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DRIP IRRIGATION WETTING PATTERNS IN A MID FLORIDA SANDY SOIL

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1 ABSTRACT

The wetting pattern of soil under drip irrigation is governed by soil texture, structure, initial water content, emitter spacing, discharge rate and irrigation frequency. Although drip irrigation is not common in central Florida "Ridge soils", the "advanced citrus production system" can hold a promising future. High frequency, short duration pulses is an important factor to consider for efficient irrigation in this very sandy "Ridge" soils. The objective of this research was to evaluate the water distribution pattern under 1.9, 4.6 and 8.6 L h^{-1} discharge rate drippers over different wetting durations using three evaluation methods: a) EC5 soil water sensors, b) blue dye tracer, and c) a simple mathematical model developed for sandy soils. Of the three methods, the dye method is labor intensive and time consuming and was used only to evaluate one pulse rate with 3 pulse durations. Soil water sensors, though relatively expensive, gave the most detailed wetting patterns under different combinations of pulse rates and wetting durations. The model overestimated the wetting depth and underestimated the wetting diameter. With the initial soil moisture at 0.055 m^3 m^{-3} and a constant application pressure of 138 kPa, the maximum achievable wetting diameter with increasing pulse rate and pulse duration was limited to 0.75 m. However, the wetting depth increased >1 m with >4.63 L h^{-1} pulse rate and 3-h duration. Preferential flow was minimal but had little influence on wetting pattern. The best combination was the 4.63 L h^{-1} emitter with a 3 h pulse that yielded the maximum wetting diameter (0.77 m) and the optimum wetting depth (0.77 m).

Keywords: Trickle irrigation, soil water sensors, FD&CC blue dye, soil water movement, water use efficiency.

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BULBO MOLHADO SOB IRRIGAÇÃO POR GOTEJAMENTO EM SOLO ARENOSO NA FLORIDA

2 RESUMO

O padrão de umedecimento do solo sob irrigação por gotejamento é regido pela textura do solo, a estrutura, o conteúdo inicial de água solo, espaçamento entre emissores, a vazão do emissor e freqüência de irrigação. Embora, a irrigação por gotejamento não seja comum no centro da Flórida, no "sistema avançado de produção de citros" pode conter um futuro promissor. Alta freqüência, pulsos de curta duração é um fator importante a considerar para irrigação eficiente

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neste solo arenoso. O objetivo deste trabalho foi avaliar o padrão de distribuição de água em diferentes vazões de gotejadores 1,9, 4,6 e 8,6 L h^{-1} ao longo de diferentes períodos de molhamento usando três métodos de avaliação : a) sensores de água no solo EC5 , b) corante azul , e c) um modelo matemático simples. Dos três métodos, o método do corante é trabalhoso e consome muito tempo, e por isso só foi utilizado para avaliar uma vazão em 3 diferentes tempos de irrigação. Sensores de água no solo, apesar de relativamente caro, deu os padrões de molhamento mais detalhados sob diferentes combinações de vazão e tempo de irrigação. O modelo superestimou a profundidade molhada e subestimou o diâmetro molhado. Com a umidade do solo inicial de 0,055 m^3 m^{-3} e uma pressão de aplicação constante de 138 kPa, o diâmetro molhado máximo obtido entre as vazões e tempos de irrigação avaliados foi de 0,75 m. No entanto, profundidade molhada ultrapassa 1 m, com 4,63 L h^{-1} de vazão do gotejador e 3 h de tempo de irrigação. Fluxo preferencial foi mínimo, mas teve pouca influência sobre o bulbo molhado. A melhor combinação foi a vazão de 4,63 Lh^{-1} com um tempo de 3 h, que produziu o diâmetro máximo de molhagem (0,77 m) e a profundidade de molhagem óptima (0,77 m).

Palavras-Chave: Irrigação localizada; sensors de água no solo; FD&CC blue dye; movimento de água no solo

3 INTRODUCTION

Efficient irrigation is essential to save water and fertilizer in intensive agricultural production systems. It also can reduce pumping costs, which is rising due to increasing energy costs. As available water resources for agriculture are limited, drip irrigation may be seen as a better option because of its relatively high application efficiency. Irrigators also prefer drip irrigation because the installation cost and maintenance requirements are lower than that of microsprinklers. Environmentalists will also prefer drip to other irrigation systems because with drips the leaching of chemicals and potential to contaminate groundwater can be minimized. However, like other irrigation systems, the system performance of drip irrigation is also influenced by soil physical and hydraulic properties. To achieve the best benefits and avoid leaching losses from drip irrigation in sandy soils, a precise design and an efficient irrigation schedule is important.

The rooting volume of a crop and the soil conditions will dictate drip system capacity, drip line spacing, and emitter spacing within a line (REVOL et al., 1991). The drip system capacity must be able to satisfy peak water requirement of the crop in the absence of precipitation by considering the water storage capacity of the soil. Improper selection of a drip line flow rate and a zone size can result in an inefficient irrigation system. The drip line spacing is dictated by the volume of crop roots, its lateral spread and soil water redistribution laterally and infiltration vertically (KELLER & KARMELI, 1974). Careful attention to drip line- and emitter- spacing is a key factor in achieving water conservation and subsurface ground water quality protection (FARES et al., 2001). The plant response and root development habits can be different when drip irrigation using multiple pulses (short duration) per day are employed. However, this study where the wetting pattern from a single pulse with varing wetting durations for different pulse rates are tested using three evaluation methods, can provide the basic information required to understand how soils are wetted and the most convenient method to evaluate that under a given soil type.

Goals of irrigation managers include optimizing crop water uptake and maximizing efficiency of application. Appropriate water discharge rate from a point source emitter and duration of an irrigation event is determined by the desired extent of wetting. Also, frequency of irrigation and application rate can influence the root distribution and the rate of plant water uptake (COELHO & OR, 1999). The wetted soil volume under an emitter and the depth of rooting is also necessary to estimate the amount of soil water that can be available to a crop.

With drip systems, soil water distribution is normally restricted to a bulb shape wetted volume below each emitter and therefore, the 3 three dimensional wetting pattern is very critical compared to that of the wetting under sprinklers. Different methods have been proposed to estimate the wetting volume from a drip. Battam, Sutton and Boughton (2003) and Barreto et al. (2008) described a detailed field method to derive design factors for a drip system. It involved monitoring the advancement of the wetting front over time from a subsurface emitter adjacent to an excavated soil pit.

Schwartzman and Zur (1986) presented a procedure based on empirical equations for computing the optimal emitter spacing and determining the maximum width and depth of the wetted soil volume for surface drip irrigation. Similar equations to estimate maximum width and depth of the wetted soil under drip system were developed by Singh et al. (2006). Soil water redistribution and flow models can be used to compute a detailed soil water distribution under a drip system (WARRICK & OR, 2007), but for a reliable estimation, the knowledge of specific soil hydraulic characteristics of the site is required (THORBURN et al., 2003). This combined with the technical skills needed to work with soil water flow models accurately, have limited their use for irrigation design.

Capacitance probes have been used by scientists to monitor soil water because they have several advantages including the capability of continuous real time measurements. Lopes et al. (2009) obtained good results using time domain reflectrometers (TDR) to estimate wetting patterns in a clay soil. Parsons and Bandaranayake (2009) used ECH_20 EC-5 probes for monitoring soil water movement, estimating soil water content, and scheduling irrigations successfully in a sandy soil.

Duval and Simonne (2003) effectively evaluated water movement in strawberry beds using water soluble blue dye solution (Sigma blue dye) in sandy soil. For visualization of water flow pathways (FLURY & FLUHLER, 1995), Brilliant Blue FCF (also called FD&C Blue dye) has been widely used. Butters and Bandaranayake (1993a; 1993b) used this blue dye to demonstrate how organic chemicals behave in sandy soils and to model movement of reactive, toxic organic chemicals with irrigation water in soil. Mon et al. (2006) has described the FD&C blue dye as moderately mobile at high concentrations.

In this study, we evaluated wetting patterns under drip irrigation in a Florida sandy soil using three methods. The main objective of this study is to evaluate effects of emitter discharge rate (application rate) and duration of an irrigation event on horizontal (wetting diameter) and vertical wetting (wetting depth) under an emitter. We observed the wetting pattern under 1.9, 4.6 and 8.6 L h^{-1} discharge rate drippers over time using; a) EC5 soil water sensors, b) FD&C blue dye tracer, and c) a simple mathematical model developed by Schwartzman & Zur (1986).

4 MATERIAL AND METHODS

This study was conducted in Candler fine sand, a hyperthermic uncoated Lamellic Quartzipsamment commonly found on the Central Florida Ridge. This soil has >95 % sand, <3 % clay, and <1 % organic matter in the top 2 m. Literature indicates that the bulk density of this soil ≈1.5 Mg m^{-3} (PARSONS & BANDARANAYAKE, 2009; ZEKRIL & PARSONS, 1999); water content at field capacity (θ_{fc}) 0.08 m^3 m^{-3} (OBREZA et al., 1997), and the saturated hydraulic conductivity (K_s) 15 to 120 cm h^{-1} (OBREZA & COLLINS, 2008). According to Alva, Prakash & Fares (1999) the K_s of this soil measured in the same site where this study conducted was 92.6 cm h^{-1} (Table 1). The experiment was set up in a 3 yr-old citrus grove (located at the University of Florida, Citrus Research and Education Center, Institute of Food and Agriculture Science, Lake Alfred, Polk County, FL, USA; 28.101864 N, 81.713366 W) (Fig. 2). A drip line with provisions to attach three drippers (pressure compensated Maxijet) at a spacing of 1.5 m between each dripper was installed 0.5 m away from the tree row, and was setup to maintain a constant pressure of 35 kPa (height 3.5 m) within the drip line by using an elevated water source (Fig. 1). The water reservoir was a plastic bottle with 225 L (60 g) volume. Three emitters with discharge rates of 1.94, 4.63 and 8.57 L h^{-1} were tested. The initial soil water content (θ_v) before irrigation was ~0.55 cm^3 cm^{-3}.

Table 1. Physical properties of mid Florida "Ridge" soil (Candler fine sand) measured in the same study site as reported by other authors at the CREC .

Soil Profile		**Texture***		**±Bulk**	**Porosity**	**±Field Capacity**	
Depth	**sand**	**silt**	**Clay**	**Density**		**(θ_v)**	*** K_s**
cm		%		cm^3	%		cm h^{-1}
0 – 15	97.3	0.9	1.8	1.40	47	6.2	92.6
16 – 30	97.4	1.2	1.4	1.57	41	5.7	
31 – 60	97.4	1.2	1.4	1.54	42	5.1	
61 – 90	97.8	0.8	1.4	1.50	43	4.8	
<90	97.6	1.5	0.9	1.51	43	4.9	

± Zekril and Parsons (1999); *Alva et al. (1999)

Figure 1. A sketch of the equipement arrangement; the drip system, the irrigation water sourse (tank), and the camera to record the dye distribution in crosssections excavated in 10 cm increments along the Y direction indicated in Fig 2a.

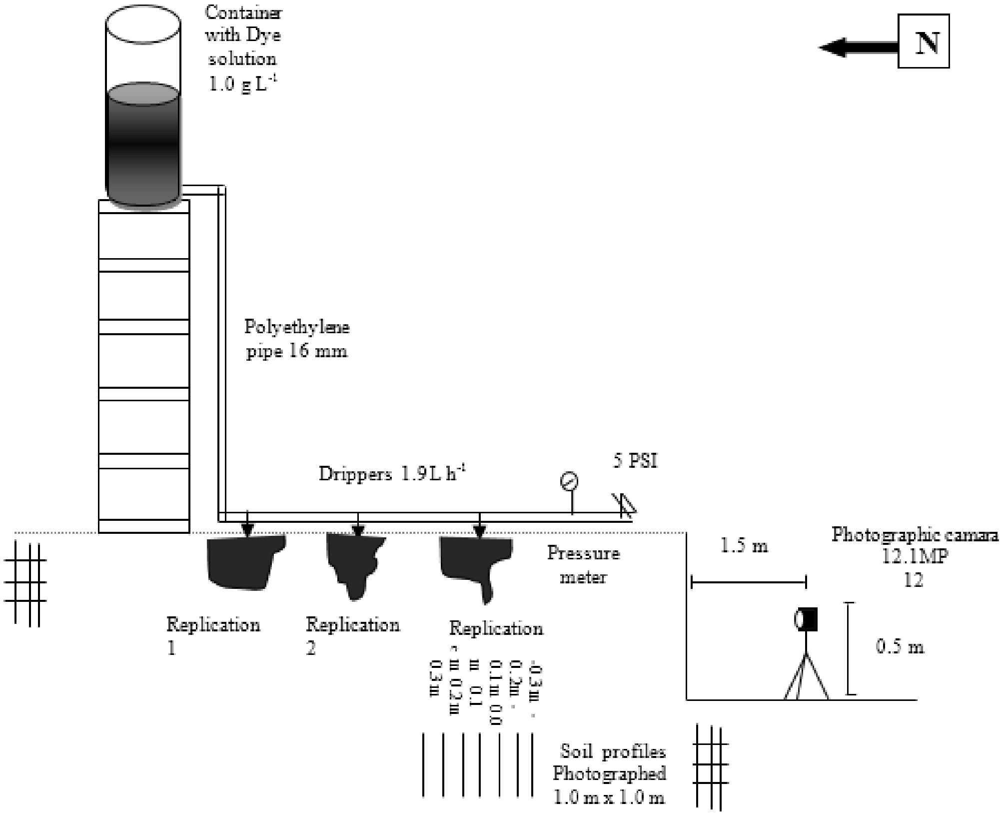
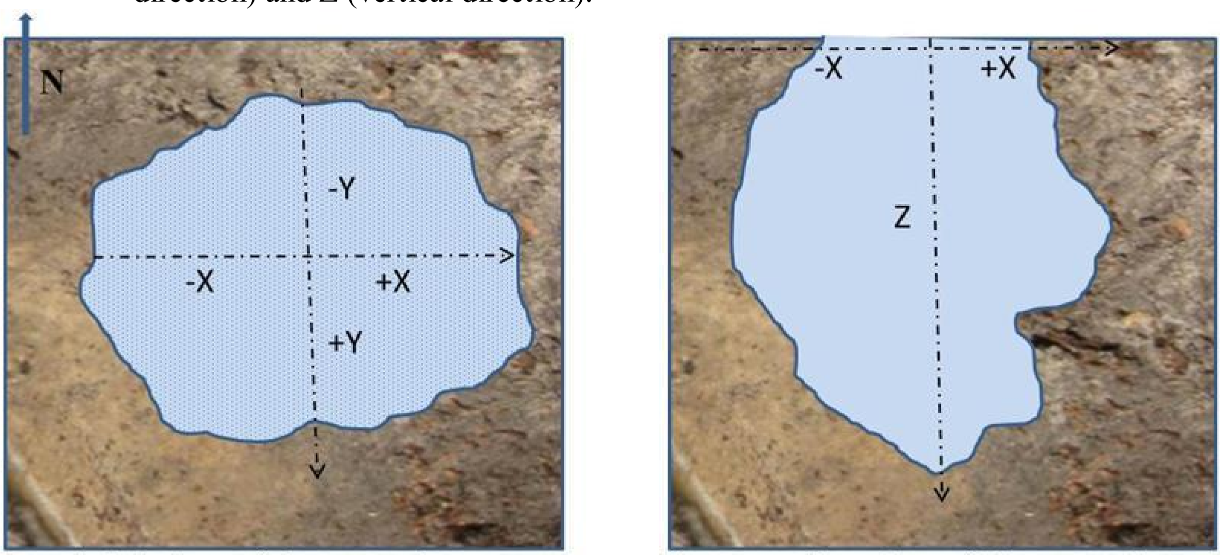


Figure 2. A - A sketch of the wetting area indicating the 2-dimensions visible from an arial view (view of the soil surface) in the X and Y direction. Emitter is placed right above where the X and Y axes intercept. B - A sketch of the wetting area indicating the 2-dimensions visible from a crosssection of the soil profile in the X (horizontal direction) and Z (vertical direction).



Arial view of the wetted area **Cross section view of the wetted area**

4.1 Wetting Depth approximations using basic soil hydraulic properties:

The desired wetting depth can be maintained using a combination of correct pulse rate, pulse frequency and pulse duration. In citrus, more than 90 % of the active roots are within the top 0.60 m (2 ft). Therefore, it is desirable to adjust the wetting depth (Z) between 0.60 to 0.75 m in this sandy soil. Table 2 gives an approximation for the Z when the water discharge rate of the emitters were 1.94, 4.63 or 8.57 L h^{-1}, the pulse durations were 0.5, 1.0, 2.0 or 3 h, the initial θ_v was between 0.050 to 0.025 m^3 m^{-3} and the wetting diameter (WD) was between 0.35 and 0.65 m. These estimations were based on the volume of water applied, the water holding capacity of the soil, initial θ_v at irrigation and the assumption that the wetting pattern of the soil is cylindrical with a piston flow pattern since there were no macro pores to generate preferential flow. If a 1.94 L h^{-1} emitter is used, it is required to irrigate 3 h or more to wet the rootzone if the WD was >0.50 m. If a 4.63 L h^{-1} emitter is used then the rootzone depth could be wetted in 2-3 h and with a 8.57 L h^{-1} emitter in 1-1.5 h. Based on these observations, we tested pulse durations between 0.5 to 3.0 h with 0.5-h increments for the 3 selected pulse rates 1.94, 4.63 or 8.57 L h^{-1} and evaluated the wetting patterns for different combinations of pulse rates and pulse durations.

Table 2. Approximated wetting depths when the initial θ_v is between 0.05 and 0.025 m^3 m^{-3}, the pulse rates are 1.94, 4.63, and 8.57 L h^{-1} and the pulse durations 0.5, 1.0, 2.0, and 3.0 h, assuming wetting diameter (WD) between 0.35 and 0.65 cm and a cylindrical shape wetting.

Emitter	**Irrigation**	**Volume**	**Wetting Depth when W. D. is 0.35, 0.50 or 0.65 m**					
Discharge	**Pulse**	**of Water**	**Initial θ_v =0.05**			**Initial θ_v =0.025**		
Rate	**Duration**	**Applied**	**0.35**	**0.50**	**0.65**	**0.35**	**0.50**	**0.65**
L h^{-1}	h	m^3	m					
1.94	0.5	$0.97*10^{-3}$	0.10	0.07	0.05	0.07	0.05	0.04
	1	$1.94*10^{-3}$	0.20	0.14	0.11	0.15	0.10	0.08
	2	$3.88*10^{-3}$	0.40	0.28	0.22	0.30	0.21	0.16
	3	$5.82*10^{-3}$	**0.60**	0.42	0.33	0.45	0.31	0.24
4.63	0.5	$2.32*10^{-3}$	0.24	0.17	0.13	0.18	0.12	0.10
	1	$4.63*10^{-3}$	0.48	0.34	0.26	0.35	0.25	0.19
	2	$9.26*10^{-3}$	0.96	**0.67**	0.52	0.71	0.50	0.38
	3	$13.89*10^{-3}$	1.44	1.01	**0.78**	1.06	0.74	0.57
8.57	0.5	$4.29*10^{-3}$	0.45	0.31	0.24	0.33	0.23	0.18
	1	$8.57*10^{-3}$	0.89	**0.62**	0.48	**0.66**	0.46	0.35
	2	$17.14*10^{-3}$	1.78	1.25	0.96	1.31	0.92	0.71
	3	$25.71*10^{-3}$	2.67	1.87	1.44	1.97	1.38	1.06

4.2 Method 1: FD&C blue dye to trace the wetting pattern

A dye solution with a concentration of 1 g of FD&C blue dye L^{-1} of water (0.1 % by weight) was fed from the reservoir to the drip line containing three drippers (3 replicates) with the same discharge rate (Fig. 1). After completion of 0.5-, 1.0-, and 2.0-h pulses using a 1.94 L h^{-1} drip emitter, soil pits were serially excavated manually to view the wetting pattern beneath the three emitters. The wetting pattern as indicated by the dye distribution was recorded by capturing it into a picture at each predetermined position (as decribed below) using a digital camera maintained in a fixed distance and height. The scaled frame when aligned in the pit indicated the distances of wetting in the 3 dimensions. The horizontal distance from the emitter to the first visible dye was noted (+Y direction) in the excavated pit (Fig 2a) and thereafter, soil was removed in about 5 cm slices and the dye profiles were recorded when Y is 30, 20, 10, 0, -10, -20 and -30 cm (Fig 2b). The average distribution of the dye between +30 and -30 cm gave an estimate of the water distribution in the Y and X direction. The cross section at Y = 0 cm (just below the emitter), provided the maximum value of water distribution along the X and Y axes. Thus, to get the average of wetting along the X axis, we needed the average of all the X values between Y = +30 to Y = -30 cm. The average value for the Z direction (wetting depth) is the grand average of Z in the X and Y directions (Fig. 2b). The photographs of the Brilliant Blue dye (FD&CC) spread in each profile, were analyzed using Adobe Photoshop CS with The 'Magic Wand tool'. Dye patterns were analyzed after conversion to black-and-white bitmap images and values for X, Y and Z were obtained using AutoCAD software.

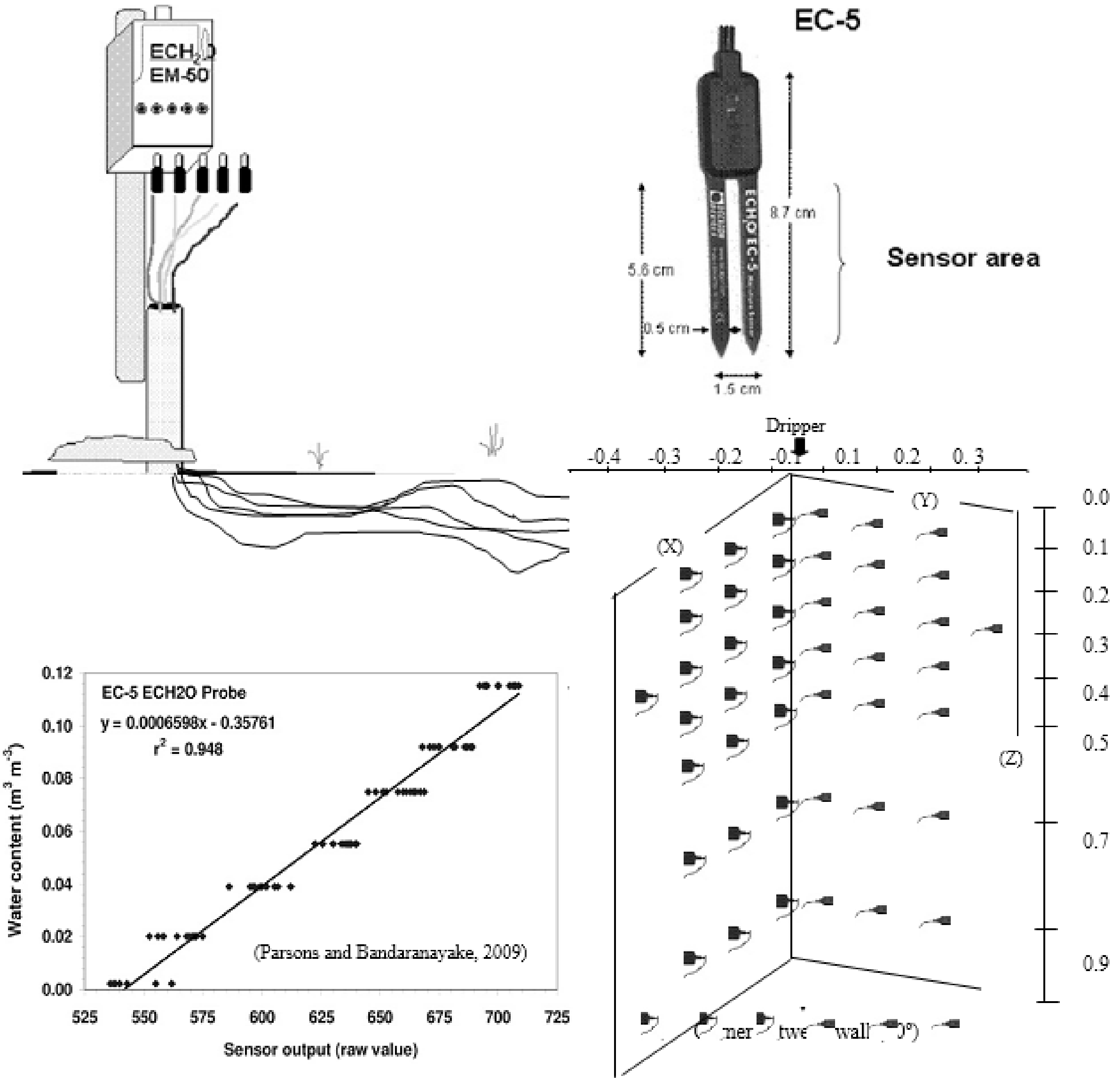
4.3 Method 2: EC5 soil water sensors (Decagon Devices Inc., Pullman, WA) to trace wetting front.

In an adjacent location in the same field, forty four EC-5 probes were distributed in 3 dimensions underneath a dripper point in a 0.4 m x 0.4 m x 1.0 m deep trench so that the water distribution during irrigation could be measured in the X, Y and Z directions using soil water sensors (Fig. 3). A trench was excavated carefully with a flat square shovel, separating soil from each 0.1 m depth layers. The probes were distributed along a hypothetical +X, +Y (horizontal directions), and Z (vertical depth of wetting) axes so that the probes were positioned in the 3 dimensions symmetrically along a central axis of the trench in grids spaced 0.10 m apart. This configuration minimized the soil disturbance during probe installation (LOPES et al., 2009). The size of the pit, the number of sensors, and their spacing along the X, Y, and Z directions were predetermined using the wetting pattern observed from the dye method. After sensor installation, the excavated soil was back filled in layers in the same order that it was removed while compacting the soil, layer by layer to bring close to the same bulk density. Final settling of the soil to restore the same bulk density was achieved by saturating the soil with a microsprinkler and letting it dry for a week.

Real time sensor readings at 10-min intervals were stored in 9 EM50 data loggers (Decagon Devices Inc., Pullman, WA) Five sensors were connected to each data logger. Data were downloaded using DataTrack software and transferred to MS Excel sheets for processing. Sensor output was converted to θ_v by using a calibration equation (Fig. 3) developed by Parsons & Bandaranayake (2009). The wetting patterns from a dripper discharging at a constant flow rate of either 1.94, 4.63 or 8.57 L h^{-1} were evaluated after 0.5, 1.0, 1.5, 2.0, 2.5 and 3 h of irrigation. The entire experiment was repeated 3 times. We used drinking quality irrigation water with temperature around 20 ^{o}C.

Finally, the advancing water front during irrigation and the spatial distribution of θ_V after allowing 2 h to redistribute the irrigated water in the soil profile were geospatially analyzed using GS+ Geostatistics for Environmental Sciences (Gamma Design Software, Plainwell, MI). Semivariograms and Kriging were used to estimate the variability within each sample grid, as described and used by Waldo & Schuman (2009).

Figure 3. A diagram an EC-5 soil water sensor, lay out of sensors with in the soil profile to capture the wetting pattern in 3-dimentions, EM50 data logger and connections, and the calibration curve and the equation.



4.4 Method 3: Use of a wetting pattern model (SCHWARTZMAN & ZUR, 1986)

We assumed that a simple model was adequate to estimate the wetting pattern in this sandy soil that has no structure or macropores to promote preferential flow, and very low clay and organic matter content to promote lateral flow. The model we tested assumes that the wetting pattern from drip irrigation system is determined by a) saturated hydraulic conductivity of the soil, b) dripper discharge rate, and c) the total volume of water applied during irrigation.

This wetting pattern model is described by equation 1 and 2 (SCHWARTZMAN & ZUR, 1986):

$$Z = 2.54 * Vw^{0.63} * \left(\frac{ks}{q}\right)^{0.45} \quad (1)$$

$$W = 1.82 * Vw^{0.22} * \left(\frac{ks}{q}\right)^{-0.17} \quad (2)$$

where:

z = wetting depth (m), w = wetting diameter (m), V_w = volume of water applied (m^3), k_s =saturated hydraulic conductivity (0.00025722 m s^{-1}), and q = emitter discharge rate (m^3 s^{-1}). Accordingly, we have two independent equations to estimate wetting depth (z; equation 1) and wetting diameter (w; equation 2).

5 RESULTS AND DISCUSSION

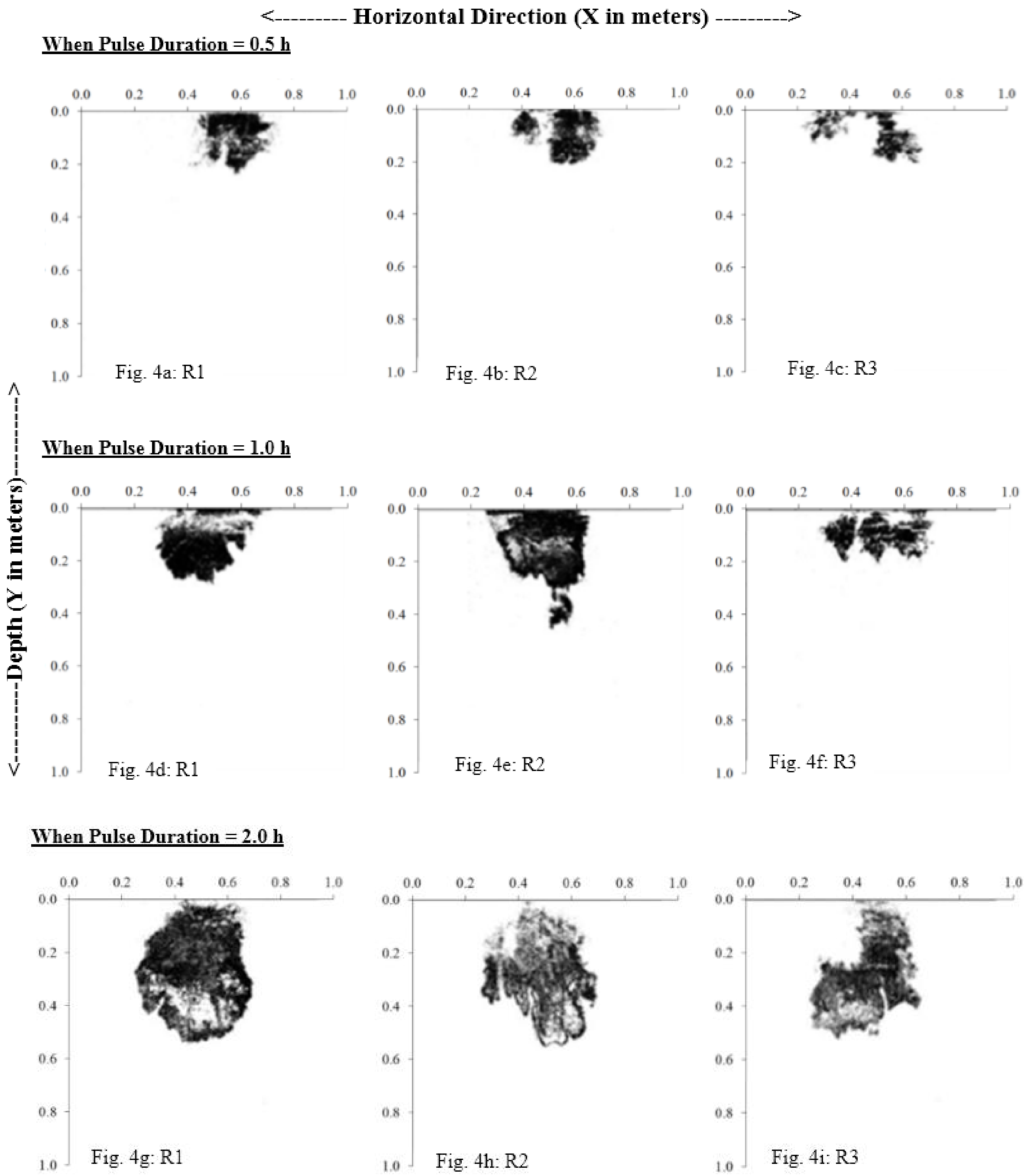
5.1 Wetting pattern observations using the dye method:

The dye method gave the most direct method of observation and therefore, the results were used to compare the results from the other two methods. Since this method is laborious, time consuming and soil profiles in sampling locations are destructive, we used only one pulse rate and three pulse durations in the testing. The estimates of the WD which is the average of $\sum_{y=30}^{y=-30}((X + Y)/2)$ and Z which is the grand average of $\sum_{y=30}^{y=-30}(z)$ and $\sum_{+X}^{-X}(z)$ for a 1.94 L h^{-1} emitter and 0.5, 1.0, and 2.0 h pulse durations are given in Table 3. The maximum Z and WD observed with the 1.94 L h^{-1} emitter and a 2-h pulse were 0.57 m (standard error was 0.007) and 0.51 m respectively. Fig 4 (a to i) demonstrates the wetting shape and variation among the three replicates when the observed soil profile was at Y = 0 (Fig. 1b). The wetting shapes (n=3) indicated tendency for fingering (preferential flow) but was not intense enough to allow water to bypass certain soil layers. If we assume the rooting depth as 0.60 m, a 1.94 L h^{-1} emitter could not completely wet the desired depth with the highest tested pulse duration which is a 2 h pulse.

Table 3. Wetting pattern along the X and Y (horizontal directions; the average of X and Y value is the wetting diameter) and Z axes (wetting depth), when the pulse rate was 1.94 and the duration of irrigation pulse was 0.5, 1.0 and 2 h and the estimated wetted volume (assuming cylindrical wetting) at each pulse event as observed directly using FD&C blue dye.

Duration	**Wetted Diameter**		**Wetted Depth**	**Wetting**	**Wetted Volume**
of Pulse	**X Axis**	**Y Axis**	**Z Axis**	**Diameter**	
	--------------------------	m	----------------------------		**m^3**
0.5 h	0.4	0.34	**0.25**	**0.37**	0.03
	0.017	*0.017*	*0.012*		
1.0 h	0.44	0.4	**0.33**	**0.42**	0.05
	0.006	*0.029*	*0.075*		
2.0 h	0.51	0.5	**0.57**	**0.51**	0.11
	0.017	*0.006*	*0.012*		

Figure 4 (a to i): Photographic shots of wetting pattern variations within the 3 replicates (R1, R2, and R3) in Candler sand with initial θv at 0.055 $m^3\ m^{-3}$ as indicated by the blue dye; wetted with a 1.94 L h^{-1} discharge rate emitter and 0.5-, 1.0-, and 2.0-h pulse durations.



5.2 Wetting pattern observations using soil moisture probes

To discuss the details of results obtained from the sensor method and the estimations from the simple model, it is necessary to make sure that results from indirect methods agree with the direct method (dye method). A comparison of the Z and the WD as estimated using the dye, the sensors and the simple model when the pulse rate was 1.94 L h^{-1} is shown in Fig. 5a and Fig. 5b respectively. It was clear from these Figs. That the Z was overestimated and the WD was underestimated by the model compared to the dye method. However, the values obtained for Z using the dye and the sensors were identical. Therefore, we will discuss only the results from the sensors any further.

Wetting pattern observations using data from the sensors gave the most detailed wetting patterns associated with different combinations of pulse rates and pulse durations. With the 1.94 L h^{-1} pulse rate, both the Z and the WD increased linearly as the pulse duration increased from 0.5 to 3.0 h ($R^2 = 1$; Fig 5a and 5b). When the pulse rate increased from 1.94 to 8.57 Lh^{-1}, the Z and WD increased linearly with the increase in pulse duration (Fig. 6a and 6b). The value for the WD has overlapped at 1.5-h pulse duration when the pulse rates were 4.63 and 8.57 Lh^{-1} (Fig. 6a). Also, the Z variation as pulse duration increased is not steady with the 4.63 Lh^{-1} pulse rate as with the 1.94 and 8.57 Lh^{-1} pulse rates. The WD could not be increased by increasing the pulse rate from 4.63 to 8.57 Lh^{-1} (Fig. 6b).

Conopy cover area under 15 yr old Hamlin orange on Carrizo rootstock grown in the same Candler sand soil was 14 m^2 (unpublished data). Although the lateral roots can grow beyond the canopy cover area and below 0.5 to 1 m (CASTLE, 1978), about 50% of the active roots are within the canopy cover and within surface 0.6 m depth (CASTLE & KREZDORN, 1977). Therefore, the soil volume that 50% of the active roots confine is 8.4 m^3. If the targeted wetting depth (Z) is between 0.6 to 1 m and with the highest possible WD of 0.6 m, the maximum wetting volume will be between 0.17 to 0.28 m^3. With a pulse rate of 4.63 and a pulse duration of 3 h, the Z and the wetting volume were 0.77 m and 0.36 m^3 respectively. With a pulse rate of 8.57 and a pulse duration of 2.5 h, the Z and the wetting volume were 0.63 m and 0.27 m^3 respectively. This wetting volume was about 3.2 to 4.3% of the rootzone soil volume that 50% of the active roots would occupy. Therefore, the best combination of the pulse rate and the pulse duration that helped to obtain the optimum wetting values were achieved with 3 h pulse duration with a 4.63 L h^{-1} pulse rate or with 2.5 h pulse duration with a 8.57 L h^{-1} pulse rate. It is important to note that this test was done when the initial water content was 0.055 m^3 m^{-3}. Under the real field conditions, the initial θ_v can drop below 0.050 m^3 m^{-3} causing the Z in this soil to decrease. Therefore, the pulse rate and the pulse duration selected should aim for a Z between 0.60 and 1m. As the results indicate Z could be increased either by increasing the pulse rate or pulse duration but it is difficult to increase the WD >0.75 m in this sandy soil by varying the pulse rate or pulse duration. When the emitter discharge rate was increased from 1.94 to 8.57 L $h^{-1}$with the wetting duration constant at 0.5 h, the WD increased from 0.34 to 0.40 m and the Z increased from 0.25 to 0.51 m. When the wetting duration was kept constant at 2 h, the WD increased from 0.47 to 0.57 m and the wetting depth increased from 0.38 to 0.78 m (Table 4). Thus, as the wetting time increased the wetting depth approximately doubled with each pulse rate but the wetting diameter increased to a maximum around 0.65 m and then remained constant.

Fig. 7 a, b and c indicate the pattern in which the wetting front advanced when the pulse rate increased from 1.94 to 8.57 Lh^{-1} and the pulse durations in 0.5 h increments between 0.5 and 3.0 h. Accordingly, if the drip size was 1.94 L h^{-1}, then it required a pulse duration > 3.0 h in order to wet about 0.6 m depth. As the pulse duration increased from 4.63 to 8.57 L h^{-1} pulse rates, the tendency to occur preferential flow was increasing. The WD is required to determine the number of drip lines necessary per crop row. The wetted width was not influenced much by changing the pulse rate or pulse duration in this soil (Fig. 7 a, b and c). However, when the WD becomes narrower, the number of drip lines required per crop row increases. This is a disadvantage because the more the drip lines required in a crop row, the higher the initial cost to establish a drip system and later to maintain it.

Table 4. Distribution of water along the X and Y (horizontal directions) and Z axes (vertical direction), when the pulse rates were 1.94, 4.63, and 8.57 L h^{-1} and the duration of irrigation pulses were changed from 0.5 to 3 h at .5-h intervals and the wetted volume at each event as estimated by the EM5 soil water sensors. Values within parenthes is under each column are the Standard Deviation.

Discharge	**X Axis**	**Y Axis**	**Z Axis**	**Volume**	**X Axis**	**Y Axis**	**Z Axis**	**Volume**
Rate	**Duration of pulse: 0.5 h**				**Duration of pulse: 1.0 h**			
L h^{-1}	m			m^3	m			m^3
1.94	0.31 *(0.023)*	0.36 *(0.012)*	0.25 *(0.006)*	0.02	0.38 *(0.006)*	0.40 *(0.012)*	0.31 *(0.006)*	0.04
4.63	0.33 *(0.023)*	0.5 *(0.012)*	0.35 *(0.006)*	0.05	0.44 *(0.031)*	0.52 *(0.012)*	0.36 *(0.033)*	0.07
8.57	0.35 *(0.015)*	0.45 *(0.029)*	0.51 *(0.009)*	0.06	0.48 *(0.050)*	0.52 *(0.066)*	0.58 *(0.006)*	0.11
Discharge	**X Axis**	**Y Axis**	**Z Axis**	**Volume**	**X Axis**	**Y Axis**	**Z Axis**	**Volume**
Rate	**Duration of pulse: 1.5 h**				**Duration of pulse: 2.0 h**			
	X Axis	**Y Axis**	**Z Axis**	**Volume**	**X Axis**	**Y Axis**	**Z Axis**	**Volume**
L h^{-1}	**m**	**m^3**			**m**	**m^3**		
1.94	0.46 *(0.009)*	0.4 *(0.012)*	0.37 *(0.006)*	0.05	0.53 *(0.030)*	0.42 *(0.020)*	0.38 *(0.010)*	0.07
4.63	0.52 *(0.025)*	0.66 *(0.012)*	0.58 *(0.013)*	0.16	0.57 *(0.032)*	0.63 *(0.015)*	0.58 *(0.010)*	0.16
8.57	0.54 *(0.030)*	0.61 *(0.027)*	0.60 *(0.006)*	0.16	0.57 *(0.035)*	0.56 *(0.045)*	0.78 *(0.020)*	0.20
Rate	**Duration of pulse: 2.5 h**				**Duration of pulse: 3.0 h**			
L h^{-1}	**X Axis**	**Y Axis**	**Z Axis**	**Volume**	**X Axis**	**Y Axis**	**Z Axis**	**Volume**
1.94	0.55 *(0.061)*	0.5 *(0.020)*	0.43 *(0.010)*	0.09	0.57 *(0.032)*	0.5 *(0.020)*	0.52 *(0.006)*	0.12
4.63	0.61 *(0.081)*	0.60 *(0.020)*	0.60 *(0.116)*	0.17	0.74 *(0.020)*	0.80 *(0.012)*	0.77 *(0.013)*	0.36
8.57	0.60 *(0.021)*	0.66 *(0.114)*	0.85 *(0.050)*	0.27	0.65 *(0.046)*	0.71 *(0.027)*	>1.00 *(0.006)*	>0.36

Figure 5a. A comparison of the wetting depth (Z) as pulse duration progressed from 0.5 to 3.0 h in 0.5-h increments as evaluated by the three methods, the dye, the sensors, and the model.

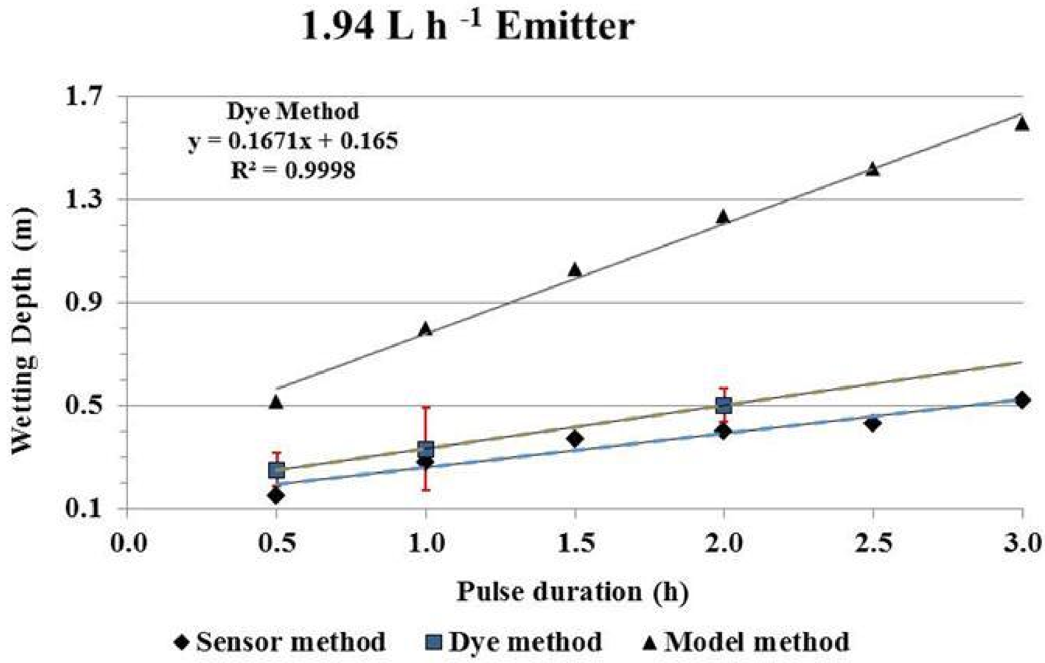


Figure 5b. A comparison of the wetting diameter (WD) as pulse duration progressed from 0.5 to 3.0 h in 0.5-h increments as evaluated by the three methods, the dye, the sensors, and the model.

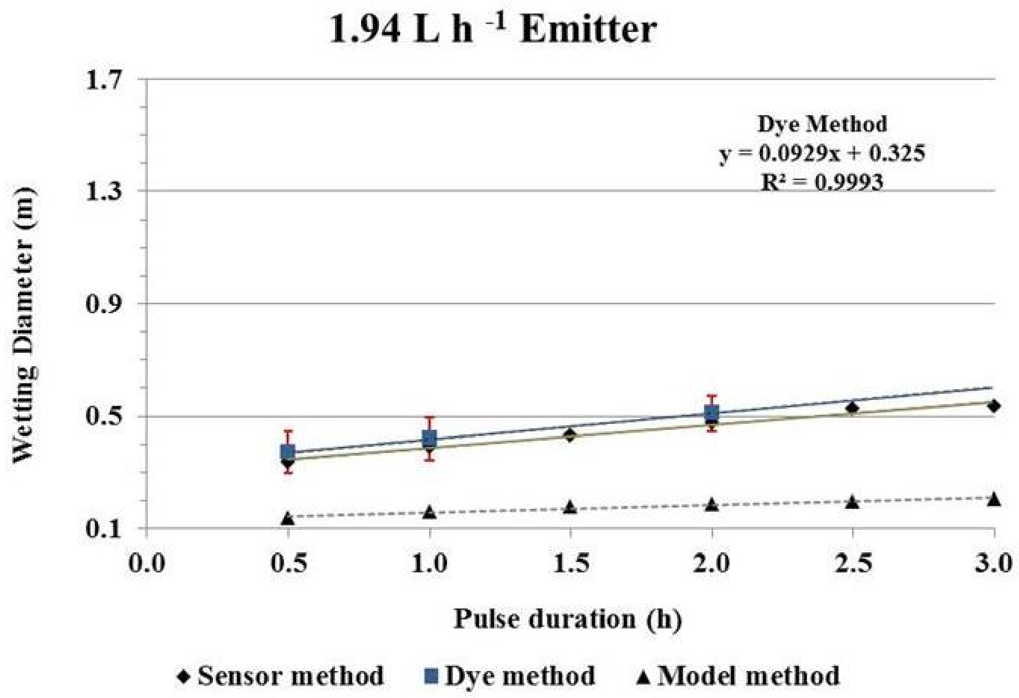


Figure 6a. The relationship between the wetting depth and the pulse duration when the pulse rate (emitter size) was 1.94, 4.63, and 8.57 L h^{-1}; evaluated using soil water sensors.

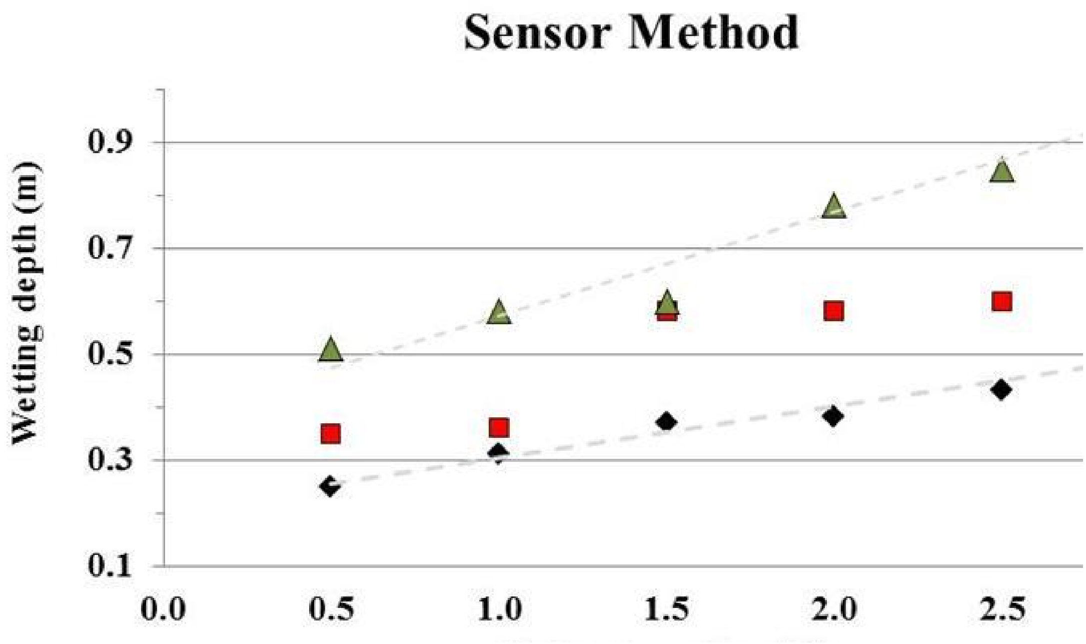


Figure 6b. The relationship between the wetting diameter (WD) and the pulse duration when the pulse rate (emitter size) was 1.94, 4.63, and 8.57 L h^{-1}; evaluated using soil water sensors.

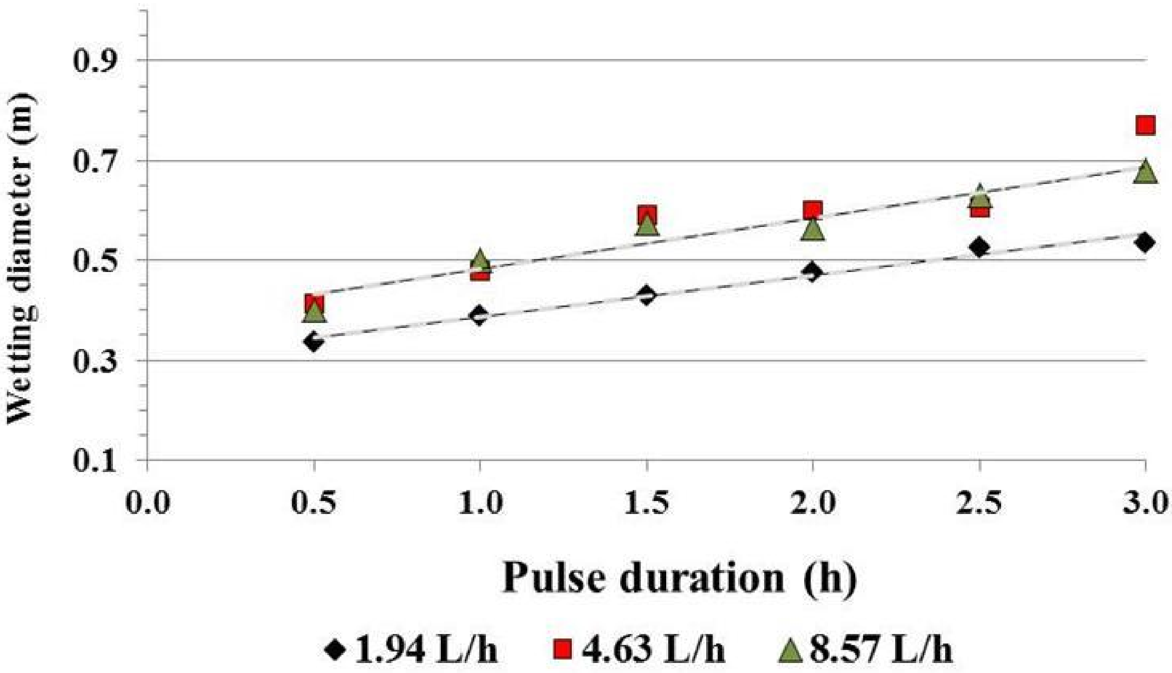


Figure 7a. The shape of the wetting bulb as wetting time (pulse duration) progressed by 0.5 h increments between 0.5 to 3.0 h in Candler Sand (central Florida Ridge Soil), when the pulse rate of the emitter 1.94 L h^{-1} and the initial water content 0.055 m^3 m^{-3} (50% depleted from the field capacity water content); estimated by the sensor method.

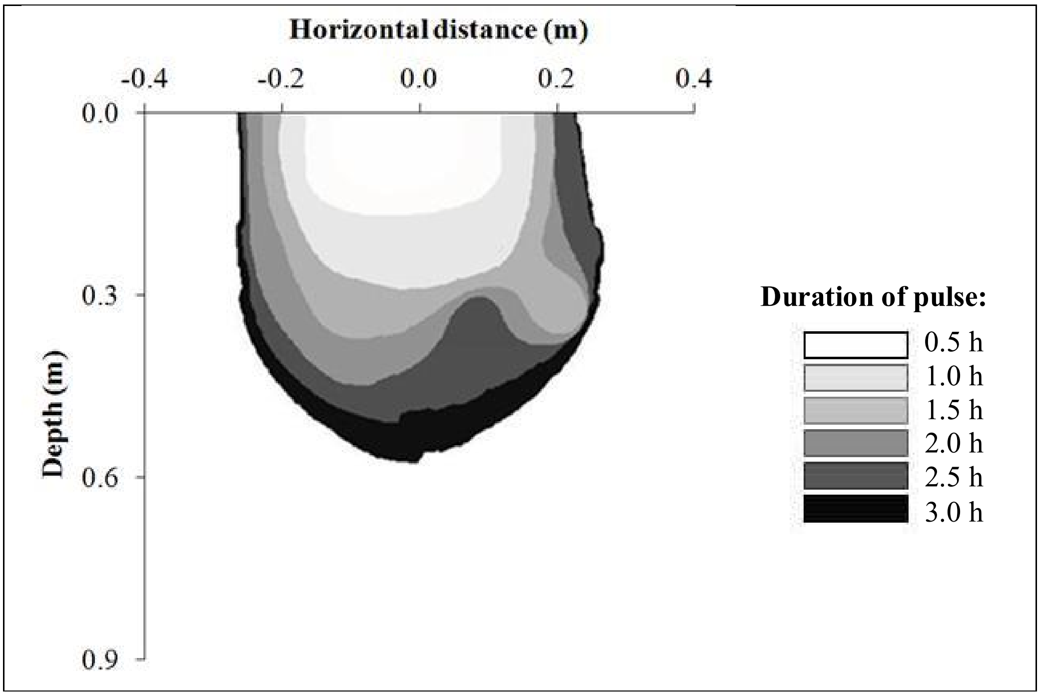


Figure 7b. The shape of the wetting bulb as wetting time (pulse duration) progressed by 0.5 h increments between 0.5 to 3.0 h in Candler Sand (central Florida Ridge Soil), when the pulse rate of the emitter 4.63 L h^{-1} and the initial water content 0.055 m^3 m^{-3} (50% depleted from the field capacity water content); estimated by the sensor method.

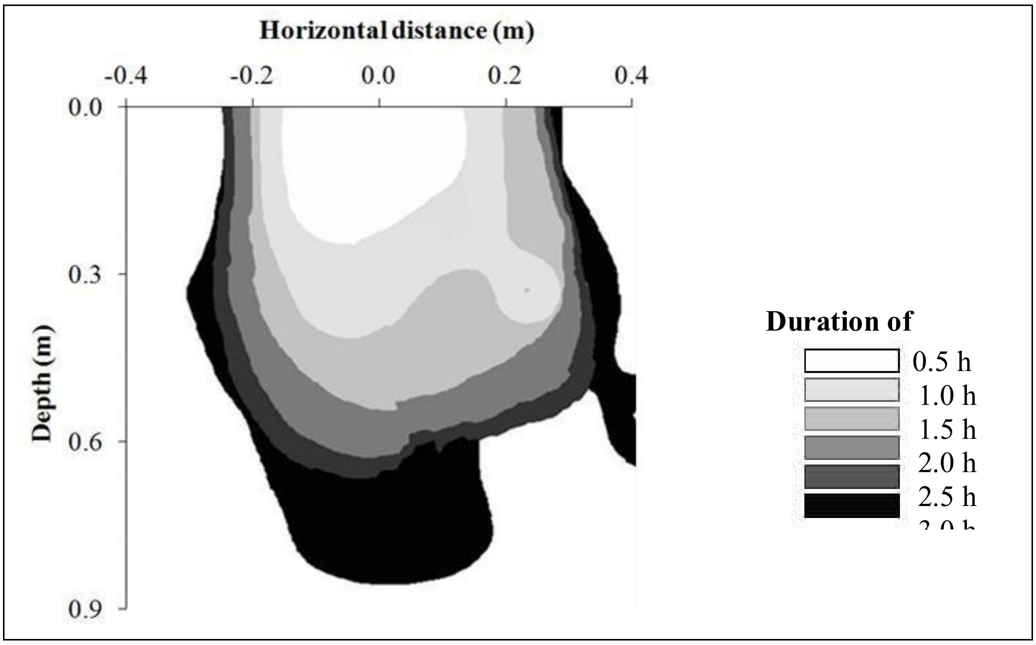
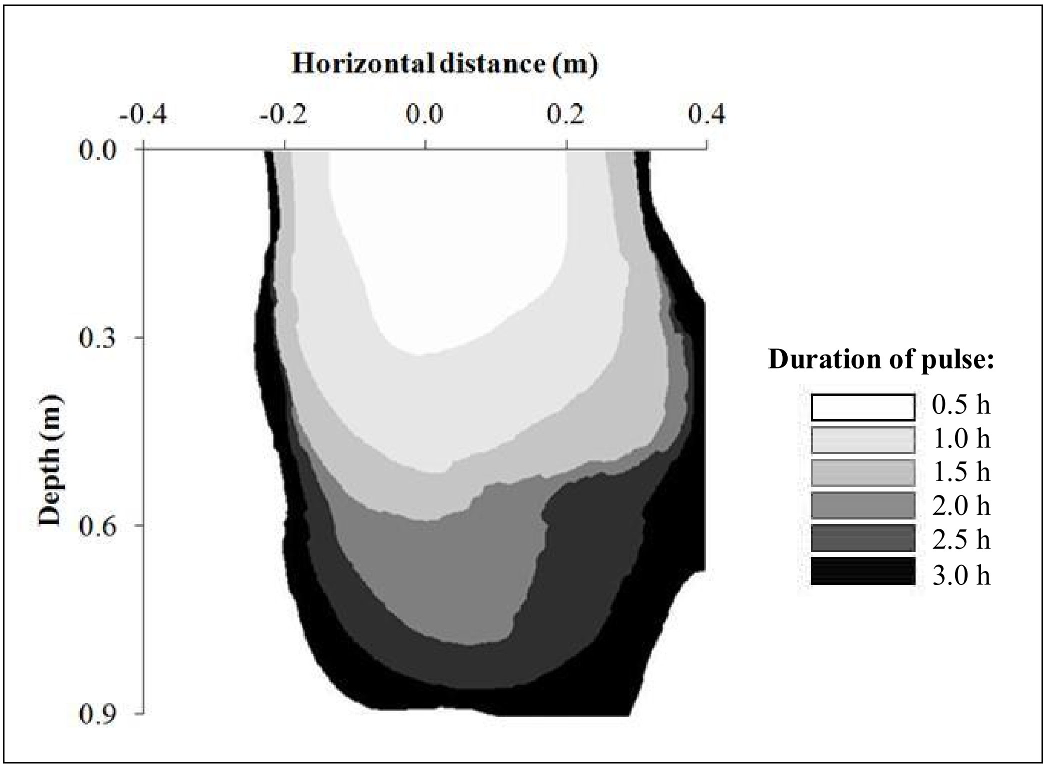


Figure 7c. The shape of the wetting bulb as wetting time (pulse duration) progressed by 0.5 h increments between 0.5 to 3.0 h in Candler Sand (central Florida Ridge Soil), when the pulse rate of the emitter 8.57 L h^{-1} and the initial water content 0.055 m^3 m^{-3} (50% depleted from the field capacity water content); estimated by the sensor method.



Semivariograms and kriging were used to describe the distribution of sensor estimated θ_v in the soil profile 2 h after the respective irrigations with different combinations of pulse rates and pulse durations (Figs. 8, 9 and 10). Common to all figures, we could observe six θ_v bands. The three bands that corresponds to higher values of θ_v (>0.13, 0.10-0.13, and 0.07 – 0.10 m^3 m^{-3}) was the results of wetting with the drip pulses. Although the, initial θ_v in this study was reported as 0.055, the three bands with lower θ_v values indicated that the initial θ_v in the test field varied between 0.01 and 0.06 m^3 m^{-3} with a greater soil mass representing the θ_v between 0.04 and 0.06 m^3 m^{-3}. The maximum θ_v achieved with any combination of pulse rates and pulse durations was 0.18 m^3 m^{-3}. The maximum saturation which is equivalent to the porosity (about 0.40 m^3 m^{-3}) was never achieved with any combination of pulse rate and pulse duration. The observed field capacity θ_v of this soil was between 0.08 and 0.10 m^3 m^{-3}. With a 1.94 pulse rate, there were two bands of θ_v, one with θ_v above 0.13 m^3 m^{-3} and the other with θ_v between 0.10 and 0.13 m^3 m^{-3}. As the pulse rate and pulse duration increased, the number of high θ_v bands also increased. The Figs. 9E and 9F, 10c, 10d, 10e, and 10f, indicated the initial stages of fingering and the resulting isolated high θ_v spots. Although the observed WD was ≤0.4 m during irrigation, Fig. 9f, 10e and 10f, indicated that during redistribution of soil water, the WD can extend beyond 0.4 m. In contrast to what we observed with a >95% sandy soil, Thabet & Zayani (2008) observed that low application rates could lead to relatively more water distribution in the horizontal direction. However, just as they observed, higher application rate in this sandy soil also favored the vertical distribution of water. In loam and clay-loam soils, high water application rates favored both vertical and lateral distributions of water (ACAR et al., 2009). Souza & Matsura (2004) showed that in clay soils, the lateral soil water distribution increases and vertical distribution decreases with an increase in the drip discharge rate.

Soil water sensors provided detailed pictures of the θ_v distribution within the soil profile under different combinations of pulse rate and pulse durations. Although there were minor soil disturbances during sensor installation, the sensor-datalogger setup once installed can be used indefinitely for years to evaluate wetting patterns under various soil and cultural management conditions. Also, the sensors can estimate real time water contents at any useful time intervals continuously over any length of time during a study period and these data could be stored in the EM50 data logger for any time length until analysis. The disadvantages with the soil sensors are the initial cost of instruments which can be over $10,000, depending on the number of data loggers and sensors required for the study and the initial soil disturbance during sensor installation. Another disadvantage of sensor method compared to the dye method was that sensors established only in the +X, +Y and Z direction and assumed wetting in the -X, -Y direction as a mirror image of wetting in the +X and +Y direction. Under the real field situations this may not be correct. However, sensors could be established in both + and – X and Y directions but the soil disturbance and the number of sensors and dataloggers can be doubled.

5.3 Wetting pattern estimations using the Model of Schwartzman & Zur:

Although we assumed that a simple model was adequate for a sandy soil with >95% sand, it was not. Schwartzman & Zur (1986) model assumed a cylindrical water flow (Fig 5a and 5b, and Table 2). The observations from this study, indicated that the wetting pattern in this sandy soil was not cylindrical. However, the advantage of the Shwartzman and Zur equations is that by fixing the Z to the rootzone depth one could determine the irrigation volume required and using this irrigation volume, it easy to find the pulse rate (q in the equation) that produce the maximum WD. The WD is what determines the number of drip lines required per crop row. Two limitation in using this model were that the equations in this model had been calibrated with laboratory tests using two soil types [Hamra silt loam (bulk density 1.56 Mg m^{-3} and Ks 9.72 cm h^{-1}) and sand (bulk density 1.72 Mg m^{-3} and Ks 33.12 cm h^{-1})] which is different to Candler sand that we tested, and the pulse rates range tested was shorter (between 0.6 and 3.0 L h^{-1}) than the range we tested (1.94-8.57 L h^{-1}).

Figure 8 (A-F). Distribution of the θ_v in the soil profile 2 h after irrigation when the pulse duration progressed by 0.5 h increments between 0.5 to 3.0 h in Candler Sand (central Florida Ridge Soil), and the pulse rate of the emitter 1.94 L h^{-1}, the initial water content 0.055 m^3 m^{-3} (50% depleted from the field capacity water content); estimated by the sensor method.

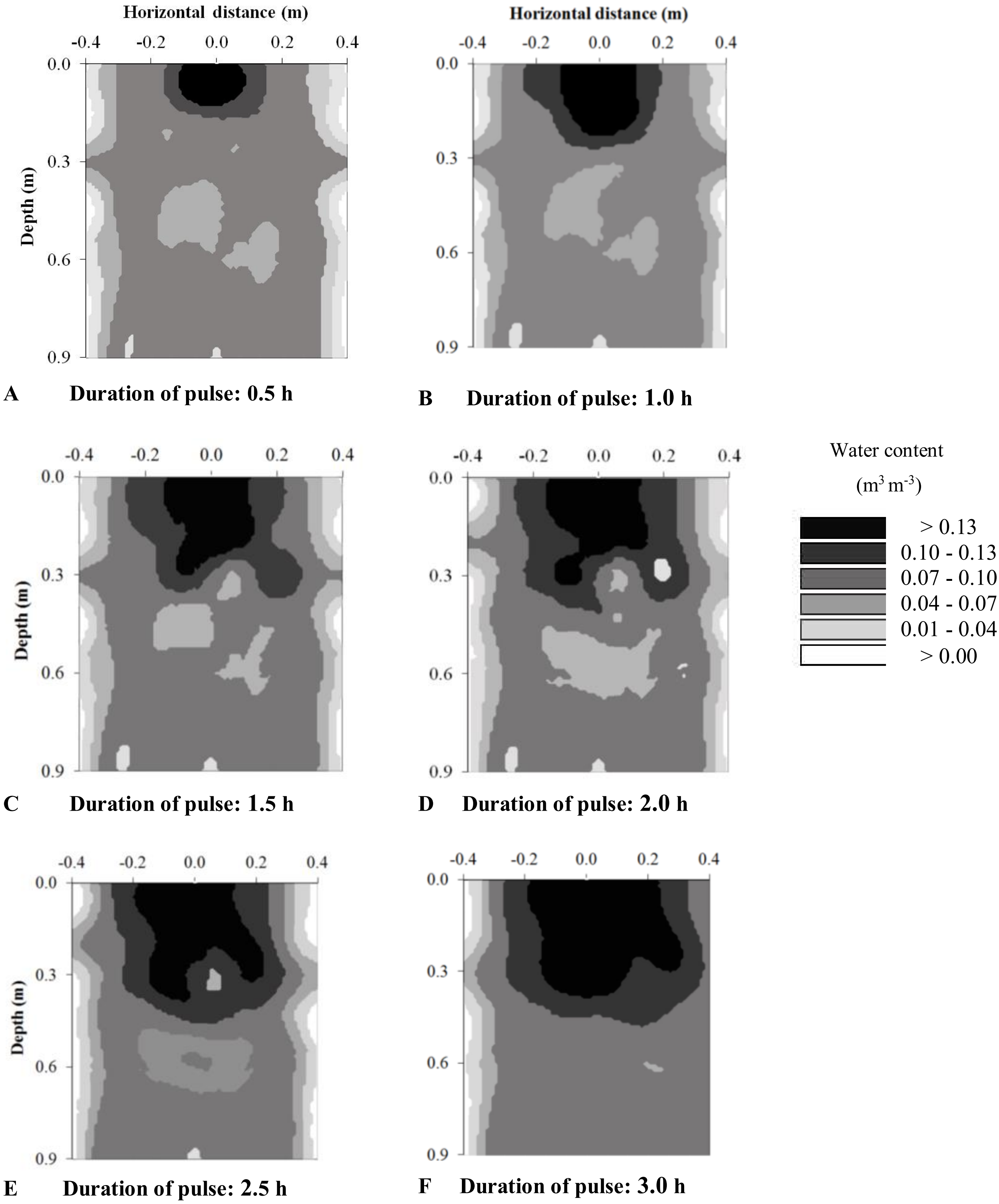


Figure 9 (A-F). Distribution of the θ_v in the soil profile 2 h after irrigation when the pulse duration progressed by 0.5 h increments between 0.5 to 3.0 h in Candler Sand (central Florida Ridge Soil), and the pulse rate of the emitter 4.63 L h^{-1}, the initial water content 0.055 m^3 m^{-3} (50% depleted from the field capacity water content); estimated by the sensor method.

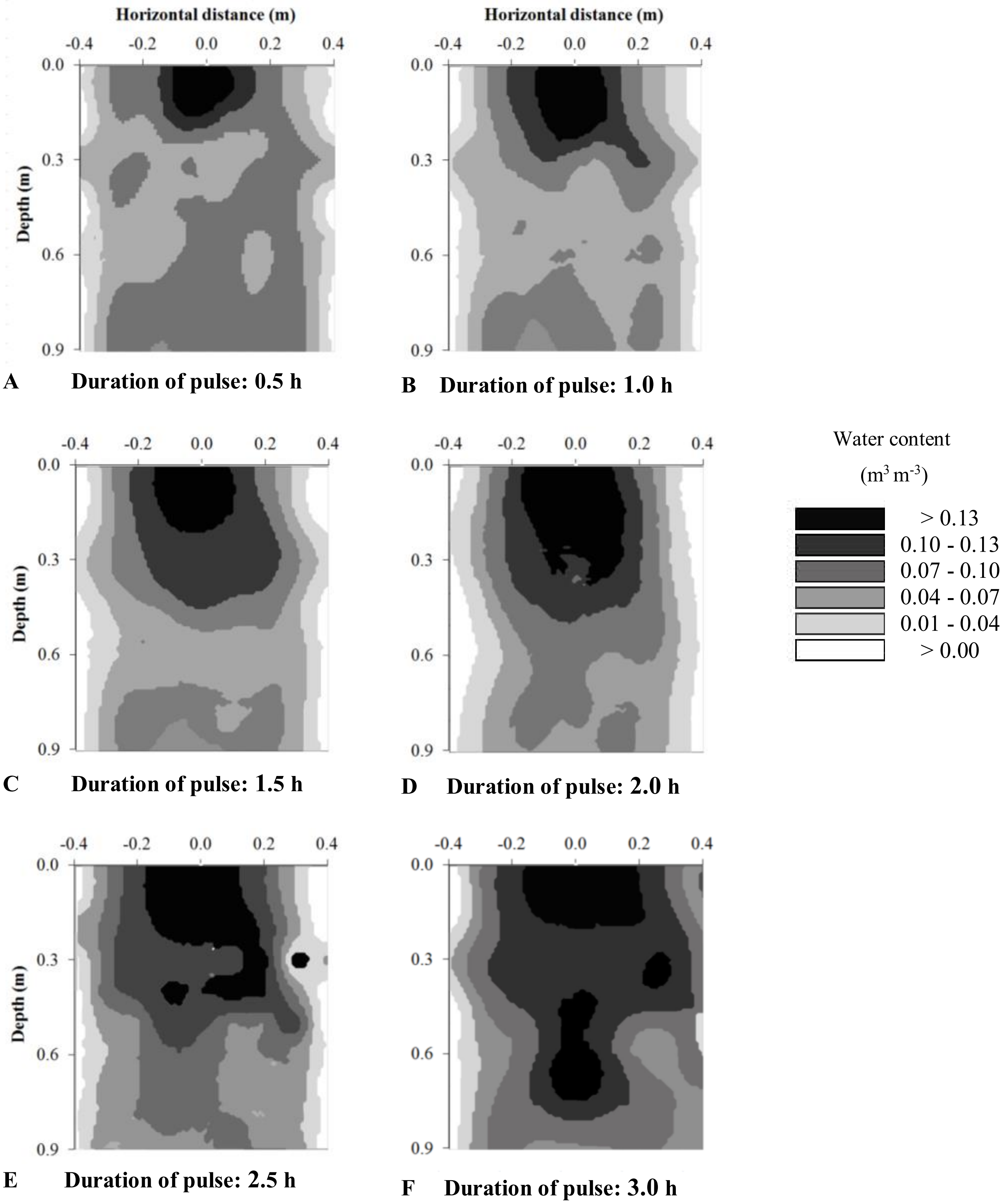
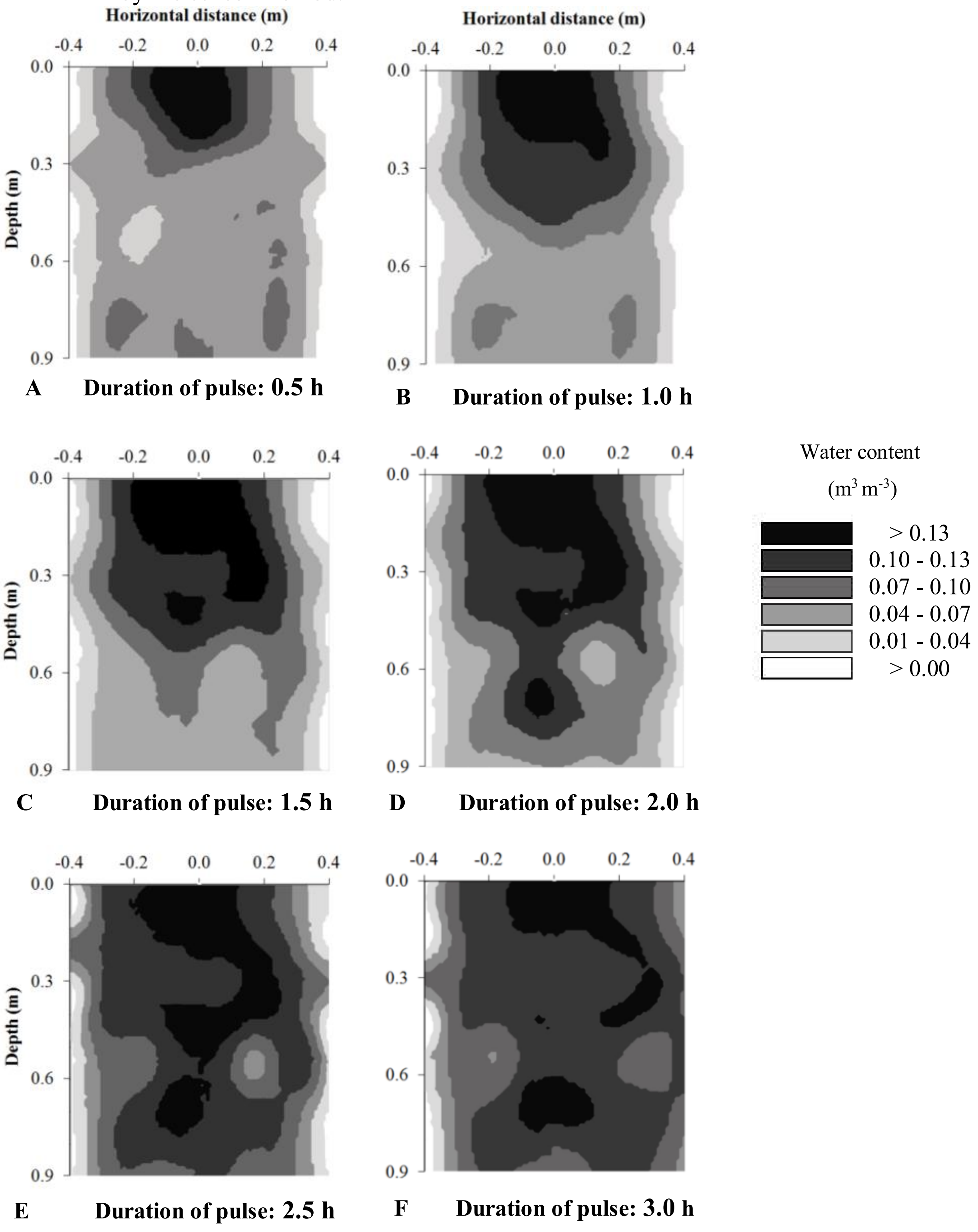


Figure 10 (A-F): Distribution of the θ_v in the soil profile 2 h after irrigation when the pulse duration progressed by 0.5 h increments between 0.5 to 3.0 h in Candler Sand (central Florida Ridge Soil), and the pulse rate of the emitter 8.57 L h^{-1}, the initial water content 0.055 m^3 m^{-3} (50% depleted from the field capacity water content); estimated by the sensor method.



6 CONCLUSIONS

Of the 3 methods, the sensor method gave the most detailed and useful information. The sensors gave a good picture of the wetting front during irrigation and the θ_v redistribution pattern after the irrigation. Compared to the dye method, the sensor method was more expensive but not tedious and does not need labor to excavate pits to observe the wetting pattern. Once the sensors were installed, it could be used over years to study any factor/s that affects wetting pattern. The greatest advantage with the dye method was that the wetting pattern was visible with the naked eye. Although, model was more convenient, the results did not agree well with the observed field data. In this sandy soil, the maximum wetting diameter was limited to about 0.60 m but the wetting depth increased with increasing pulse rates and durations. There was some indication of preferential flow but was minimal and had limited influence on the wetting pattern. Increasing the pulse duration did not help to increase the wetting diameter even with a lower pulse rate (1.94 L h^{-1}). The wetting depth exceeded 1 m with a pulse duration > 3 h and pulse rate >8.0 L h^{-1}. The highest wetted volumes were achieved with 4.63 and 8.57 L h^{-1} emitters with a pulse-duration of 3 h. The wetted volume was 0.36 m^3 (4.3% of the rootzone soil volume that 50% of the active roots would occupy) with 4.63 L h^{-1} and with the 8.57 L h^{-1} the wetting depth exceeded 1 m. The best combination was a 4.63 L h^{-1} emitter with 3 h pulse duration which yielded the WD and Z both 0.77 m. These results can be useful in designing a drip irrigation system (dripper spacing, dripline spacing and application rate and time) in sandy soils.

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