Simulation of Soil Water Dynamics using the Hydrus-1d Model for Sweet Corn under Drip Irrigation

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ABSTRACT

Water is extremely sacred resource, and there is a need to preserve it for future generations. Water is life because no one can live without water. A significant portion of water is consumed for agriculture, industrial production, and domestic purposes. In agriculture, most crops are irrigated using traditional methods, which result in greater water waste. Drip irrigation is the most efficient irrigation system, which saves water by slowly delivering water to the roots of crop. The information on water movement in the root zone during drip irrigation is essential for studying soil water movement and plant water uptake across different soil layers to plan irrigation scheduling.

Appropriate calibration and validation of a numerical model can reduce the time and cost required to study soil water movement in the root zone. HYDRUS is one such model; a suite of Windows-based modeling software can be used to simulate soil water movement. Hence, the experiment was conducted during *kharif* 2022 at the field irrigation laboratory, Department of Soil and Water Conservation Engineering, Dr. N.T.R. College of Agricultural Engineering, Bapatla, Andhra Pradesh, to study soil water dynamics in a drip-irrigated sweet corn crop using the Hydrus-1D model.

The study primarily aimed to calibrate, validate, and simulate soil moisture dynamics for a sweet corn crop under different irrigation scenarios. The experiment consisted of six treatments with different irrigation levels through drip irrigation namely T_1(0.6 ETc), T_2(0.7 ETc), T_3(0.8 ETc), T_4(0.9 ETc), T_5(1.0 ETc) and T_6(without drip irrigation i.e., traditional watering method). A randomized block design with four replications of each treatment was laid out in the field, resulting in a total of 24 plots. Crop water requirement was estimated as 332 mm using CROPWAT 8.0 model. A total of 5 access tubes were installed in the first replication of each drip-irrigated treatment. Frequency Domain Reflectometry (FDR) was used to measure soil moisture content through the installed access tubes in the field up to a depth of 100 cm. The moisture reading was taken before the start of irrigation, immediately after irrigation, 3h after irrigation, 6h after irrigation, and 24h after irrigation.

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Calibration and validation of the model were done for 25 DAS and 55 DAS, respectively. The statistical indices of the observed and predicted values during validation indicate that there is a good agreement between observed and predicted values during calibration with the high values of NSE (99.29 to 99.39 %) & R^2 (0.9968 to 0.9987) and low values of RMSE (0.083 to 0.122) & RE (2.67 to 2.95). Thus, the model performed well with the calibrated hydraulic conductivity parameter.

Simulation of soil moisture was performed for the entire crop-growing period using calibrated and validated parameters in the Hydrus-1D model. In a drip emitter with 2 lph, soil moisture content in the top layers up to 50 cm depth is well distributed and holds sufficient water in the root zone. There were no percolation losses observed below the active root zone during the application of water at a low rate (2 lph) through drip irrigation. Hence, the Hydrus-1D model can be effectively used to study the moisture movement in the soil.

INTRODUCTION

Land and water resources are the basic needs of agriculture and of a country's economic development. Water is life because no one can live without water. Water is needed to ensure our food security, industrial production and to conserve the biodiversity of the ecosystem. Water has become a scarce commodity in recent decades; more than 300 million people in 26 countries are facing water shortages (Farad and Jayasree, 2010). The per capita availability of water will decline from 1341m^3yr^{-1} in 2001 to as low as 1140 m^3yr^{-1} in 2050 (Boaz, 2014).

A major portion of water is consumed for agriculture, industrial production, and domestic purposes. Wang *et al*., reported in 2001 that more than 80% of water resources have been exploited for agricultural irrigation. In agriculture, most crops are irrigated using traditional methods, which result in greater water waste. Under the present circumstances of meagre availability of surface water and dwindling ground water sources day by day, the only alternative is to adopt the well-developed pressurized irrigation systems i.e., either the drip or sprinkler irrigation systems to cope up the needs of the food security of growing population by bringing more area under cultivation by way of utilizing the available scarce resources of water judicially. Drip irrigation has field-level application efficiencies of 80-90%, 25-100% increases in yields and 15-30% reductions in operating and crop production costs, as losses from deep percolation and surface runoff are very low (Tiwari *et al*., 2003; Yuan *et al*., 2003).

The Crop Water Requirement (CWR) is necessary to design the irrigation system. Several computer models are available to estimate the crop water requirement. CROPWAT 8.0, a computer program developed in the Netherlands, calculates the CWR and Irrigation Water Requirement of various crops under different climatic conditions. The Penman Monteith method has been recommended by FAO to calculate the crop evapotranspiration (ETc) under different conditions, which gives accurate and wider suitability (Patel *et al.,* 2017) compared to Penman, Blaney Criddle, and other methods.

The information on water movement in the root zone during drip irrigation is essential for studying soil water movement and plant water uptake across different soil layers to plan irrigation scheduling. Appropriate calibration and validation of a numerical model can reduce the time and cost required to study soil water movement in the root zone. HYDRUS is one such model; a suite of Windows-based modeling software can be used to simulate soil water movement (e.g., soils) (Yang *et al*., 2017). The Hydrus-1D model, which solves the Richards equation for soil water movement, is a widely used model. The HYDRUS software package is one of the most comprehensive for simulating soil water dynamics and has been used in several hydrological studies (Simunek *et al*, 2008 and 2016). Cheng *et al.,* (2013) showed that HYDRUS-1D performed well in simulating the observed soil

water contents in both homogeneous and layered soils during *Caragana korshinkii* kom cultivation.

Sweet corn is one of the most popular vegetables in the USA, Europe, and other developed countries worldwide. Sweet corn, a member of the Gramineae family, is available in wide varieties worldwide (Swapna *et al.*, 2020). It is rich in carbohydrates and sugars and contains valuable amounts of vitamins A, B3 (which supports metabolism, the nervous and digestive systems), and vitamin C. It also contains folic acid, fibre, minerals, and protein (Gebhardt and Mattews, 1981). Unlike field corn varieties, which are harvested when the kernels are dry and fully mature (dent stage), sweet corn is picked when immature (milk stage) and can be harvested 75-80 days after planting and eaten as a vegetable rather than as grain (Schultheis, 1994). It is becoming very popular in the urban areas of our country; therefore, its cultivation is remunerative for peri-urban farmers (Dagla *et al.,* 2014). Besides green cobs, green fodder is also available to the farmers for their cattle. Sweet corn is a high resource user in terms of both water and nutrients, and the integrated management of these two resources through the drip method could result in a substantial increase in yields, besides saving both resources.

MATERIALS AND METHODS

Location of Study Area

The field experiment was carried out at the field irrigation laboratory, Department of Soil and Water Engineering, Dr.N. T. R. College of Agricultural Engineering, Bapatla, Bapatla district, Andhra Pradesh, India. The experiment was conducted on the sweet corn crop during the kharif season of 2022. The experimental site is located at 16°, 88°E, with an altitude of 6 m above sea level.

Collection of Meteorological Data

The meteorological data from the past 10 years were collected from the meteorological observatory located at the Agricultural College Farm, Bapatla. The average values of temperature, R.H., wind speed, and total rainfall were calculated over 10 years (2012-2021) to estimate crop water requirements using CROPWAT 8.0.

Properties of Soil in the Study Area

Soil properties of the experimental plot were collected from the Department of Soil and Water Engineering at Dr. N. T. R. College of Agricultural Engineering, Bapatla, where the experiment was conducted.

Experiment details

Drip irrigation system: soil moisture movement was studied. Laterals with inline drip emitters spaced at 30 cm with a discharge rate of 2 lph were laid at 1.2 m intervals. A total of 24 plots were designed for the entire field area of 54 m x 18 m (972 m²). Three laterals in each plot were laid with a net plot size of 8.0 m x 3.6 m (28.6 m²). Of the 24 plots, four were designated as control plots. In each plot, a control valve was provided to regulate irrigation.

The experiment was conducted on the sweet corn crop of the hybrid variety AMRUTH (DSCH-9909) under drip irrigation using a Randomized Block Design. The experiment, with six irrigation treatments and four replications, was conducted during *kharif* 2022. On August 3rd 2022, seeds of the sweet corn crop were sown in a paired row system with row-to-row and plant-to-plant spacing of 40 cm and 20 cm, respectively [(80 cm + 40 cm) x 20 cm]. For control plots, the seeds were sown with a plant-to-plant spacing of 20 cm and a row-to-row spacing of 60 cm. Treatment details are as follows:

T_1 = Drip irrigation at 0.6 ET_C

T_2 = Drip irrigation at 0.7 ET_C

T_3 = Drip irrigation at 0.8 ET_C

T_4 = Drip irrigation at 0.9 ET_C

T_5 = Drip irrigation at 1.0 ET_C

T_6 = Without drip irrigation

During the crop-growing season, irrigation was applied on alternate days via drip irrigation, planned according to crop water requirements.

Measurement of Soil Moisture Content

To achieve the objectives of the research work, it is necessary to measure soil moisture content during irrigation, i.e., before the start of irrigation, immediately after irrigation, 3h after irrigation, 6h after irrigation, and 24h after irrigation, at 25 and 55 DAS. Frequency Domain Reflectometry (FDR) was used to measure the moisture content at different depths.

Diviner 2000 is a portable soil monitoring system that records data from all levels of the soil profile up to the probe depth (1 meter). A total of 5 access tubes were installed in the experimental field near the emitter for each drip treatment in the first replication.

Table 2.1 Weather parameters recorded during the crop growing period (*Kharif* 2022).

Month	Average daily Temperature (° C)		Relative Humidity (%)		Average wind speed (km/day)	Total Rainfall (mm)	Average daily evaporation (mm)
	Max.	Min.	Max.	Min.			
August	34.22	25.54	96.48	64.81	142	123.20	3.32
September	33.90	25.37	98.13	66.30	112	54.90	3.29
October	31.97	23.58	99.58	72.84	88	159.80	2.59

Table 2.2 Soil properties of the experimental plot.

Soil depth from surface (cm)	Mineral content (% mass)			Textural class	Hydraulic conductivity (cm/h)	Bulk density (g/cm³)	Field capacity (% vol)	Permanent wilting point (% vol)
	Clay	Silt	Sand					
0-15	35	10	55	Sandy clay loam	0.94	1.37	21.48	6.73
15-30	35	10	55	Sandy clay loam	0.50	1.57	27.17	9.12
30-45	30	10	60	Sandy clay	0.46	1.53	28.24	10.56
45-60	35	5	60	Sandy clay loam	0.96	1.63	27.69	10.92
60-75	35	5	60	Sandy clay loam	0.96	1.63	27.73	11.61
75-90	30	5	65	Sandy clay loam	0.95	1.67	26.62	10.75

The HDRUS-1D model, which solves Richard's equation, was used to simulate soil moisture movement. The governing equation of the HYDRUS-1D model was

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K\left(\frac{\partial h}{\partial x} + \cos\alpha\right)\right] - S$$

where,

θ = volumetric water content [$L^3 L^{-3}$],

t = time [T],

h = water pressure head [L],

x = spatial coordinate (positive upward) [L],

S = sink term [$L^3 L^{-3} T^{-1}$],

α = angle between the flow direction and the vertical axis (i.e., $\alpha = 0°$ for vertical flow, 90° for horizontal flow, and $0° < \alpha < 90°$ for inclined flow),

K = unsaturated hydraulic conductivity function [LT^{-1}], and it is given by

$K(h, x) = K_s(x)K_r(h, x)$

Simulations of water flow were performed for a soil profile of depth Z= 100 cm by placing a drip emitter at the ground surface. Atmospheric boundary conditions with surface runoff were considered as the upper boundary, and the lower boundary was free drainage. Van Genuchten-Mualem (1980) analytical model was used for the estimation of soil hydraulic properties. Water retention θ (h) and hydraulic conductivity K (h) functions were the required soil properties. Parameters such as saturated water content (θ_s), residual water content (θ_r), empirical factors (α, n), and saturated hydraulic conductivity (K_s) were estimated using a Neural network prediction model available in HYDRUS-1D.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$$

Calibration, validation, and simulation of the HYDRUS-1D model

For any model, calibration and validation are necessary to establish parameter values. Calibration was done on 25 DAS for the period of 48 hours after irrigation by changing the hydraulic properties of the soil profile, mainly the hydraulic conductivity of the sandy clay loam soil during *kharif* 2022, and the

validation of the model was done on 55 DAS for the period of 48 hours after irrigation, and simulation was done for the season. Then, simulation was conducted for different irrigation regimes.

The HYDRUS-1D model was evaluated for performance using statistical indices such as the coefficient of determination (R^2), root mean square error (RMSE), relative error (%), and model efficiency.

a. Coefficient of Determination (R^2)

$$R^2 = \frac{(\sum(X - \bar{X})(Y - \bar{Y}))^2}{\sum(X - \bar{X})(Y - \bar{Y})^2}$$

b. Root Mean Square Error (RMSE)

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

c. Relative Error (RE) (%)

$$RE = \frac{|O_i - P_i|}{O_i} \times 100$$

d. MModel Efficiency (NSE)

where,

X = Observed values

$\bar{X}$ = Mean of observed values

Y = Simulated values

$\bar{Y}$ = Mean of simulated values

$=O_i$ $^{:h}$ Observed value

P_i = ith Predicted value

n = No. of observations

$\bar{O}$ = Mean of observed value

RESULTS AND DISCUSSION

The crop water requirement of sweet corn during the growing period was calculated at 332 mm using CROPWAT 8.0. The amount of water applied through irrigation was tabulated as follows (Table 3.1)

Distribution of soil moisture during the crop growing period

Soil moisture distribution is studied at 25 and 55 days after sowing. A volumetric moisture content reading is taken very near to the emitter using a Frequency Domain Reflectometry (FDR) probe. Reading is taken before irrigation, immediately after irrigation, 3 hours after irrigation, 6 hours after irrigation, and 24 hours after irrigation in all drip-irrigated treatments.

The highest moisture content before irrigation at 25 DAS is observed at the 20-30 cm depth in all drip-irrigated treatments, with values of 14.57%, 16.48%, 18.66%, 19.67% and 22.02% for T_1, T_2, T_3, T_4, and T_5, respectively. At a depth of 10-20 cm, all drip-irrigated treatments have the second-highest moisture percent. Moisture content at 0-10 cm depth is observed to be low in all drip-irrigated treatments, which might be a reason for higher evaporation loss in the surface layer of the soil.

Moisture content at 0-10 cm depth was observed to increase more immediately after irrigation in all drip-irrigated treatments. Since water is applied through drip irrigation, the vertical movement of water would be greater than the lateral movement. Water is distributed in the first two layers immediately after irrigation in all drip-irrigated treatments, since the soil is sandy clay loam. Water is moved gradually from the upper layer to the lower layer of the soil profile at 3, 6, and 24 hours of irrigation, until a depth of 40

Table 3.1 Applied irrigation water in different treatments during the cropping period

Month	Applied water (mm)					
	T_1	T_2	T_3	T_4	T_5	T_6
August	40.19	46.89	53.59	60.28	66.98	145
September	98.93	115.42	131.91	148.39	164.88	150
October	39.12	45.64	52.16	58.68	65.20	70
Total	178.23	207.94	237.64	267.34	297.06	365

cm. At a depth of 40 cm, the soil layer is classified as sandy clay, which holds water for longer, slowing the movement of water to lower layers. Due to the shallow rooting depth of the sweet corn crop, sufficient water is available in the soil for effective extraction of water by the roots for development.

A similar trend was observed at 55 DAS. The highest moisture content before irrigation is observed at the 20-30 cm depth in all drip-irrigated treatments with values T_1, T_2, T_3, T_4 and T_5 are 18.58%, 20.64%, 22.63%, 23.81% and 25.89% respectively. The overall moisture content in the soil profile (0-100 cm depth) is higher than at 25 DAS, which favors meeting the required water for crop growth at different stages.

The overall soil moisture distribution at 25 DAS and 55 DAS is presented in the Fig. 3.1 and Fig. 3.2

Calibration of Hydrus-1D Model

Calibration is carried out for the drip irrigation treatment T_3 (0.8 ETc). Calibration is performed using field-observed data from the 25 DAS field experiment and compared with the model-simulated data. The input parameters required by the model are obtained from field observations, and some parameters are generated by the model itself. The results of the calibration for soil moisture content at 25 DAS for 3h, 6h, and 24h after irrigation are shown in Fig. 3.3(a)-3.5 (b).

Volumetric moisture content in percent is shown on the horizontal scale, and depth in cm is shown on the vertical scale. The predicted values are taken from the Hydrus-1D output file, and the graphs are plotted against predicted and observed soil moisture data in Microsoft Excel. And using these values, the model's performance is evaluated. Since the rooting depth is 45 cm, the prediction is done only up to a 60 cm depth of the soil profile.

From Figures 3.3(a), 3.4(a), and 3.5(a), it is observed that the simulated and observed moisture content is decreasing with an increase in depth. The Root Mean Squared Error (RMSE) value indicates the difference between observed and predicted values. RMSE value ranges from 0 to 1. A low RMSE indicates that the model performs well, meaning there is no difference between the observed and predicted data. Model efficiency is used to evaluate the model; higher values indicate better agreement. The coefficient of determination (R^2) indicates the degree of linear correlation between the observed and predicted values, with 0 to 1, in which

a higher value indicates better simulation quality. The graph is plotted of observed values against predicted values to determine R^2, as shown in Fig. 3.3(b), 3.4(b), and 3.5(b). The statistical indices of the observed and predicted values during calibration are presented in Table 3.2, and it indicated that there is a good agreement between observed and predicted values during calibration with the high values of NSE (99.24 to 99.95 %) & R^2 (0.9988 to 0.9994) and low values of RMSE (0.041 to 0.147) & RE (1.9 to 2.6).

Validation of Hydrus-1D Model

A calibrated Hydrus-1D model is used for validation of observations made at 55 DAS. The validation results are shown in Fig. 3.6, 3.7, and 3.8. The statistical indices of the observed and predicted values during validation are presented in Table 3.3 and they indicated that there is a good agreement between observed and predicted values during calibration with the high values of NSE (99.29 to 99.39 %) & R^2 (0.9968 to 0.9987) and low values of RMSE (0.083 to 0.122) & RE (2.67 to 2.95). The validation results indicated good agreement between the predicted and observed values. The model performed well with the calibrated hydraulic conductivity parameter. A validated Hydrus-1D model can be used to simulate soil moisture movement in the crop.

Simulation of Soil Moisture Using the Hydrus-1D Model

Calibrated and validated, Hydrus-1D is used to simulate soil moisture dynamics for the entire growing period of the crop for treatment T_3 (0.8 ETc). As water movement beyond 50 cm depth is negligible, the simulation is done up to 50 cm depth in the soil profile. Simulation is carried out from the day of treatment imposed (8 DAS). Simulation is carried out with a 2 lph emitter at 10 to 50 cm depth with 10 cm intervals for 3h after irrigation, 6h after irrigation, and 24h after irrigation, as shown in Fig. 3.9, 3.10, and 3.11.

The moisture content at the time of sowing is high, as complete appication of water at sowing is essential for proper germination of sweet corn seeds. The moisture content after 3h of irrigation in the second decade is decreased, which might be due to greater evaporation losses at the soil surface, as the crop canopy is very low and water is applied during the initial stage of the crop. In the third decade, moisture content started increasing, reached a maximum at the
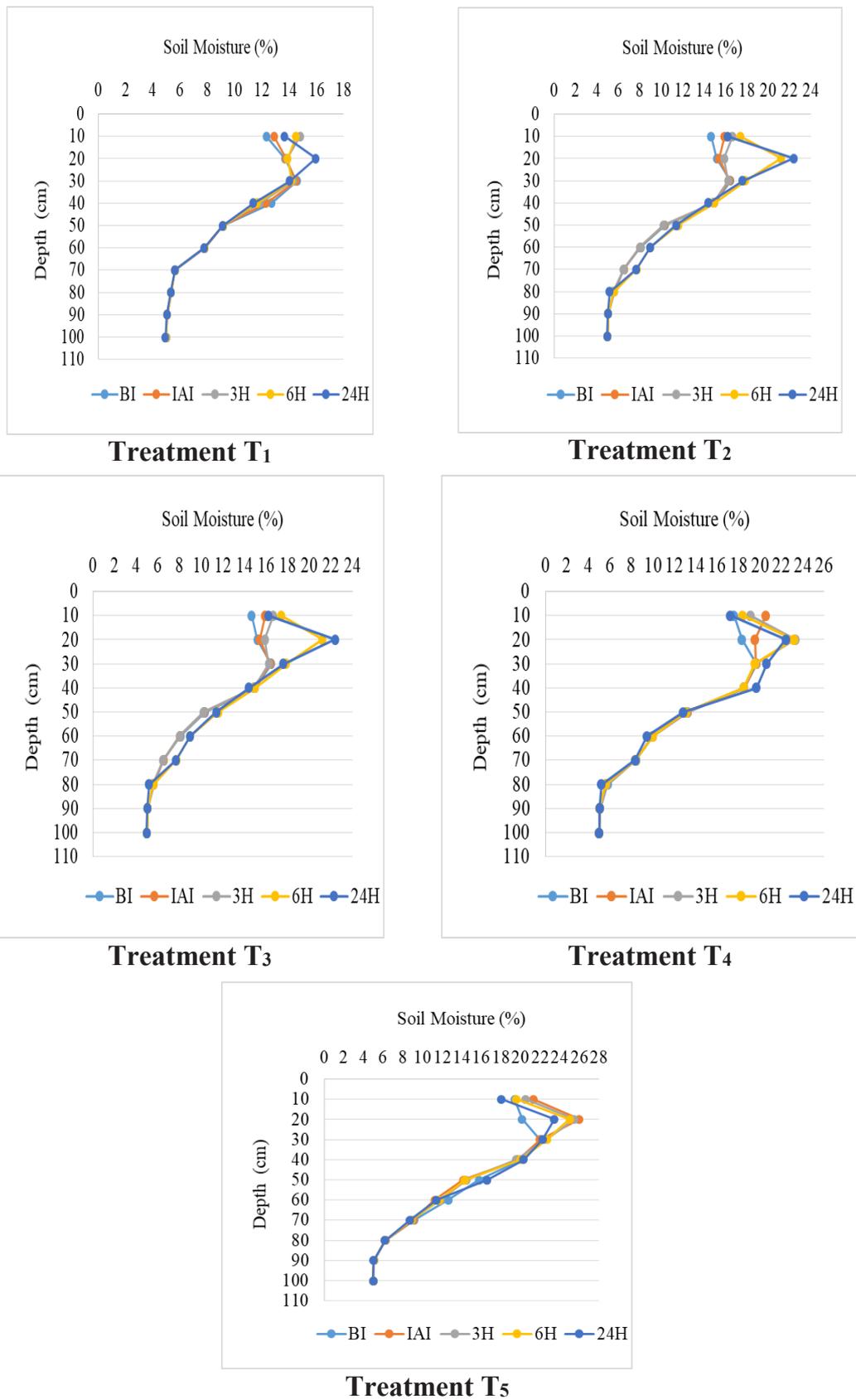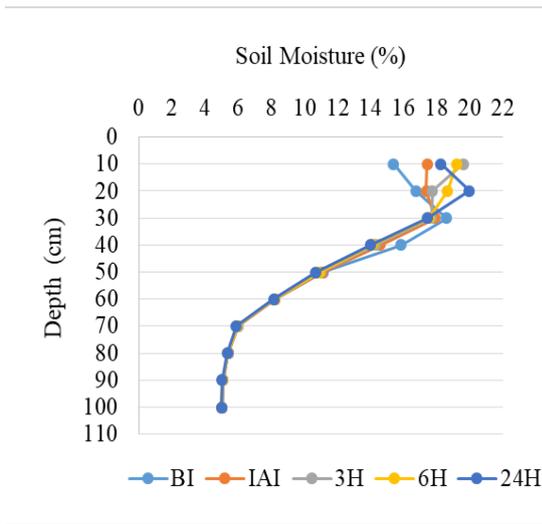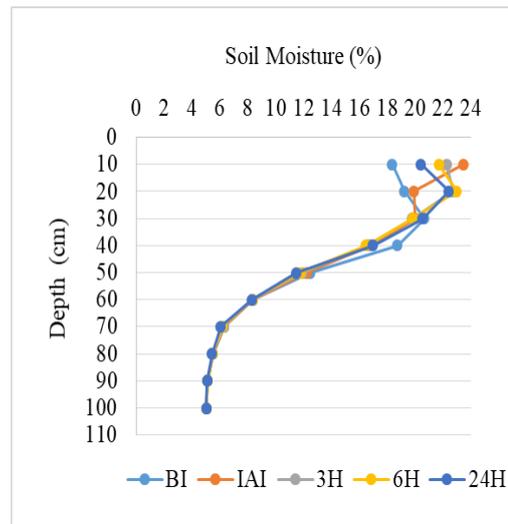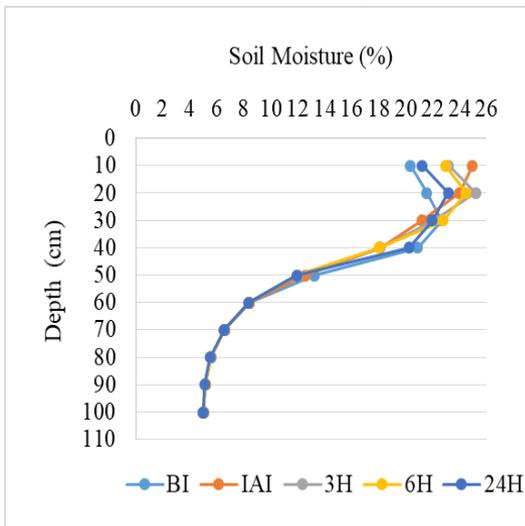
Fig. 3.1 Soil moisture distribution at 25 days after sowing.
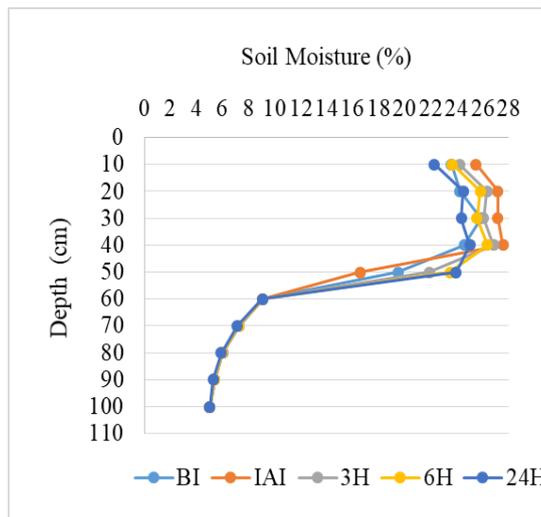
Treatment T₁

Treatment T₂

Treatment T₃
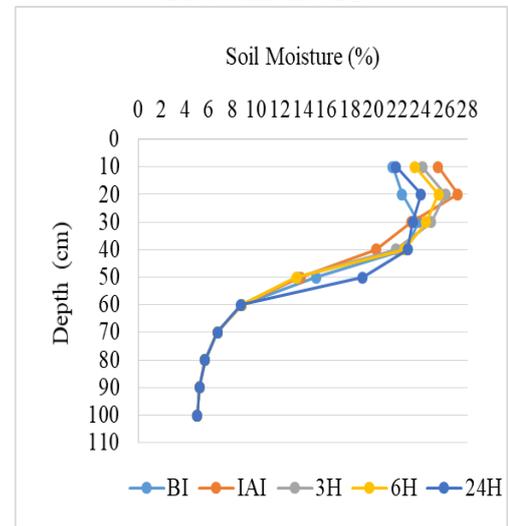
Treatment T₄

Treatment T₅

Fig. 3.2 Soil moisture distribution at 55 days after sowing.

Table 3.2 Evaluation of model during calibration at 25 DAS

After irrigation	R²	RMSE	RE (%)	NSE (%)
3h	0.9988	0.069	1.9	99.95
6h	0.9989	0.147	2.6	99.24
24h	0.9994	0.041	2.0	99.56

Table 3.3 Evaluation of model during validation at 55 DAS

| After irrigation	R²	RMSE	RE (%)	NSE (%)
3h	0.9982	0.121	2.95	99.33
6h	0.9968	0.083	2.88	99.29
24h	0.9987	0.122	2.67	99.39
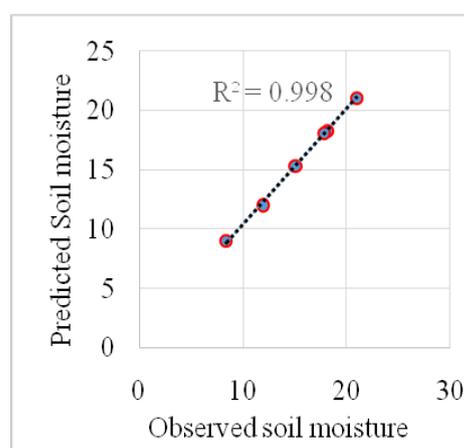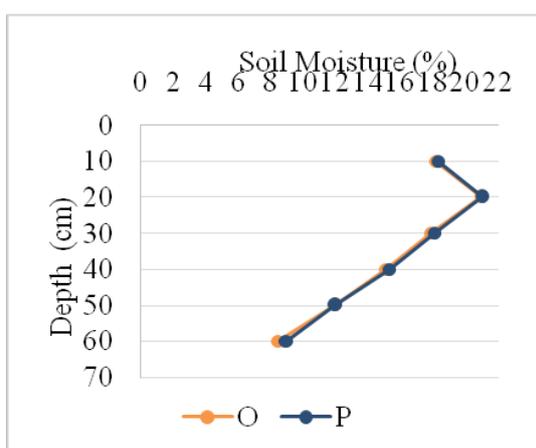
Fig. 3.3 (a) Simulated and observed moisture content at 25 DAS for 3 h after irrigation.
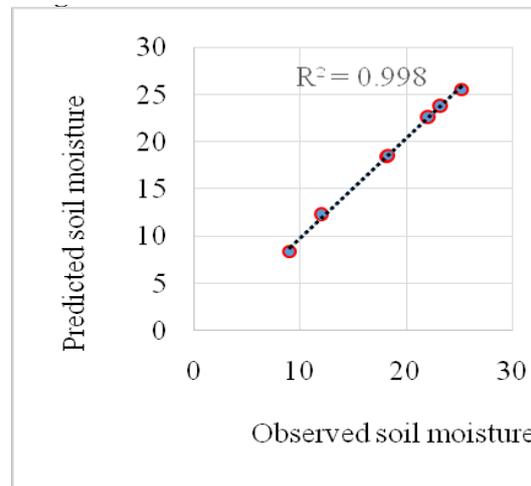

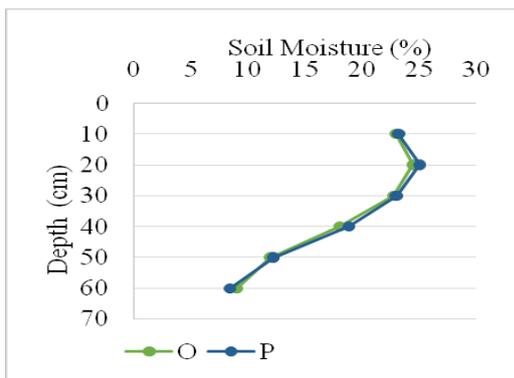**Fig. 3.3 (b) Scattered diagram of soil moisture content at 25 DAS for 3 h after irrigation.**
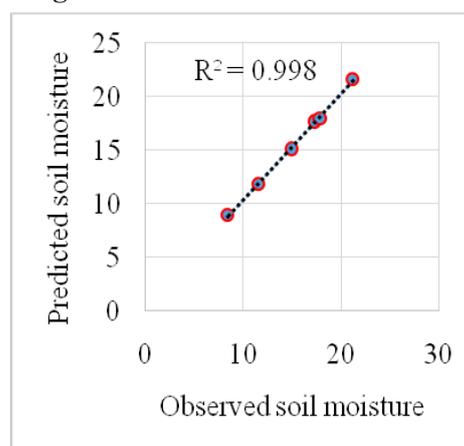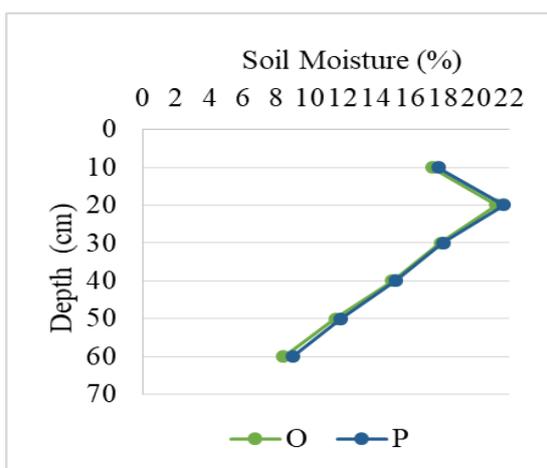
Fig. 3.4 (a) Simulated and observed moisture content at 25 DAS for 6 h after irrigation.
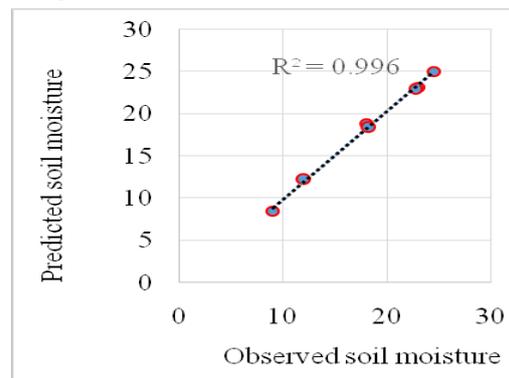

Fig. 3.4 (b) Scattered diagram of soil moisture content at 25 DAS for 6 h after irrigation.
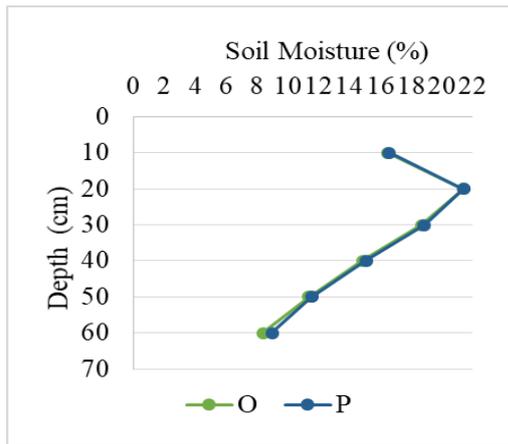
Fig. 3.5 (a) Simulated and observed moisture content at 25 DAS for 24 h after irrigation.
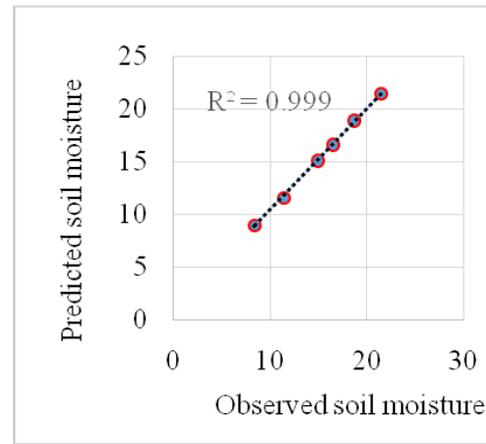
Fig. 3.5 (b) Scattered diagram of soil moisture content at 25 DAS for 24 h after irrigation.
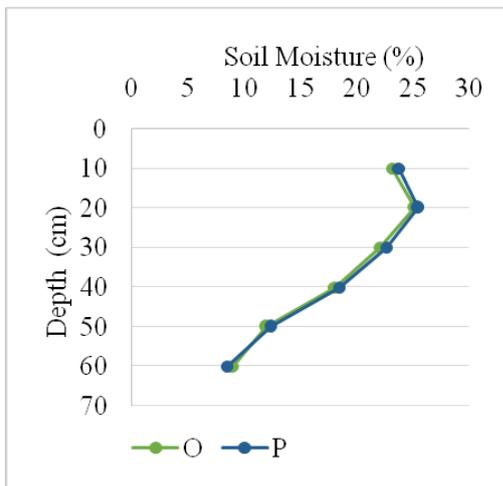
Fig. 3.6 (a) Simulated and observed moisture content at 55 DAS for 3 h after irrigation.

Fig. 3.6 (b) Scattered diagram of soil moisture content at 55 DAS for 3 h after irrigation.

Fig. 3.7 (a) Simulated and observed moisture content at 55 DAS for 6 h after irrigation.

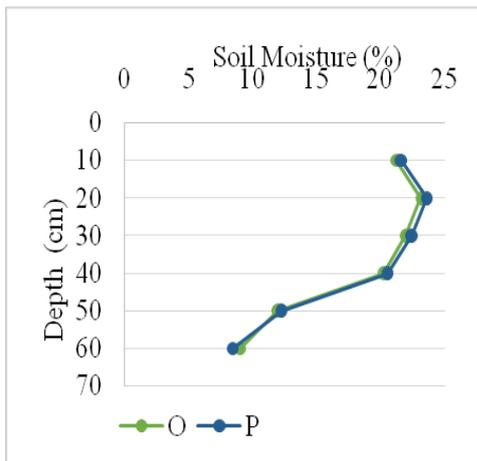**Fig. 3.7 (b) Scattered diagram of soil moisture content at 55 DAS for 6 h after irrigation.**

Fig. 3.8 (a) Simulated and observed moisture content at 55 DAS for 24 h after irrigation.
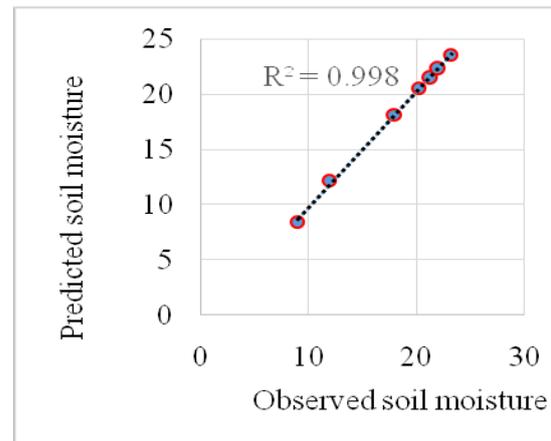

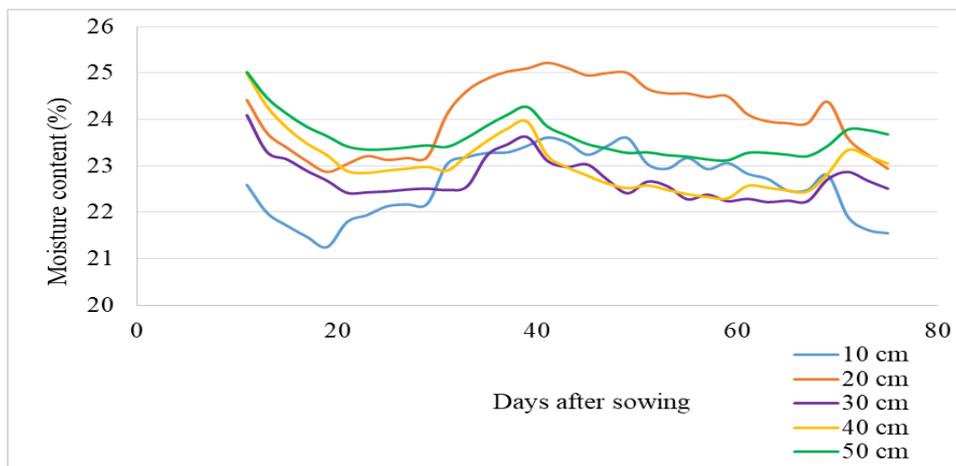**Fig. 3.8 (b) Scattered diagram of soil moisture content at 55 DAS for 24 h after irrigation.**

Fig. 3.9 Simulated soil moisture content at 3h after irrigation.

reproductive stage, and then decreased again. After 3h of irrigation, most of the soil moisture is accumulated at a depth of 20 cm.

A similar trend is observed 6h after irrigation. But the moisture content in the upper layers started declining, and the moisture content in the lower layers increased, indicating that irrigation water (moisture) is gradually moving downward through the profile over time after irrigation.

After 24h of irrigation, the moisture content at 0-30 cm in the soil profile decreased further due to evaporation losses and the consumption (uptake) of water by the crop root system to support photosynthesis and crop development. Some amount of water is moved downward through the profile, so moisture content increases in the lower layers (30-50 cm depth).

Summary and Conclusion

Hydraulic conductivity is the most sensitive parameter for calibration of the Hydrus-1D model. In drip emitter with 2 lph, soil moisture content in the top layers up to 50 cm depth is distributed well and holds sufficient water. The plant can easily extract water from this zone. There was no percolation losses observed below the active root zone after applying water at a low rate (2 lph) through drip irrigation. Therefore, drip irrigation on alternate days is appropriate for sandy clay loam soils for the cultivation of a sweet corn crop.

Hence, the HYDRUS-1D model can be used effectively to simulate the soil water dynamics in the soil profile to obtain a suitable irrigation system with a suitable irrigation schedule.
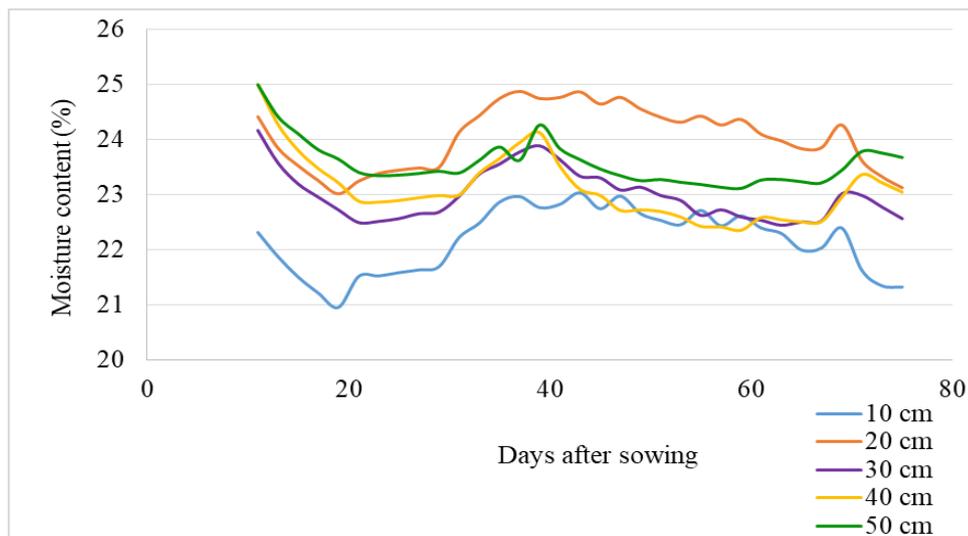
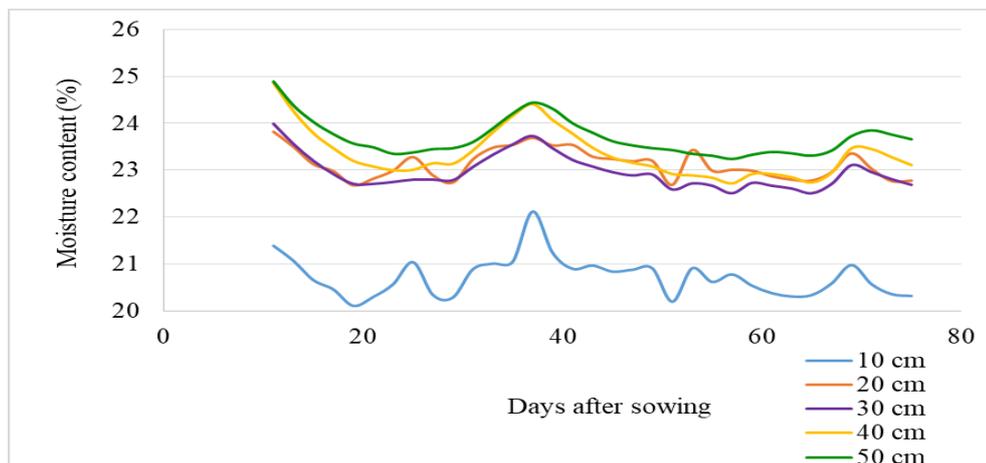**Fig. 3.10 Simulated soil moisture content at 6h after irrigation.**

Fig. 3.11 Simulated soil moisture content at 24h after irrigation.

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