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Capability of Hydrus-2D Model for Simulation of Water Distribution in Irrigation Systems

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ABSTRACT: Study of water distribution in the soil is essential for appropriate design of drip irrigation system. Water distribution in the soil depend on the hydraulic properties of the soil and emitter discharge. Experiments were conducted with the Research Farm of Bastam Agricultural Center, Shahrood, Iran to investigate the water distribution pattern under sandy loam soil. A water and solute transport model Hydrus-2D was calibrated with observed data to simulate the water distribution pattern for different type of soil under varying emitter discharge. HYDRUS-2D is a finite element model, which solves the Richard's equation for variably-saturated water flow and convection-dispersion type equations for heat transport. The model can deal with prescribed head and flux boundaries, controlled by atmospheric conditions, as well as free drainage boundary conditions. The simulations were done for a soil profile of depth Z = 60 cm and radius r = 30 cm, with a trickle emitter placed at the surface. The flux radius was taken equal to the wetted radius considering emitter in centre. Surface area for irrigation without causing pounding was determined from the flux radius and subsequently flux per unit area, resulting from single emitter was estimated. Simulation result revealed that for all the soils water content was more in middle layer. Even after 48 hrs from irrigation adequate water content is available in the active root zone of the onion. This indicates that irrigation interval of 48 hr is appropriate. Amount of percolation below root zone was highest in sandy loam and negligible in silty clay loam soil.

Keyword: Water Distribution, Simulation, Boundary Condition, Drip Irrigation, Water Content.

INTRODUCTION

In design of drip irrigation systems, the volume of soil wetted by single emitter is important. This must be known in order to determine the total number of emitters required to irrigate the volume of soil to a level that plants do not suffer from water stress. The volume of soil wetted by an emitter is primarily a function of soil texture, soil structure, emitter discharge and the total amount of water applied (Lubana and Narda, 1998). Though some guidelines are available to install, maintain and operate drip irrigation systems (Hanson, 1996). There are no clear guidelines for design and managing drip irrigation systems that account for differences in soil hydraulic properties (Cote *et al.,* 2003). Conducting field experiments in large number of soils with varying emitter discharge rates to investigate water and nutrient distribution for evolving appropriate design and management option is a costly and time consuming affair. A properly calibrated and validate flow and solute transport model can reduce time and cost required for studying the water and nutrient dynamics under drip irrigation system. Flow and solute transport models could simulate the water and nutrient distribution in the soil. These models provide an understanding of the relationship amongst the amount and timing of water and nutrient application, the crop root uptake, yield and soil hazard and groundwater pollution (Antonopoules, 2001). However, selection of an appropriate model is very important. Several models have been developed to simulate water flow, nutrient transport, heat flux, crop water and nutrient uptake and biological transformation of nutrients in the soil (Bergstrom *et al.*, 1991; Huston and Wagenet, 1991; Jarvis, 1995; Gabriella and Kengni, 1996; Breve *et al.*, 1997; Lafolie *et al.*, 1997).

Water and solute transport models enrich the understanding of their movement in the soils and nutrient uptake by plants and can be valuable tools in designing drip fertigation system. Several models have been used for simulating the water and nutrient movement in drip fertigation system. However, most of these models describe the early stage of infiltration and provide an estimate of water content behind the wetting front (Clothier and Scotter, 1982). Although they are easy to implement, they deal mainly with

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design considerations of the drip source (Cote *et al.,* 2003). Analytical solutions of transient axi-symmetrical infiltration (Warrick, 1974; Revol *et al.,* 1997) can simulate the dynamic condition associated with the drip irrigation but their application was limited in simulation of water and nutrient movement under drip fertigation system under simple boundary conditions. Numerical solution of water and solute transport equations can be an effective tool for simulating the time dependent flux and other boundary conditions. These solutions can implement wide range of boundary conditions, irregular boundary and soil variability.

In the present study, data pertaining to water and nutrient distributions were collected from the drip fertigated onion crop. Since nitrogen is an important nutrient for the crops and a major pollutant of groundwater, only this was considered in the study.

MATERIALS AND METHODS

Experiments were conducted with Azar Shahr variety of onion. Onion was transplanted on 21 March 2006 in 12 plots. Area of each plot was 9 m^2. Plant to plant and row to row spacing were 15 cm and 30 cm, respectively. The applied fertilizers were 96 kg/ha of N, 50 kg/ha of P and 70 kg/ha of K. Experimental site was located at the Bastam Agricultural Center Farm, Shahrood, Iran which lies the latitudes of 36° 27′ 33.29″ N and longitudes of 54° 58′ 31.85″ E. Climate of Shahrood is categorized as semi-arid, subtropical with hot dry summer and cold winter. The mean annual temperature is 14.4°C. July and August are the hottest months with 40 years normal maximum temperature of 42°C. January and February are the coldest months with a mean temperature of –14° however, the minimum temperature dips to as low as 1°C. The mean annual rainfall is 156.5 mm of which as much as 75% is received during spring season (March to June).

To evaluate the physical properties of soil, soil samples were collected from different layers from surface till the depth of 0.9 m and analyzed to determine physical and chemical properties. Values of the physical properties such as particle size distribution, bulk density, field capacity, permanent wilting point and hydraulic conductivity are presented in Table 1.

DRIP FERTIGATION SYSTEM

In this research work a drip irrigation system was designed for onion crop transplanted in sandy clay loam soil using the standard design procedures. The control head of the system consisted of sand filter, screen filter flow control valve, pressure gauges etc. The system was connected with fertigation tank which was used for the application of fertilizers. A PVC sub main line (50 mm outer diameter, 4 kg/cm^2 working pressure) was laid for the experimental area. Lateral lines (10 mm diameter) were taken out from the sub main line for the irrigation of the onion crop. The lateral lines were spaced at 60 cm interval. The lateral lines were laid in such a manner that the same lateral line supplied water and fertilizer to all the randomized replicated plots. This caused zigzag path of laterals in the experimental area.

Drip emitters with 4 l/h rated discharge were placed on the lateral line at a spacing of 50 cm. Each lateral line was provided with flow control valve at the start of the line. Average emitter discharge observed in the field condition was 4 l/h. Drip laterals were spaced at 0.60 m. The emitter to emitter spacing was 0.50 m. Each lateral served two plant rows. Total number of emitter in each plot was 35. Irrigation scheduling is determination of amount, time, interval and duration of irrigation. Water requirement of onion crop was estimated using the pan evaporation method. Five years average daily pan evaporation values were multiplied with the pan and crop coefficients to estimate the daily crop water requirements. Irrigation requirement was estimated by subtracting corresponding effective rainfalls. Irrigation was applied on every alternate day. On an average irrigation was applied 3 days in a week. Amount of water applied was 5130 m^3/ ha.

Table 1: Physical Properties of Soil of the Experimental Field

Depth (cm)	*Mineral Content % Mass*			*Textural Class*	*Hydraulic Conductivity (cm/h)*	*Bulk Density (g/cm^3)*	*FC (% vol)*	*PWP (% vol)*
	Clay	*Silt*	*Sand*					
0–15	9	28	63	Sandy loam	1.31	1.58	22.17	7.49
15–30	12	17	71	Sandy loam	1.15	1.61	23.27	9.13
30–45	10	21	69	Sandy loam	1.11	1.57	24.11	9.34
45–60	11	19	70	Sandy loam	1.09	1.60	25.36	10.35
60–75	20	21	59	Sandy loam	1.03	1.61	26.12	11.88
75–90	18	23	59	Sandy loam	1.01	1.60	27.89	10.81

OBSERVATIONS

To determine the amount of water in the various layers of the soil and their spatial and temporal distribution, soil samples were collected from different depths (0–15, 15–30, 30–45, 45–60 cm) at different times using tube auger as per sampling schedule. Determination of soil moisture was done by gravimetric method.

DESCRIPTION OF HYDRUS-2D MODEL

In this research work a water and solute transport model Hydrus-2D was used to simulate the water distribution. Hydrus-2D is a finite element model, which solves the Richard's equation for variably-saturated water flow and convection-dispersion type equations for heat transport. The flow equation includes a sink term to account for water uptake by plant roots. The model uses convective-dispersive equation in the liquid phase and diffusion equation in the gaseous phase to solve the solute transport problems. It can also handle nonlinear nonequilibrium reactions between the solid and liquid phases, linear equilibrium reactions between the liquid and gaseous phases, zero-order production, and two first–order degradation reactions: one which is independent of other solutes, and one which provides the coupling between solutes involved in sequential first-order decay reactions. The program may be used to simulate water and solute movement in unsaturated, partially saturated, or fully saturated porous media. The model can deal with prescribed head and flux boundaries, controlled by atmospheric conditions, as well as free drainage boundary conditions. The governing flow and transport equations are solved numerically using Galerkin-type linear finite element schemes. The current version 2.0 of Hydrus-2D also includes a Marquardt-Levenberg parameter optimization algorithm for inverse estimation of soil hydraulic and/or solute transport and reaction parameters from measured transient or steady state flow and/or transport data. A detail description of model and related theory is presented in the report documents version 2.0 of Hydrus-2D (Simunek *et al.*, 1999).

The simulations were done for a soil profile of depth $Z = 60$ cm and radius $r = 30$ cm, with a trickle emitter placed at the surface. The flux radius was taken equal to the wetted radius considering emitter in centre. Surface area for irrigation without causing ponding was determined from the flux radius and subsequently flux per unit area, resulting from single emitter was estimated. Figure 1 shows the conceptual diagram of simulated area and the imposed boundary conditions. No flux was allowed through the lateral boundaries. Bottom boundary was considered as free drainage boundary. Surface boundary was considered as variable flux boundary (up to the radius of 25 cm) and atmospheric boundary for the remaining 5 cm radius. The system was conceptually divided into four layers depending the variability of the soil physical properties.

Initial distribution of the water content in different soil layers within the flow domain was kept as observed in the experimental field. For the purpose of investigating the influence of drip emitter discharge, soil hydraulic properties and frequency of water input on wetting patterns, a time dependent flux boundary condition at the surface in a radius of 25 cm from emitter position emitter was used. This was done to take into account the irrigation and no irrigation periods and temporal changes in duration of irrigation in the growing period. In the present case, water table was situated far below the domain of interest and therefore free drainage boundary condition at the base of the soil profile was considered. On the sides of the soil profile, it was assumed that no flux of water took place and hence no-flux boundary condition was chosen, which in Hydrus-2D is specified for impermeable boundaries where the flux is zero perpendicular to the boundary.

SOIL HYDRAULIC PARAMETERS

The various input parameters required in Hydrus-2D namely saturated water content (θs), residual water content (θr), empirical factors (α, n) and saturated hydraulic conductivity (Ks).The important hydraulic parameters of the soil as required by Hydrus-2D are presented in Tables 2 and 3.

Table 2: Input for Hydrus- 2D: Water Flow Parameters

Soil Layer	Q_r (θ_r)	Q_s (θ_s)	*Alpha* (α) (cm^{-1})	*n*	K_s *(cm/h)*	*l*
1	0.0340	0.3941	0.0088	1.4002	1.31	0.6
2	0.0380	0.3809	0.0065	1.4533	1.15	0.6
3	0.0328	0.3711	0.0055	1.4502	1.11	0.6
4	0.0242	0.3700	0.0131	1.4048	1.09	0.6

RESULTS AND DISCUSSION

Calibration of Model

For prediction of water distribution in soil with the measured water content Hydrus-2D was calibrated. The inputs parameters required by Hydrus-2D were either determined by field experiment or taken from the published literature.

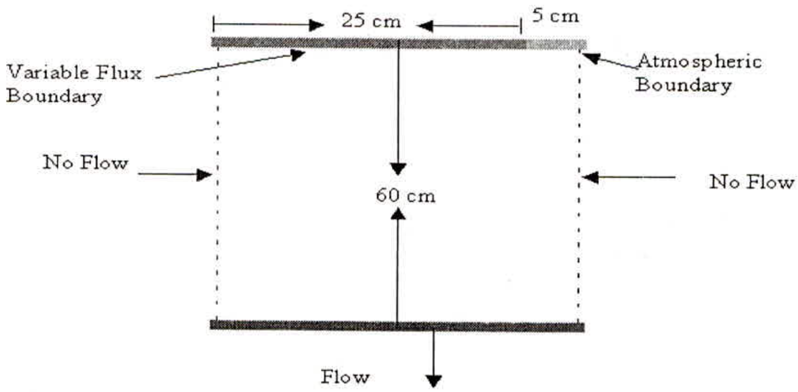

Fig. 1: Conceptual diagram of model

Table 3: Time Variable Boundary Conditions (shown only for one week)

Time (h)	*Precip. (cm/h)*	*Evap. (cm/h)*	*Transp. (cm/h)*	*HCritA (cm)*	*RGWL (cm/h)*	*GWL (cm)*
0.166	0	0.07690	0.0031	10000	−1.27	0
0.33	0	0.09219	0.0031	10000	−1.27	0
48	0	0.08867	0.0029	10000	0	0
48.33	0	0.07835	0.0023	10000	−1.27	0
96	0	0.06380	0.0033	10000	0	0
96.33	0	0.05448	0.0037	10000	−1.27	0
168	0	0.03842	0.0040	10000	0	0

The model was calibrated mainly for hydraulic conductivity values of the sandy loam soil. Model worked well with the measured hydraulic conductivity values. Results of the calibration for water distribution at the end of first month after transplanting is presented through Figure 2. X-axis of this figure shows volumetric water content and Y-axis shows depth from the soil surface. Field observations for water content in the soil were taken at the end of first month and at 2, 4, 12, 24, 48 and 72 h (24 h after next irrigation). Simulated and observed values of water at 2, 4 and 12 h after irrigation were used to evaluate the performance of the model.

Figure 2 shows that simulated and observed water contents follow a similar trend and there is not much difference between simulated and observed values. Values of simulated and observed water content at the end of 2, 4 and 12 h after irrigation varied from 15 to 35%, 13 to 35% and 12 to 35% respectively.

Correlation coefficient between observed and simulated water contents were determined to find out the closeness between them. The higher R^2 values (varying from 0.96–0.99) showed that simulated and observed values are closely related.

SIMULATION OF WATER DISTRIBUTION

Spatial distribution of water content at the end of first month after transplanting 2, 4 and 12 h after irrigation

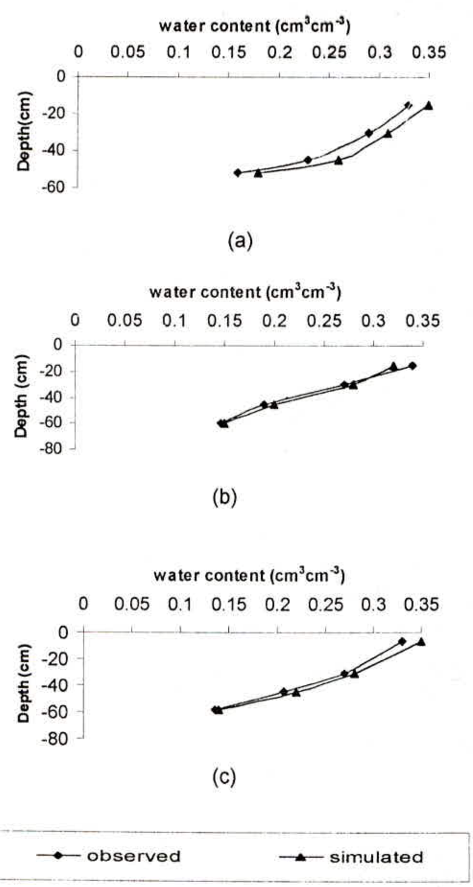

Fig. 2: Simulated and observed water content (a) 2 h after irrigation (b) 4 h after irrigation (c) 12 h after irrigation

with emitter discharge of 4 l/h for sandy loam soil is presented in Figure 3 through color spectrum. It may be mentioned that initial moisture content was kept same in various soil layers. The duration of irrigation was 1 h. The color spectrums in this figure shows simulated values of water content 2 h, 4 h and 12 h after irrigation. X-axis of this figure shows 30 cm radial distance from emitter and Y-axis shows depth from the soil surface. This figure shows that 2h after irrigation amount of water content was highest in first layer of soil which means in this duration only first layer of soil has got maximum water content. Figure 3 (b) shows that 4 h after irrigation amount of soil moisture coming down and it is effecting second layer of soil (middle layer). Figure 3 (c) shows that 12 h after irrigation effect of water distribution increasing in lower layers. Scale of colure spectrum reveals that adequate soil moisture is available even 12 h after irrigation in all soil layers.

Simulated water content 24 h, 36 h and 48 h after irrigation is presented in Figure 4. This figure reveals that water content at 48 h after irrigation is nearly same in radial direction. This may be due to the fact that the emitter discharge was distributed uniformly over the radius of 25 cm as the time dependent variable boundary condition at the soil surface. This figure shows water distribution in sandy loam soil under 4 l/h emitter discharge and at 24, 36 and 48 h after irrigation. Analysis of this figure shows that water content in the first layer decreases at a little faster rate with the elapsed time after irrigation compare to other layers. Applied flux was calculated from the emitter discharge rate of 4 l/h distributed uniformly over the radius of 25 cm. In this case, duration of irrigation was 60 minutes. It may be mentioned that 24 h after irrigation the initial moisture content in first, second, third and forth layers were 0.25, 0.24, 0.22, 0.20.

Simulated water content 4 h after first irrigation in various soils at surface and 15 cm from emitter under 4 l/h emitter discharge rate are presented through Figure 5. This figure reveals that water content at 4 h after first irrigation is nearly same in radial direction for each soil. This may be due to the fact that the emitter discharge was distributed uniformly over the radius of 25 cm as the time dependent variable boundary condition at the soil surface. However, simulated moisture content varied with the soil type near the surface as well as 15 cm depth. In both the cases, water content was lowest in case of sandy loam soil and highest in all soils. Water content in case of sandy loam was higher than the sandy clay loam soil and lower than the silt and same the silty clay loam soil. Interpretation of this figure reveals that percentage of water content 4 h after irrigation in 15 cm depth is more than the soil surface.

PERCOLATION BELOW ROOT ZONE OF ONION

The amount of water percolating below the root zone depth (in this case the simulated depth of 60 cm) was obtained from the cumulative free drainage boundary flux available as output from Hydrus-2D.

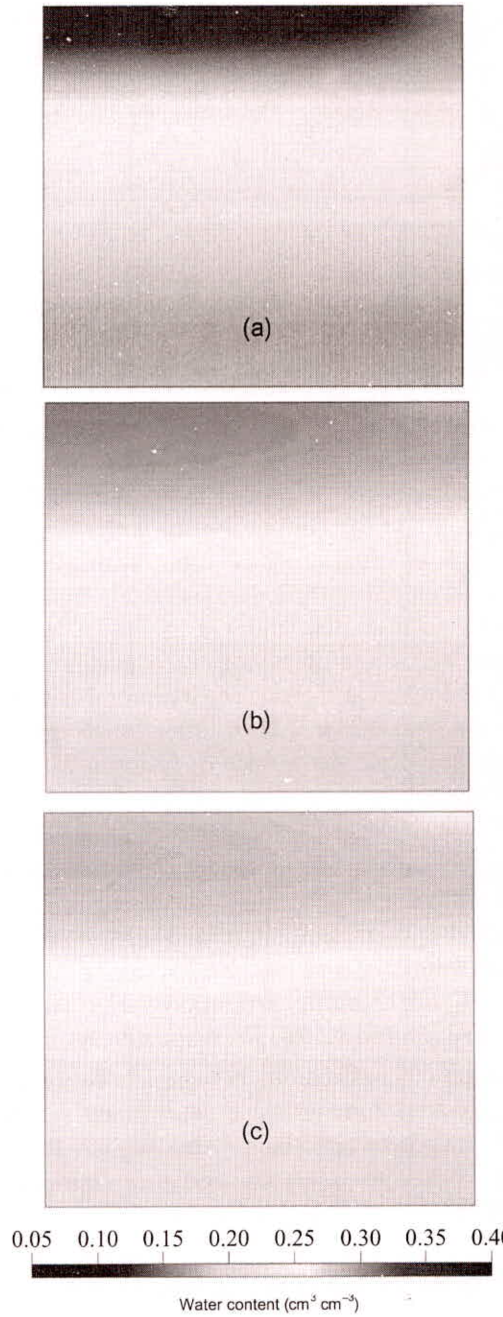

Fig. 3: Simulated water distribution in soil (a) 2 h after irrigation (b) 4 h after irrigation (c) 12 h after irrigation

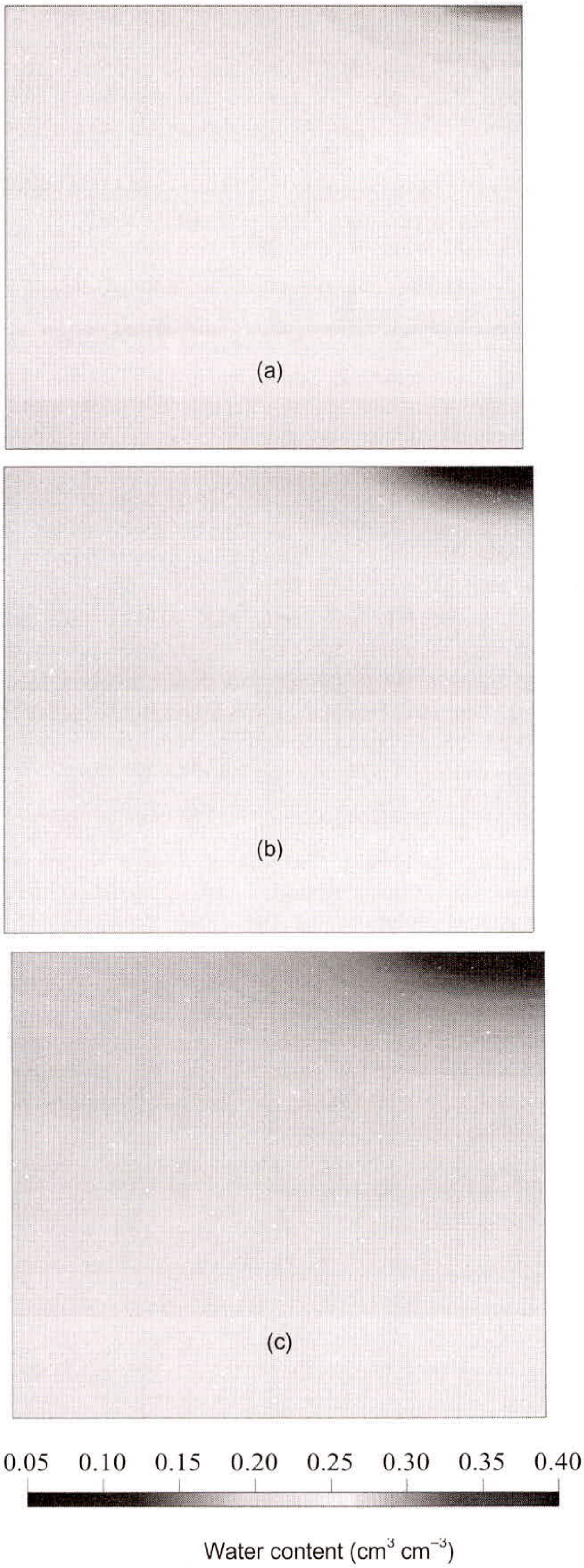

Fig. 4: Simulated water distribution in soil (a) 24 h after irrigation (b) 36 h after irrigation (c) 48 h after irrigation

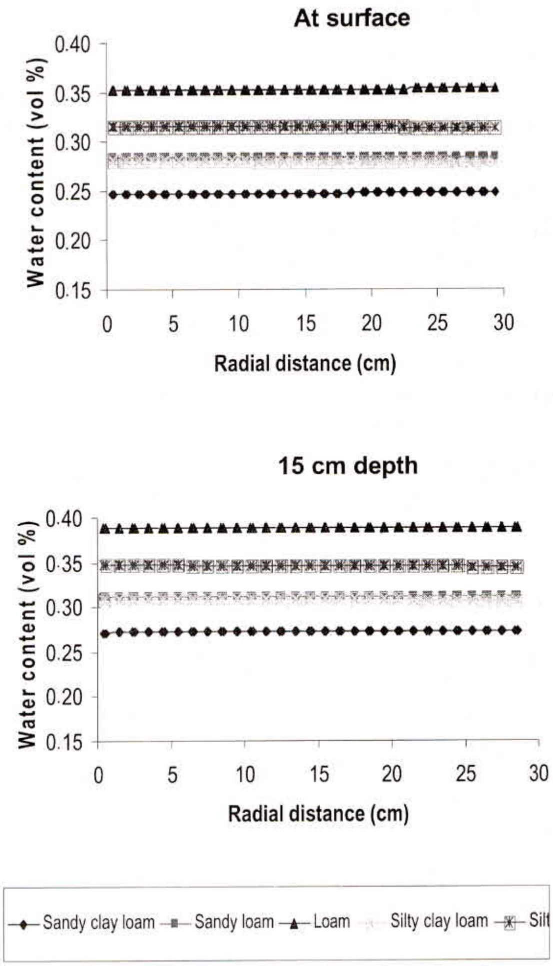

Fig. 5: Simulation of water distribution 4 h after irrigation in different type of soils and 4 l/h emitter discharge

Cumulative free drainage for each soil type was divided with the amount of applied water to determine the free drainage as a percentage of applied water (Table 4). It can be seen from the table that the free drainage percentage was negligible in case of silt and silty clay loam soils followed by loam, sandy clay loam and sandy loam soils. This implies that the soil hydraulic properties play major role in controlling the free drainage component, which is very important in design and operation of drip irrigation system.

Table 4: Free Drainage below 60 cm in Different Soils for 4 l/h Emitter Discharge

Soil Type	*Free Drainage (cm^3)*
Sandy Clay Loam	245
Sandy Loam	990
Loam	220
Silt	4
Silty Clay Loam	Neg.

CONCLUSIONS

In a modeling study, observed moisture contents at various points in the root zone were used to calibrate the water and solute transport model, Hydrus-2D. Field experimental was also conducted to study the water distribution in a sandy loam soil with onion crop irrigated by drip irrigation system. Simulation of water distribution in various soils were done with average emitter discharge rate of 4 l/h. Simulation studies and experimental work have led to conclude that adequate water content was maintained in the active root zone in different soil types up until 48 hr after irrigation. Further, this research suggests that irrigation scheduling on alternate day bases is an appropriate cycle. It has also been shown that free drainage component was negligible in all types but sandy loam soils which demonstrates that a properly designed drip irrigation system minimizes percolation losses.

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