IMPACT OF SOIL HYDRAULIC PROPPERTIES ON ALTERNATE PARTIAL ROOT-ZONE DRIP IRRIGATION (APRDI) WITH BRACKISH WATER

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ABSTRACT

Agriculture consumes the lion share of the available water resources in the developing countries and sustainability of its development depends mainly on irrigation. In this study, a multi-purposes finite element model, HYDRUS-2D/3D, was used to investigate the joint effects of using brackish irrigation water and soil hydraulic properties on soil moisture and salinity distribution and crop water consumption under alternate partial root-zone surface drip irrigation (APRDI; water saving irrigation technique) of tomato growing. Three soil types in El-Salam Canal cultivated land, namely, sand, loamy sand, and sandy loam and three irrigation water salinity levels (0, 1, and 2 dS m-1) were considered during simulation. Simulation results showed that the vertical component of the wetted soil volume in sand was larger than its lateral component. However, the lateral extension of the wetting bulb was larger than the vertical extension in loamy sand and sandy loam. It was also noted that soil salinity at soil surface especially below the plant trunk was higher in sand as opposed to loamy sand and sandy loam. On the other hand, soil salinity at top 30 cm soil layer reached higher salinity values in the scenarios of irrigation water salinity of 1 and 2 dS/m. Based on simulation results, APRDI with non-saline irrigation water is recommended especially for shallow root plants in initially saline soil. However when using brackish water, APRDI is recommended in loamy sand and sandy loam soils than in sand soil especially for shallow root plants

Keywords: Alternate partial root-zone drip irrigation, Soil salinity, Soil hydraulic properties, HYDRUS-2D/3D.

1 INTRODUCTION

Water security is the major concern in the developing countries especially in upstream countries of Nile basin (e.g., Egypt). In these regions, agriculture consumes the lion share of the available water resources and sustainability of its development depends mainly on irrigation. Alternate partial root-zone irrigation (APRI) is an irrigation technique in which a considerable volume of irrigation water can be saved without significant yield reduction (e.g., Du et al., 2005). In this techniques, part of the root system is subjected to drying soil while the remaining part is irrigated normally (e.g., McCarthy et al., 2002; Kang and Zhang, 2004; Fig. 1). Switching of irrigation between the two parts depends on soil moisture content level in the drying soil, crop type, growing stage, soil texture, etc. (e.g., Saeed et al., 2008).

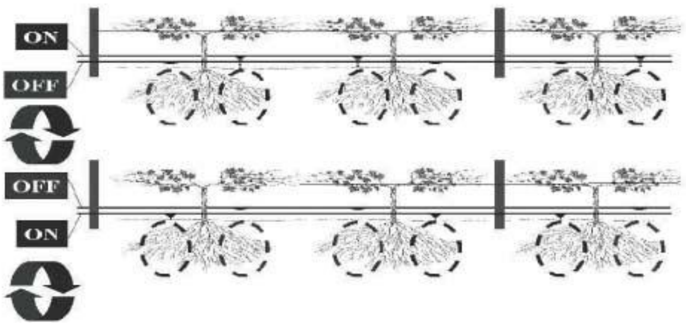

Figure 1. Alternate partial root-zone irrigation (McCarthy et al., 2002).

With using brackish water (i.e, agricultural drainage water), the overuse of fresh water resources in Egypt can be reduced. The annual amount of drainage water is about 18 billion m3 while only 5 billion m3 of this water used for irrigating lands (El-Gamal, 2007). Most of studies dealing with using brackish water in agricultural purposes have been focused on the quality of water itself and its effect on crop yield. Few studies were conducted to address the influence of brackish water on soil salinity and crop water consumption by using a dynamic modeling techniques. However, very few studies were carried out to investigate the effect of using brackish irrigation water associated with APRI on root water uptake and salinity distribution in the root zone (Selim et al., 2011; 2012).

Previous studies dealing with APRI focused mainly on comparing ARPI with other irrigation techniques regarding the yield and water use efficiency under different crops. Kang et al. (2000) investigate the root development for maize under three different furrow irrigation techniques (alternate, fixed, and conventional furrow irrigation) in an arid area. They noted that the number of the roots, their density, and their dry weight were the highest in alternate furrow irrigation. In addition, high grain yield with 50% saving in irrigation amount were obtained with alternate furrow irrigation. Therefore, they ended to that alternate furrow irrigation improves root development as compared to other irrigation techniques. Gencoglan et al. (2006) compared the green bean yield under two drip irrigation techniques, namely, conventional subsurface drip irrigation (SDI) and alternate partial root-zone subsurface drip irrigation (APRSDI). They showed that about 50% of irrigation amount was saved in APRSDI as compared to SDI with approximately same yield. Same conclusion was attained by Huang et al. (2010) when comparing potato yield and water use efficiency under SDI and APRSDI. Kaman et al. (2006) monitored the effect of APRI on soil salinization as compared to other ordinary irrigation techniques. They considered two different crops under different planting conditions. The first was tomato crop which was planted in a greenhouse with conventional drip irrigation. While the second crop was cotton growing in open field with conventional furrow irrigation. They showed that the effect of APRI on soil salinization was limited to the upper 30 cm depth of soil profile. Moreover, the soil salinity at the end of the growing season was higher by 35% in APRI as compared to other techniques, however, soil salinity did not exceed the salt tolerance threshold for both tomato and cotton crops.

Although field experiments reflect the reality, they are still cost and labor consuming. The lack in finance is considered a limiting factor when designing field experiment which in turn will affect the quality of the results. Numerical modeling, on the other hand, is considered cheap, rapid, and labor saving tool that can be used to overcome the obstacles that facing field experiments. Also by using numerical modeling, many factors and conditions can be considered. The HYDRUS-2D/3D model (Šimůnek et al., 2016a) is considered the widely used software for simulating water flow and solute transport in variably saturated porous media with or without crops under different boundary conditions and irrigation techniques (e.g., Selim et al., 2013; Mguidiche et al., 2015; Šimůnek et al., 2016b). Although HYDRUS-2D/3D model was extensively used worldwide to simulate water flow and salinity distribution under different irrigation techniques with or without crops, very few researchers used it to simulate APRI (Zhou et al., 2007, Selim et al., 2011; 2012). Selim et al. (2011) investigated the impact of inter-plant emitter distance (IPED) on soil salinity distribution and root water uptake under APRDI. They only considered one soil type (i.e. loamy sand) and three salinity levels of irrigation water (0, 1, 2 dS m^{-1}). They concluded that short IPED is recommended in APRDI when using brackish irrigation water especially for plants with shallow root system. Selim et al. (2012) used HYDRUS-2D/3D model to investigate the impact of geometric design of alternate partial root-zone subsurface drip irrigation (APRSDI) with brackish water for growing tomato on salinity distribution. They also considered loamy sand soil only. They found that short IPED is recommended in APRSDI with or without brackish irrigation water regardless of the emitter depth. In the view of the above, the aim of this study is to investigate the joint effects of using brackish irrigation water and soil hydraulic properties on soil water and salinity distribution patterns under APRDI of tomato growing.

2 METHODS AND MATERIALS

In the present work, a multi-purposes finite element model, HYDRUS-2D/3D, was used to investigate the joint effects of using brackish irrigation water and soil hydraulic properties on soil water and salinity distribution, root water uptake under (APRDI) of tomato growing within El-Salam Canal region. The simulated APRDI domain was shown in Figure 2. The depth of the simulation domain was 100 cm while its width was 140 cm. Two surface drip irrigation lines were used to irrigate each row of tomato crop which located in the mid-distance between drip lines. The distance between drip lines was 40 cm while the distance between emitters was 35 cm. Unstructured triangular mesh with 3239 2-D elements was used to spatially discretize the simulation domain. Also, mesh refinement was done closer to the soil surface where rapid change in flux occurs.

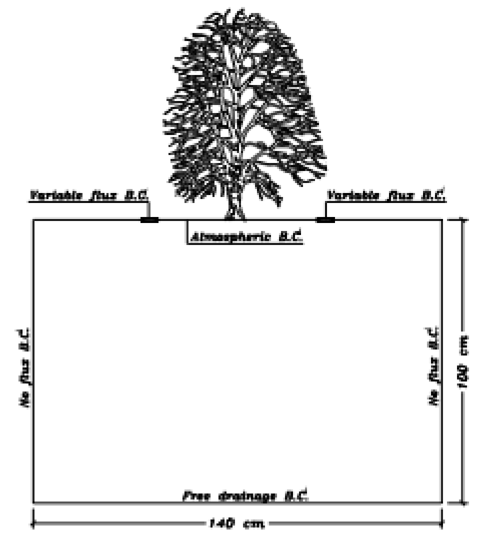

Figure 2. Conceptual diagram of simulated area.

Initial water content throughout the flow domain was assumed uniform so that the effective saturation was the same for all soil types while initial soil salinity was set according to field measurements (Abou Lila et al., 2005). Pressure plate apparatus was used to estimate soil hydraulic parameters for the collected soil samples from El-Salam Canal cultivated lands to estimate soil hydraulic parameters "Table 1".

Table 1. Hydraulic parameters of simulated soil types

Soil type	θ_r	θ_s	α	n	K_s (cm d^{-1})	l
Sand	0.024	0.447	0.124	1.78	878.20	0.50
Loamy sand	0.074	0.453	0.045	1.72	288.5	0.50
Sandy loam	0.038	0.486	0.025	1.72	194.06	0.50

θ_r: residual water content
θ_s: saturated water content
K_s: saturated hydraulic conductivity
α: inverse of the air-entry value
n: pore-size distribution index
l: pore-connectivity parameter

For model execution, solute parameters should be assigned. Longitudinal dispersivity (ε_L) was set equal to one-tenth of the depth of simulation domain while transversal dispersivity (ε_T) was taken as $0.1\varepsilon_L$ (Beven et al., 1993; Cote et al., 2001). Molecular diffusion and adsorption isotherms were ignored during simulation. Salinity transport was simulated based on the hypothesis that the solutes were non-reactive and there was neither net solubilization nor dissolution.

Zero flux boundary condition was selected along the vertical sides of the simulation domain while free drainage boundary was assigned at the bottom boundary as the water table is situated 1.50 m below the soil surface. Atmospheric boundary condition permitting crop evapotranspiration (ET_c) was set along the top edge of simulation domain except the location of emitters. Variable flux boundary condition was assumed at the location of emitters during irrigation and zero flux in fallow time. Crop ET_c was taken as Selim et al. (2012) where same study area was considered during the present study. During simulation, potential evapotranspiration was partitioned into potential evaporation (E_p = 0.05 ET_c) and potential transpiration (T_p = 0.95 ET_c). In addition, the applied irrigation water was set equal to 75% of the amount used in case of ordinary drip irrigation. The irrigation duration during the day was estimated based on the applied irrigation water and emitter discharge of 1 l h^{-1}. A third type Cauchy boundary condition at the location of emitter was used to consider the impact of irrigation water salinity during irrigation events. In the present study, the solute was accompanied with the irrigation water and irrigation water salinity was taken equal to 0, 1.0, and 2.0 dS m^{-1}.

Feddes model (Feddes et al., 1978) was employed to simulate water uptake from the soil during simulation. The following parameters were used in simulation: P_o = -1, P_{opt} = -2, P_{2high} = -800, P_{2low} = -1500, P_3 = -8000 cm, r_{2high} = 0.5 cm d^{-1}, r_{2low} = 0.1 cm d^{-1}. Threshold model (Mass, 1990) was used to deem the osmotic effects with threshold = 2.5 dS m^{-1} and a slope of 9.9%. The Vrugt model (Vrugt et al., 2001) was used to illustrate the root distribution for tomato. The root distribution for tomato crop "Fig. 3" was set as used by Selim et al. (2011).

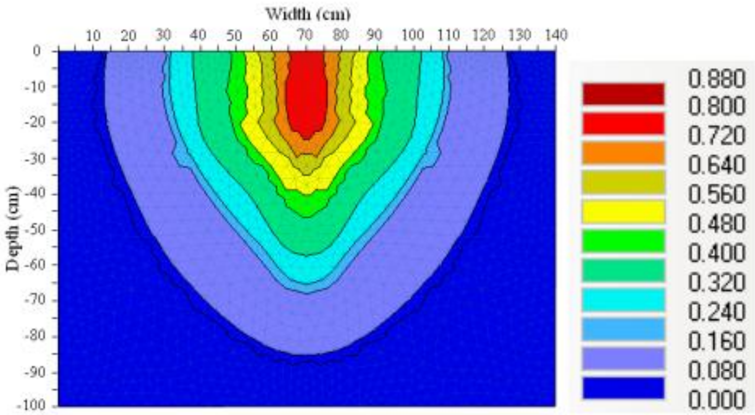

Figure 3. Root distribution used for HYDRUS-2D simulation (units: percentages of the total roots; Selim et al., 2011).

Series of simulation scenarios were performed for 40 days simulation period including three different soil types in El-Salam Canal cultivated land (sand, loamy sand, and sandy loam) and three irrigation water salinity levels (0, 1, and 2 dS m^{-1}).

3 RESULTS AND DISCUSSIONS

3.1 Wetting Patterns

Figure 4 shows the spatial distribution of soil moisture content for different soil types at the end of first irrigation event and at the end of simulation period. As expected for all soil types, the vertical and lateral extensions of the wetting bulb increased with irrigation with maximum soil moisture content close to the emitter. As the distance from the emitter increased, soil moisture content decreased. Between irrigation events soil moisture content decreased due to root water uptake and redistribution process. Similar wetting and drying patterns took place during the entire simulation period.

In sand, the vertical component of the wetting bulb was larger than the horizontal component. At the end of first irrigation event the wetted diameter at soil surface was about 30 cm while wetted depth was about 33 cm directly below the emitter. This is due the low holding capacity of sand and due to that the gravity force governs water flow. In loamy sand and sandy loam, the lateral extension of the wetting bulb was larger than the vertical extension. In loamy sand, the wetted diameter and depth were 40 and 25 cm at the end of first irrigation event respectively. While it were 44 and 24 cm in sandy loam respectively. This can be attributed to small pores size that reduced the infiltration capacity. The limited infiltration capacity force water to move laterally. It was also noted that the lateral component of the wetting bulb was slightly larger in sandy loam than loamy sand. This is due to lower hydraulic conductivity and higher water holding capacity of sandy loam as compared to loamy sand.

Figure 4 also illustrates that at the end of simulation period, soil moisture content values in the maximum root density zone were higher in case of fine-textured soil than in coarse-textured soil. Therefore, APRDI is recommended in loamy sand and sandy loam soils than in sand soil especially for shallow root plants.

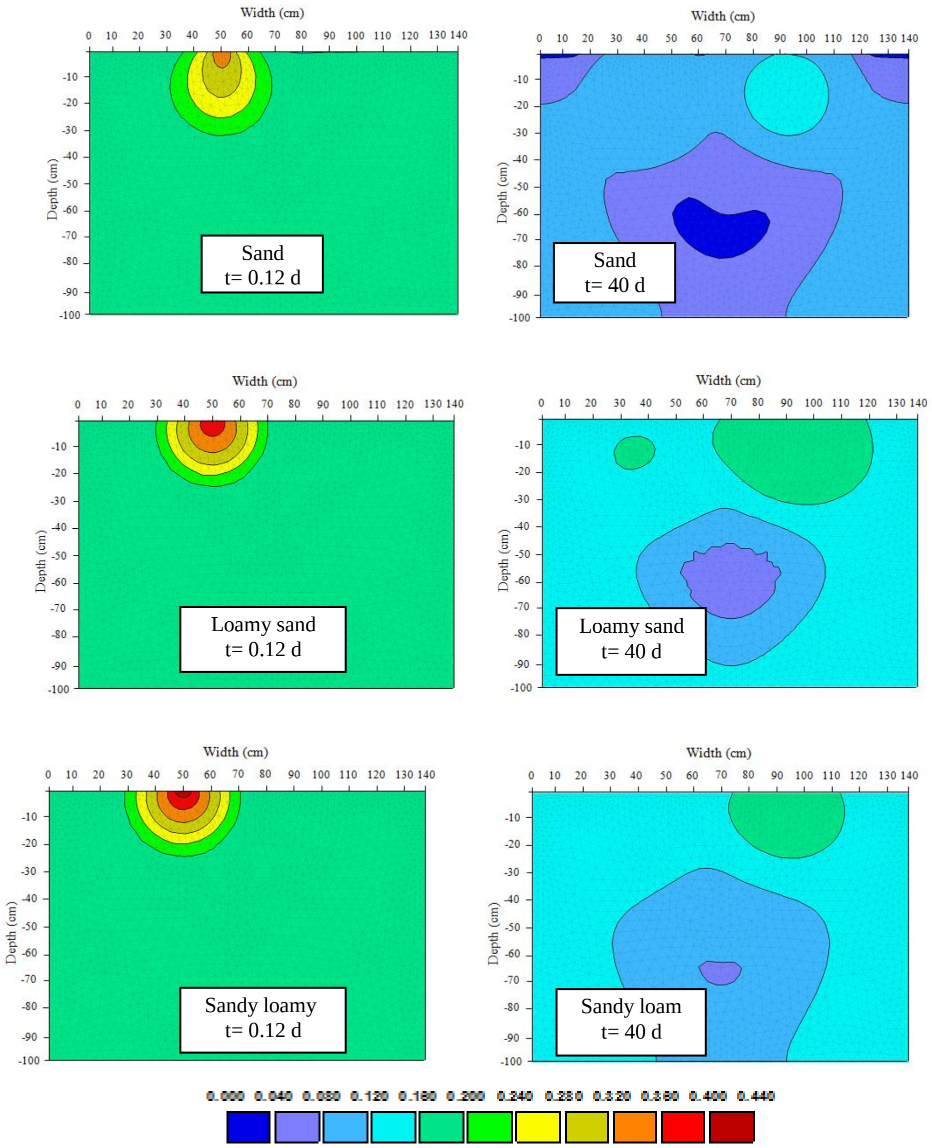

Figure 4. Spatial distribution of soil moisture content at the end of first irrigation event and at the end of simulation period (Units: $m^3\ m^{-3}$).

3.2 Soil Water Salinity

Higher salinity values in the zone of maximum root density generally has an adverse impact on plant growth and yield since it reduces transpiration and root water uptake rates. In all scenarios, at the end of the first irrigation event, significant salt leaching took place within the wetting bulb with maximum reduction in soil salinity near the emitter. Soil salinity decreased to levels lower than initial value in the region of the wetting bulb. As the distance from emitter increased the reduction in soil salinity decreased. Figure 5 visualizes soil salinity distribution in the flow domain at the end of simulation period. It was noted that for all simulation scenarios surface soil salinity reached its highest values at the edges of the simulation domain followed by the middle of simulation domain (i.e., below plant trunk). It was also noted that soil salinity at soil surface especially below the plant trunk was higher in sand as opposed to loamy sand and sandy loam. This may be attributed to the limited lateral extension of the wetting bulb in sandy soil as compared to other soil types. On the other hand, soil salinity at top 30 cm soil layer reached higher salinity values in the scenarios of irrigation water salinity of 1 and 2 dS m^{-1}. Therefore, APRDI with non-saline irrigation water is recommended especially for shallow root plants. Nevertheless, APRDI with low irrigation water salinity (i.e, 1 dS m^{-1}) can be used in loamy sand and sandy loam for crops of small lateral root extension. It is worth mentioning that periodic leaching is required in this case to avoid the harmful salinity effects on affects seed germination and crop establishment.

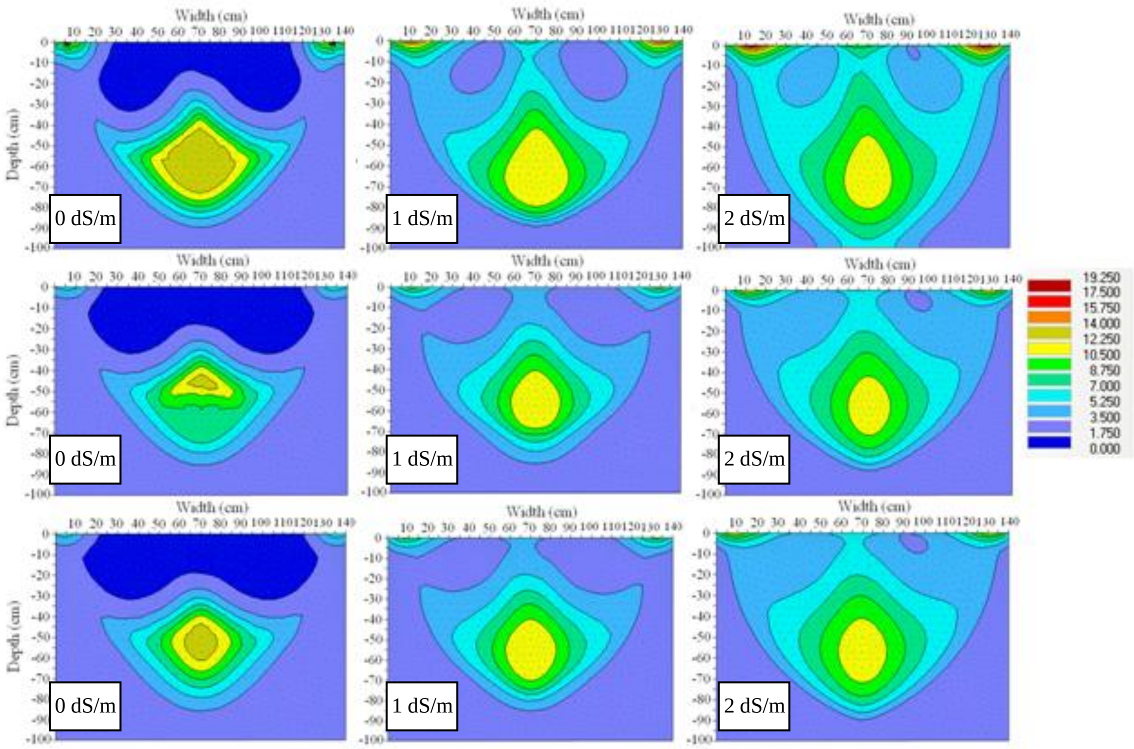

Figure 5. Spatial distribution of soil salinity at the end of simulation period (top row: Sand, mid row: loamy sand, and bottom row: sandy loam; plant trunk in the middle of simulation domain).

3.3 Effect of Irrigation Water Salinity on Root Water Uptake

Soil moisture content and soil salinity significantly affect root water uptake rate. Figure 6 shows the temporal variation in water uptake by plant roots during the simulation period for different soil types and irrigation water salinity levels. The figure manifests that the salinity of irrigation water has a great effect on the amount of water consumed by plant roots. As the salinity of irrigation water increased root water uptake rates decreased. In addition, the joint effect of irrigation water salinity and soil hydraulic properties had a significant influence on root water uptake rate. For sandy soil, the root water uptake rate decreased during simulation period from 0.72 to 0.55 cm d^{-1}, from 0.72 to 0.48 cm d^{-1}, and from 0.72 to 0.41 cm d^{-1} with irrigation water salinity levels of 0, 1, and 2 dS/m, respectively. For loamy sand soil, the root water uptake rate decreased during simulation period from 0.72 to 0.57 cm d^{-1}, from 0.72 to 0.51 cm d^{-1}, and from 0.72 to 0.44 cm d^{-1} with irrigation water salinity levels of 0, 1, and 2 dS/m, respectively. For sandy loam soil, the root water uptake rate decreased during simulation period from 0.72 to 0.59 cm d^{-1} with non-saline irrigation water. For irrigation water salinities of 1 and 2 dS/m, root water uptake rates had same values as in loamy sand soil. The lower values of root water uptake in sand soil as compared to other soil types were attributed to the higher soil salinity levels at the zone of maximum root density and directly below the plant trunk. Therefore, APRDI is recommended in fine-textured soil than in coarse-textured soil when using brackish irrigation water.

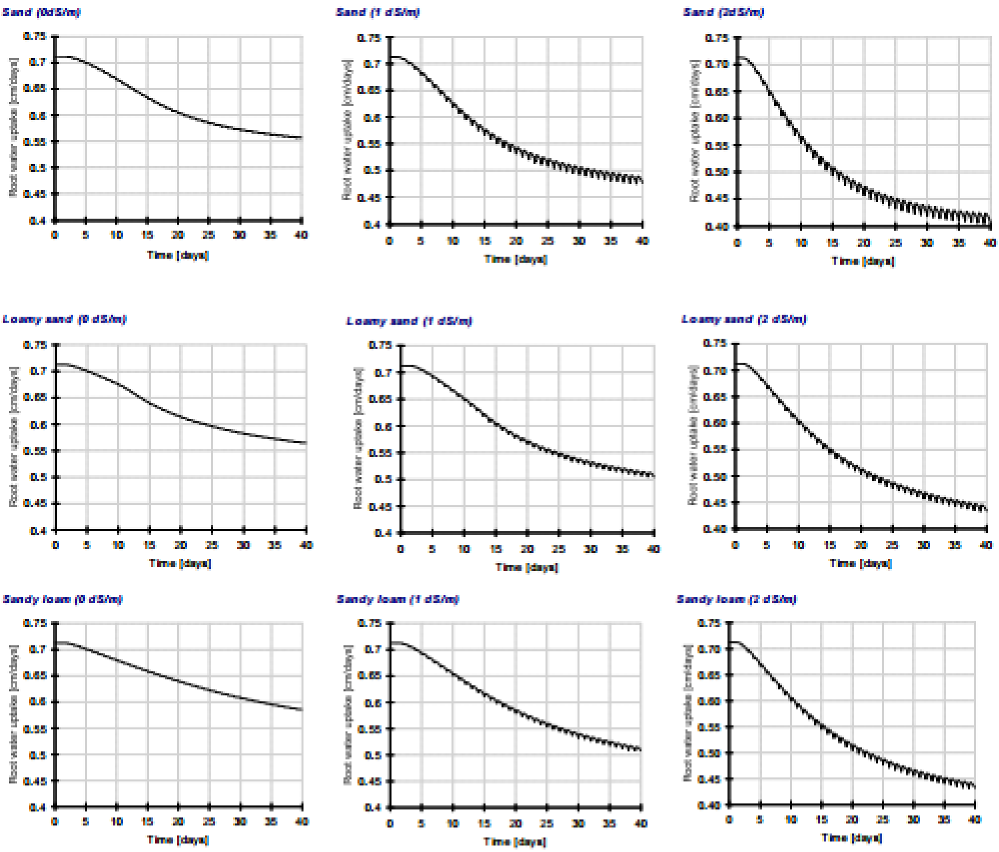

Figure 6. Temporal variation in root water uptake

4 SUMMARY AND CONCLUSION

APRDI is considered one of the most efficient water saving irrigation techniques in which a considerable amount of irrigation water can be saved without significant reduction in crop yield. With using brackish water simultaneously with APRDI, more fresh water can be saved. In the current study, HYDRUS-2D/3D model was used to investigate the joint effects of using brackish irrigation water and soil hydraulic properties on soil moisture and salinity distribution and crop water consumption under APRDI of tomato growing. Simulations were conducted for three different soil types in El-Salam Canal cultivated land, namely, sand, loamy sand, and sandy loam during a 40-day simulation period considering three irrigation water salinity levels (0, 1, and 2 dS m^{-1}). The applied irrigation water was assumed 25% less than conventional surface drip irrigation system. Simulation results revealed that soil moisture content values were higher in the zone of maximum root density in case of fine-textured soil than in coarse-textured soil. Also, due to the limited lateral component of the wetting bulb in sand soil as compared to other soil types, surface soil salinity below the plant trunk was higher in sand as well as in the top 30 cm soil depth. The higher salinity values causes a significant reduction in root water uptake rate in sand as compared to other soil types. Also, as the salinity of irrigation water increased, root water uptake decreased. Based on simulation results, APRDI is recommended with non-saline irrigation water especially in initially saline soil to reduce the adverse impact of soil salinity on seed germination. However when using brackish water, APRDI is recommended in loamy sand and sandy loam soils than in sand soil especially for shallow root plants.

REFERENCES

Abou Lila, T., Balah, M. & Hamed, Y. (2005) Solute infiltration and spatial salinity distribution behavior for the main soil types at El-Salam Canal project cultivated land. *Port Said Eng. Res. J*, 9, pp.242-253.

Beven, K., Henderson, D. & Reeves, A. (1993). Dispersion parameters for undisturbed partially saturated soil. *J. Hydrol*, 143, pp.19–43.

Cote, C., Bristow, K., Charlesworth, P., Cook, F. & Thorburn, P. (2003) Analysis of soil wetting and solute transport in subsurface trickle irrigation. *Irrig. Sci*, 22, pp.143–156.

Du, T., Kang, S., Hu, X. & Yang, X. (2005) Effect of alternate partial root-zone drip irrigation on yield and water use efficiency of cotton. *Sci Agri Sinica*, 38, pp.2061-2068.

El-Gamal, F. (2007) Use of non conventional water resources in irrigated agriculture. Water saving in Mediterranean agriculture and future research needs [Vol. 2]. *Proc. Int. Conf. WASAMED Project*, Valenzano, Italy.

Feddes, R., Kowalik, P. & Zaradny, H. (1978). *Simulation of field water use and crop yield*. John Wiley & Sons, New York.

Gencoglan, C., Altunbey, H. & Gencoglan, S. (2006). Response of green beanto subsurface drip irrigation and partial root-zone drying irrigation. *Agric. Water Manage*, 84, pp.274–280.

Huang, Z., Qi, X., Fan, X., Hu, C., Zhu, D., Li, P. & Qiao, D. (2010). Effects of alternate partial root-zone subsurface drip irrigation on potato yield and water use efficiency. *Ying Yong Sheng Tai Xue Bao*, 21, pp.79–83.

Kaman, H., Kirda, C., Cetin, M. & Topcu, S. (2006) Salt accumulation in the root zones of tomato and cotton irrigated with partial root-drying technique. *Irrig. Drain*, 55, pp.533-544.

Kang, S., Liang, Z., Pan, Y., Shi, P. & Zhang, J. (2000) Alternate furrow irrigation for maize production in arid area. *Agric. Water Manag*, 45, pp.267-274.

Kang, S. & Zhang, J. (2004) Controlled alternate partial root-zone irrigation: its physiological consequences and impact on water use efficiency. *J. Experim. Bot*, 55, pp.2437-2446.

Maas, E. (1990) Crop salt tolerance. In: Tanji, K.K. (Ed.), Agricultural Salinity Assessment and Management. *ASCE Manuals and Report on Engineering Practice 71*. American Society of Civil Engineers, New York, pp. 262–304.

McCarthy, M., Loveys, B. & Dry, P. (2002) Regulated deficit irrigation and partial rootzone drying as irrigation management techniques for grapevines. Deficit Irrigation Practices, *Water Reports Publication n. 22*, FAO, Rome, pp.79–87.

Mguidiche, A., Provenzano, G., Douh, B., Khila, S., Rallo, G. & Boujelben, A. (2015) Assessing Hydrus-2D to simulate soil water content(SWC) and salt accumulation under an SDI system: Application to a potato crop in a semi-arid area of central Tunisia. *Irrig. Drain,* 64, pp.263-274.

Selim, T., Berndtsson, R., Persson, M., Somaida, M., El-Kiki, M., Hamed, Y. & Mirdan, A. (2011) Assessment of inter-plant emitter distance and effects of irrigation water salinity on APRDI using Hydrus-2D. *Europ. J. Sci. Res*, 58(2), pp.266-277.

Selim, T., Berndtsson, R., Persson, M., Somaida, M., El-Kiki, M., Hamed, Y., Mirdan, A. & Zhou, Q. (2012) Influence of geometric design of alternate partial root-zone subsurface drip irrigation (APRSDI) with brackish water on soil moisture and salinity distribution. *Agr. Water Manag*, 103, pp.182-190.

Selim, T., Bouksila, F., Berndtsson, R. & Persson, M. (2013) Soil water and salinity distribution under different treatments of drip irrigation. *Soil Sci. Soc. Amer. J,* 77, pp.1144-1156.

Šimůnek, J., Van Genuchten, M. & Sejna, M. (2016a) Recent developments and applications of the HYDRUS computer software packages. *Vadose Zone J*, 15(7),pp.25, doi:10.2136/vzj2016.04.0033, 2016.

Šimůnek, J., Bristow, K., Helalia, S. & Siyal, A. (2016b) The effect of different fertigation strategies and furrow surface treatments on plant water and nitrogen use. *Irrig. Sci*, 34, pp.53-69.

Vrugt, J., van Wijk, M., Hopmans, J. & Simunek, J. (2001) One-, two-, and threedimensional root water uptake functions for transient modeling. *Water Resour. Res*, 37, pp2457- 2470.

Zhou, Q., Kang, S., Zhang, L. & Li, F. (2007) Comparison of APRI and Hydrus-2D models to simulate soil water dynamics in a vineyard under alternate partial root-zone drip irrigation. *Plant Soil,* 291, pp. 211-223.