Indian Journal of Agricultural Sciences **81** (1): 25–32, January 2011

Simulation and modeling of water movement in potato (*Solanum tuberosum*) under subsurface drip system

NEELAM PATEL[1] and T B S RAJPUT[2]

Water Technology Centre, Indian Agricultural Research Institute, New Delhi 110 012

Received: 4 November 2009; Revised accepted: 30 September 2010

ABSTRACT

Hydrus–2D model was selected for simulation and modeling of soil water under subsurface drip system in 'Kufri Anand' potato (*Solanum tuberosum* L.) crops grown during winter (*rabi*) season 2002–03 through 2004–05. Potato was sown at a depth of 15 cm in the raised ridges prepared during the third week of October at ridge spacing of 30 cm×60 cm, respectively. The study consisted of three different irrigation levels of 60, 80 and 100% of the crop evapotranspiration (ie 0.6V, 0.8V and 1.0V) and five depths of placement of drip tapes including one at the surface and the others at 5, 10, 15 and 20 cm soil depths. Drip tape of 0.3 mm thickness was buried manually at different depths. It was observed that by changing the position of water source from surface to subsurface, the wetted width was increased by 25–50%. Maximum potato yield of 33.3 tonnes/ha was recorded at 10 cm depth of drip tape at 100% of the crop evapotranspiration.

Key words: Depth of drip tapes, Deficit irrigation; Numerical modeling, Potato, Subsurface drip

Potato (*Solanum tuberosum* L.) was officially dubbed as the 'food of the future' at the recently concluded flagship event of the United Nations International Year of the Potato in Cusco, Peru (Anonymous 2008). Average national yield of potato in India is about 18.9 tonnes/ha which is only about half of the corresponding maximum yield in Netherlands (44.7 tonnes/ha). The gaps between potential and realizable yields are around 50 to 100% which can be minimized by designing drip irrigation system matching with soil characteristics and crop water needs. Subsurface drip irrigation is the most advanced method of irrigation, which enables the application of small amounts of water through the drippers placed below the soil surface with discharge rates generally in the same range as that in surface drip irrigation. Subsurface drip irrigation offers many advantages over the surface drip irrigation such as reduction in evaporation and deep percolation losses and elimination of surface runoff (Freddie and Trooien 2003). They hypothesized that improved yields from subsurface drip systems are most likely due to more water being available to the plants, as compared to surface drip because of less evaporation in subsurface drip system. Claire *et al.* (2003) noted that crop evapotranspiration would be less for a well-watered crop with dry soil and plant surfaces (that is possible with subsurface drip system) than if the crops were to be irrigated with a method that wets the soil and plant surfaces. Determining the appropriate depth placement of the drip laterals requires consideration of soil properties and the crop's root development pattern. These considerations prevent general recommendations for the depth of lateral pipe placement for subsurface drip systems.

Knowledge of soil water distribution in the root zone is therefore essential for the design and management of subsurface drip system. The knowledge can be obtained either by conducting field experiments or through modeling. Efforts were made to study the impact of subsurface drip on crop yield in comparison to surface drip by many researchers (Camp and Lamm 2003). Lack of understanding of how distributions of soil water content are affected by the unsaturated soil hydraulic properties has sometimes resulted in suboptimal management and low water-use efficiency, particularly in subsurface drip system. The shape and total volume of the wetted soil region below a dripper varies widely with irrigation and soil hydraulic parameters. Research was conducted to acquire better understanding of soil water distribution and simulation model Hydrus–2D (Simunek *et al.* 1999) was selected for the current study for simulation and modeling of soil water under subsurface drip system for potato crop.

MATERIALS AND METHODS

The present study was conducted at the Precision Farming

Based on a part of Ph D thesis submitted to IARI during 2007

[1] Senior Scientist (e mail: neelam@iari.res.in), [2] Principal Scientist (e mail: tbsraj@iari.res.in).

Development Centre, Water Technology Centre, Indian Agricultural Research Institute, New Delhi, India (Latitude 28°37’30" –28°30’0" N, Longitude 77°8’45" –77°10’24" E and AMSL 228.61 m) during October to February 2002–05. The soil profile depth was taken as 60 cm for analysis of physical and chemical properties. The soil of the experimental area was deep, well-drained sandy loam comprising 69.3% sand, 14.1% silt and 16.6% clay. The bulk density of soil was 1.53g/cm^3 and saturated hydraulic conductivity 1.11 cm/hr, respectively. The average rainfall received during crop period was 7.51, 3.12 and 3.02 cm during 2002–03, 2003–04 and 2004–05, respectively. A field plot of size 27 m×50 m was selected for experimental studies. The field plot was divided into 3 equal plots of 9 m×50 m. Each plot of 9 m×50 m size was divided into 15 equal plots of 0.6 m×50 m, representing a single treatment. The experiment was laid out following the split-plot design consisted of three different irrigation levels of 60, 80 and 100% of the crop evapotranspiration (ie 0.6V, 0.8V and 1.0V) and five depths of drip tapes including one at the surface and the others at 5, 10, 15 and 20 cm soil depths and three replications. Tubers of 30 g weight of ‘Kufri Anand’ potato were placed at a depth of 15 cm in the raised ridges prepared during the third week of October at a tuber and ridge spacing of 30 cm×60 cm, respectively. The base width and height of ridges were kept 60 cm and 30 cm, respectively. Drip tape of 0.3 mm thickness (T-Tape, Australia, model TSX 515–30–250) was buried manually at the depths of 0 (surface), 5, 10, 15 and 20 cm in the middle of ridges formed for placing of potato under different treatments. The installed drip system had drippers spaced at 30 cm, each with an application rate of 0.72 litre/hr. Time domain reflectometry (TDR) was used for the determination of volumetric soil water content (TRIME –FM, Probe P3, No. 14836). The access tubes of TDR were installed at 0 and 15 cm away from drip tape up to a depth of 60 cm for measurement of soil water.

Potato is about 130 days duration crop and may be divided in to 4 stages, namely initial: 25 days, developmental: 30 days, middle: 45 days and tuber maturity: 30 days. The actual crop evapotranspiration was estimated by multiplying reference evapotranspiration with crop coefficient ($ET = ET_o \times K_C$) for different months based on crop growth stages by using Penman-Monteith’s semi-empirical formula. The crop coefficients during the crop season 2002–03, 2003–04 and 2004–05 were adopted as 0.50, 0.65, 1.15 and 0.75 at initial, developmental, middle and tuber maturity stages, respectively (Table 1). During the initial and developmental growth stages, until tuber formation, the frequency of irrigation during this period was kept daily. During the second growth phase, ie tuber development and tuber maturity, irrigation frequency was reduced and water was applied once in every three days to allow efficient plant respiration for intensifying growth rate. To meet the nutritional requirements of crop, 180 kg N, 100 kg P_2O_5 and 150 kg K_2O/ha was applied. Following the recommended practice of fertilizer application, nitrogen was applied into two split doses (1/3 at planting and 2/3 at crop emergence stage). Matured potato was manually dug during 12–15 February. Yield of potato under each treatment and replications was recorded. Non-parametric test (Friedman’s test) and standard analysis of variance (ANOVA) were used to evaluate the effects of the treatments on the yield and to determine the significance of the main treatments and its interaction with subtreatments. Least Significance Differences (LSD) test was used for comparing the two main treatments and subtreatments.

Hydrus–2D model was developed at US Salinity Laboratory, Agricultural Research Station, Riverside, California. Hydrus–2D simulates the 3-dimensional axially symmetric and vertical water flow, solute transport, root water and nutrient uptake based on finite-element numerical solutions of the flow equations. The water flow in the model is detailed with prescribed head and flux boundaries, atmospheric and free drainage boundary conditions. Hydrus–2D implements a Marquardt-Levenberg type parameter estimation scheme (Marquardt 1963). The flow transport for variably saturated medium and vertical flow (inline drip) of water was determined by the Richards’ Equation (Richards 1931). The governing flow equation was solved numerically using Galerkin-type linear finite element schemes based on the mass conservative iterative scheme.

The layout for application of irrigation water with its dimensions including drip tape placement are presented in Fig 1. The drip tapes have multiple outlets along their lengths and work as a line source of water. Simulation was done using line-source model with rectangular geometry. The soil profile depth was taken as 30 cm and water leached below 30 cm depth was considered unavailable to the plant. Wetting width of 30 cm along each drip tape was required therefore radius

Table 1 Crop evapotranspiration (ETc), precipitation and irrigation water applied

Month	ETC (mm)			Precipitation (mm)			Irrigation water applied (mm)		
	2002–03	2003–04	2004–05	2002–03	2003–04	2004–05	2002–03	2003–04	2004–05
October	49.6	53.3	54.6	2.0	0.0	0.0	48.4	53.3	54.6
November	60.8	52.6	56.3	0.0	0.0	0.0	60.8	52.6	56.3
December	74.6	63.5	69.8	16.8	21.3	0.0	71.6	57.6	69.8
January	43.0	47.4	50.7	41.6	9.9	2.2	38.9	44.8	51.4
February	20.8	20.6	17.6	14.7	0.0	28.0	20.4	21.0	13.2

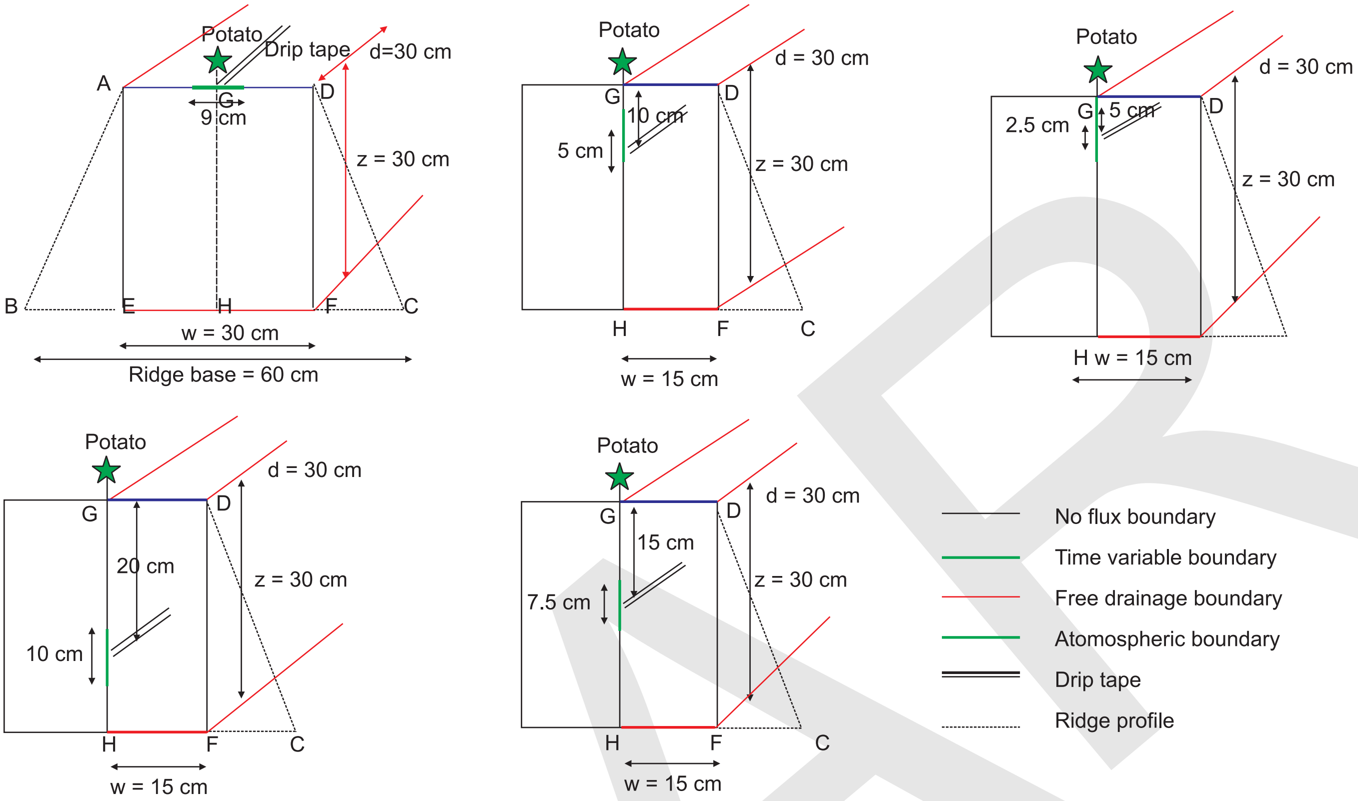


Fig 1 System geometry for simulation of water distribution

Table 2 Predicted soil hydraulic parameters

Soil depth (cm)	□ (m^3 m^{-3})	□ m^3 m^{-3})	□ m^{-1})	N	Ks (m/hr)	I
0-15	0.0443	0.4002	3.68	1.34	0.015	0.5
15-30	0.0535	0.3806	3.10	1.38	0.012	0.5
30-45	0.0582	0.3791	2.95	1.36	0.0096	0.5

for simulation was taken as 15 cm. Soils with in the root zone under drip irrigation system remains at near saturation throughout the crop season, therefore van Genuchten analytical model without hysteresis was used to represent the soil hydraulic properties. Sand, silt and clay content of soil were taken as input and by Artificial Neural Network prediction; the soil hydraulic parameters were obtained and are given in Table 2 (Schaap and Leij 1998). Feddes' root water uptake model was adopted and parameters were selected from Feddes' parameter (1978) available in the Hydrus–2D crop database. Simulation was done for 3120 hr (130 days) equal to the growing period of potato. Water fluxes during each irrigation event were 0.028, 0.05, 0.025, 0.017 and 0.013 m/hr in treatments T_1, T_2, T_3, T_4 and T_5, respectively. The crop evapotranspiration (ETc) was computed from the product of potential evapotranspiration (ET_0), crop coefficient (Kc) and the irrigated area, A = 0.3 m^2/m length of drip tape. ETc was partitioned into potential evaporation (Ep) and potential transpiration (Tp). Ep (5% of ETc) and Tp (95% of ETc) were given as inputs in F(t) time variable boundary condition table (Gardenas *et al.* 2005). Details of treatments are T_1: Drip tape placed at the surface with 100% irrigation water requirement; T_2: drip tape placed at 5 cm depth with 100% irrigation water requirement; T_3: drip tape placed at 10 cm depth with 100% irrigation water requirement; T_4: drip tape placed at 15 cm depth with 100% irrigation water requirement; T_5: drip tape placed at 20 cm depth with 100% irrigation water requirement; $0.8T_1$: drip tape placed at the surface with 80% irrigation water requirement; $0.8T_2$: drip tape placed at 5 cm depth with 80% irrigation water requirement; $0.8T_3$: drip tape placed at 10 cm depth with 80% irrigation water requirement; $0.8T_4$: drip tape placed at 15 cm depth with 80% irrigation water requirement; $0.8T_5$: drip tape placed at 20 cm depth with 80% irrigation water requirement; $0.6T_1$: drip tape placed at the surface with 60% irrigation water requirement; $0.6T_2$: drip tape placed at 5 cm depth with 60% irrigation water requirement; $0.6T_3$: drip tape placed at 10 cm depth with 60% irrigation water requirement; $0.6T_4$: drip tape placed at 15 cm depth with 60% irrigation water requirement, and $0.6T_5$: drip tape placed at 20 cm depth with 60% irrigation water requirement

To check the performance of Hydrus–2D model, three performance indicators, namely Average error (%), root mean square error (%) and coefficient of efficiency ($C_{eff.}$) were used, which compared the observed and the simulated values (Singh *et al.* 2006).

RESULTS AND DISCUSSIONS

Observed soil water distribution

Subsurface application of water is aimed directly at the root zone. Water distribution in the soil around a buried dripper mainly depend on soil texture, dripper discharge and root water uptake. The downward movement of water was more than its lateral movement at all growth stages of crop due to gravity force playing a predominant role in comparison to the capillary force in the sandy loam soil of the experimental plot. Vered (2002) reported that the potato roots spread up to a radius of 25 cm from the dripper discharge point and most were contained within 30–40 cm width and 25 cm depth. Soil water distributions at different growth stages in treatments T_1, T_3 and T_5 are shown in Fig 2, 3 and 4. SDI system, installed in the potato crop was a low discharge system and irrigation frequency was relatively low. Therefore the soil around the dripper was almost at field capacity throughout the crop season.

Soil surface remained relatively dry in treatments T_3, T_4 and T_5. Soil surface appeared moist but did not get saturated when depth of placement of drip tape was more than 5 cm at all growth stages of potato. When drip tape was placed at the surface, the water content at 15 cm depth was greater than 18%. But at 30 cm depth the soil water content was about 12% (Fig 2). In treatment T_2, soil water content at the surface varied from 20.5 to 22.5% at different growth stages of crop (data not shown). In treatment T_3, the upward capillary movement of water was not sufficient and soil water content at the surface decreased significantly (av. 15.5%) in comparison to treatments T_1 and T_2 (Fig 3). Wetted soil bulb of 20 cm in width and 25 cm depth had more than 18% soil water content, which was very conducive for good tuber formation resulting in higher yields in treatments T_1, T_2 and T_3. In treatment T_4, adequate amount of water was available around the plant roots but in treatment T_5, crop was under stress and lesser amount of water was available for the plant, as water moved beyond the ridge base, ie below 30 cm soil depth. In treatments T_1, T_2, T_3 and T_4, very little soil water content moved beyond the ridge base. In potato, the tubers formation was found confined within the ridge, ie only up to

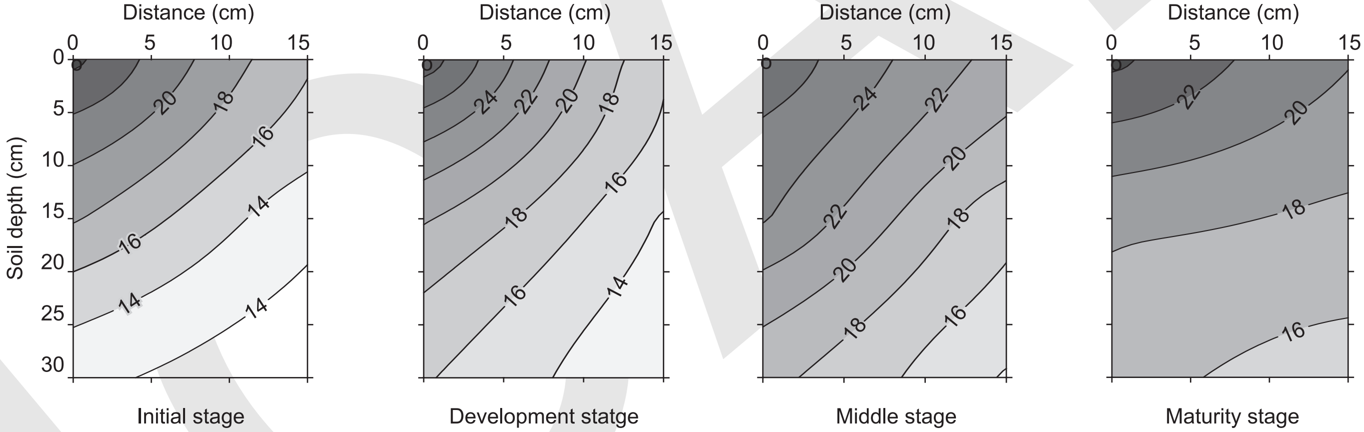


Fig 2 Observed soil water distribution when drip tape placed at the surface with 100% irrigation water requirement (treatment T1)

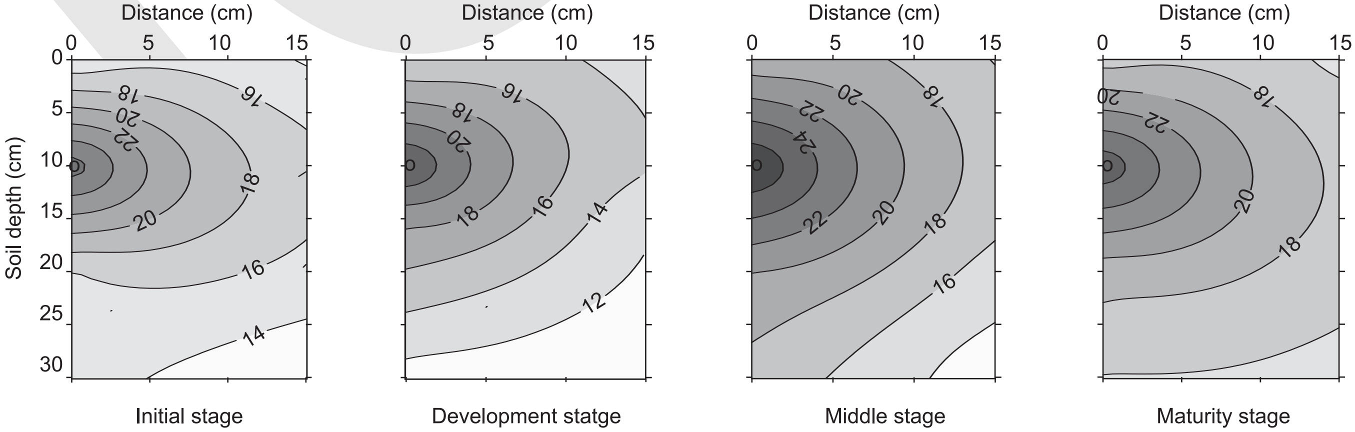


Fig 3 Observed soil water distribution when drip tape placed at 10 cm depth with 100% irrigation water requirement (treatment T3)

30 cm depth from ridge top. Water that moved beyond the ridges was not available for plants at any stage of growth. The high water content of the soil around the drippers facilitates better water transmission to the surrounding soil and keeps on replenishing the crop root zone. Therefore, keeping the drip tape within the crop root zone and sufficiently below the soil surface replenishes the root zone effectively due to gravity flow in light soils and simultaneously cuts of evaporation losses due to restricted upward capillary flow.

Effect of depth of placement of drip tape on crop yield

Highest yield was recorded in treatment T_3 (33.3 tonnes/ha) and lowest in case of $0.6T_1$ (18.5 tonnes/ha). Similar trend continued in 2002–03 and 2004–05 but in 2003–04 potato yield was maximum in treatment T_4 (33.7 tonnes/ha). Potato yield was higher under subsurface drip than surface drip irrigation system during all years of experimentation (Table 3). The effect of depth of placement of drip tape had significant effect on the yield of potato during all the three years excepting in treatment T_5 during 2002–03 and treatment T_1 during 2003–04 and 2004–05 ($P<0.05$) (Table 3). The maximum yield was recorded in treatment T_3 during 2002–03 and 2004–05, which was followed by the treatment T_4 and T_2 in 2002–03 and 2004–05, respectively. Potato yield was significantly affected by the placement of drip tape and maximum yield was obtained by placing the drip tape at 10 cm soil depth ($P<0.05$) (Table 3).

Table 3 Potato yield at different irrigation levels and depth of placement of drip tape

	Potato yield (tonnes/ha)		
	2002–03	2003–04	2004–05
Irrigation levels			
V	31.4	31.6	31.9
0.8V	27.3	27.3	27.2
0.6V	19.6	19.6	19.2
LSD (5%)	0.99	0.81	1.6
Depth of placement of drip tape			
0 cm (surface)	25.1	25.8	25.5
5 cm	29.2	25.5ns	25.4ns
10 cm	31.3	28.2	28.6
15 cm	30.8	27.2	27.1
20 cm	24.8ns	24.1	24.2
LSD (5%)	0.99	0.97	1.1
Irrigation levels and drip tape depth interaction			
V			
0 cm (surface)	30.2	30.8	31.2
5 cm	31.0 ns	32.2	32.8
10 cm	33.5	32.6	33.8
15 cm	32.4	33.7	32.7
20 cm	29.8 ns	28.7	29.2
0.8V			
0 cm (surface)	26.5	27.5	27.1
5 cm	29.2 ns	28.5	29.5
10 cm	31.8	30.2 ns	30.6 ns
15 cm	30.4 ns	30.5 ns	31.0 ns
20 cm	24.4	24.0	23.7
0.6V			
0 cm (surface)	18.5	19.0	18.1
5 cm	27.5	27.2	28.1
10 cm	28.5	27.8	27.5
15 cm	29.5 ns	29.2	29.9 ns
20 cm	20.2	19.7	19.7
LSD (5%)	1.4	1.4	1.5

ns, Non-significant

Difference in yield in treatment T_2 and T_3 was not significant ($P<0.05$). It was observed that the drip tape buried either at 10 or 15 cm depth had no significantly different effect on potato yield (LSD at 5% were 0.6, 0.55 and 0.66 during 2002–03, 2003–04 and 2004–05). Levels of irrigation and depth of placement of drip tape significantly affected the mean yield of tuber in all the three years ($P<0.05$). If sufficient amount of irrigation water is available to potato growers, higher yield (33.3 tonnes/ha) can be achieved by placing the drip tape at 10 cm soil depth. But in the water deficit condition, potato yield will reduce by 7.8 and 12.9% by corresponding saving of 20 and 40% of irrigation water by burying the drip tape at 10 and 15 cm soil depth. One of the reasons to achieve higher yield with deficit water supply because of 7.5, 3.12 and 3.0 cm of rainfalls were received during tuber development and maturity stage of crop in 2002–03, 2003–04 and 2004–05, respectively. Similar types of results were reported by Shock and Feibert (2000). They observed that reduction in total yield of potato due to the progressive deficit irrigation treatments averaged 6.7, 10 and 14% with corresponding water savings of 25, 36 and 40%.

Simulated soil water distribution

Hydrus–2D was calibrated to predict the soil water distribution in the root zone of potato crop with the help of observed soil water. Most of the input parameters required to use Hydrus–2D were determined by detailed field experimentation, however a few were taken from published literature matching to our soil and crop condition. To obtain the initial values for model parameters the calibration of the Hydrus–2D was conducted on computer through simulation runs using the input data. It was done against two factors: depth of placement of inline drip tape in potato and differential amount of irrigation water. The simulated soil water distribution patterns for treatments T_1, T_3 and T_5 are shown in Figs 5, 6 and 7. The wetting pattern of elliptical shape was found when drip tape was placed at deeper depths (more than 15 cm) (Fig 7). Wetted depth was found larger than the surface wetting which resulted into high water content below dripper because of dominance of gravity force in comparison to capillary forces in sandy loam soils in treatment T_5 (Fig 7). The interaction among the dripper discharge rate, soil properties and the depth of placement of

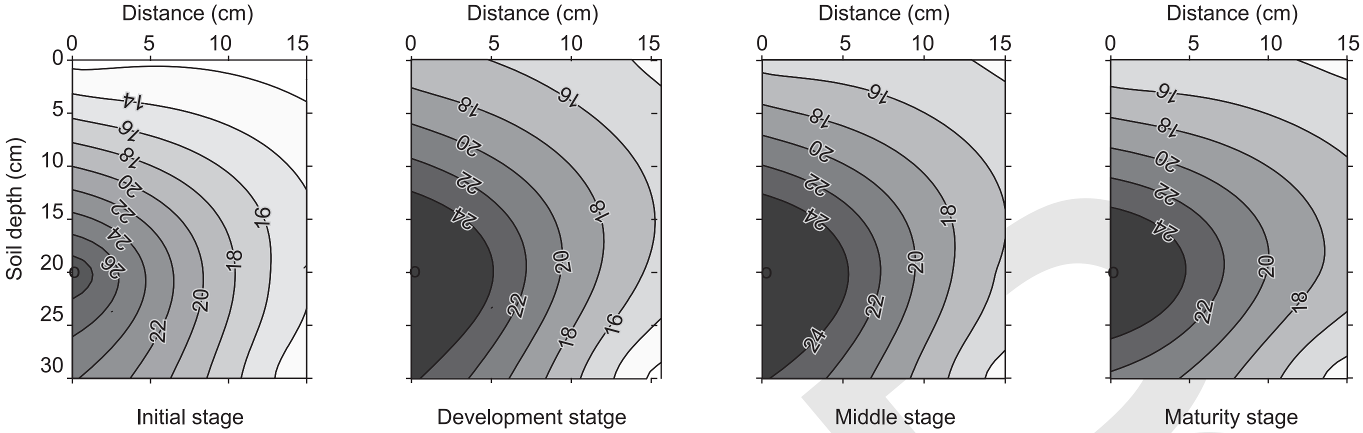


Fig 4 Observed soil water distribution when drip tape placed at 20 cm depth with 100% irrigation water requirement (treatment T_5)

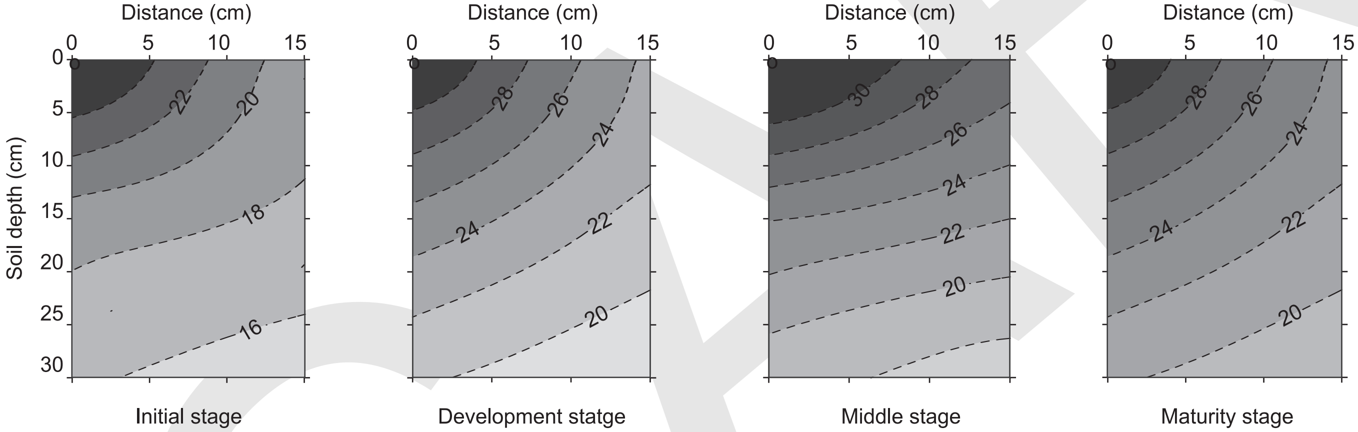


Fig 5 Simulated soil water distribution when drip tape placed at the surface with 100% irrigation water requirement (treatment T_1)

drip tapes governs the spatial distribution of water. Both the experimental and numerical analysis of soil water movement demonstrates that water drains easily from the root zone in treatments T_4 and T_5 (Figs 6, 7). Saturated radius was taken constant from where flux entered because the meshgen facility of Hydrus–2D was not available with us. Difference observed between experimental and simulated soil water distribution may be attributed to the differences in saturated hydraulic conductivity of soil (observed and simulated by the model as an intermediate step), capillary and gravitational forces.

We evaluated the model performance in simulating soil water by comparing the measured and predicted values. Closeness between the simulated and observed data was

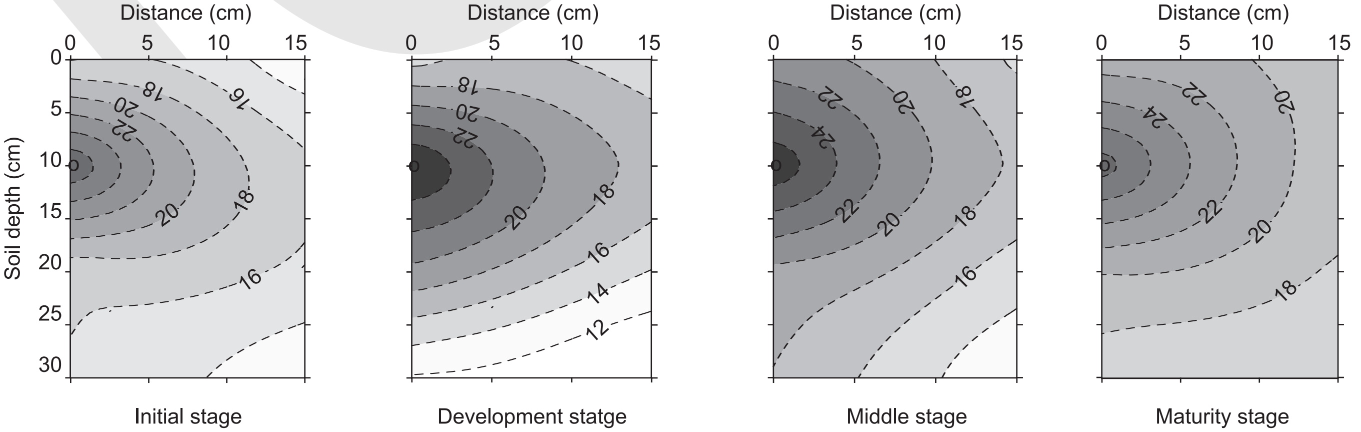
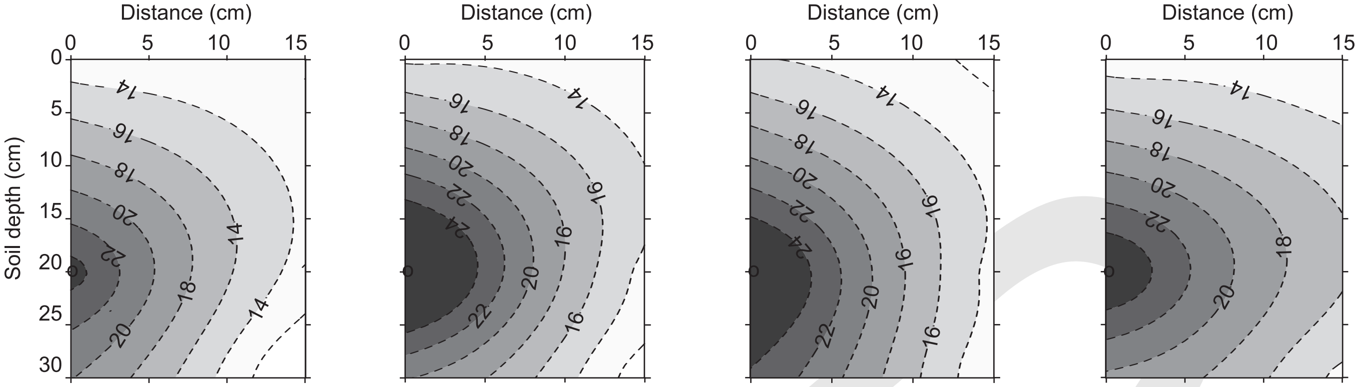


Fig 6 Simulated soil water distribution when drip tape placed at 10 cm depth with 100% irrigation water requirement (treatment T_3)



Initial stage Development statge Middle stage Maturity stage

Fig 7 Simulated soil water distribution when drip tape placed at 20 cm depth with 100% irrigation water requirement (treatment T_5)

ascertained through average error, RMSE and C_{eff}. The value of average error varied from 3.67 to –1.51% in different treatments (Table 4). Average error was found maximum (3.67%) in treatment T_1 and minimum (0.83%) in treatment T_3. It was also observed that Hydrus–2D under-predicted the soil water content in treatment T_5 but over-predicted in treatment T_3. RMSE averaged over four growth stages of crop development varied from 1.47 to 4.35%. RMSE followed the trend similar to that of AE. It was low at the initial and developmental stages, but increased at the maturity stage of crop (data not shown here). C_{eff}. averaged for all the four growth stages of potato crop varied from 0.54 to 0.88 for different treatments (Table 4). Table 4 depicts that the Hydrus–2D predicted soil water distribution accurately particularly in treatment T_3 in comparison to other treatments.

Table 4 Statistical parameters indicative of performance of model for potato

Treatment	Performance indicators		
	AE (%)	RMSE (%)	Ceff.
Drip tape placed at the surface with 100% irrigation water requirement (T_1)	3.67	4.35	0.54
Drip tape placed at 5 cm depth with 100% irrigation water requirement (T_2)	2.38	3.67	0.72
Drip tape placed at 10 cm depth with 100% irrigation water requirement (T_3)	0.83	1.47	0.88
Drip tape placed at 15 cm depth with 100% irrigation water requirement (T_4)	1.17	2.14	0.62
Drip tape placed at 20 cm depth with 100% irrigation water requirement (T_5)	-1.51	2.13	0.88

AE, Avarage error; RMSE, root mean square error; ceff., coeficient of efficiency

Distribution of soil water, as observed during the field experiment and that predicted by the model at different growth stages was not significantly different and good agreement was found between the field experiment and model simulated values (Friedman's non-parametric statistical test, $P<0.01$). Many researchers have tried this model and reported its usefulness for simulation and modeling of water distribution (Ajdary *et al.* 2007; Cote *et al.* 2003; Jiusheng *et al.* 2004; Gardenas *et al.* 2005). By analyzing the outputs of the Hydrus–2D model one may improve the design and management strategies of subsurface drip system.

The simulation model (Hydrus–2D) was used and tested in potato crop irrigated through subsurface drip system during 2002–03, 2003–04 and 2004–05. The wetting pattern of elliptical shape was found when drip tape was placed at deeper depths (more than 15 cm). Wetted depth was found larger than the surface wetting radius resulting in more water below dripper in treatments T_4 and T_5 because of the dominant of gravity force in comparison to capillary forces in sandy loam soils. Subsurface drip in sandy loam soil resulted in 25–30 cm depth-width dimensions of soil wetting with dripper discharge of 0.72 litre/hr. An increase in dripper discharge would tend to increase the geometry deeper and narrower in sandy loam soil. To achieve a shallow geometry for the sandy soil, for shallow rooted crops like potato, subsurface placement of dripper having discharge of about 0.72 litre/hr could be used, to get square geometry of 30 cm×30 cm dimension. Maximum potato yield was recorded in treatment T_3 (33.3 tonnes/ha) and lowest in case of $0.6T_1$ (18.5 tonnes/ha). The model performance was evaluated by comparing the measured and predicted values of soil water distribution by estimating the AE, RMSE and C_{eff}.

Distribution of soil water under field experiment and as predicted by model simulation at different growth stages was not significantly different. In the water deficit condition, potato yield will reduce 7.8 and 12.9% by corresponding saving of 20 and 40% of irrigation water by burying the drip tape at 10 and 15 cm soil depth. One of the reasons to achieve higher yield with deficit water supply because 7.5, 3.12 and 3.0 cm rainfalls were received during tuber development and maturity stage of crop in 2002–03, 2003–04 and 2004–05, respectively. Increasing the depth of placement of drip tapes by keeping the quantity of applied water the same, increased soil water content at deeper depth and decreased the average water content at initial and developmental stage of crop in the crop root zone. Subsurface drip irrigation systems resulted in a slight increase in the dimensions of the wetted area as well as soil water content in the root zone. By analyzing the outputs of the Hydrus–2D model one may improve the design and management strategies of subsurface drip system.

ACKNOWLEDGEMENT

Authors are thankful to the National Committee on Plasticulture Applications in Horticulture (NCPAH), Department of Agriculture and Cooperation, Ministry of Agriculture, Government of India for providing the necessary funds to conduct this research.

REFERENCES

Ajdary K, Singh D K, Singh A K and Khanna M. 2007. Modeling of nitrogen leaching from experimental onion field under drip Fertigation. *Agricultural Water Management* **89** (1–2): 15–28.

Anonymous. 2008. Potato Science for the poor-challenges for the new millennium – A working conference to celebrate the International year of the potato held during 25–28 March, 2008 at Cuzco, Peru.

Camp C R and Lamm F R. 2003. Irrigation systems, subsurface drip. Marcel Dekker, New York, NY. *Encyclopedia of Water Science*: 560–4.

Claire M Cote, Bristow Keith L, Philip B Charlesworth, Freeman J Cook and Peter J Thorburn. 2003. Analysis of soil wetting and solute transport in subsurface trickle irrigation. *Irrigation Science* **22**: 143–56.

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.

Feddes R A, Kowalik P J and Zaradny H. 1978. *Simulation of Field Water Use and Crop Yield*. John Wiley and Sons, New York.

Freddie R Lamm and Todd P Trooien. 2003. Subsurface drip irrigation for corn production: a review of 10 years of research in Kansas. *Irrigation Science* **22**: 195–200.

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

Jiusheng Li, Zhang J and Rao M. 2004. Wetting patterns and nitrogen distributions as affected by fertigation strategies from a surface point source. *Agricultural Water Management* **67**: 89–104.

Marquardt D W. 1963. An algorithm for least squares estimation of nonlinear parameters. SIAM. *Journal on Applied Mathematics* **11**: 431–41.

Richards L A. 1931. Capillary conduction of liquids through porous mediums. *Physics* **1** (5): 318–33.

Schaap M G and Leij F L. 1998. Database-related accuracy and uncertainty of pedotransfer functions. *Soil Science* **10**: 765–79.

Shock C C and Feibert E B G. 2000. Deficit irrigation of potato. *Deficit Irrigation Practices*, Water Reports 22, 109 pp.

Simunek J, Sejna M, Genutchen MT Van. 1999. The HYDRUS-2D software package for simulating two dimensional movement of water, heat and multiple solutes in variably saturated media, Ver.2.0 Rep. IGWMC-TPS-53, Int. Ground Water Model. Cent., Colo. School of Mines, Golden.

Singh D K, Rajput T B S, Singh D K, Sikarwar H S, Sahoo R N and Ahmad T. 2006. Simulation of soil-wetting pattern with subsurface drip irrigation from line source. *Agricultural Water Management* **83**: 130–4.

Vered Eli. 2002. Growing potatoes under drip irrigation, http: // www.netafim.com. Accessed 12 October 2006.