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USING HYDRUS-2D MODEL TO EVALUATE WATER CONTENT IN VERTICAL DIRECTION FOR LETTUCE UNDER SUBSURFACE DRIP IRRIGATION

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Abstract

Produce can become contaminated with viral or bacterial pathogens in the irrigation water The contamination of romaine lettuce (*Lactuca sativa* L.) by irrigation water was assessed by modeling a subsurface drip irrigation (SDI) system with HYDRUS-2D. The model simulated the water movement in the soil to ensure that the soil surface does not become wet and consequently contaminated. An application efficiency of 95% for subsurface drip irrigation on Gila loam was used. The results obtained from this modeling study aim to prove that subsurface irrigation systems may effectively reduce the risk of contamination. HYDRUS 2D/3D simulations revealed that water would not wet the soil to a distance of 20 cm above the drip emitter in an SDI system. Thus, a dripline placed 20 cm below the surface should avoid soil surface wetting in this type of soil. This means that so long as the soil surface remains dry, subsurface irrigation has excellent potential to reduce health risks when microbial-contaminated water is used since the above-ground portion of the plant would never get in direct contact with the contaminated water. Hence, the simulations confirmed that by keeping the soil surface dry and understanding the water root-zone fluxes, crop contamination could be prevented with SDI while at the same time meeting the leafy greens water requirements.

Keywords: HYDRUS-2D, modeling, subsurface drip irrigation, contamination, lettuce.

Introduction

Produce can become contaminated with viral or bacterial pathogens in the irrigation water (Beuchat, 2002). Outbreaks of foodborne illnesses have been linked to the consumption of leafy greens and vegetables. The most common pathogen associated with these outbreaks is *Escherichia coli* O157:H7 (Mootian et al., 2009). The 2018 outbreak linked to *Escherichia coli* O157:H7–contaminated romaine lettuce resulted in 210 confirmed cases, 96 hospitalizations, and 5 deaths in the United States (CDC, 2018).

Research efforts to ensure the safety of produce have been conducted. Water movement and wetting patterns of the soil surface appeared to be directly associated with crop contamination (Song, 2004). Several studies have suggested that subsurface drip irrigation (SDI) can be an alternative technique for safer irrigation with contaminated water (Reyes and Slack, 2021). SDI involves drip application equipment installed below the soil surface (ASAE 2005). In addition to the benefits related to increasing crop yields and water use efficiency (Schneider and Howell 2001; Camp 1998), it has been suggested that SDI systems can also reduce health risks from reclaimed water use by minimizing the exposure of the irrigation water to people or agricultural produce (Reyes-Esteves and Slack, 2021; Reyes-Esteves, 2020; Slack et al., 2017; Enriquez et al., 2003; Alum et al., 2000; Oron et al., 1995, 1992, 1991; Phene and Ruskin, 1995; Ruskin, 1992). Applications of SDI using wastewater began to appear in the 1990s (Song, 2004). Since irrigation water does not usually reach the soil surface due to direct irrigation to the crop root zone, the exposure of irrigation water to produce would be minimized (Reyes-Esteves and Slack, 2020; Absar et al., 2000). It is alleged that the soil acts as a living filter to remove pathogenic microorganisms (Oron et al., 1995).

Numerical simulation is a fast and inexpensive approach for studying and optimizing design and management practices. HYDRUS-2D is a two-dimensional, finite element model developed at the US Department of Agriculture Salinity Laboratory in Riverside, CA (Šimůnek et al., 2008). It provides a numerical solution of the Richards' equation to simulate soil moisture and water flow in unsaturated soils. HYDRUS 2D/3D simulations have been validated and calibrated with experimental data in many successful research studies (Provenzano G., 2007). The main objective of this study was to determine if SDI systems with the appropriate design and management can reduce or eliminate the contamination of the edible portions of a leafy green vegetable when contaminated irrigation water is used. Thus, an evaluation of a minimum depth at which SDI dripline could be placed in a typical Gila loam soil to leafy greens in growing Arizona regions was carried out to investigate design approaches associated with SDI to suggest design solutions by utilizing the software HYDRUS-2D.

Materials and Methods

Numerical Modeling with HYDRUS-2D

HYDRUS-2D is a software package for simulating water, heat, and solute movement in two and three-dimensional variably saturated media (Šimůnek et al., 2008). The HYDRUS-2D predictions of water content distribution have been found to be in excellent agreement with field data (Reyes-Esteves and Slack, 2019). The literature supports the use of HYDRUS-2D as a tool for research, irrigation engineering, and management practices (Provenzano G., 2007). Therefore, the two-dimensional module of the HYDRUS-2D version 2.05 (Šimůnek et al., 2008) was used to model the water flow in an SDI system.

HYDRUS-2D simulated the soil water flow and computed the spatial and temporal distributions of soil water potential and soil water content. Root water uptake, *ETc*, and water flux rates were input data as well as a distance of 20 cm from the water source simulating a dripline depth of a typical SDI for lettuce in that region. HYDRUS-2D, provided a numerical solution of the Richards' equation (1931) to simulate soil moisture and water flow in unsaturated soils:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial x} + K(h)\right] - S(h) \quad (1)$$

Where θ is the soil's volumetric water content (cm^3 cm^{-3}), h is the soil water pressure head (cm), $S(h)$ is a sink term (cm^3 cm^{-3} day^{-1}) representing plant root water uptake, t is time (day), $K(h)$ is the unsaturated hydraulic conductivity function (cm day^{-1}), and x and z are the horizontal and vertical spatial coordinates (cm).

To solve Eq. (1), required the use of the soil hydraulic properties of Gila loam, a soil typical of the type used for crop production in Arizona, as defined by the soil water retention function, $\theta(h)$, and unsaturated hydraulic conductivity function, $K(h)$, Table 1. The unsaturated hydraulic properties were calculated using the Mualem (1976) and van Genuchten (1980) equations and represented the effective saturation, S_e by:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{(1 + |\propto_{VG} h|^n)^m} \quad (2)$$

And the unsaturated hydraulic conductivity as:

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{\frac{1}{m}}\right)^m\right]^2 \quad (3)$$

Where θ_r is the residual water content (cm^3 cm^{-3}), θ_s is the saturated water content (cm^3 cm^{-3}), S_e is the effective water saturation, K_s is the saturated hydraulic conductivity (cm day^{-1}), α_{VG} is the inverse of the air entry value (cm^{-1}), n is an index parameter related to the pore size distribution, $m = 1 - 1/n$, and l is a pore connectivity parameter.

Table 1. Soil hydraulic function parameters of Gila soil. Killen (1988).

Soil type	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α_{VG} (cm^{-1})	n	K_s (cm day^{-1})	l
Gila Loam	0.078	0.39*	0.036	1.56	5.02*	0.5

Lettuce, like other greens, is shallow-rooted and develops quickly. Lettuce roots tend to grow to a depth of approximately 20 cm – 25 cm. Root distribution was assumed to have a maximum rooting density near the dripline. The vertical root distribution was set to a maximum rooting depth of 25 cm depth and a depth of maximum intensity of 15 cm. The sink term, *S(h)*, in Eq. (1) is the volume of water removed per unit time from a unit volume of soil due to plant water uptake. Feddes et al. (1978) defined it as:

$$S(h) = \propto (h)\ x\ S_p \qquad (4)$$

Where *α(h)* is a dimensionless root water-uptake response function with values between 0 and 1, to account for soil water stress, and S_p is the potential water uptake rate (day^{-1}). The variable *Sp* (cm^3 cm^{-3} day^{-1}) is equal to *S(h)* during periods of no water stress when *α (h)* = 1.

Water uptake *α(h)* is assumed to be zero close to saturation and also close to the wilting point pressure head. If the soil is too dry or too wet at any given location (*x, z*), then $\alpha < 1$, and the uptake at position (*x, z*) is linearly reduced with the magnitude determined by the reduction function parameters for lettuce as selected from a database (Taylor and Ashcroft, 1972). The potential root water uptake rate, S_p, is calculated from (Šimůnek and Hopmans, 2009):

$$S_p(x, y) = \beta(x, z) L_x T_p \qquad (5)$$

Where β *(x, z)* (cm^{-2}) is the normalized root density for any coordinate in the two-dimensional soil domain, L_x (cm) denotes the width of the soil surface associated with the potential plant transpiration, T_p (cm day^{-1}).

Lettuce Water Requirements

Crop evapotranspiration of lettuce *ETc* was calculated (See Fig. 1) with the Penman-Monteith equation (Allen et al., 1998):

$$ET_c = K_c * ET_o \qquad (6)$$

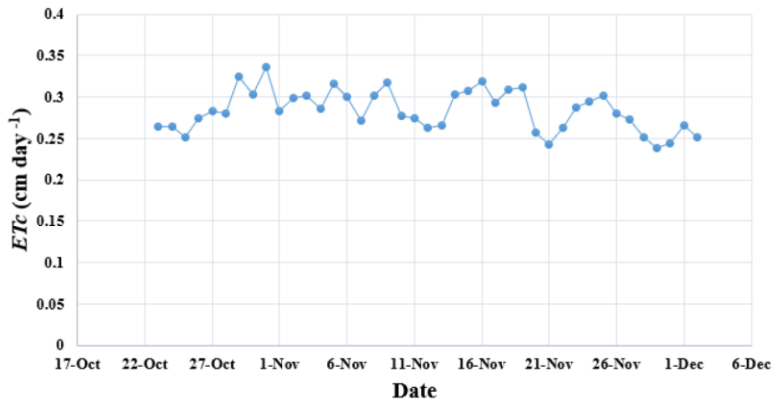

Figure. 1 Lettuce ETc during the simulated period (Oct 23, 2019 − harvesting Dec 2, 2019).

The crop coefficient K_c was assumed to be 0.26 at the initial growth stage, between 0.26 and 1 at the development stage, 1 at the mid-season, and 0.90 at the late-season based on Oliveira (2005) as adapted from Martin and Gilley (1993) for the lettuce crop coefficient curve for arid zones and moderate winds. The reference evapotranspiration ET_o was calculated using the Hargreaves method (Hargreaves and Samani, 1985).

$$ET_0 = 0.0023 R_a (T_{mean} + 17.8) TD^{0.5} \quad (7)$$

Where ET_o is the reference crop evapotranspiration (cm d^{-1}), R_a is the extraterrestrial solar radiation in (cm d^{-1}), T_{mean} is the mean air temperature (°C), and TD is the average daily temperature (°C).

Water Flux Simulations with HYDRUS-2D

Space domains are in two dimensions and represent a typical plant bed used for lettuce production in Southern Arizona. The field domain represented half of a bed.The spatial domain was characterized in HYDRUS-2D using finite triangular elements with element size gradually increasing with distance from the emitter. A free drainage boundary condition was applied along the bottom boundary and an atmospheric boundary condition along the top boundary. All other remaining boundaries were assigned a zero-water flux condition. The initial condition for the pressure head was −400 cm or −0.3 bar that represented field capacity.

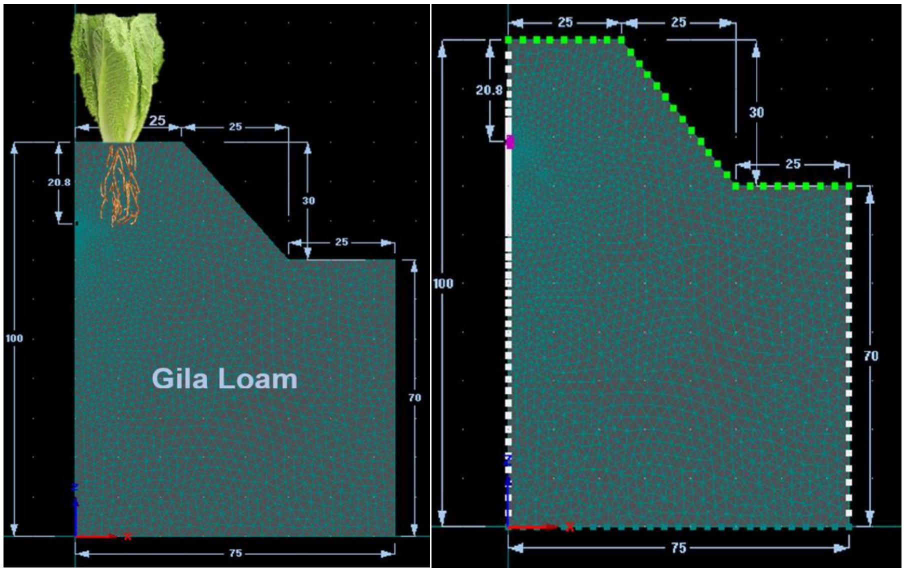

Figure 2. Space domain, finite-element mesh, and boundary conditions of SDI of the field simulations.

Design and Management of Subsurface Irrigation

Two irrigation scenarios were modeled with HYDRUS-2D, Table 2. For scenarios 1 the net irrigation requirement was set equal to *ETc* in cm day^{-1} because no precipitation was taken into account in order to evaluate the potential of SDI in terms of maintaining the soil surface dry, which means no direct contact of the edible portion with contaminated water. Gross irrigation was obtained by dividing that net irrigation in cm day^{-1} by 0.95. For scenarios 2, a water flux discharge of 0.51 cm day^{-1} (300 ml/day) was simulated.

Table 2. Two modeling scenarios were utilized in HYDRUS 2D/3D.

Scenario	Flux water discharge (cm day^{-1})
1	Gross irrigation (0.25 – 0.35) according ET_c variations.
2	Gross irrigation of 0.51 (300 ml)

An irrigation schedule of every other day was used for the period of Nov. 3, 2019 – Nov. 20, 2019 (development and mid-stage of lettuce). The authors decided to model daily irrigation the last twelve days of the growing season to simulate the maximum exposure lettuce could have to contaminated water right before harvesting when the plant is fully developed and ready to be eaten by consumers. Thus, the irrigation that irrigation period started on Nov. 20, 2019, and was carried out for 12 days in a row before harvest (Nov. 20, 2019 – Dec. 1, 2019). See Table 3. for the full irrigation schedule.

Table 3. Irrigation scheduling of lettuce at the greenhouse

Day #	Date	ET_c (cm day^{-1})	Net Irrigation (cm day^{-1}) for scenario 1	Gross Irrigation (cm day^{-1}) for scenario 1	Net Irrigation (cm day^{-1}) for scenario 2	Gross Irrigation (cm day^{-1}) for scenario 2	Event
1	23-Oct-19	0.26	0.26	0.27	0.48	0.51	Irrig. 1
2	24-Oct-19	0.26	0.26	0.28	0.48	0.51	Irrig. 2
3	25-Oct-19	0.25	0.25	0.26	0.48	0.51	Irrig. 3
4	26-Oct-19	0.27	0.27	0.29	0.48	0.51	Irrig. 4
5	27-Oct-19	0.28	0.28	0.30	0.48	0.51	Irrig. 5
6	28-Oct-19	0.28	0.28	0.30	0.48	0.51	Irrig. 6
7	29-Oct-19	0.32	0.32	0.34	0.48	0.51	Irrig. 7
8	30-Oct-19	0.30	0.30	0.32	0.48	0.51	Irrig. 8
9	31-Oct-19	0.34	0.34	0.35	0.48	0.51	Irrig. 9
10	1-Nov-19	0.28	0.28	0.30	0.48	0.51	Irrig. 10
11	2-Nov-19	0.30	0.30	0.00	0.00	0.00	No irrigation
12	3-Nov-19	0.29	0.29	0.30	0.48	0.51	Irrig. 11
13	4-Nov-19	0.32	0.32	0.00	0.00	0.00	No irrigation
14	5-Nov-19	0.30	0.30	0.32	0.48	0.51	Irrig. 12
15	6-Nov-19	0.27	0.27	0.00	0.00	0.00	No irrigation
16	7-Nov-19	0.30	0.30	0.32	0.48	0.51	Irrig. 13
17	8-Nov-19	0.32	0.32	0.00	0.00	0.00	No irrigation
18	9-Nov-19	0.28	0.28	0.29	0.48	0.51	Irrig. 14
19	10-Nov-19	0.27	0.27	0.00	0.00	0.00	No irrigation
20	11-Nov-19	0.26	0.26	0.28	0.48	0.51	Irrig. 15
21	12-Nov-19	0.27	0.27	0.00	0.00	0.00	No irrigation
22	13-Nov-19	0.30	0.30	0.32	0.48	0.51	Irrig. 16
23	14-Nov-19	0.31	0.31	0.00	0.00	0.00	No irrigation
24	15-Nov-19	0.32	0.32	0.34	0.48	0.51	Irrig. 17
25	16-Nov-19	0.29	0.29	0.00	0.00	0.00	No irrigation
26	17-Nov-19	0.31	0.31	0.33	0.48	0.51	Irrig. 18
27	18-Nov-19	0.31	0.31	0.00	0.00	0.00	No irrigation
28	19-Nov-19	0.31	0.31	0.00	0.00	0.00	No irrigation
29	20-Nov-19	0.24	0.24	0.25	0.48	0.51	Irrig. 1 CW
30	21-Nov-19	0.26	0.26	0.28	0.48	0.51	Irrig. 2 CW
31	22-Nov-19	0.29	0.29	0.30	0.48	0.51	Irrig. 3 CW
32	23-Nov-19	0.29	0.29	0.31	0.48	0.51	Irrig. 4 CW
33	24-Nov-19	0.30	0.30	0.32	0.48	0.51	Irrig. 5 CW
34	25-Nov-19	0.28	0.28	0.30	0.48	0.51	Irrig. 6 CW
35	26-Nov-19	0.27	0.27	0.29	0.48	0.51	Irrig. 7 CW
36	27-Nov-19	0.25	0.25	0.26	0.48	0.51	Irrig. 8 CW
37	28-Nov-19	0.24	0.24	0.25	0.48	0.51	Irrig. 9 CW
38	29-Nov-19	0.24	0.24	0.26	0.48	0.51	Irrig. 10 CW
39	30-Nov-19	0.27	0.27	0.28	0.48	0.51	Irrig. 11 CW
40	1-Dec-19	0.25	0.25	0.26	0.48	0.51	Irrig. 12 CW
41	2-Dec-19	0.25	0.00	0.00	0.00	0.00	Harvesting

CW: Contaminated Water

With this modeling approach, adequate water was delivered to the lettuces without creating a soil water deficit or excess that would have reached the soil surface.

Results and Discussion

HYDRUS 2D/3D Irrigation Modeling Results

Subsurface irrigation water moves upward from the driplines in an SDI system. To investigate the relationship between crop contamination and surface soil dryness, soil water movement underneath the harvested lettuce was modeled to estimate soil moisture. The following figures clearly show that the surface soil moisture content remained dry, which could produce no direct contact of contaminated water and plants.

Figs. 3 − 5 show the water content vs. depth from the SDI system simulations for the Gila loam soil. Fig. 3 represents the first irrigation with contaminated water, Fig. 4 shows the very last irrigation with contaminated water, and Fig. 5 illustrates the water content during the harvesting day (no irrigation). From these figures, it can be seen that the soil is saturated around the emitter, and the soil is wetted for a distance of about 10 cm above the emitter (located at 20 cm below the surface). Thus, a 20 - 25 cm depth of placement in an SDI system will be required in a Gila loam soil. This is similar to the findings of Song et al. (2006), who found that drip tapes placed at 15 cm below the surface in a sandy loam soil resulted in minimal surface wetting. Thus, an emitter depth below the surface of 20 cm would be satisfactory. Consequently, a placement at a 20 cm depth is indeed recommended for Gila loam soil if one was irrigating lettuce with water containing pathogens in Arizona.

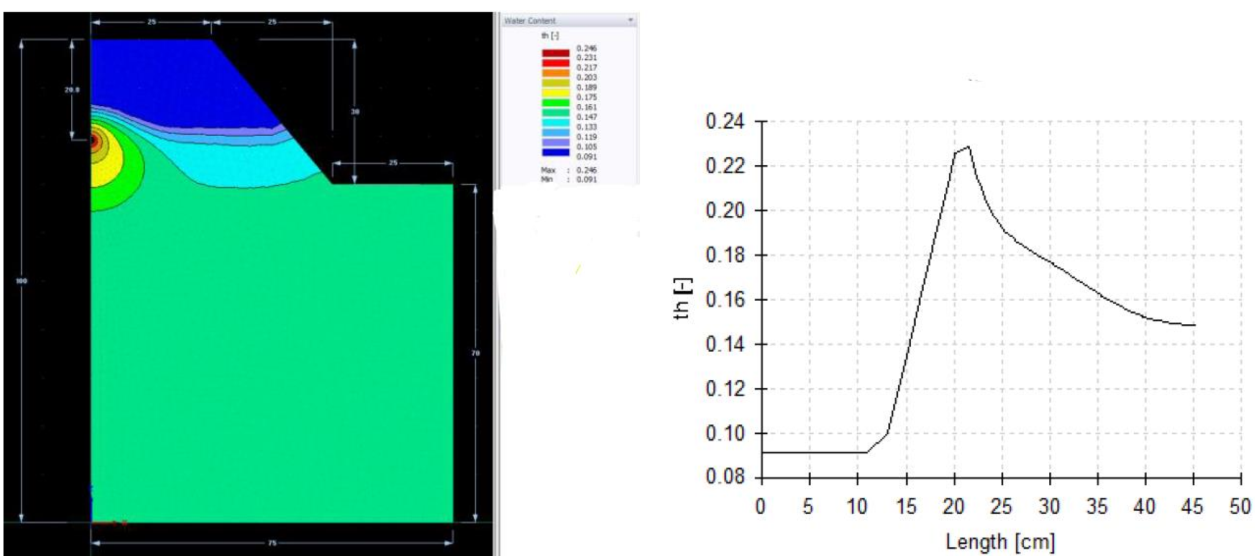

Figure 3. HYDRUS-2D simulation results of the 1st day of SDI irrigation with contaminated water (Nov. 20, 2019).

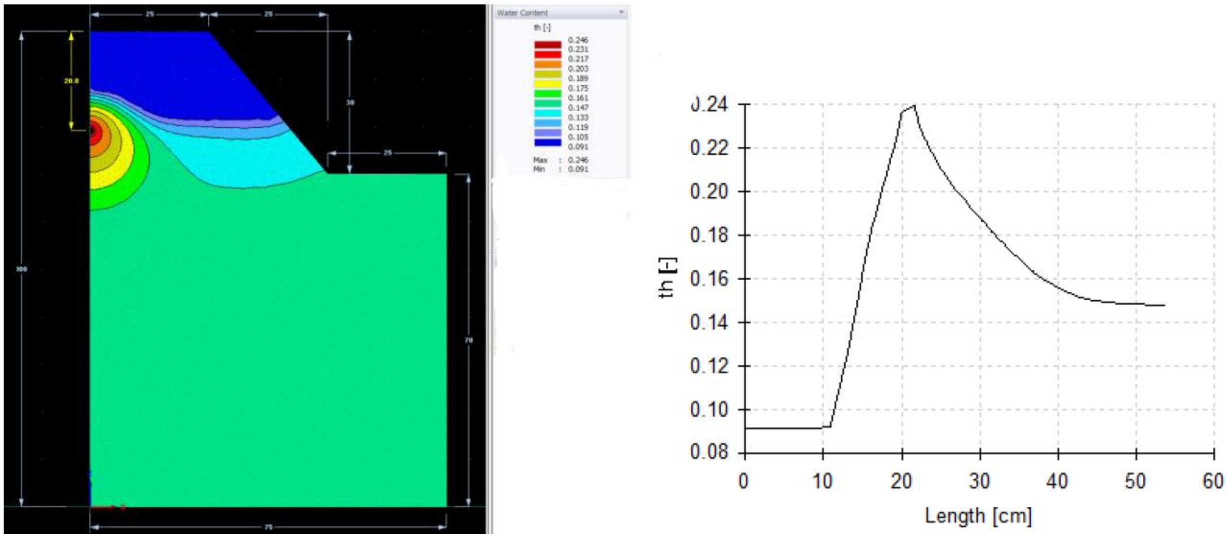

Figure 4. HYDRUS-2D simulation results of the last day of SDI irrigation with contaminated water (Dec. 1st, 2019).

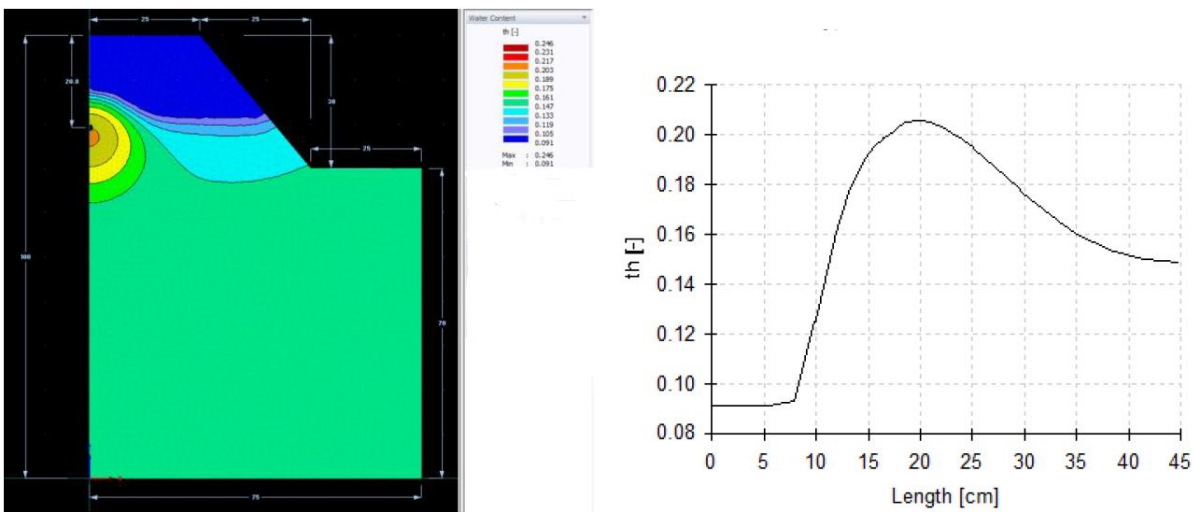

Figure 5. HYDRUS-2D simulation results of the soil moisture on the harvesting day (Dec. 2, 2019).

One of the main components of irrigation management is water application according to the crop water requirements. This irrigation management approach does provide enough water throughout the simulated growing cycle that resulted in dry soil surfaces, no water deficit, and, therefore, no water stress.

Conclusions

The present study evaluated subsurface irrigation relative to the potential for crop contamination by irrigation. Subsurface irrigation with proper management showed great potential in reducing crop contamination when microbial-contaminated water is used for irrigation water. Assuming that contaminated irrigation water had reached the soil surface, the most vulnerable areas to contamination would be in the vicinity of the stem or sprout on the base of the plant. It suggests that an installation depth of drip tapes (20 cm) for an SDI system and frequent irrigations eliminate or minimize soil surface wetting in subsurface drip-irrigated plots and thereby reduce potential contamination due to direct contact with contaminated water never occurs. Such practices may guarantee dry surfaces and can be particularly useful to prevent health risks when wastewater or otherwise contaminated water is used for irrigation in arid and semiarid regions. In summary, the results obtained in this study suggest that subsurface irrigation may provide a great alternative to other irrigation techniques when resources and the infrastructure may limit the use of extensively treated wastewater effluents.

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