Indian Journal of Agricultural Sciences **83** (1): 63–70, January 2013/Article

Soil water distribution and simulation under subsurface drip irrigation in cotton (*Gossypium hirsutum*)

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Received: 27 July 2011; Revised accepted: 16 November 2012

ABSTRACT

To see the effect of salinity of irrigation water under subsurface drip irrigation on cotton (*Gossypium hirsutum*) yield, a field experiment was conducted on loamy soils at Precision Farming Development Center, Water Technology Center, IARI, New Delhi, during 2009 and 2010 *kharif*. Irrigation water having four levels of salinity (EC_1= 2 dS/m (ground water), EC_2= 5 dS/m, EC_3= 8 dS/m and EC_4=11 dS/m) taken as main plot treatment was used as drip with laterals placed at three depths (at the surface, 15 cm and 30 cm below the soil surface) as sub-plot treatments in a split plot design with three replications. The results indicated that cotton yields were not influenced by irrigation water salinity up to 8 dS/m and different lateral depths during two years but decreased by 37.3, 44.3 and 36.0% in 2009 year and 26.6, 35.1 and 42.2 % in 2010 years at 11 dS/m as compared with EC_1, EC_2 and EC_3 treatments, respectively. Distribution of soil moisture data showed a horizontal decrease in soil water content at a distance of 20 and 40 cm away from drip line and vertical soil depths. Distribution of soil moisture was simulated by Hydrus 2D model. The model evaluated by AE and RMSE showed a good correspondence on soil water distribution between observed data from field experiment and simulated by model. The AE ranged from –0.015 to –0.002 and RMSE from 0.003 to 0.015.

Key words: Cotton, Hydrus 2D model, Moisture distribution, Subsurface drip irrigation

Due to the shortage of good quality water resources, saline groundwater and treated wastewater has become an important consideration in the arid and semi arid region (Beltran, 1999). Cotton (*Gossypium hirsutum*) is an important natural fiber of the 20th century. The area under cotton production in the world is estimated at around 30-31 million hectares. India has the largest area under cotton cultivation. Cultivation of hybrids, Bt cotton varieties, using latest production technology and plant protection technologies with adoption of scientific and agronomic practices, increase in the area under cotton. Government policies to give priority to research and development in cotton, encouraging use of quality seeds and pesticides and price support, are all responsible for the present drastic changes in Indian cotton scenario. However, India still has to go long way to catch up with the world average yield of 735 kg/ha (2009-10) of cotton. Average cotton yield in India is only 505 kg/ha (Pal, 2010). Cotton is considered a moderately to fairly salt tolerant crop with a threshold level of 7.7 dS/m (Maas 1986), yet its yield is drastically reduced due to poor germination and subsequent abnormal plant development under saline conditions (Khan *et al.* 2001).

Many researchers attempted to study the application of saline water for irrigation in the last five decades. Volkan-levy *et al.* (1998) studied the effect of salinity varied from 2 to 7.5 dS/m on the yield of cotton. The maximum yield was obtained using water having salinity of 4.0 to 5.0 dS/m. Mantell *et al.* (1985) determined the effect of four levels of water quality (E_C = 1.0, 3.2, 5.4 and 7.3 dS/m) on cotton yield using the drip method of irrigation. Salinity did not reduce yield even at the highest level of water salinity. The highest seed cotton yield was obtained using ground water for irrigation (E_C =3.2 dS/m). Hou *et al.* (2009) reported that soil salinity of 10.8 dS/m decreased cotton yield while soil salinity varied from 2.5 to 6.3 dS/m, increased seed cotton yield significantly. Water salinity of 17 dS/m also resulted in the reduction in cotton yield to the tune of 50% (Ahmad *et al.* 2002). Whitaker *et al.* (2008) compared crop maturity, lint yield, and fiber quality of cotton irrigated by subsurface drip irrigation. Cotton maturity was affected by irrigation treatment as non-irrigated cotton matured at the earliest, whereas over irrigated cotton matured at the last. Subsurface drip irrigated cotton produced similar or higher lint yields than overhead irrigation.

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Shirahatti *et al.* (2007) found the soil moisture distribution in the vertical direction in drip irrigation increased while laterally it decreased. Soil water content decreased by distance from dripper and horizontal transects at 30 cm depth was as a function of distance from the emitter while vertical transects crossing the drip line was as a function of soil depth (Bufan *et al*. 2011). Malash *et al.* (2008) found soil water content decreased gradually by increasing laterally distance from dripper. Drip irrigation system will provide an advantage using saline water with more frequent irrigation to keep a high soil matric and low salt concentration in the root zone (Malash *et al.* 2005, Abdelgawad *et al.* 2005, Yurtseven *et al*. 2005). In arid and semi-arid regions, salt accumulation near the soil surface with SDI is high because of high rates of evapotranspiration and low rainfall. Regions having annual rainfall of more than 450 mm, leaching of salt from soil will probably be sufficient to maintain soil salinity below harmful concentrations (Thompson *et al*. 2010).

The wetting patterns of drip irrigation depend on discharge and soil type (Dasberg and Or 1999). Cook *et al*. (2003) and Thorburn *et al*. (2003) found that the wetting pattern with SDI is a function of texture and soil hydraulic properties, which can control the wetted distance above the drip line and the amount of water that reaches the surface and the resulting salt accumulation by lateral depth. Wetting patterns can be obtained either by direct measurement of soil wetting in the field, which is site specific or by simulation using some models (Dabral *et al*. 2011). Numerical simulation is an efficient approach to investigating optimal drip management practices and simulating water flow and solute transport in soils (Schmitz *et al.* 2002, Cote *et al*. 2003, Mmolawa and Or 2003, Skaggs *et al*. 2004, Lazarovitch *et al*. 2007, Provenzano 2007). The The Hydrus 2D mathematical simulation model has been used to simulate drip irrigation systems and proven to be a viable predictor of both water and solute dynamics (Mmolawa and Or 2003, Skaggs *et al*. 2004, Gardenas *et al*. 2005). Kandelous and Simunek (2010) compared Hydrus 2D simulation of soil water from subsurface drip irrigation (30 cm) and found that corresponding between simulation and observation was very good. RMSE varied between 0.011 and 0.045 for volumetric water content.

The information about depths, pattern of the wetted zone under drip irrigation application has a great importance in design, management and decision about emitter spacing and system pressure for delivering required amount of water to the plant. The present investigation was carried out to study the distribution of wetting pattern in loamy soil for cotton crop under drip irrigation.

MATERIALS AND METHODS

This research was conducted at Precision Farming Development Center, Water Technology Center, Indian Agricultural Research Institute (IARI),New Delhi, India with the latitudes of 28°37′22″ N and 38°39′00″ N and longitudes of 77°8′45″ E and 77°10′24″ E. Average elevation was 230 m above mean sea level. Amount of rainfall during crop season 2009 and 2010 was 570.4 and 940 mm of which 86.4 and 93.3% of rainfall was during monsoon (July to September), respectively. Rainfall occurred during the crop season is shown in Fig 1.

The soil type of the experimental field was loam. Soil samples were taken before sowing for measurement of soil physical properties up to 1 m. The results of soil analysis are shown in Table 1.

The collected soil samples were air dried and passed through 2 mm mesh sieve. Soil texture was measured by the hydrometer method. Undisturbed soil samples collected by core sampler were used to determine saturated hydraulic conductivity (K_s) by the permeameter method. Ring soil dry mass divided by the ring volume yielded the soil dry bulk density (B_d). Soil moisture at the field capacity (FC) and

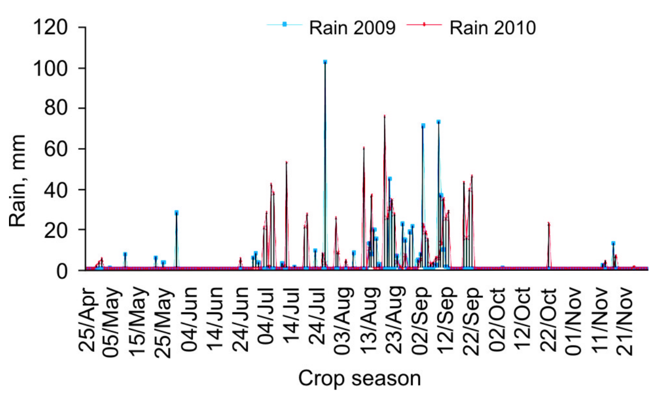

Fig 1 Rainfall during crop season 2009 and 2010

Table 1 Soil physical properties at the experimental field

Soil depth (cm)	Sand (%)	Clay (%)	Silt (%)	Bulk density (g/cm)	Field capacity (cm³/cm)	Wilting point (cm³/cm)	Hydraulic conductivity (cm/h)	EC (dS/m)
0-15	45.4	36.3	18.2	1.48	0.249	0.084	1.01	0.69
15-30	45.4	34.4	20.2	1.51	0.261	0.087	1.05	0.57
30-45	43.4	34.4	22.2	1.50	0.253	0.090	0.99	0.32
45-60	44.4	34.4	21.2	1.53	0.244	0.097	1.10	0.39
60-90	39.4	38.0	22.6	1.52	0.267	0.082	1.12	0.52

permanent wilting point (PWP) was measured by using the pressure plate. Electrical conductivity was determined by using conductivity meter.

Seeds of Hybrid cotton, variety RCH 134 were sown on 23rd May in 2009 and 26th April in 2010. Plant to plant distance and row to row distance were 0.6 and 0.9 m, respectively. To meet the nutrient requirement, nitrogen, phosphorus and potassium @ 120, 70 and 70 kg/ha supplied from different fertilizers were applied through irrigation using fertilizer injection system (venturi). All agronomic practices were kept same in all the treatments. The size of experimental field was 38.6 m × 29.2 m having 12 plots each of 8.1 m × 8.4 m. The experimental design was strip split plot with three replications. Different levels of water salinity: EC_1=2 dS/m (salinity of ground water), EC_2= 5 dS/m, EC_3= 8 dS/m and EC_4= 11 dS/m was taken as main plot treatments, whereas depths of lateral placement: lateral placed at soil surface (D_1), buried at 15 cm (D_2) and 30 cm (D_3) as subplot treatments.

Salts of sodium chloride (NaCl) and calcium chloride ($CaCl_2$) were used in the 1:1 ratio for making water having different salinity. Electrical conductivity (dS/m) of saline water was checked by portable EC meter. Water was supplied to cotton crop through drippers having discharge rate of 4 Lph at 1 kg/cm^2 pressure and distance between dripper and laterals were 0.6 and 0.9 m, respectively. Average of 10-year daily Class A pan evaporation data was used for finding crop water requirement after multiplying pan coefficient (0.75) and crop coefficient for different growth stage. Irrigation was applied every alternate day in all treatments.

In order to determine the distribution of soil water, soil moisture was measured by time domain reflectometer (TDR) during different growth stages of crop. Access tubes were installed up to 90 cm soil depth at near, 20 cm and 40 cm horizontally from dripper for all irrigation systems. Soil samples were taken at 4, 24 and 48 hr after irrigation from depths of 0–15, 15–30, 30–45, 45–60 and 60–90 cm.

Hydrus 2D model

Hydrus-2D is a finite element model for simulating the movement of water, heat and multiple solutes in variably saturated media. The model requires the user to input soil and soil-water parameters, time stepping parameters, parameters defining the geometry, root water uptake patterns, solute transport parameters, time variable boundary conditions. The computer program Rosetta was used to determine the Van Genuchten and the empirical parameters which include volumetric residual water content θ_r, volumetric saturation water content θ_s, saturated hydraulic conductivity K_s and the empirical parameters α and n. Rosetta offers a hierarchical set of five PTFs to calculate Van Genuchten-Mualem type hydraulic parameters depending on available information. The percentage of sand, silt and clay, bulk density, volumetric soil moisture at field capacity were chosen as input data. The results are shown in Table 2. In addition to the Van Genutchen-Mualem hydraulic parameters, Hydrus-2D/3D requires initial values of soil water content and solute, boundary condition, soil water evaporation (E_v), transpiration (T_r), precipitation, and irrigation.

Table 2 Input data of water flow parameters for Hydrus 2D

Soil layer	θ_r	θ_s	Alpha (α) (cm)	n	K_s(cm/h)	l
1 (0–15)	0.0518	0.384	0.0151	1.394	1.10	0.5
2 (15–30)	0.0549	0.384	0.0144	1.378	1.15	0.5
3 (30–45)	0.0569	0.387	0.017	1.372	1.10	0.5
4 (45–60)	0.0544	0.377	0.0185	1.362	1.18	0.5
5 (60–90)	0.0569	0.381	0.0137	1.376	1.25	0.5

A rectangular geometry with dimension of soil depth (Z = 90 cm) and half of the lateral distance (X = 45 cm) was selected. A variable flux boundary was used around the drippers. A free drainage boundary condition was used at the bottom of the soil profile. On the right and left sides of the soil profile, a no-flux boundary was used, because symmetry in the soil water content between the inside and outside of the geometry domain was assumed (Skaggs *et al*. 2004).

The root water uptake (transpiration) and salinity stress parameters were estimated using method proposed by Feddes *et al.* (1978) and modified by van Genuchten (1987). Solute stress model was used by considering multiplicative threshold model. The water stress parameters proposed by Feddes *et al.* (1978) were considered as $P_0 = -10$ cm, $P_{opt} = -25$ cm, $P_{2H} = -200$ cm, $P_{2L} = -6000$ cm and $P_3 = -14000$ cm.

The Hydrus 2D model is not able to separate evaporation and transpiration and need to separate these parameter and input in the time variably boundary condition. Daily evaporation from soil surface and transpiration by crop was estimated from daily calculated crop evapotranspiration. Crop evapotransipiration ET_C was calculated based on dual approach of the FAO 56 paper by penman monteith equation (Allen *et al.* 1998).

RESULTS AND DISCUSSION

Cotton yield

The results of cotton yield under different levels of salinity during 2009 and 2010 have shown in Fig 2. There was no significant difference between EC_1, EC_2, EC_3 treatments, but they had the significant differences by EC_4 treatment during two years. The lowest yield 1 333 and 1 268 kg/ha was recorded in treatment EC_4 during 2009 and 2010 years, respectively. Yield reduction in EC_4 treatment was 37.3, 44.3, 36.0 % in 2009 year and 26.6, 35.1, 42.2 % than EC_1, EC_2, EC_3 treatments, respectively.. This is because of leaching of salt due to monsoon rainfall in the semi-arid region of India. Total yield in second year decreased about

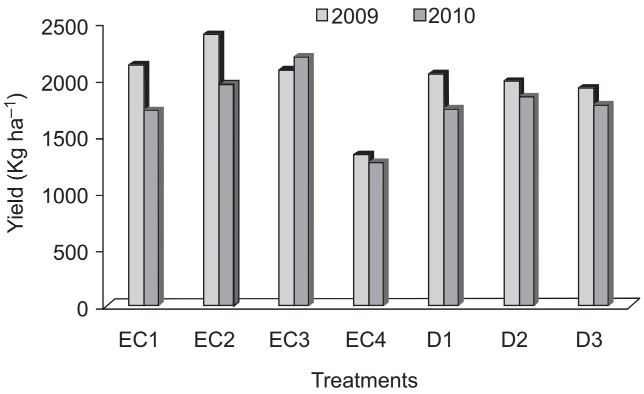

Fig 2 The effect of different levels of salinity and lateral depths on cotton yield during 2009 and 2010 years

10 % than the first year. Rainfall and temperature in 2010 were more than 2009 years at flowering, boll formation and boll developing stages of cotton, resulted to shedding of some flowers and yield reduction than 2009 years. Before monsoon, crop height in treatment EC_4 was less due to high salinity, which ultimately resulted in the reduction of yield. Cotton is considered tolerant to salinity but the crop had started showing salinity stress beyond water salinity of 7.7 dS/m. Similar results were reported by Mantell *et al.* (1985), Vulkan-levy *et al.* (1998) and Hou *et al.* (2009).

Different depths of placement of drip laterals up to 30 cm depth had no effect on cotton yield during two years. When laterals were placed at 30 cm depth, upward capillary moisture movement was not sufficient enough to support the crop at early stages (after sowing) because roots were not fully developed at this stage to extract water from lower depths. This resulted in poor germination and delay in growth. At later growth stages, roots were developed and sufficient rainfall takes place, ultimately less reduction in the yield.

Soil water distribution

Distribution of soil water content at different distance from dripper and time after irrigation under lateral placed at the soil surface, lateral buried at 15 cm and 30 cm are shown in Fig 3, 4 and 5. When lateral placed at the soil surface, soil moisture at the surface and near the dripper was high and decreased with increasing soil depth and distance from the dripper at all times after irrigation (Fig 3). Soil water after 4 hr of irrigation was high at the surface (more than the field capacity) while after 24 and 48 hr of irrigation, soil water decreased to 25.5 and 22.4 per cent, respectively. Soil water after 4, 24 and 48 hours of irrigation at 20 and 40 cm distance from dripper was 28.6, 23.2, 20.8 per cent and 25.7, 21 and 19.2 per cent, respectively. Decrease in soil water from the soil surface at 24 hr and 48 hr after irrigation was 5.7 and 8.8 per cent at the dripper while at 20 and 40 cm away from dripper were 5.4, 7.8, 4.7 and 6.5 per cent, respectively. Variation in soil water in deeper soil layer was less than surface soil (Fig 3). In a subsurface drip system (lateral placed at 15 cm soil depth), the upward capillary movement was good throughout the crop season. Soil water content was high at the depths of 15-45 cm beyond that soil water decreased (Fig 4). Less upward capillary movement was observed, especially at the time of sowing and germination in case of lateral placed at a depth of 30 cm. After development of the root system, soil water uptake starts from the lower soil depth. It is recommended in regions where we need to irrigate regularly after sowing, depth of lateral can be up to 20 cm in subsurface drip. Soil water was high at the depths of 30-60 cm, when lateral was placed at 30 cm depth. Uniformity of soil moisture distribution in the lateral placed at 30 cm soil depth was better than surface placed lateral and 15 cm soil depth. Soil surface was drier in all times after irrigation, which resulted in less evaporation loss from the soil surface and reduced weed infestation (Fig 5).

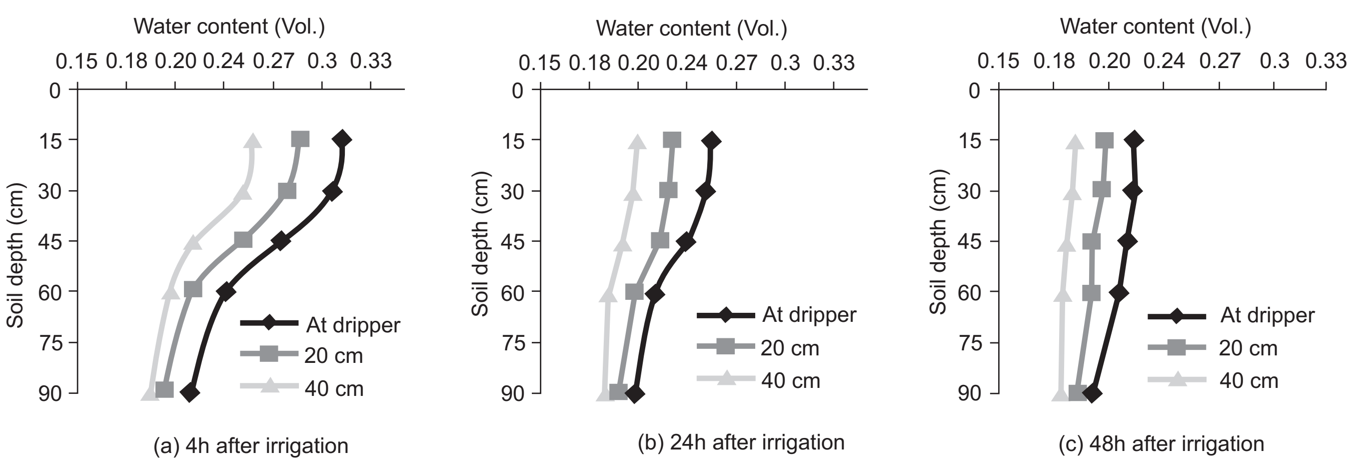

Fig 3 Soil water distribution at different distance from dripper and times after irrigation in lateral placed at the soil surface

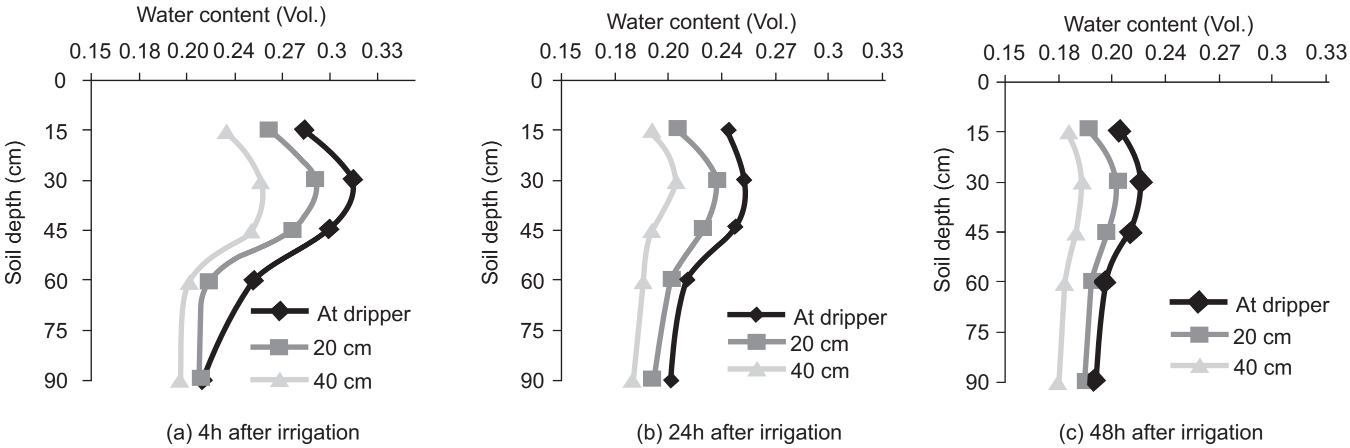

Fig 4 Soil water distribution at different distance from dripper and times after irrigation in lateral buried at the 15 cm soil depth

Soil water content after 24 hr of irrigation near dripper was found to be close to the field capacity in all the three depths of placement of drip laterals. The lowest soil water (17.5%) at the soil surface 48 hr after irrigation was observed at a distance of 40 cm from the dripper (Fig 5). Soil water after 4 hr of irrigation was more than field capacity but after 24 hr of irrigation it reached field capacity near the dripper (Fig 3). After 48 hr of irrigation, soil water was found to be slightly less than field capacity in the root zone (up to 60 cm soil depth). The optimum soil water for cotton was reported as field capacity to 20% of water availability (Majumdar 2000). In this experiment, according to soil texture and field capacity, optimum soil water was 22.5 to 21%. This indicated that cotton crop needed to be irrigate after 48 hr, i e every other day. Therefore, for cotton crop grown in loamy soil, irrigation should be scheduled on every alternate day to maintain optimum soil water. In general, soil water content was high near the dripper, and it decreased with increasing

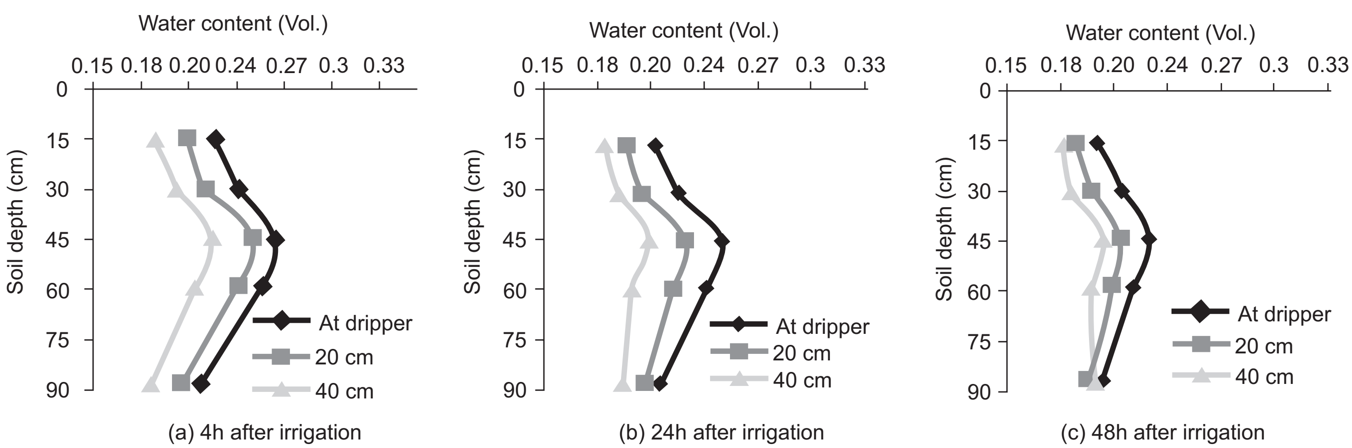

Fig 5 Soil water distribution at different distance from dripper and times after irrigation in lateral placed at the 30 cm soil depth

Table 3 Statistical parameters of model performance for soil water distribution at initial stage of cotton crop

Lateral depth	Parameters	4 hr after irrigation			24 hr after irrigation			48 hr after irrigation		
		0	20 cm	40 cm	0	20 cm	40 cm	0	20 cm	40 cm
0	AE	–0.014	–0.010	–0.010	–0.014	–0.012	–0.010	–0.013	–0.011	–0.008
	RMSE	0.015	0.011	0.009	0.014	0.012	0.011	0.013	0.011	0.009
15 cm	AE	–0.009	–0.015	–0.010	–0.009	–0.009	–0.009	–0.013	–0.009	–0.008
	RMSE	0.009	0.015	0.010	0.009	0.009	0.010	0.013	0.009	0.008
30 cm	AE	–0.006	–0.011	–0.006	–0.004	–0.004	–0.002	–0.003	–0.003	–0.003
	RMSE	0.008	0.012	0.006	0.005	0.004	0.004	0.004	0.003	0.004

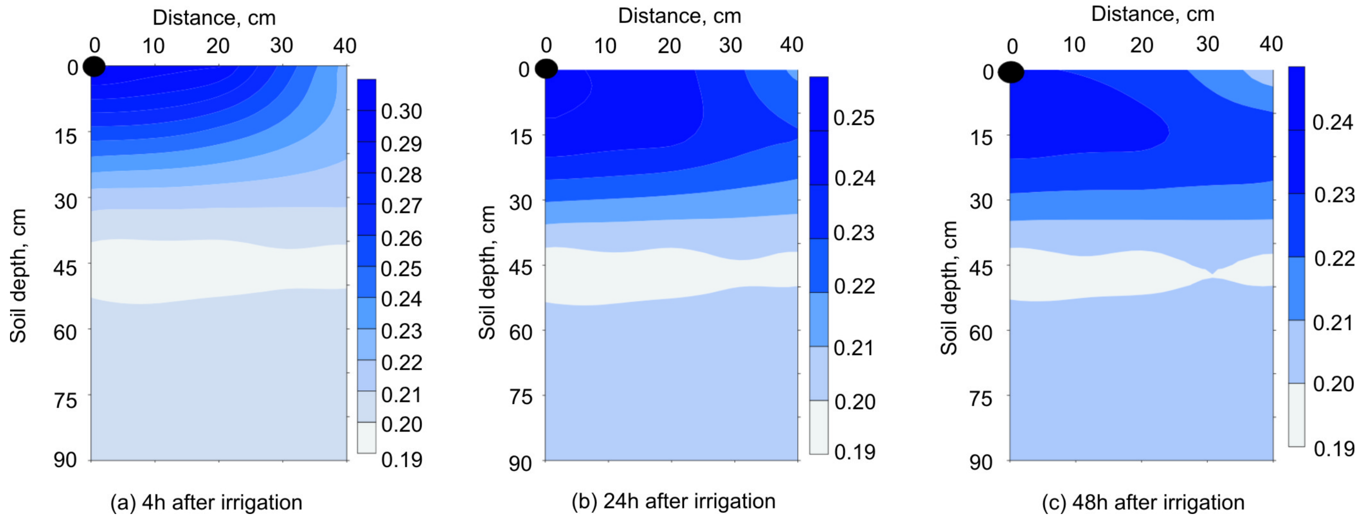

Fig 6 Simulation of soil water distribution at different times after irrigation under lateral placed at the soil surface

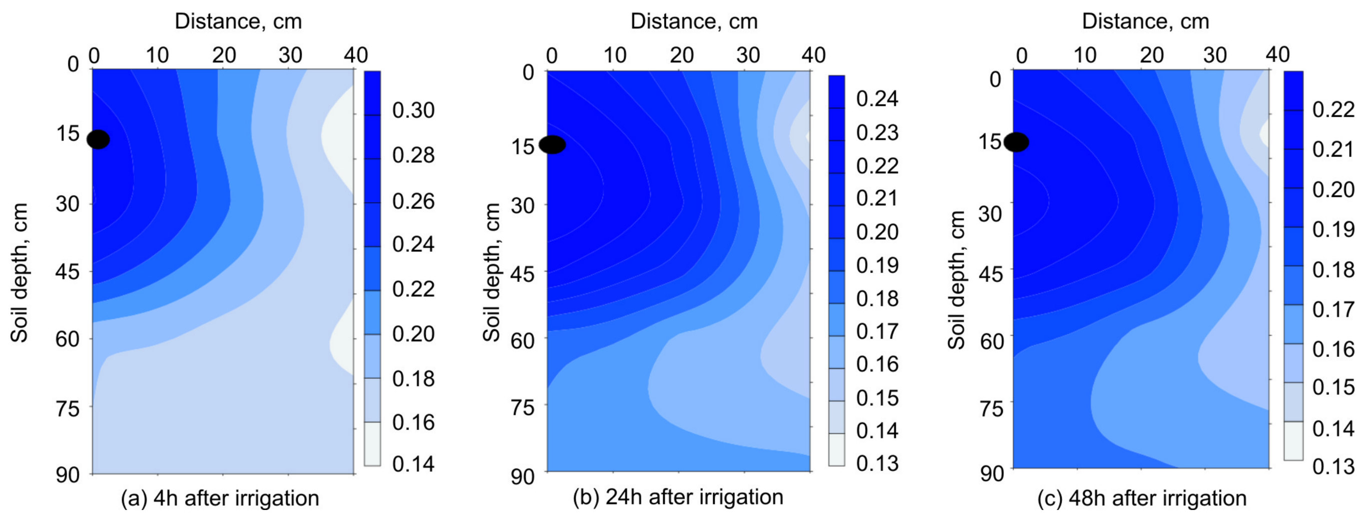

Fig 7 Simulation of soil water distribution at different times after irrigation under lateral buried at 15 cm soil depth

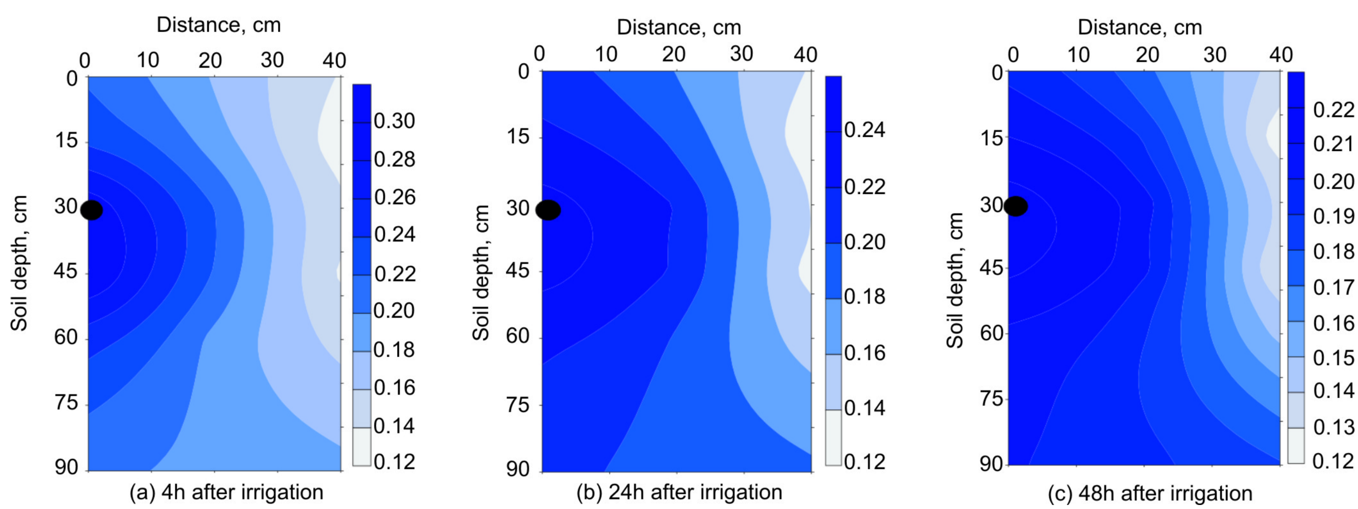

Fig 8 Simulation of soil water distribution at different times after irrigation under lateral buried at 30 cm soil depth

distance from dripper (Hayens 1990, Mishra 2001, Souza *et al.* 2003, Patel and Rajput 2008, Malash *et al*. 2008).

Soil water simulation by Hydrus 2D model

The Hydrus-2D model was calibrated for prediction of soil water content in the root zone of the crop. The model was calibrated for soil hydraulic conductivity of the experimental area having loamy soil. Most of the input parameters for running of Hydrus-2D model were determined by field experiment. Calibration was done for initial stages of cotton crop for surface and subsurface drip irrigation systems. Model predicted values were compared with observed values and the values of the calibrated parameters were selected during model operation when there was no significant difference between the predicted and observed values. Model performance was evaluated by estimating the average error (AE), root mean square error (RMSE) parameters. The results are shown in Table 3 for different irrigation systems, distance from dripper and time after irrigation. Model calibration results indicated a good agreement between the observed and the predicted values of soil moisture with AE and RMSE ranging from –0.014 to –0.002, and 0.0033 to 0.015, respectively. Many researchers have used Hydrus-2D model for simulation of soil water distribution and reported the similar results (Skaggs *et al*. 2004, Lazarovitch *et al*. 2007, Provenzano 2007, Kandelous and Simunek 2010).

The results of simulation of soil water distribution by Hydrus-2D model have shown in Fig 6 to 8 for surface and subsurface drip irrigation systems. Soil water at the soil surface near dripper was more and decreases as distance from dripper and soil depth increases (Fig 6). The wetting pattern of elliptical shape was observed when dripper was placed at 15 and 30 cm of soil depth (Fig 7 and 8). In subsurface drip irrigation due to domination of gravity force as compared with capillary force, wetting pattern and depth was found better than surface drip irrigation. Soil surface was drier in the lateral buried at 15 cm and 30 cm depth than surface drip irrigation, therefore evaporation loss was very less in subsurface drip irrigation at 30 cm depth. Soil surface appeared moist but did not get saturated when depth of placement of drip lateral was more than 15 cm at all growth stages of cotton prior to monsoon.

In surface drip irrigation, soil water content near dripper was 0.303 (volumetric) after 4 hr of irrigation and decreased 17.2% and 24.1% after 24 hr and 48 hr of irrigation, respectively. Soil moisture decreased to 0.226 at 40 cm horizontal distance away from dripper and decreased to 0.217 and 0.203 after 24 hr and 48 hr of irrigation (Fig 6). When laterals were buried at 15 cm and 30 cm, soil moisture near dripper was more and decreased to 17.5% and 25.8% after 24 hr and 48 hr of irrigation. Soil moisture when lateral buried at 15 cm ad 30 cm was 0.135 and 0.123 at the soil surface and 48 h after irrigation, which indicated drier soil surface and less evaporation (Fig 7 and 8).

Finally, the application of saline water up to 8 dS/m did not decrease cotton yield while increasing salinity to 11.8 dS/m significantly decreased cotton yield during two crop season. Soil water content near dripper was more and decreased to horizontally distance away from dripper. Uniformity of soil moisture was better in subsurface drip irrigation and evaporation losses decreased as compared with surface drip irrigation. Model Hydrus 2D is able good predict behavior of soil water content in soil profile under drip irrigation system and correspondence between observed data and predicted by model was good.

ACKOWLEDGMENTS

The first author is thankful to the Agricultural Research, Education and Extension organization (AREEO) of Iran and Cotton Research Institute of Iran for sanctioning his study leave; the Post Graduate School of IARI, New Delhi for admitting in the Ph D degree programme and for providing all the facilities for conducting the study. All the authors are thankful NCPAH, Ministry of Agriculture, GoI, for providing the necessary funds to conduct this research. The use of trade names is for information purpose only and does not indicate the endorsement of any particular product.

REFERENCES

Abdelgawad G, Arslan A, Gaihboe A and Kadour F. 2005. The effects on saline irrigation water management and salt tolerant tomato varieties on sustainable production of tomato in Syria. *Agricultural Water Manage* **78**: 39–53.

Ahmad S, Khan N I, Iqbal M Z, Hussain A and Hassan M. 2002. Salt tolerance of cotton (*Gossypium hirsutum* L.). *Asian Journal of Plant Science* **16**(6): 715–9.

Allen R G, Pereira L S, Raes D and Smith M. 1998. Crop evapotranspiration, guidelines for computing crop water requirements. FAO irrigation and drainage paper 56, Food and Agriculture Organization of the United Nations (FAO), Rome.

Beltran J M. 1999. Irrigation with saline water: benefits and environmental impact. *Agric. Water Manage*. **40**: 183–94.

Bufon V B, Lascano R S, Bednarz C, Booker J D and Gitz D C. 2011. Soil water content on drip irrigated cotton, comparison of measured and simulated values obtained with the hydrus-2D model. *Irrigation Science* DOI 10.1007/s00271–011–0279–z.

Cook F J, Thorburn P J, Fitch P and Bristow K L. 2003. WetUp: a software tool to display approximate wetting pattern from drippers. *Irrigation Science* **22:** 129–34.

Cote C M, Bristow K L, Charlesworth P B, Cook F J and Thorburn P J. 2003. Analysis of soil wetting and solute transport in subsurface trickle irrigation. *Irrigation Science* **22:** 143–56.

Dabral P P, Pandey P K, Pandey A, Singh K P and Sanjey singh M. 2011. Modeling of wetting pattern under trickle source in sandy soil of Nirjula, Arunachal Pradesh (India). *Irrigation Science* DOI 10.007/s00271–011–0283–3.

Dasberg S, and Or D. 1999. *Applied Agriculture: Drip Irrigation,* p 162. Springer Verlag, Berlin Germany.

Feddes R A, Kowalik P J and Zaradny H. 1978. Simulation of field water use and crop yield. Simulation monographs. Pudoc, Wageningen, 189 p.

Gardenas A I, Hopmans J W, Hanson B R and Simunek J. 2005. Two dimensional modeling of nitrate leaching for various fertigation scenarios under micro-irrigation. *Agric. Water Manage*. **74:** 219–42.

Hayens R J. 1990. Principles of fertilizer use for trikle irrigation crops. *Fertilizer Resaerch* **6**(2): 235–55.

Hou Z, Chen W, Li X, Xiu L and Wu L. 2009. Effect of salinity and fertigation practice on cotton yield and N recovery. *Agri. Water Manage*. **96**: 1 483–9.

Kandelous M M and Simunek J. 2010. Numerical simulations of water movement in subsurface drip irrigation system under field and laboratory condition using HYDRUS 2D. *Agric. Water Manage*. **97**: 1 070–6.

Khan T M, Saeed M, Mukhtar M S and Khan A M. 2001. Salt tolerance of some cotton hybrids at seedling stage. *Int. J. Agri. Biology* **3**: 188–91.

Lazarovitch N, Warrick A W, Furman A and Simunek J. 2007. Subsurface water distribution from drip irrigation described by moment analyses. *Vadose Zone Journal*. **6** (1): 116–23.

Majumder D K. 2000. Irrigation water management, module 3, irrigation engineering principles. http//nptel.itm.ac.in/courses/ web course-content.

Malash N, Flowers T J, and Ragab R. 2005. Effect of irrigation systems and water management practices using saline and non-saline water on tomato production. *Agri. Water Manage*. **78**: 25–38.

Malash N M, Flowers T J and Ragab R. 2008. Effect of irrigation methods, management and salinity of irrigation water on tomato yield, soil moisture and salinity distribution. *Irrigation Science* **26**: 313–23.

Mantell A, Frenkel H, and Meiri A. 1985. Drip irrigation of cotton with saline-sodic water. *Irrigation Science* **6**: 95–106.

Mishra P. 2001. 'Studies on water and potassium dynamics in soil under fertigation and furrow irrigation in radish.' M Sc thesis, Division of Agricultural Engineering, IARI, New Delhi.

Mmolawa K, and Or D. 2003. Experimental and numerical evaluation of analytical volume balance model for soil water dynamics under drip Irrigation. *Soil Science of Ameraica Journal* **67**: 1 657–71.

Pal S. 2010. Indian cotton production: current scenario. *Indian Textile Journal* March 2010: 28–39.

Patel N and Rajput T B S. 2008. Dynamics and modeling of soil water under subsurface drip irrigation. *Agric. Water Manage*. **95**: 1335–49.

Provenzano G. 2007. Using HYDRUS-2D simulation model to evaluate wetted soil volume in subsurface drip irrigation systems. *J. Irrig. Drain. Eng*. **133** (4): 342–9.

Schmitz G H, Schutze N and Petersohn U. 2002. New strategy for optimizing water application under trickle irrigation. *J. Irrig. Drain. Eng. ASCE* **128** (5): 287–97.

Shirahatti M S, Itnal C J and Mallikarjunappa Gouda D S. 2007. Impact of differential methods of irrigation on yield levels of cotton in red soils. *Karnataka Journal of Agricultural Science* **20**(1): 96–8.

Skaggs T H, Trout T J, Simunek J and Shouse P J. 2004. Comparison of HYDRUS-2D simulations of drip irrigation with experimental observations. *J. Irrig. Drainage Eng-ASCE* **130**: 304–10.

Souza C F and Matsura E. 2003. Multi wire time domain reflectometry (TDR) probe with electrical impedance discontinuities for measuring water content distribution. *Agric. Water Manage.* **59**: 205–216.

Thompson T L, Roberts T and Lazaroyitch N. 2010. Managing soil surface salinity with subsurface drip irrigation. 19 th World Congress of Soil Science, Soil Solutions for a Changing World, 1-6 August 2010, Brisbane, Australia, pp 40–2.

Yurtseven E, Kesmez G D and Unlukara A. 2005. The effects of water salinity and potassium levels on yield, fruit quality and water consumption of a native central Anatolian tomato species (*Lycopersicon esculentum*). *Agric. Water. Manage*. **78**: 128–35.

Van Genuchten M Th. 1987. A numerical model for water and solute movement in and below the root zone. Research Report 121, USDA-ARS, US Salinity Laboratory, Riverside.

Vulkan-Levy R, Ravina I, Mantell A and Frenkel H. 1998. Effect of water supply and salinity on pima cotton. *Agric. Water Manage*. **37**(2): 121–32.

Whitaker J R, Ritchie G L , Bedarz C W and Mills CI. 2008. Cotton subsurface drip and overhead irrigation efficiency, maturity, Yield, and quality. *Agronomy Journal* **100**: 1 763–8.