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Full Length Research Paper

Simulated and measured soil wetting patterns for overlap zone under double points sources of drip irrigation

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Water resource scarcity is a serious problem hampering agricultural development in the arid and semi-arid region. Drip irrigation is one of the most useful methods that is widely used in the arid and semi-arid region. Intersection is a however, common event under drip irrigation and the crops are always planted in the overlap zone, hence a suitable design and operation of the system is very important for crop yield. In this study, experimental and simulated soil wetting pattern of overlap were investigated for drip irrigation at different emitter discharge, irrigation volume and emitter spacing, respectively. Simulations of the water content and wetting front were close to the observed data. To evaluate the effects of various parameters on wetting, additional simulations were carried out with HYDRUS. After the simulation under the HYDRUS environment, we therefore recommended a larger irrigation volume, larger wetting pattern; and when the emitter spacing is shorter, then the wetting patterns should be larger. Due to the heterogeneity of soil texture, the horizontal and vertical distance are almost uniformly in the loam and silt, inversely in loamy sand.

Key words: Drip irrigation, HYDRUS, intersection, soil wetting pattern.

INTRODUCTION

Improving water use efficiency is very important for agriculture in arid and semi-arid region. Xinjiang is a typical arid region in China, with water resource only 7.93 × 10^8 m^3, severe evaporation and less rainfall. High efficiency irrigation technical must therefore be applied in this region. In the last two decades, drip irrigation was widely used in Xinjiang whose purpose is to increase crop yield, improve water application uniformity, save labor force and cost reduction, save energy and also reduce water deep percolation. Hence, it is necessary to design suitable drip irrigation system.

Drip irrigation is partial wetting in the soil with a proper wetting pattern. Wetting volume is affected by some factors, including emitter discharge rate, water application, emitter spacing and various soil texture. Many researchers have developed a series of methods to measure and simulate wetting front and soil moisture pattern, amongst whom are Philip (1968), Warrick (1974), Bresler (1978), Schwartzman and Zur (1986), Angelakis et al. (1993), Chu (1994), Ben-Asher and Phene (1996), Assouline (2002), Moncef et al. (2002), Cote et al. (2003), Cook et al. (2003), Gärdenäs et al. (2005), Singh et al.(2006), Wang et al. (2006) and Lazarovitch et al. (2007). With the development in computer technology, many researchers have employed numerical models to simulating wetting pattern.Today HYDRUS-2D is a well-known computer software package widely used simulating water, heat, and/or solute movement in two-dimensional, variably-saturated porous media. Some researchers have proved that this model can simulate the soil wetting. For example, Skaggs et al. (2004)

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Table 1. Soil characteristics of the experiment field.

Depth (cm)	Bulk density (g cm^{-3})	Clay (%)	Silt (%)	Sand (%)
10	1.53	5.3	22.7	72
20	1.51	6.6	26.9	66.5
30	1.48	5.9	24.8	69.3
40	1.49	5.9	24.5	69.6
50	1.45	5.6	23.3	71.1
60	1.59	2.4	8.8	88.8
Average	1.51	5.3	21.8	72.9

demonstrated that HYDRUS-2D simulations of drip irrigation were in agreement with detailed field measurements.

Many studies focus on simulating wetting pattern under single point source and/or double point source drip irrigation, respectively, although a few studied wetting pattern in overlap zone. In the field, this occurs in intersection and crop are always planted in overlap zone, hence clearly knowing wetting pattern in the zone is very important for designing irrigation system and crop yield. The objective of this study was to simulate with the HYDRUS (2D/3D) software package (Šimůnek et al., 2006) soil wetting under double points resources drip irrigation on sandy soil. The purpose was to investigate relationships among the physical parameters, hydraulic and soil wetting patterns. Based on the results, we designed a suitable drip irrigation system aimed at promoting a sustainable agricultural development in Xinjiang.

MATERIALS AND METHODS

The experimental site

Field experiments were conducted in 2010 at the management of irrigation station of BaZhou, Kuerle Country (41°35′N, 86°10′E, and altitude 903 m). The region is classified as a warm-temperate arid zone with continental climate and an average of yearly precipitation of approximately 53.3~62.7 mm, most of which falls between June and August. Average of yearly evaporation from a free water surface is from 2273 to 2788 mm, average of relative humidity 45 to 47%, average yearly temperature 10.5°C, with a maximum of 43.6 and minimum of -9.4°C, total radiation of 633 kJ/m^2 with average of yearly sunshine of 3036 h. Average of yearly accumulated temperature is higher than 10°C, exceeding 4285°C and no frosting of 188 days.

The experimental layout

Experiment 1

Field experiments were carried out on a sandy soil. For the first experiment: the emitter discharge was 2.2 L/h, the emitter spacing was 40 cm and irrigation volumes were 8, 10 and 12 L, respectively. The average volumetric water content was 0.043 cm^3 cm^{-3}.

Experiment 2

For the second experiment, the emitter discharge and the emitter spacing were 2.2 L/h, 2.2 L/h and 30, 40 cm, respectively. For both cases, irrigation volumes were 10 L, while the average volumetric water content was 0.038cm^3cm^{-3}.

At the end of the irrigation event, the soil surrounding the emitter was excavated and soil samples were taken in four locations (0, 10, 20 and 30 cm away from the center of intersection) and at six depths (0, 10, 20, 30, 40, 50 and/or 60 cm). The type of soil physical properties included the determination of soil bulk density and percentage sand, silt, and clay for the depths 0 to 10, 10 to 20, 20 to 30, 30 to 40, 40 to 50, 50 to 60 cm. The measured values for these physical properties are presented in Table 1. Also, the water content of each sample was determined gravimetrically: samples were weighed as collected, dried at 105°C, then re-weighed to determine soil moisture and convert the gravimetric water content to volumetric water content.

Numerical modeling

Water flow simulation

The governing Equation for water flow in three-dimensional form is the 3D Richards Equation:

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

Where θ is the volumetric water content (cm^3 cm^{-3}), t is the time (min), x is the horizontal space coordinate (cm), y is the vertical space coordinate (cm), z is the vertical space coordinate (cm) and K is the hydraulic conductivity (cm min^{-1}). The soil hydraulic properties were specified according to the van Genuchten model:

$$\theta(h)=\begin{cases}\theta r+\dfrac{(\theta s-\theta r)}{(1+|\alpha h|^{n})^{m}}, & h<0\\ \theta s, & h\geq 0\end{cases} \quad (2)$$

$$K(h)=\begin{cases}K_{s}S_{e}^{\,l}\left[1-\left(1-S_{e}^{\,1/m}\right)^{m}\right]^{2}, & h<0\\ K_{s}, & h\geq 0\end{cases} \quad (3)$$

Where

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}, \quad m = 1 - \frac{1}{n} \qquad (4)$$

And where θs is the saturated water content ($cm^3\ cm^{-3}$), θr is the residual water content ($cm^3\ cm^{-3}$), Ks is the saturated hydraulic conductivity ($cm\ day^{-1}$), α is an empirical constant that is inversely related to the air-entry pressure value (cm^{-1}), n is an empirical parameter related to the pore-size distribution (no unit) and l is a shape parameter. HYDRUS-3D uses the finite element method to solve Equations 1 to 3.

Initial and boundary condition

For the experiment studied, the initial condition and upper boundary condition were:

$$\theta(z,0) = \theta_i(z) \qquad (5)$$

$$D_x(\theta)\frac{\partial h}{\partial x} + D_y(\theta)\frac{\partial h}{\partial y} + D_z(\theta)\frac{\partial h}{\partial z} - k(\theta) = -R(t) \qquad (6)$$

Where θi (z) is the initial soil water content in the soil, k (θ) hydraulic conductivity ($cm\ min^{-1}$) and R (t) is water supply strength. The free drainage was to be considered as lower boundary condition:

$$\frac{\partial \theta}{\partial z} = 0 \qquad (7)$$

At the end of the irrigation event, the upper boundary became a zero-flux boundary. During and after irrigation, zero-flux boundary conditions were also used in all the directions. Due to shield by an umbrella, evaporation could be neglected and a zero-fluboundary was used at the soil surface.

Running HYDRUS-3D required specifying the hydraulic parameters θs, θr, Ks, α, n and l, hence we estimated the hydraulic parameters using the inverse solution that is included in the HYDRUS software package. The parameters were estimated to be θr = 0, θs = 0.37, α = 0.1058 cm^{-1}, n = 1.993, Ks = 2.447 $cm\ min^{-1}$ and l = 0.5.

Statistical analysis

The root-mean-square-error (RMSE) and coefficient of determination (R^2) for both simulated and measured volumetric water contents and wetting dimensions were calculated to provide a quantitative comparison of the goodness-of-fit between measured and simulated data. These parameters are defined as (Willmott, 1982):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}} \qquad (8)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2} \qquad (9)$$

Where *N* is the total number of data points; P_i is the ith simulated data point; O_i is the ith observed data; $\bar{O}$ is the mean of observed.

RESULTS AND DISCUSSION

Compared measured and simulated wetting

Figures 1 to 5 show the measured and simulated volumetric water content distributions for drip irrigation in the field (irrigation volume,; 8, 10 and 12 L; emitter spacing, 40, 30 and 40 cm; irrigation volume, 10 L). Each Figure shows measured and simulated volumetric water content in selected soil profile. The contour plots show the distribution of water content in the soil profile of overlap zone drawn by a Kriging interpolation algorithm. From the contour plots shown in Figures 1 to 5, it is clearly that simulated water content distribution was very close to the observed, and the results of transect plot was also in agreement between the observed and simulated. Figure 6 shows the measured and simulated the wetting front with time changed. From the Figures shown, it is clear that the relationship between simulated and observed data is very close.

To evaluate the accuracy of the model, we calculated the observed and simulated data by the root mean square and the coefficient of determination (R^2). Table 2 contains the calculated value for water content and wetting front with irrigation water 8, 10 and 12 L; emitter spacing 30 and 40cm, respectively. The water content value of RMSE and R^2 ranged from 0.0146 to 0.017 and 0.86 to 0.92, respectively. The wetting front value of RMSE and R^2 also ranged from 4.98 to 6.9 and 0.98 to 0.99, respectively. Based on these results, it was therefore confirmed that this model is a suitable tool and guide for designing drip irrigation system.

Various parameters' effect on wetting pattern

There are some parameters' effects on the wetting pattern, including irrigation volume, emitter spacing, emitter discharge rate and soil texture. To have knowledge of these parameters' effect on the wetting pattern, we conducted the simulations with HYDRUS. The data of simulations are presented in Table 3.

Irrigation volume

Figures 1 to 3 show the simulated and observed wetting

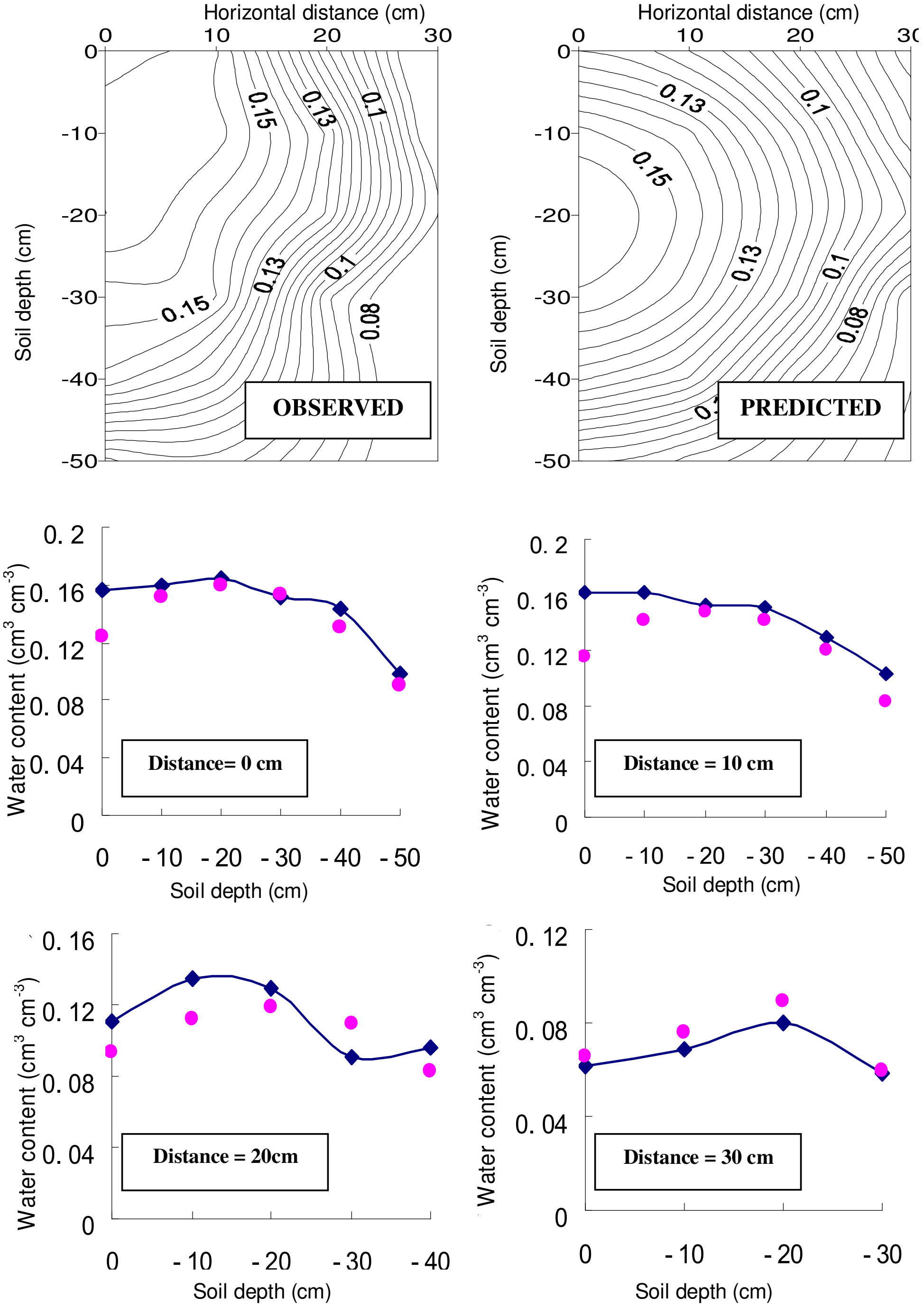

Figure 1. Measured and predicted water contents with irrigation volume of 8 L. The upper plots show the observed and predicted water content contour map in the soil profile. The lower plots compare measured (solid line) and predicted (solid circle) water content along selected transects.

pattern and wetting front, respectively. From the Figures, it is clear that both wetting pattern and wetting front increases with increase in water application. Wetting front followed a power function with time changes in horizontal and vertical direction, respectively. In the field, we always observed that the problem with wetting front can be observed in horizontal, but cannot in vertical direction. Hence, to solve this problem, we used the results of 8 L volume irrigation experiment and constructed the relationship formula (Equations 9 and 10) between

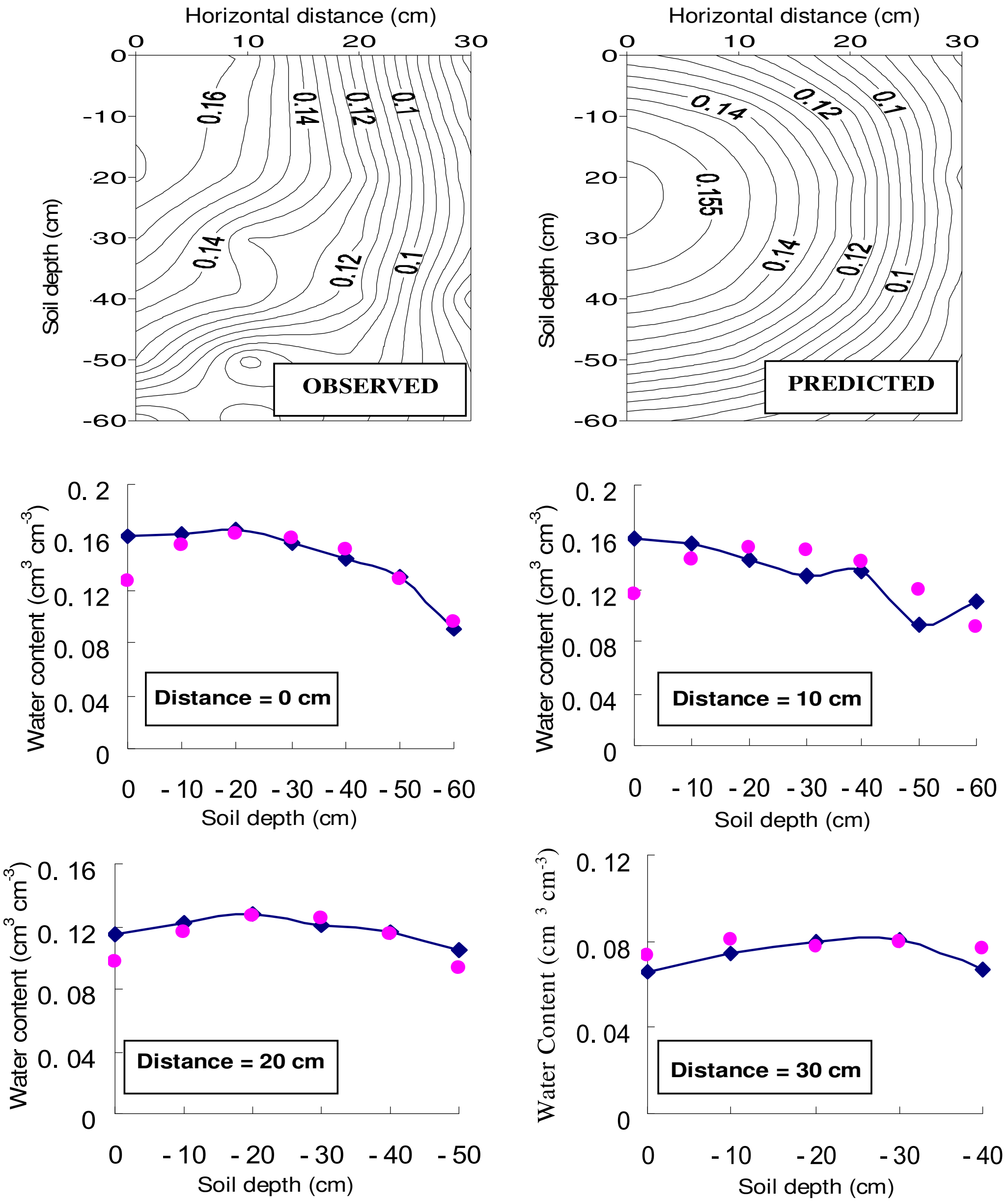

Figure 2. Measured and predicted water contents with irrigation water volume of 10 L.

horizontal distance and vertical distance. To verify the accuracy of the expressions, we employed irrigation volume 10 and 12 L experiments results, with results shown in Table 4. Comparing the observed and simulated data, we observed that both were very close and thus proved that the expression could be used to simulating wetting front in the sand soil.

$$X_{if} = 1.77 t^{0.6358} (t_1 \le t \le t_2) \tag{10}$$

$$X_{if} = 1.06 Z_{if} \tag{11}$$

Where X_{if} and Z_{if} are the wetting front for intersection zone in horizontal and vertical direction, respectively (cm); t_1 and t_2 are the intersection time and final time, respectively (min).

Emitter spacing

Figures 4 to 6 showed the measured and simulated wetting pattern and water content distribution. Results indicated that the wetting front increases with shorter emitter spacing, while water content is the same. The reason is that time of intersection is faster with shorter emitter spacing. We should therefore select shorter

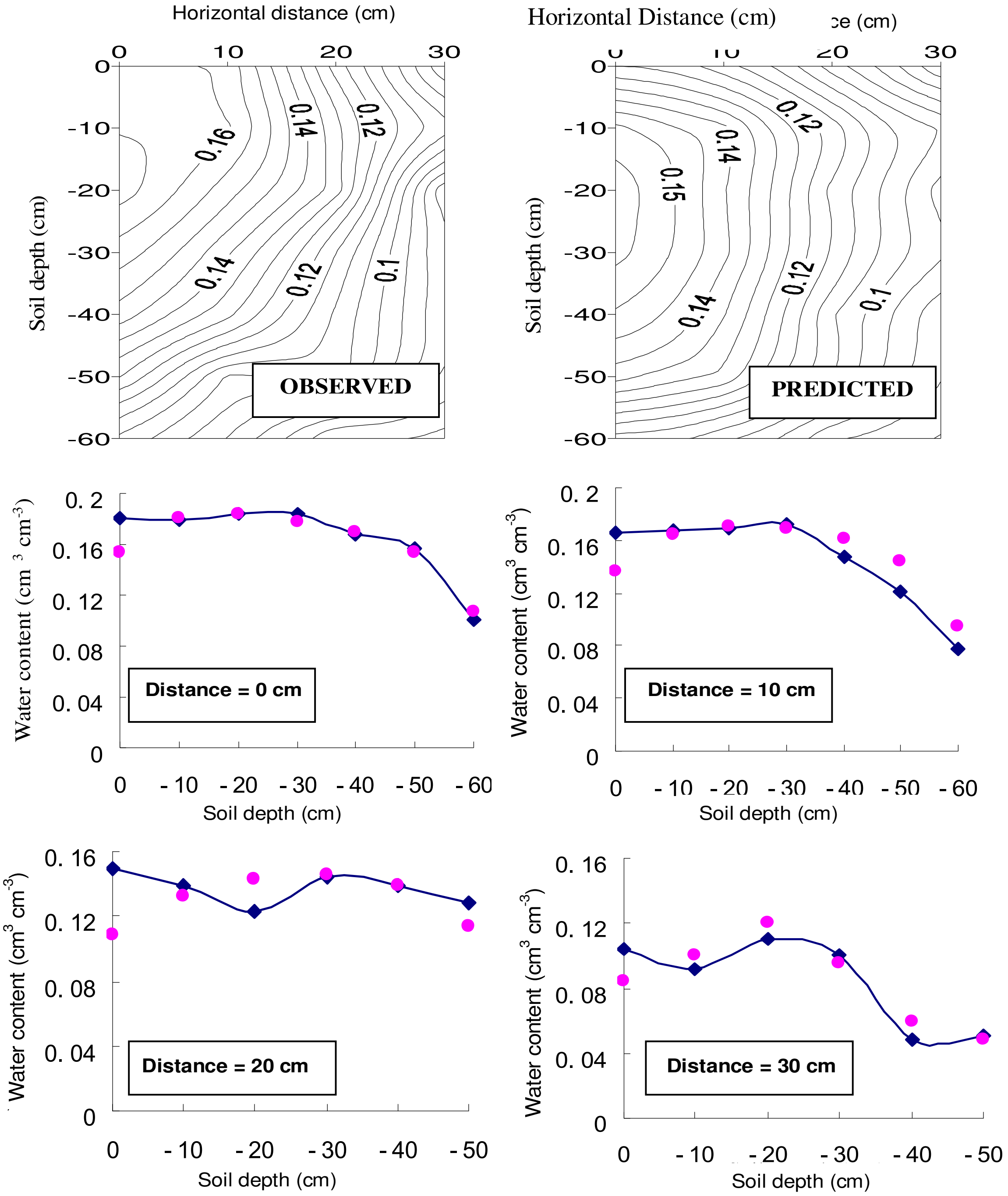

Figure 3. Measured and predicted water contents with irrigation volume12 L.

emitter spacing, since under the same field condition we can increase the wetted area, thus improving water content and water use efficiency.

Emitter discharge

The effect of emitter discharge on the shape of the wetted zone was demonstrated in Figure 7. The Figure showed that the wetting pattern increases with emitter discharge. Based on the predicted results, relationship between wetting area and emitter discharge were constructed and the expression is:

$$y = 1097.8x^{0.8842} \tag{12}$$

According this expression, we could calculate wetted

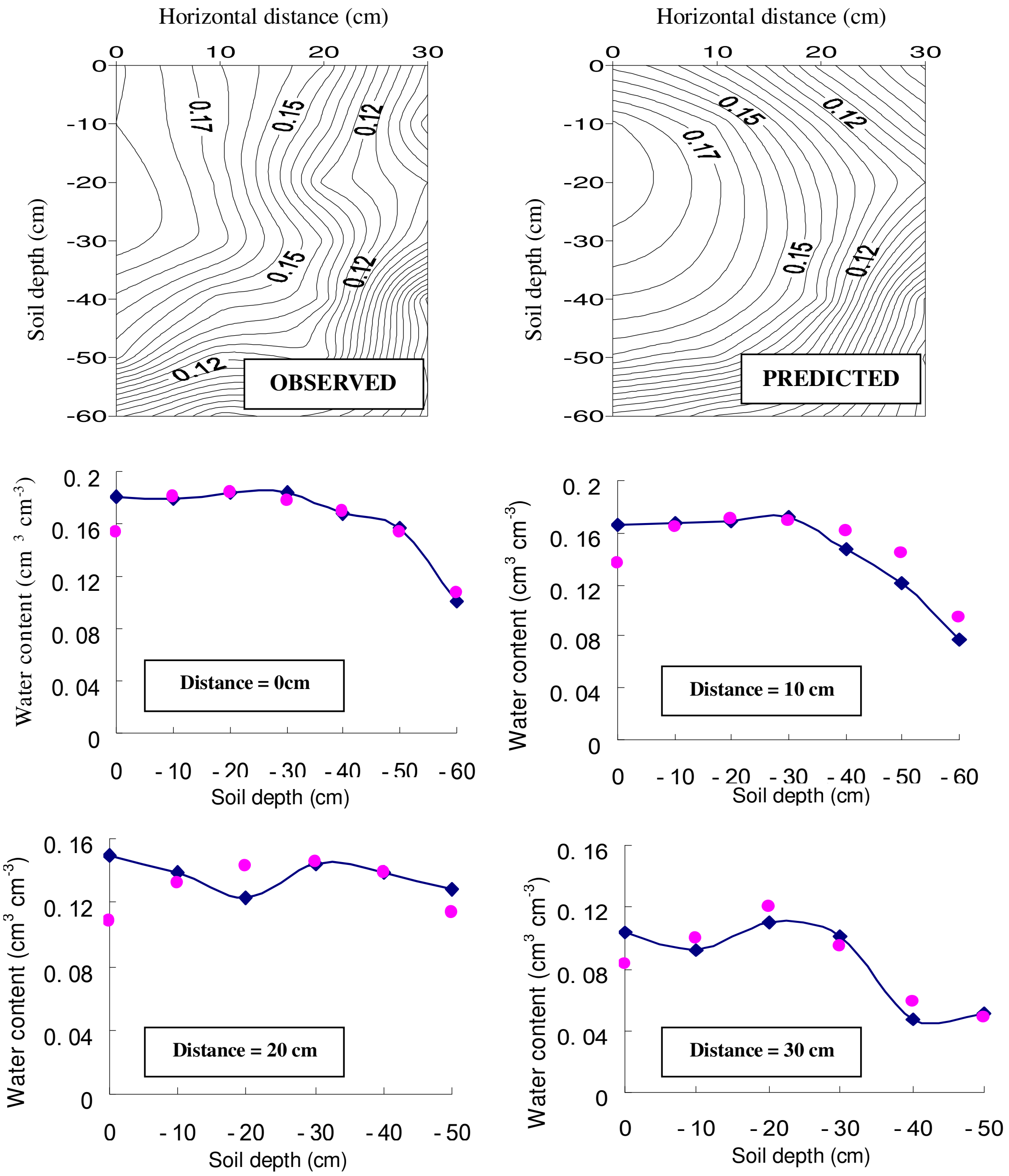

Figure 4. Measured and predicted water contents with emitter spacing 30 cm.

area with different emitter discharge under loam soil in the field.

Soil texture

The effect of soil texture on the shape of the wetted zone (Case II) was investigated using the soil hydraulic parameter values given in Table 5, which are typical values for particular soil texture classes (Carsel and Parrish, 1988). The predicted wetting fronts for overlap zone under double points sources drip irrigation are plotted in Figure 8. The Figure shows that vertical distance was longer than horizontal distance in selected soil and the reason is due to gravity action. Also, since the loamy sand has the larger hydraulic conductivity, infiltration depth is the deepest. However, the horizontal distance is the shorter in loamy sand. Comparing the patterns of wetted zone, it was clearly shown that the distance of finer soil is almost equal in horizontal and vertical direction. Based on this conclusion, we could estimate the vertical distance according to the horizontal distance for the finer soil in the field. However, as for the loamy sand, we need to construct a relationship between horizontal and vertical distance, so as to be able to estimate vertical distance.

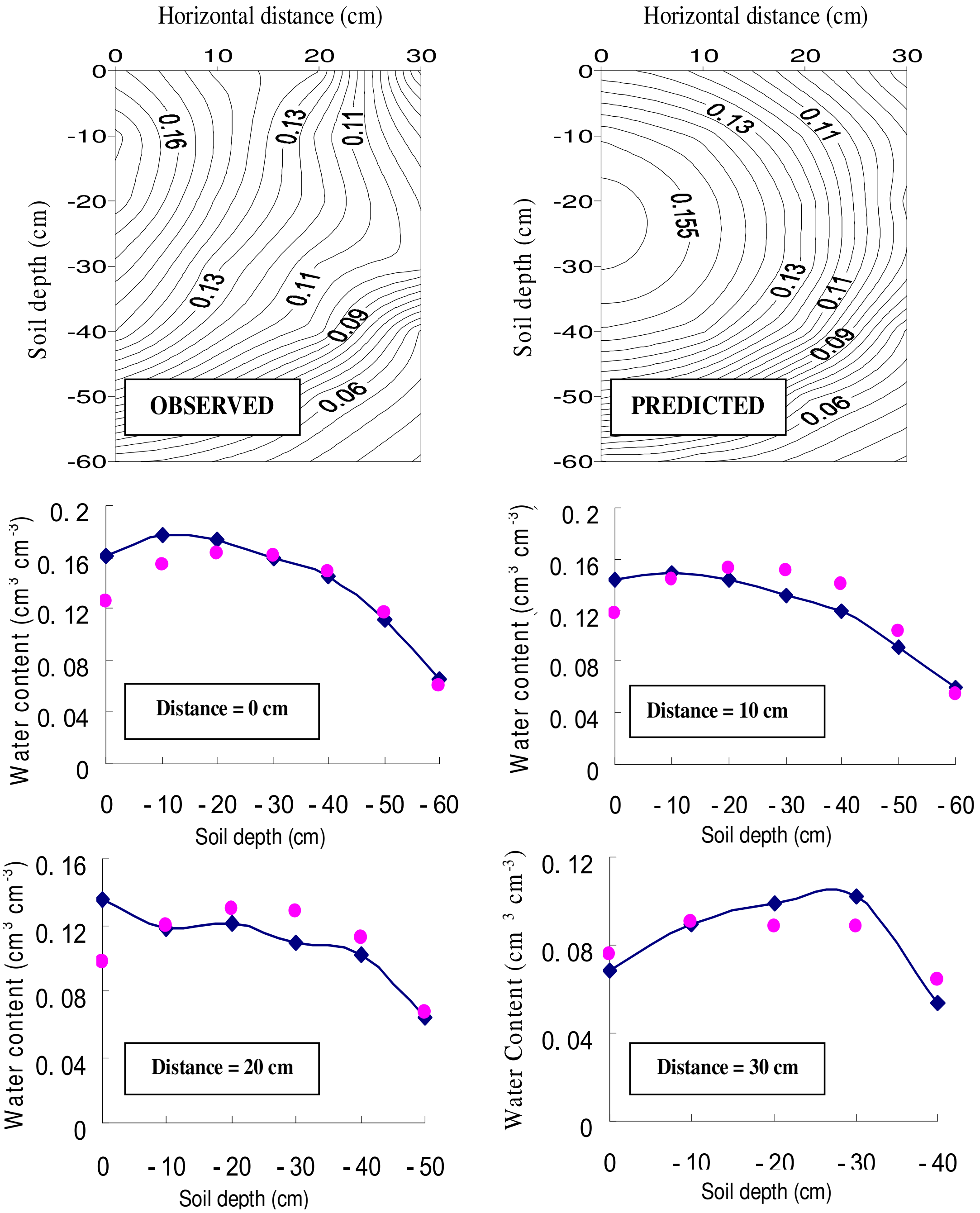

Figure 5. Measured and predicted water contents with emitter spacing 40 cm.

Conclusion

Water resource scarcity is a serious problem which hampers the development of agriculture in Xinjiang. Drip irrigation is an effective method to solve the problem. In this work, observation and simulation studies were carried out to investigate soil wetting patterns for overlap zone under double points resource drip irrigation on sand soil. Soil water distributions and wetting front predicted with HYDRUS (2D/3D) were very close to experimental measurements in overlap zone. Based on the calculated root mean error and coefficient of determination, it could be concluded that the model can help designing drip irrigation system in practical.

More also, based on the results of the simulations, it is concluded that as irrigation volume increases, the size of the wetted zone should be increased. Emitter spacing and wetted zone showed inverse correlation such that as

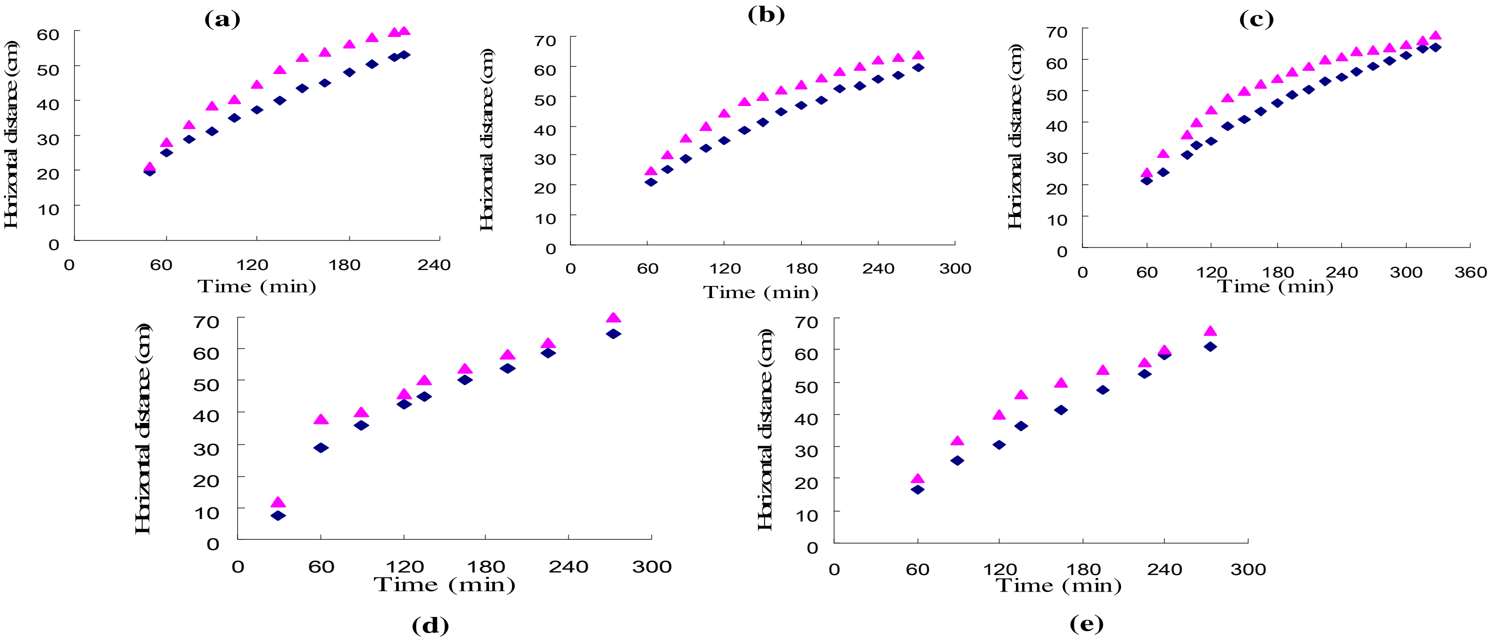

Figure 6. A comparison of measured and simulated wetting dimensions for (a) 8 L, (b) 10 L, (c) 12 L and distance; (d) 30 cm and (e) 40 cm field experiments, respectively (▲—simulation, ■—observations)

Table 2. Statistical comparison of measured and simulated data for field experiments.

Measurement	Emitter discharge (L h^{-1})	Emitter spacing (cm)	Irrigation volume (L)	R^2	RMSE*
Soil water contents	1.8	30	8	0.92	0.017
	2.2	30	10	0.88	0.015
	3	30	12	0.86	0.0146
	2.2	30	10	0.92	0.0151
	2.2	40	10	0.89	0.0158
Wetting dimensions	1.8	30	8	0.99	6.9
	2.2	30	10	0.98	6.8
	3	30	12	0.98	6.72
	2.2	30	10	0.99	4.98
	2.2	40	10	0.98	6.5

*Root-mean-square-error was evaluated for the soil water content in volumetric units (cm^3 cm^{-3}) and for wetting dimensions in cm.

Table 3. Parameters used in HYDRUS-3D simulations.

Case	Soil type	Emitter spacing (cm)	Emitter discharge (L h^{-1})	Irrigation volume (L)	Water content (cm^3 cm^3)
I	Loam	40	1.8,2.4,3	12	0.15
II	Loam, loamysand, silt	40	1.8	12	0.15
III	Loam	40	2.4	12	0.1,0.15,0.2

Table 4. A comparison of measured and simulated wetting front in horizontal and vertical, respectively.(■-observed ▲-simulated).

Irrigation volume (L)	Wetting dimension of overlap zone (cm)			
	Horizontal		Vertical	
10	60.5■	62.5▲	57■	61▲
12	64.5■	70▲	61■	63▲

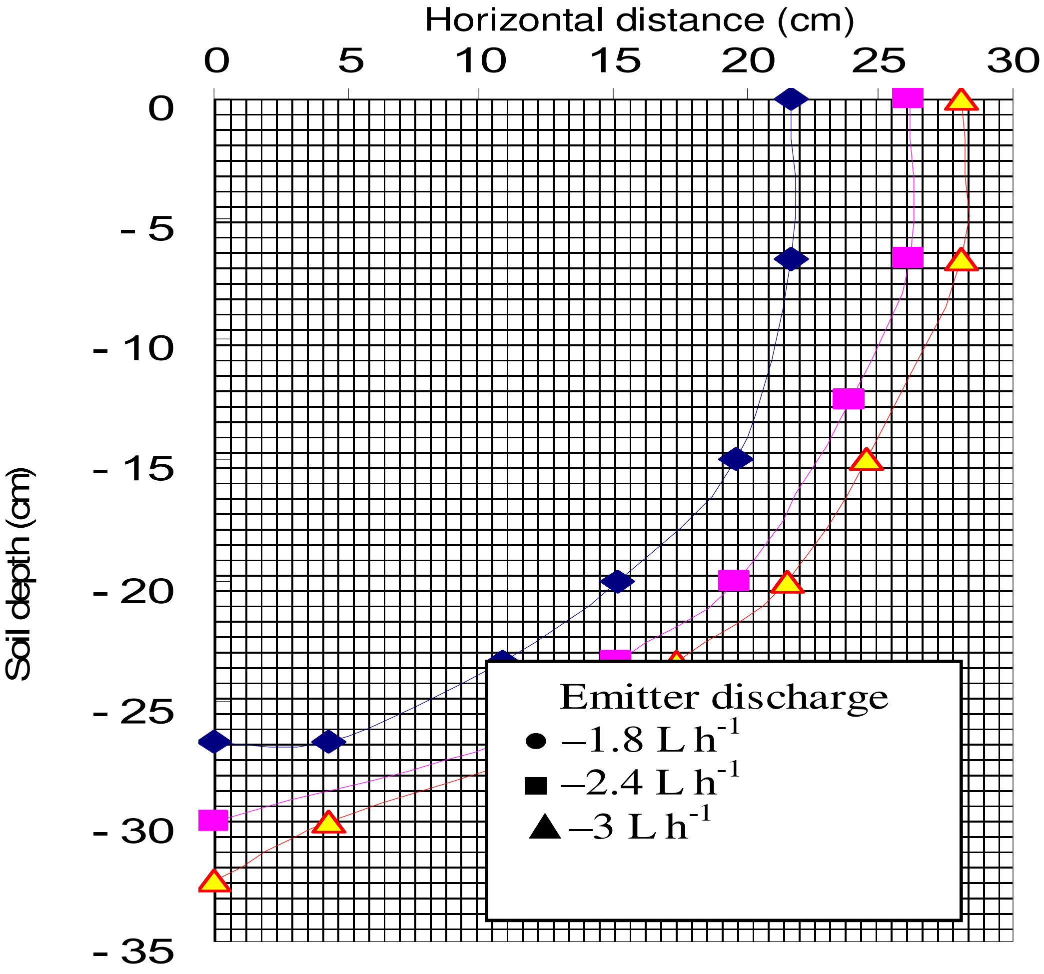

Figure 7. Predicted wetting front for intersection zone under different emitter discharge of drip irrigation.

the larger the emitter discharge, the larger the wetted zone. Relationship between wetted area and emitter discharge thus followed a power function due to soil texture diversity, which leads to has larger impact on wetting geometry. Overall, the horizontal and vertical distances were nearly uniform in the loam and silt, but

Table 5. Hydraulic parameter value typical of particular soil textural classes (Carsel and Parrish, 1988).

Textural class of soil	Θr (cm^3cm^{-3})	θs (cm^3cm^{-3})	α (cm^{-1})	Ks (cm min^{-1})	n	l
Loam	0.078	0.43	0.036	1.56	0.0173333	0.5
Loamy sand	0.057	0.41	0.124	2.28	0.243194	0.5
silt	0.034	0.46	0.016	1.37	0.00416667	0.5

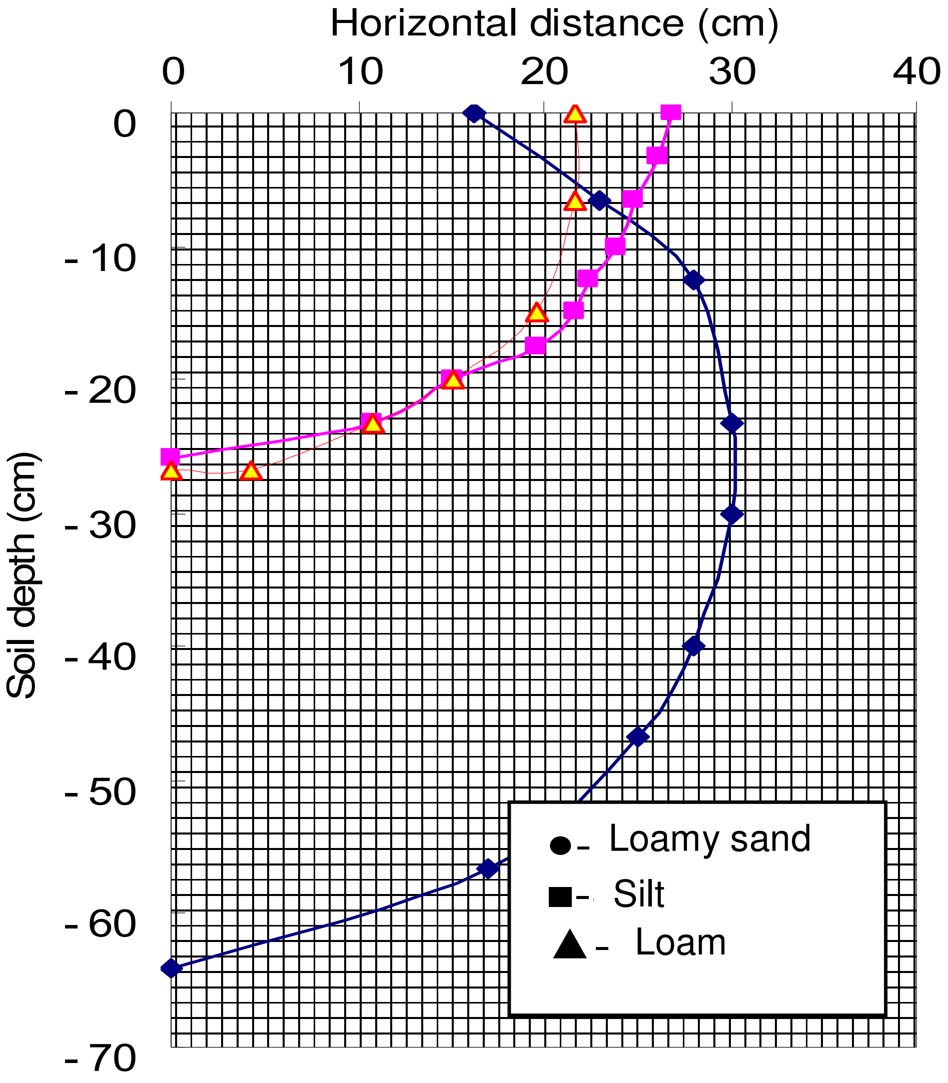

Figure 8. Predicted wetting front for overlap zone under different soil texture of drip irrigation.

inverse in loamysand.

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