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# Simulation of Soil Water Dynamics in the Rice and Mustard Cropped Field using Hydrus 2D for Sustainable Agriculture in Eastern India

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*Abstract—Eastern India is bestowed with an annual rainfall ranging from 1200 to1700 mm, two-third of which is occurring during monsoon season spanning from June to September. Where rice (Oryza sativa L.) followed by mustard (Brassica juncea L.) are the two predominant crops grown in monsoon and winter seasons, respectively. The spatial and temporal variability of rainfall create situation like surface flooding that causes a lot of soil and nutrient erosion on one hand and at the other, water scarcity at the critical crop growth stages. Thus, understanding of soil water dynamics under such monsoon climate is important for developing proper water management strategy for agricultural production system.*

*In the present study, water dynamics in the rice and mustard cropped field was simulated using HYDRUS-2D model. Simulation for soil water regime for 7 soil layers for mustard and 3 for rice (15 cm increment) fields was carried out with respect to observation nodes in the model domain and field observation points. Calibration and validation of HYDRUS-2D model was based on three years of field experiments and resulted high coefficient of determination (more than 0.72), and low root mean square error (less than 0.032) revealing its suitability to predict soil water dynamics in the effective root-zone of rainfed rice and mustard under varying saturated condition. The slope of the regression line is close to unity, which further indicates good agreement between the observed and simulated soil water content indicate that HYDRUS-2D model. In addition to scattered and regression presentation, the performance of HYDRUS-2D model was also evaluated using error statistics such as prediction efficiency (PE) and root mean square error (RMSE). Thus, the fate of the millions of farmers in the rainfed ecosystem can be greatly improved by adopting the effective rainwater conservation and management practices for sustainable agriculture in eastern India.*

## 1. INTRODUCTION

Eastern India is bestowed with ample rainfall resources with average annual rainfall of 1500 mm, 80% of which is concentrated during monsoon season(June-September) but during winter season (October- January) most of the areas lie barren due to lack of supplemental irrigation facilities. In eastern India, rice (*Oryza sativa L.*) followed by mustard (*Brassica juncea L.)* are the two predominant crops grown in monsoon and winter seasons, respectively [2] and [8]. Conventional water management in the rice cultivation aims at keeping the fields continuously submerged. But, excess ponding causes nutrient imbalance and reduction in yield and also inundation problem of rice and complete damage of seedlings and matured crop in low lands downstream. Experiments conducted with different water saving irrigation (WSI) techniques in various regions demonstrated that continuous submergence is not essential for increasing rice yields [6], whereas irrigation to rice at near saturation gives comparable yield with continuous submergence and saves a substantial amount of water [3] and [13]. So, understanding of soil water dynamics is important for developing proper water management strategy for crop production system.

Simulation modeling for understanding soil water dynamics and daily water balance is an appropriate alternative to understand the water use as well as irrigation and drainage requirements of the crops. The said approach is increasingly being used as an alternative to develop appropriate strategies for the efficient management of water resources for sustainable production and to transfer the results for multi-location trials in farmer's field [5] and [9]. Computer models are becoming increasingly important tools for analyzing complex problems involving water flow and solute transport in the vadose zone [1]. However, studies simultaneously estimating water flow and solute transport parameters for transient variably-saturated media are less common e.g. [4], especially in a layered soil-profile and for field conditions. Among the simulation models, HYDRUS-2D is a rather simple for simulating the water and solute transport under variable saturated conditions [4], [11] and [7]. Therefore, the present study was undertaken to assess the water dynamics under variable soil water regimes in rice and mustard fields using HYDRUS-2D model for sustainable agriculture.

## 2. MATERIALS AND METHODS

### 2.1. Experimental site and farming practices

In order to study the feasibility of the simulation models for the quantification of water balance parameters in the cropped field, three years (2002, 2003 and 2004) of field experiments were undertaken in the experimental farms of Agricultural and Food Engineering Department, Indian Institute of Technology (IIT), Kharagpur, West Bengal, India. It is located at latitude of 22$^o$ 19' N, longitude of 87$^o$ 19' E with an altitude of 48 m above the mean sea level.

The experimental plots of upland in nature (without allowing standing water in the plots) with very close rainwater harvesting structure to store excess rainwater were selected for sustainable production of monsoon rice (*Oryza sativa* L., Variety MW-10), and winter mustard (*Brassica juncea* Coss. Variety B-54). Rice seeds @100 kg ha$^{-1}$ were sown on dry tilled soil in line with 200 mm spacing between the rows at the onset day of monsoon in all the fields. Pre-treated mustard seeds @ 5 kg ha$^{-1}$ were sown in line with 200 mm spacing. Mustard seeds were sown 15 days after the harvest of rice. Rice and mustard seeds were sown in line by hand racking.

In the present study, a water-saving irrigation technique was considered in which, SI from nearby rainwater harvesting structure to the rice and mustard might be applied during critical growth stages. The duration of critical growth stage (CGS) of rice (30 days) was found to start at the 45$^{th}$ day after germination of seed (booting stage) and continued up to the end of the milking stage. SI to rice may be provided when the management-allowable deficit (MAD) during the critical growth stage was 40% depletion of soil moisture content from the volumetric saturation moisture content in the 45 cm effective root-zone depth [14]. SI was applied to rice for raising the soil moisture content up to field capacity or the effective depth of available water from nearby rainwater harvesting structure. The soil water required for seed germination of mustard is 75% available soil moisture (ASM) in the seeding zone depth of 15 cm [15]. So, 75% of ASM was kept as lower limit for PSI/SI to the mustard.

The soil profile of the experimental field could be divided into three and seven layers considering the effective root-zone of rice (45 cm) and mustard (105 cm) with each layer of 15 cm. These layers were decided for in situ measurements of soil physical properties, soil hydraulic parameters, and soil water characteristics at different depths in the effective root-zone of crops. The soil moisture content, matric suction, and piezometric head, saturated hydraulic conductivity in each depth was determined by falling head method. The average soil texture, bulk densities, residual soil moisture content ($\theta_r$), and saturated soil moisture content ($\theta_s$) measured at different root-zone depths of the cropped field are given in Table 1.

**Table 1: Soil Texture and hydraulic properties of soil layers in the cropped field.**

| Soil layers (cm) | Sand (%) | Silt (%) | Clay (%) | Bulk density (g cm$^{-3}$) | $K_s$ (cm day$^{-1}$) | $\theta_s$ (cm$^3$ cm$^{-3}$) | $\theta_r$ (cm$^3$ cm$^{-3}$) |
|---|---|---|---|---|---|---|---|
| 0-15 | 66.4 | 18.6 | 15.0 | 1.65 | 12.24 | 0.37 | 0.0306 |
| 15-30 | 62.5 | 21.5 | 16.0 | 1.60 | 7.01 | 0.39 | 0.0364 |
| 30-45 | 63.0 | 20.6 | 16.4 | 1.58 | 5.94 | 0.38 | 0.0386 |
| 45-60 | 64.2 | 20.0 | 15.8 | 1.60 | 4.01 | 0.40 | 0.0405 |
| 60-75 | 62.8 | 20.5 | 16.7 | 1.62 | 3.19 | 0.42 | 0.0407 |
| 75-90 | 62.7 | 20.8 | 16.5 | 1.61 | 2.14 | 0.42 | 0.0428 |
| 90-105 | 62.5 | 19.5 | 18.0 | 1.68 | 1.01 | 0.43 | 0.0470 |

The meteorological parameters namely rainfall, solar radiation, wind velocity, air temperature, and relative humidity were collected for three years (2002-2004) from the meteorological center as well as Automatic Weather Station of IIT, Kharagpur, which is located in the close vicinity of the experimental site. The site is coming under sub-humid and sub-tropical climate. It receives average annual rainfall of 1525.50 mm of which 1155.50 mm contribute during monsoon. Total seasonal rainfall during monsoon varies from 787 to 1600 mm. However, the annual rainfall varies from 1034 to 2100 mm. The annual and seasonal rainy days varies from 46 to 124 and 34 to 83 days, respectively.

Instruments such as aqua-pro soil water sensor and tensiometer were installed to monitor the soil water content in different soil layers with 15 cm intervals in the crop effective root zone depths (45 cm for rice and 105 cm for mustard) on daily basis. The digital aqua-pro water sensor and tensiometer were calibrated using the gravimetric measurements and the soil moisture characteristic curve for each layer were developed to transfer the readings from the instruments into soil moisture information.

### 2.2. Hydrus-2D model simulation

Owing to large-scale variation in climate during monsoon and post-monsoon seasons, physical measurement of soil water becomes difficult and in such situation modeling studies are often adopted to simulate soil water. HYDRUS-2D [12] has been used for simulating soil water dynamics in the rice and mustard fields under variable saturated conditions. The model was calibrated and validated after defining the domain geometry with finite element mesh (FEM), observation nodes, initial and boundary conditions of the rice and mustard field cross sections.

Maximum root-zone depth of crops (45 cm for rice and 105 cm for mustard) was considered as the model domain. Soil profile of the rice and mustard fields was divided into 3 and 7 layers of 15 cm intervals, respectively. Soil water contents measured at different layers on the first day of simulation was specified as initial boundary conditions.

Daily rainfall/supplemental irrigation and potential evapo-transpiration for the entire simulation period of 120 days for monsoon rice including 15 days of turn-in period (period between harvest of rice to sowing of mustard) and 75 days for winter mustard were used as a time-variable boundary at the soil surface. The soil surface was assumed to have atmospheric boundary condition for the model domain. The bottom boundary at the root-zone depth was assigned to have free drainage boundary condition for vertical percolation. The vertical boundaries were assigned as no-flow boundary conditions.

The measured values of hydraulic parameters for different soil layers of the cropped fields were input to different layers of the model domain. Using inverse modeling approach, HYDRUS-2D model was calibrated for the simulation of daily soil water content and to get optimized calibrating parameters at 95% confidence intervals. The calibrated parameters such as coefficient ($\alpha$) and exponent (n) in soil water retention function for each soil layer were estimated using neural network prediction and van Genuchten and Mualem (VGM) hydraulic model. The optimized calibrated parameters of HYDRUS-2D for soil layers of cropped field were used for the simulation of soil water dynamics in different soil layers for rice and mustard fields under variably saturated condition.

The model performance was evaluated using regression analysis (coefficient of determination), scattered diagram and error statistics (root mean square error and prediction efficiency) of simulated and observed daily data.

**Table 2: Initial and optimized calibrated parameters for soil layers of cropped field.**

| Depth (cm) | $\alpha$ ($cm^{-1}$) | | n | |
|---|---|---|---|---|
| | Initial | Optimized | Initial | Optimized |
| 0-15 | 0.0070 | 0.0072 | 1.4634 | 1.4500 |
| 15-30 | 0.0077 | 0.0057 | 1.4893 | 1.4749 |
| 30-45 | 0.0122 | 0.0039 | 1.5000 | 1.5619 |
| 45-60 | 0.0094 | 0.0036 | 1.5000 | 1.5611 |
| 60-75 | 0.0070 | 0.0035 | 1.5000 | 1.5669 |
| 75-90 | 0.0070 | 0.0034 | 1.2000 | 1.5597 |
| 90-105 | 0.0070 | 0.0018 | 1.2000 | 1.6945 |

## 3. RESULTS AND DISCUSSION

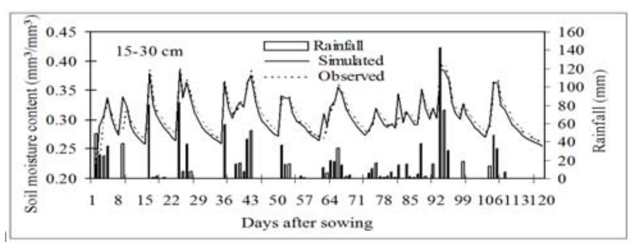
Using optimized calibrated parameters, HYDRUS-2D model was used to simulate soil moisture content for rice and mustard fields under variably saturated conditions. In addition to scattered and regression presentation, the performance of HYDRUS-2D model was also evaluated using error statistics such as prediction efficiency (PE) and root mean square error (RMSE) for simulation of SMC in different soil layers of mustard and rice fields for the year 2002, 2003, and 2004. The details of the results are presented in the following sections.

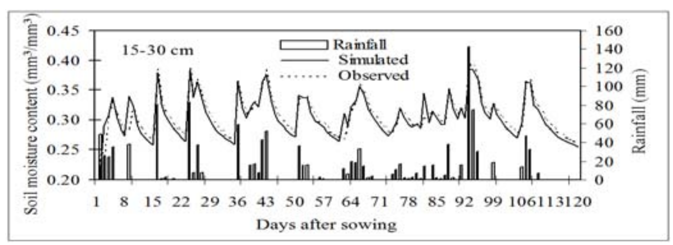
### 3.1. Soil moisture dynamics in the rice field

Daily variation of simulated and observed soil moisture content for three soil layers of rice field for the three experimental years are shown in Fig. 1, 2, and 3, respectively. In rice fields variation of soil water content in different soil layers of crop root-zone was found to have cyclic experience due to variation in rainfall. However, during the period when there was no rainfall or no supplemental irrigation is applied, soil water content was found to decline gradually because of uptake of water by the plant roots and vertical percolation from the root-zone.

The regression analysis of observed and simulated SMC for different soil layers of mustard field for the experimental year 2002 are shown in Fig. 1. The slope of the regression line is close to unity, which further indicates good agreement between the observed and predicted SMC. The clustering of observed and predicted SMC around the 1:1 line and the high value of $R^2$ (more than 0.72) indicate that HYDRUS-2D model is quite efficient in predicting daily variation of SMC in the crop root-zone in the rainfed ecosystem.

In addition to scattered and regression presentation, the performance of HYDRUS-2D model was also evaluated using error statistics such as prediction



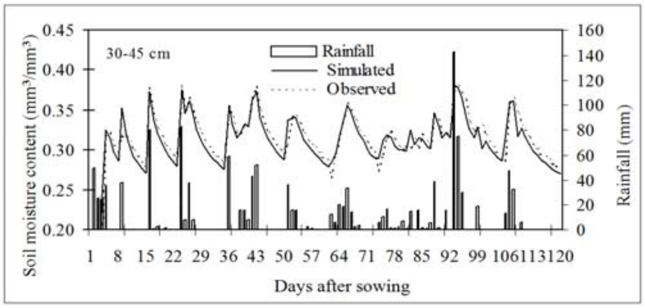



**Fig. 1. Daily variation of simulated and observed soil moisture content in soil layers of rice field for 2002**

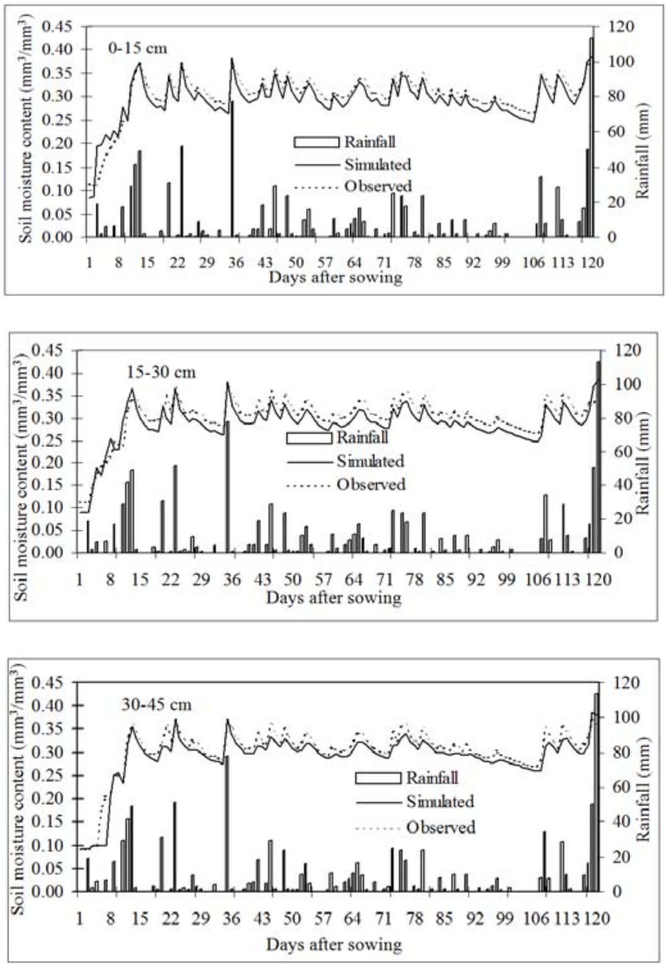
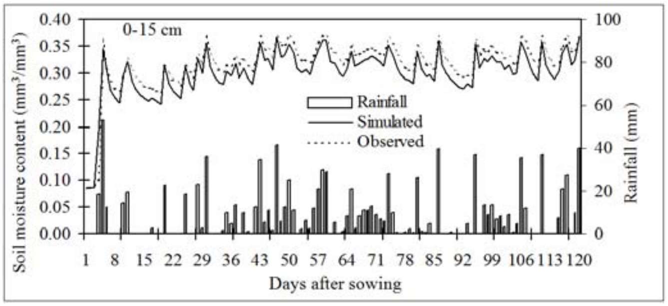



**Fig. 2. Daily variation of simulated and observed soil moisture content in soil layers of rice field for 2003**



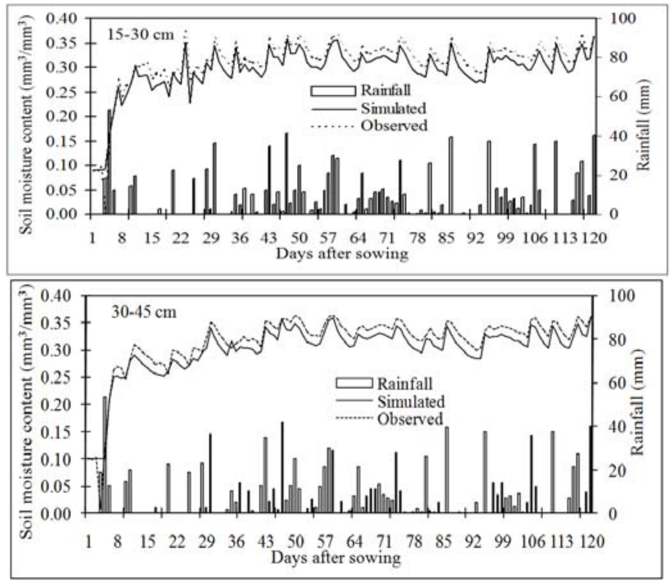




**Fig. 3: Daily variation of simulated and observed soil moisture content in soil layers of rice field for 2004**

efficiency (PE) and root mean square error (RMSE) for simulation of SMC in different soil layers of rice fields for the year 2002, 2003, and 2004 (Table 3).

**Table 3: Error statistics for hydrus-2d simulation of soil moisture content in soil layers of rice field.**

| Soil layer (cm) | 2002 | | 2003 | | 2004 | |
|---|---|---|---|---|---|---|
| | PE | RMSE | PE | RMSE | PE | RMSE |
| 0-15 | 0.9326 | 0.0230 | 0.9132 | 0.0263 | 0.9523 | 0.0207 |
| 15-30 | 0.9475 | 0.0225 | 0.9360 | 0.0209 | 0.9623 | 0.0278 |
| 30-45 | 0.9531 | 0.0221 | 0.9525 | 0.0294 | 0.9709 | 0.0191 |

The error statistics revealed that the PE and RMSE values are within the acceptable limit. The high value of $R^2$, PE (more than 0.90), and low value of RMSE (less than 0.032) indicates that the HYDRUS-2D model is quite efficient in predicting daily variation of SMC in the cropped field with variably saturated condition.

### 3.2. Soil water dynamics in the mustard field

Daily variation of simulated and observed soil moisture content for three soil layers of mustard field for the three experimental years are shown in Fig. 4, 5, and 6, respectively. During the mustard growing period, soil water content in different soil layers of crop root-zone depths was found varying due to supplemental irrigation over a period of time. The variation in soil water content in upper three layers of crop root-zone depths (0-45 cm) was found higher than the lower depths (45-105 cm) during three years of experiment. The variation in soil water content in upper layers of crop root-zone depths affects the availability of water and nutrient to mustard and ultimately affects crop yields.

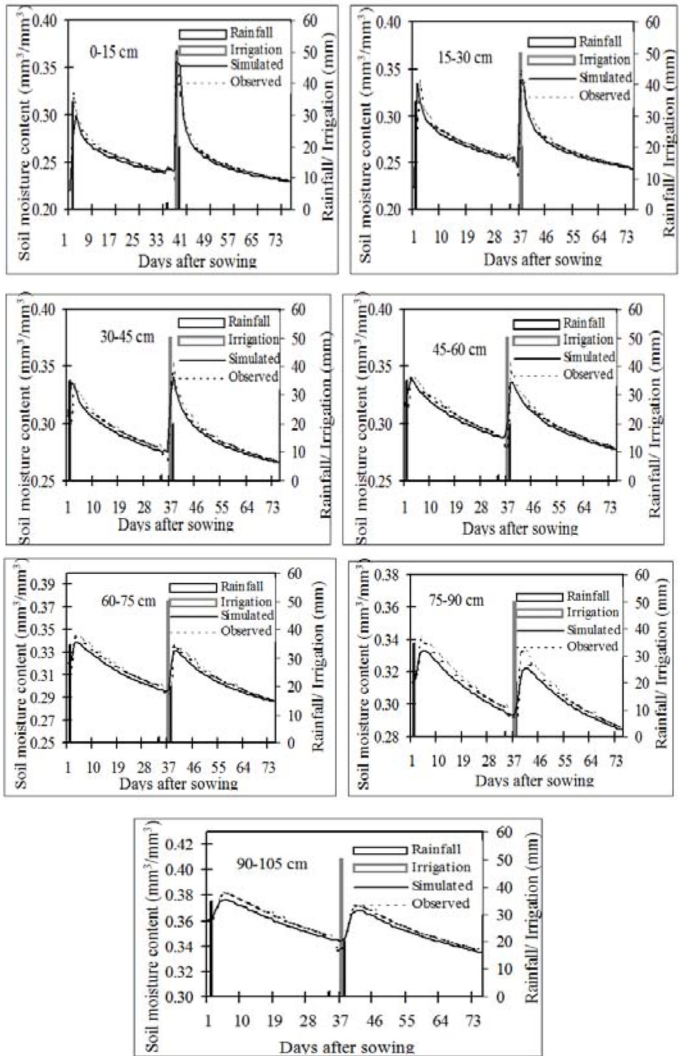
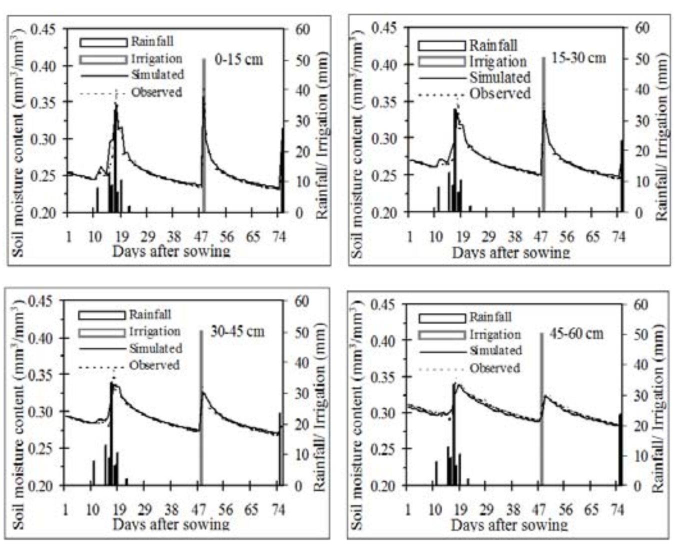



**Fig. 4: Daily variation of simulated and observed soil moisture content in soil layers of mustard field for 2002.**



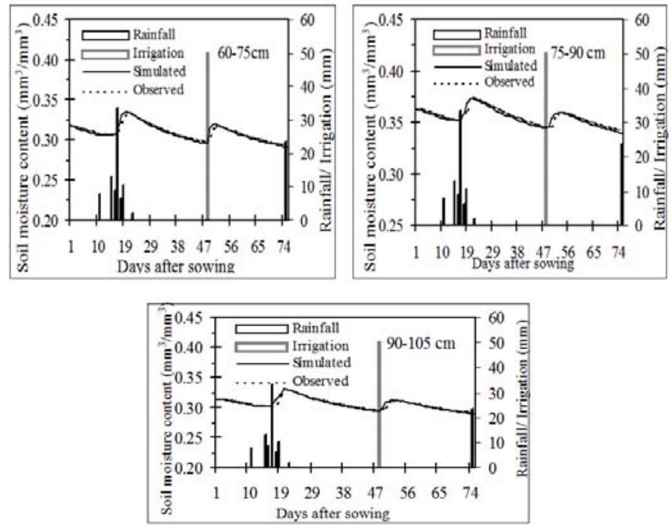




**Fig. 5: Daily variation of simulated and observed soil moisture content in soil layers of mustard field for 2003**

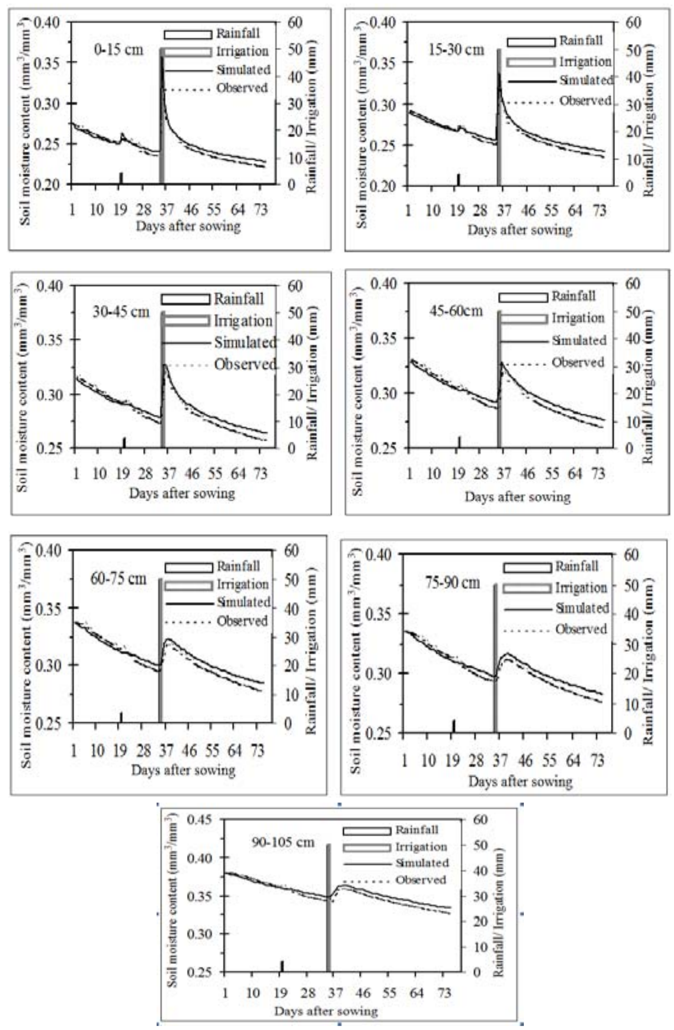



**Fig. 6: Daily variation of simulated and observed soil moisture content in soil layers of mustard field for 2004.**

The error statistics such as prediction efficiency (PE) and root mean square error (RMSE) for simulation of SMC in different soil layers of mustard fields for the year 2002, 2003, and 2004 (Table 4).

**Table 4: Error statistics for hydrus-2d simulation of soil moisture content in soil layers of mustard field.**

| Soil layer (cm) | 2002 | | 2003 | | 2004 | |
|---|---|---|---|---|---|---|
| | PE | RMSE | PE | RMSE | PE | RMSE |
| 0-15 | 0.9337 | 0.0317 | 0.9335 | 0.0318 | 0.9620 | 0.0239 |
| 15-30 | 0.9342 | 0.0315 | 0.9345 | 0.0313 | 0.9530 | 0.0266 |
| 30-45 | 0.9432 | 0.0291 | 0.9353 | 0.0311 | 0.9503 | 0.0273 |
| 45-60 | 0.9457 | 0.0283 | 0.9518 | 0.0266 | 0.9588 | 0.0247 |
| 60-75 | 0.9612 | 0.0240 | 0.9525 | 0.0263 | 0.9442 | 0.0289 |
| 75-90 | 0.9700 | 0.0211 | 0.9616 | 0.0236 | 0.9408 | 0.0297 |
| 90-105 | 0.9796 | 0.0174 | 0.9708 | 0.0263 | 0.9357 | 0.0309 |

The error statistics revealed that the PE and RMSE values are within the acceptable limit. The high value of $R^2$, PE (more than 0.90), and low value of RMSE (less than 0.032) indicates that the HYDRUS-2D model is quite efficient in predicting daily variation of SMC in the cropped field with variably saturated condition.

## 4. CONCLUSIONS

Based on the simulation of soil water dynamics simulated by Hydrus-2D model and three years of field experimental studies, the following conclusions have been drawn:

(i) Simulation of Hydrus-2D model based on three years of field experiments resulted high coefficient of determination (more than 0.72), and low root mean square error (less than 0.032) revealing its suitability to predict soil water dynamics in the effective root-zone of rainfed rice and mustard under varying saturated condition.
(ii) In rice fields, soil water content was found cyclic due to the variation of rainfall. However, no supplemental irrigation was applied to rice as soil water content was not depleted 40% below saturation during critical growth stage while in mustard; the variation in soil water content in the root-zone affects the availability of water and nutrient and ultimately impact on crop yields.
(iii) Excess rainwater generated from the cropped field with water saving irrigation conditions could render better scope for rain water harvesting structure and sustainable crop production in north east of India.

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