspiration. *Irrigation and Drainage, 59*(2), 203-214.

Van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal, 44*(5), 892-898.

Van Genuchten, M. T. (1987). *A numerical model for water and solute movement in and below the root zone*. Washington D. C.: United States Department of Agriculture Agricultural Research Service US Salinity Laboratory.

Vrugt, J., Hopmans, J., & Šimunek, J. (2001). Calibration of a two-dimensional root water uptake model. *Soil Science Society of America Journal, 65*(4), 1027-1037.

Wesonga, J. M., Wainaina, C., Ombwara, F. K., Masinde, P. W., & Home, P. G. (2014). Wick material and media for capillary wick based irrigation system in kenya. *International Journal of Science and Research, 3*(4), 2319-7064.