Evaluation of non-linear root water uptake model under different agro-climates

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The present study examines the effectiveness of a non-linear root water uptake (RWU) model for different agro-climates. Evaluation of O-R model is performed for three agro-climates considering secondary data of Roorkee (semi-arid), Solan (sub-temperate sub-humid) and primary data of Hamirpur (humid subtropical region). Field experiments on maize (\textit{Zea mays}), Indian mustard (\textit{Brassica Juncea}) and wheat (\textit{Triticum aestivum}) were conducted at different locations. The RWU model with a numerical simulation was developed for predicting moisture movement in the crop root zone. The predicted results were compared with the observed field data. Qualitative and quantitative evaluations were performed on the basis of soil moisture profile in the crop root zone, soil moisture depletion and soil moisture variation during crop period at different root zone depths. The model-predicted and field-observed values were found to be in strong agreement for all the parameters indicating the efficacy of the numerical model coupled with non-linear RWU model in predicting soil moisture dynamics in root zone.

Keywords: Crop root zone, crop evapotranspiration, lysimeter, numerical model, O-R model.

In developing countries like India, where water availability is scarce, scientific approaches are necessary for effective utilization of the water resources. Irrigation sector alone accounts for more than 70\% of water abstractions. Hence, it is imperative to conserve water and optimize crop yield through efficient irrigation.\textsuperscript{1} This is generally achieved through development of optimal irrigation schedules which necessitate precise information on water requirements of crops. The crop water requirements are essentially governed by soil, crop and climatic variables under consideration.\textsuperscript{2,3} Root uptake is a significant component of field water balance study. It has been observed that each crop possesses its own root water uptake (RWU) behaviour.\textsuperscript{4}

Generally, RWU is described as a function of actual transpiration, soil moisture availability and vertical root distribution to the crops.\textsuperscript{5,6} Numerous RWU models based on different moisture movement pattern are available in literature of which the most prominent models are constant\textsuperscript{7}, linear\textsuperscript{8}, non-linear\textsuperscript{9} and exponential\textsuperscript{10,11}. Numerical simulation of soil moisture dynamics considering RWU models has been widely reported in several studies.\textsuperscript{4,12–21} Ojha \textit{et al.}\textsuperscript{22} carried out a comparative evaluation of different RWU models considering primary data (field experiments) and secondary data.\textsuperscript{23} The results indicated that the non-linear model performed better than other RWU models in estimating moisture extraction by crops. Kumar \textit{et al.}\textsuperscript{24} reviewed numerous RWU models and suggested that non-linear and exponential models provide better moisture extraction prediction efficiency.

The non-linear RWU model (hereinafter referred to as O-R model) is an improvement over the linear RWU model by including a non-linearity coefficient. The non-linearity coefficient accounts for the non-linear behaviour of RWU by crops.\textsuperscript{9} Shankar \textit{et al.}\textsuperscript{25} developed a method for computing the optimal value of non-linearity coefficient from crop physiological parameters, i.e. maximum daily transpiration, time and maximum root depth to attain the maximum transpiration value. The O-R model has been tested for uniform vis-à-vis multi-layered crop root zone and results indicated its efficacy for multilayer soils with varying soil properties for different depth.\textsuperscript{25} Studies commented on the utility of O-R model under different agro-climates; however, only a handful attempts have been made in the past. The agro-climate of a region has considerable effect on crop water requirements and soil moisture dynamics, thereby governing the yield of the crops.\textsuperscript{26} Moreover, the description of agro-climate enables research effort to be more focused.\textsuperscript{27} The present study is focused on evaluating the potential of O-R model under different agro-climates to establish its efficacy.

For present study, maize, wheat and Indian mustard are considered, since they are cultivated in a wide range of climates and are popular in hilly terrains as well.\textsuperscript{14,28} The study considers three agro-climates which includes secondary data for two agro-climates (semi-arid and...
sub-temperate sub-humid) and primary data (humid sub-tropical) for the third one.

Materials and methods

Numerical model

The Richards (mixed form) equation representing vertical moisture (one-dimensional) flow in a cropped soil is written as

\[
\frac{\partial}{\partial z} \left[ k(\psi) \left( \frac{\partial \psi}{\partial z} \right) + 1 \right] + S(z,t) = \frac{\partial \theta}{\partial t},
\]

where \( K \) (a function of \( \psi \)) is the hydraulic conductivity; \( S \) (a function of \( z, t \)) = sink term accounting moisture uptake; \( \psi \) the pressure head; \( \theta \) (a function of \( \psi \)) = volumetric moisture content; \( t \) the time and \( z \) the vertical distance measured positive upward.

Constitutive relationships

**\( \theta - \psi \) relationship:** Van Genuchten\(^{31} \) has given the constitutive relations between moisture content, pressure head and hydraulic conductivity

\[
\Theta = \left[ \frac{1}{1 + |\alpha\psi|^{n}} \right]^{m}.
\]

For \( \psi < 0 \), for \( \psi \geq 0 = 1 \),

\[
\theta - K \text{ correlation}
\]

\[ K = K_{sat} \Theta^{1/2}[1 - (1 - \Theta^{1/m})^{2}] \quad \text{For} \ \psi < 0 \]

\[ = K_{sat} \Theta \quad \text{For} \ \psi \geq 0, \]

where \( K_{sat} \) is the soil saturated hydraulic conductivity.

**Root uptake model**

In the present study, the root water uptake \( S(z, t) \) in eq. (1) is O-R model given by Ojha and Rai\(^{9} \). The soil water uptake rate \( S_{max} \) is given by non-linear O-R model given as

\[
S_{max} = \left[ \frac{T_{j}}{z_{rj}} (\beta + 1) \left( 1 - \frac{z}{z_{rj}} \right)^{\beta} \right] 0 \leq z \leq z_{rj},
\]

where \( T_{j} \) is the transpiration on \( j \)th day, \( \beta \) the nonlinearity coefficient, \( z \) the depth below soil surface and \( z_{rj} \) the root depth on \( j \)th day. For \( z = z_{rj} \), \( S_{max} \) value is zero (eq. (4)). \( S_{max} \) attains a maximum value at \( z = 0 \).

Initial and boundary conditions

The solution of eq. (1) requires boundary conditions for specific solution. Initially the soil is assumed to have uniform pressure throughout its domain, i.e.

\[
\begin{align*}
\psi &= \psi_{measured}(z) \quad 0 \leq z \leq L, \ t = 0, \\
\psi &= \psi_{measured}(z) \quad t = 0,
\end{align*}
\]

where \( \psi_{measured}(z) \) is the measured pressure head value in the field; \( \psi_{rj} \) the pressure head corresponding to the field capacity (in absence of field measured values) and \( L \) the length of solution domain.

Upper boundary condition (flux type) that includes soil evaporation (\( E_{r} \)) at upper layer of soil and a Dirichlet type boundary condition during irrigation/rainfall were used in present study.

\[
\begin{align*}
K(\psi) \left( \frac{\partial \psi}{\partial z} + 1 \right) &= E_{r}, \ z = L, \ \text{in absence of irrigation}, \\
\psi &= \psi_{rj}, \ z = L, \ \text{during irrigation/rainfall}, \\
K(\psi) \left( \frac{\partial \psi}{\partial z} + 1 \right) &= -K(\psi) \quad t \geq 0, \ z = 0.
\end{align*}
\]

where \( \psi_{rj} \) is the pressure head corresponding to saturated moisture content (\( \psi = 0 \)), during irrigation or rainfall. The \( E_{r} \) is partitioned component of the crop evapotranspiration (\( ET_{c} \)).

At lower boundary, gravity drainage type condition is taken, i.e.

\[
\begin{align*}
-K(\psi) \left( \frac{\partial \psi}{\partial z} + 1 \right) &= -K(\psi) \quad t \geq 0, \ z = 0.
\end{align*}
\]

Non-linear parameter \( \beta \)

Shankar et al.\(^{25} \) developed an empirical relationship for computation of non-linear parameter \( \beta \) of O-R model using plant physiological parameters, i.e. maximum root depth, maximum daily transpiration and time to attain the maximum transpiration. The relationship developed is

\[
\beta = 5.1128 T_{t}^{2} - 6.117 T_{t} + 3.1545; 0.07 \leq T_{t} \leq 0.98,
\]

where \( T_{t} \) is the maximum value of daily transpiration; \( Z_{r} \) max the maximum value of root depth; \( t_{\text{peak}} \) the time to
Table 1. Locations of various agro climatic stations

| Station   | State          | Latitude | Longitude  | Altitude (m) | Climate               |
|-----------|----------------|----------|------------|--------------|-----------------------|
| Roorkee   | Uttarakhand    | 29°52'N | 77°53'E    | 274          | Semi-arid             |
| Solan     | Himachal Pradesh | 30°50'N | 77°11'E    | 1260         | Sub-temperate sub-humid |
| Hamirpur  | Himachal Pradesh | 31°68'N | 76°52'E    | 738          | Humid sub-tropical    |

Table 2. Details of depth wise classification of soil and moisture characteristics

| Lysimeter | Soil depth (cm) | \( \delta_{\text{bulk}} \) (g/cc) | Gravel (%) | Sand (%) | Silt (%) | Clay (%) | \( \delta_{\text{pore}} \) (g/cc) | \( K_s \) (cm/h) | \( \theta_c \) (cm²/cm³) | \( \theta_{\text{wp}} \) (cm²/cm³) |
|-----------|----------------|-------------------------------|------------|----------|----------|----------|--------------------------------|----------------|--------------------------|--------------------------|
| 1         | 0–20           | 1.52                          | 17.1       | 43.4     | 28.2     | 11.3     | 2.62                           | 1.02            | 0.208                    | 0.068                    |
|           | 20–40          | 1.56                          | 12.6       | 49.6     | 23.4     | 14.4     | 2.64                           | 0.98            | 0.208                    | 0.068                    |
|           | 40–60          | 1.62                          | 11.3       | 46.3     | 24.8     | 17.6     | 2.58                           | 0.95            | 0.208                    | 0.068                    |
|           | 60–80          | 1.68                          | 8.5        | 49.8     | 25.6     | 16.1     | 2.61                           | 1.10            | 0.208                    | 0.068                    |
|           | 80–100         | 1.72                          | 19.8       | 42.4     | 23.2     | 14.6     | 2.60                           | 1.35            | 0.208                    | 0.068                    |
| 2         | 0–20           | 1.23                          | 35.0       | 47.4     | 31.2     | 21.4     | 2.45                           | 1.05            | 0.240                    | 0.130                    |
|           | 20–40          | 1.30                          | 40.4       | 39.6     | 35.2     | 25.6     | 2.54                           | 0.90            | 0.230                    | 0.120                    |
|           | 40–60          | 1.31                          | 36.0       | 41.0     | 32.6     | 26.4     | 2.51                           | 0.86            | 0.240                    | 0.130                    |
|           | 60–80          | 1.35                          | 20.0       | 39.6     | 36.4     | 24.0     | 2.48                           | 0.80            | 0.240                    | 0.120                    |
|           | 80–100         | 1.36                          | 18.4       | 37.8     | 35.2     | 27.0     | 2.46                           | 0.84            | 0.230                    | 0.120                    |
| 3         | 0–20           | 1.51                          | 27.0       | 54.9     | 23.8     | 21.1     | 2.54                           | 2.96            | 0.220                    | 0.070                    |
|           | 20–40          | 1.56                          | 32.4       | 57.4     | 24.4     | 18.1     | 2.59                           | 2.78            | 0.212                    | 0.072                    |
|           | 40–60          | 1.63                          | 24.7       | 59.2     | 24.3     | 16.4     | 2.61                           | 2.44            | 0.208                    | 0.058                    |
|           | 60–80          | 1.67                          | 26.0       | 55.1     | 29.6     | 15.3     | 2.63                           | 2.35            | 0.206                    | 0.066                    |
|           | 80–100         | 1.64                          | 29.4       | 57.2     | 26.3     | 16.5     | 2.65                           | 2.41            | 0.208                    | 0.058                    |

Numerical simulation

The differential eq. (1) was solved using initial and boundary conditions given in eqs (5)–(8) for formulating a numerical code. For constitutive relationship eqs (2)–(3) were used. The numerical model is based on a mass conservative, fully implicit finite difference scheme proposed by Celia et al.30. The solution includes spatial and temporal approximating in the equation by finite differences. Further, the non-linear equations is linearized by Picards’ method33 and the resulting equation is solved using the Thomas algorithm34. At successive advancing times, the model yields spatial distribution of pressure head and moisture content of the soil in the crop root zone (CRZ). The model computed moisture contents, moisture depletion values at different root zone depths.

Description of agro-climates

The present study is focused on the utility of O-R model in predicting soil moisture dynamics in CRZ and establishing its efficacy across different agro-climates having variations in meteorological parameters and soil properties. Table 1 lists the details of the agro-climatic locations considered in the study. Field crop experiments conducted under controlled conditions by Shankar et al.25 at Roorkee and Kumar et al.17 at Solan for three major crops, i.e. maize, wheat and Indian mustard were used as secondary data in the present study. Field experiments on maize, wheat and Indian mustard for present study were conducted at Hamirpur and are used as primary data.

Details of experimental setup

Lysimeters were installed for field crop experiments at Roorkee (hereinafter this study is referred as LS-1), Solan (hereinafter this study is referred as LS-2) and Hamirpur (hereinafter this study is referred as LS-3). LS-1 was installed at Field Research Station of Civil Engineering Department, Indian Institute of Technology Roorkee (Uttarakhand, India). LS-2 was installed at the experimental station of Dr Y. S. Parmar University of Horticulture and Forestry, Solan (Himachal Pradesh, India). LS-3 was installed in the Agricultural Experimental Station of Civil Engineering Department, National Institute of Technology Hamirpur (Himachal Pradesh, India). Two drainage Lysimeters (150 cm deep with a surface area of 1 sq. m) were installed in an open field at each station to simulate actual field dynamics under controlled conditions. Soil within the Lysimeters was kept same as that of surrounding agricultural plot. Details of soil texture for...
Figure 1. Representation of Lysimeter setup in experimental station.

Table 3. Details of the field crop experimental data

| Crops (Variety sown) | Date of sowing | Duration (days) | Growth stages (days) I II III IV | Irrigation provided (day) | Spacing (cm) |
|----------------------|----------------|----------------|----------------------------------|--------------------------|--------------|
| Maize (Zea mays)     | 1 May 2014     | 114            | 20 34 36 24                      | 22nd, 36th, 48th         | 50 × 20      |
| Wheat (Triticum aestivum) | 30 November 2014 | 154          | 30 46 50 28                      | 26th, 44th, 56th         | 25 × 5       |
| Indian mustard (Brassica Juncea) | 4 November 2015 | 114          | 19 32 38 25                      | 11th, 25th, 37th         | 40 × 15      |

Soil moisture characteristic (SMC) curve represents the functional relationship between the volumetric moisture content (θ) and the pressure head (ψ) in the unsaturated porous medium. The SMC curve for LS-1 and LS-2 is given in Shankar and Kumar et al. respectively. In case of LS-3, experimental SMC is obtained using pressure plate apparatus (M/s Soil Moisture Equipment Corporation, USA). The experimental SMC is well described by realistic Van-Genuchten model, with values of unsaturated soil hydraulic parameters θr, θs, α, and n as 0.056 cm³ cm⁻³, 0.36 cm³ cm⁻³, 5.9 m⁻¹ and 1.83 respectively. Figure 2 expresses the functional relationship between θ and ψ in SMC curve for the present study.

Crop details

The entire crop growth period for the wheat, maize and Indian mustard was divided into four stages (initial, crop development, midseason and late season). Table 3 gives the details of crop duration, crop stages, spacing and irrigation events pertaining to these crops for field experiments conducted at Hamirpur.

Leaf area index (LAI) values, which are required for the partitioning of the ETc into plant transpiration and soil evaporation, were measured by the direct method. Root
depth was measured by the trench profile method complemented with the field-observed soil moisture depletion method. Crop height was measured by taking the average of 10 plants selected at random. During the initial stages, the plant height, root depth and LAI were measured at 10–12 day intervals; at later stages, this interval was reduced to 7 days. Figures 3–5 show the plant height, root depth and LAI for maize, wheat and Indian mustard for LS-3. The plant height, root depth and LAI for maize, wheat and Indian mustard for LS-1 and LS-2 are detailed in Shankar et al.25 and Kumar et al.17 respectively.

**Crop water requirements**

Crop evapotranspiration ($ET_c$) is determined as the product of daily crop coefficient ($K_c$) and reference evapotranspiration ($ET_0$). FAO-56 Penman–Monteith equation is used to compute $ET_0$ for the present study. The meteorological data (temperature, humidity, rainfall, solar radiation and wind speed) required for the estimation of $ET_0$ was recorded with the help of Automatic Weather Station located at National Institute of Technology, Hamirpur. Penman–Monteith equation is given as

$$ET_0 = \frac{0.408\Delta (R_n - G) + \gamma \frac{900}{T + 273} u(e_s - e_a)}{\Delta + \gamma(1 + 0.34u)},$$

where $R_n$ is net radiation at the crop surface (MJ m$^{-2}$ day$^{-1}$), $G$ the soil heat flux density (MJ m$^{-2}$ day$^{-1}$), $T$ the mean daily air temperature at 2 m height ($^\circ$C), $u_2$ the wind speed at 2 m height (m s$^{-1}$), $e_s$ the saturation vapour pressure (kPa), $e_a$ the actual vapour pressure (kPa), $e_s - e_a$ the saturation vapour pressure deficit (kPa), $\Delta$ the slope of vapour pressure curve (kPa $^\circ$C$^{-1}$) and $\gamma$ is the psychrometric constant (kPa $^\circ$C$^{-1}$).

Soil evaporation ($E_s$) is obtained as the partitioned component of $ET_c$ using relationship proposed by Eberbach and Pala given as

$$E_s/ET_c = \exp(-\delta * LAI),$$

where $\delta$ is the soil evaporation fraction.
$\delta$ is empirical coefficient whose value is 0.58, 0.47 and 0.50 for maize, wheat and Indian mustard respectively$^{44-46}$. The modified values of $K_{c_{\text{ini}}}$, $K_{c_{\text{mid}}}$ and $K_{c_{\text{end}}}$ are 0.41, 1.79 and 0.51 for maize, 0.58, 1.17 and 0.40 for wheat and 0.56, 1.16 and 0.31 for Indian mustard. The partition of $ET_{c}$ into plant transpiration and soil evaporation for Indian mustard is shown in Figure 6.

**Model performance indicators**

Performance of the field-observed and model-predicted percentage moisture depletion for the present study is evaluated using coefficient of determination ($R^2$)$^{47}$, Nash–Sutcliffe efficiency (NSE)$^{48}$ and mean bias error (MBE)$^{49}$. $R^2$ denotes the degree of linear dependency, NSE is used to verify the credibility of models and that the maximum value for both evaluation indices is 1 whereas MBE signifies the over or under estimation capacity of the model. The performance of a model is considered better when $R^2$ and NSE are higher and MBE is lower having small range of values. The equations for these indicators are given as

$$R^2 = \frac{\sum_{i=1}^{n} (\bar{\theta}_f - \bar{\theta}_m)(\bar{\theta}_{mi} - \bar{\theta}_{mi})}{\sqrt{\sum_{i=1}^{n} (\bar{\theta}_f - \bar{\theta}_m)^2 \sum_{i=1}^{n} (\bar{\theta}_{mi} - \bar{\theta}_{mi})^2}},$$  \hspace{1cm} (13)

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n} (\theta_f - \theta_{mi})^2}{\sum_{i=1}^{n} (\theta_f - \bar{\theta}_f)^2},$$  \hspace{1cm} (14)

$$\text{MBE} = n^{-1} \sum_{i=1}^{n} e_i = \bar{\theta}_{mi} - \bar{\theta}_f,$$  \hspace{1cm} (15)

where $n$ is the number of observations, $\theta_f$, $\theta_{mi}$ the field-observed and model-predicted values, $\bar{\theta}_f$, $\bar{\theta}_{mi}$ the field-observed and model-predicted average values.

**Results and discussion**

The efficacy of O-R model in simulating soil moisture dynamics in the CRZ is investigated through qualitative and quantitative evaluation. The qualitative evaluation is performed through graphical comparisons between field-observed and model predicted values. The quantitative evaluation is based on model performance indicators as explained earlier. The parameters considered for evaluation are percentage soil moisture depletion within two wetting events, soil moisture profile along depth for a particular time and soil moisture variation throughout the crop period at different depths.

**Non-linear parameter computation**

The parameter $\beta$ in the O-R model characterizes the non-linearity in RWU, and determines the type of irrigation and fertilizer application activities that would be most efficient in terms of plant use. The empirical equation (eq. (9)) was used to compute the values of $\beta$ for maize, wheat and Indian mustard in all three agro-climates. Table 4 shows the detail of parameters used in $\beta$ calculation.

**Depletion of soil moisture at different depth**

Soil moisture depletion (SMD) determined from the CRZ of maize, wheat and Indian mustard for LS-1, LS-2 and LS-3 were used to analyse the moisture uptake efficacy of the model. Comparison of model-predicted SMD values in the CRZ with field-observed values for maize, wheat and Indian mustard for the three agro-climates were plotted.

The comparison for maize for different locations is shown in Figure 7, whereas for wheat it is shown in Figure 8. The model-predicted values are found to have reliable agreement with field-observed values for three different agro-climates.

The quantitative evaluation between the field-observed and model-predicted SMD in the CRZ was carried out using model performance indicators, and the results of the evaluation are summarized in Table 5. The $R^2$ values for maize, wheat and Indian mustard at Hamirpur ranged between 0.65 and 0.71, 0.70 and 0.75 and 0.69 and 0.73 respectively. For Roorkee and Solan, it ranged from 0.65 to 0.71 (maize); 0.67 to 0.73 (wheat); 0.69 to 0.72 (Indian mustard) and 0.68 to 0.73 (maize); 0.66 to 0.74 (wheat); 0.68 to 0.72 (Indian mustard) respectively. The NSE values were, maize: 0.69–0.73, wheat: 0.70–0.73 and Indian mustard: 0.72–0.74 at Hamirpur, whereas for Roorkee and Solan, it was 0.67–0.70 (maize); 0.68–0.74 (wheat); 0.70–0.74 (Indian mustard) and 0.68–0.72 (maize); 0.66–0.73 (wheat); 0.69–0.73 (Indian mustard) respectively.
Table 4. Optimal non-linearity coefficients for maize, wheat and Indian mustard for LS-3

| Crop              | $T_{\text{max}}$ (mm day$^{-1}$) | $Z_{\text{max}}$ (m) | $t_{\text{peak}}$ (days) | Specific transpiration ($T_s$) | $\beta$ |
|-------------------|----------------------------------|----------------------|--------------------------|------------------------------|---------|
| Maize             | 6.06                             | 0.92                 | 72                       | 0.474                        | 1.40    |
| Wheat             | 3.86                             | 0.96                 | 91                       | 0.366                        | 1.60    |
| Indian mustard    | 1.8                              | 0.65                 | 70                       | 0.194                        | 2.16    |

The MBE values were, maize: $-0.11$ to $0.15$, wheat: $-0.15$ to $0.14$ and Indian mustard: $-0.14$ to $0.18$ at Hamirpur whereas for Roorkee and Solan, it was $-0.13$ to $0.17$ (maize); $-0.19$ to $0.16$ (wheat); $-0.14$ to $0.13$ (Indian mustard) and $-0.14$ to $0.16$ (maize); $-0.15$ to $0.17$ (wheat); $-0.14$ to $0.12$ (Indian mustard) respectively. Error statistics of model-predicted and field-observed SMD at different stages of growth period for various crops showed good agreement for three different agroclimates.
It is evident from Figures 7 and 8 and error statistics range discussed above that the differences between model-predicted and field-observed SMD values in the middle layers are less pronounced. In active root zone of the crops, based on the observation from the model-predicted SMD patterns, the model underestimates the SMD in the top layers and overestimates the moisture depletion in bottom layers. However, it is notable that this tendency significantly diminishes in the durations falling in the development and mid-season crop stages. Both these stages are important from the point of precise estimation of crop water requirement.

**Soil moisture profile in crop root zone**

The comparison of model-predicted and field-observed soil moisture profiles in the CRZ establishes the existence of non-linearity in RWU. For brevity, field-observed and model-predicted soil moisture profiles in the root zone at discrete times in the crop period were plotted for maize, wheat and Indian mustard for the considered agro-climates. Figures 9–12 illustrate the pattern of soil moisture variation in the root zone on particular days for maize and wheat respectively, well establishes the existence of non-linearity in RWU and confirms the qualitative agreement between field-observed and model-predicted profiles.

For Roorkee, the error statistics for maize is in the range of; $R^2$: 0.65 to 0.69, NSE: 0.68 to 0.72, MBE: −0.18 to 0.13, for wheat; $R^2$: 0.66 to 0.72, NSE: 0.67 to 0.71 and MBE: −0.17 to 0.14 and for Indian mustard; $R^2$: 0.66 to 0.69 and MBE: −0.15 to 0.14. For Solan, the error statistics in case of maize follow the range; $R^2$: 0.66 to 0.71, NSE: 0.67 to 0.73 and MBE: −0.14 to 0.13 and in case of wheat follow the range; $R^2$: 0.66 to 0.71, NSE: 0.65 to 0.71 and MBE: −0.15 to 0.15. For Hamirpur, the error statistics for maize; $R^2$: 0.69 to 0.73, NSE: 0.68 to 0.73 and MBE: −0.19 to 0.13, for wheat; $R^2$: 0.67 to 0.71, NSE: 0.65 to 0.69 and MBE: −0.15 to 0.14.

### Table 5. Error Statistics of soil moisture depletion at different times of growth period for maize, wheat and Indian mustard

| Location       | Roorkee   | Solan     | Hamirpur  |
|----------------|-----------|-----------|-----------|
|                | Period (DAS) | $R^2$ | NSE | MBE | Period (DAS) | $R^2$ | NSE | MBE | Period (DAS) | $R^2$ | NSE | MBE |
| Maize          |            |         |      |     |            |         |      |     |            |         |      |     |
|                | 25–32      | 0.65    | 0.67 | −0.13 | 23–35      | 0.67    | 0.73 | −0.11 |
|                | 34–41      | 0.66    | 0.69 | 0.14  | 37–47      | 0.65    | 0.69 | 0.13  |
|                | 43–50      | 0.71    | 0.70 | 0.17  | 49–63      | 0.71    | 0.72 | 0.15  |
| Wheat          |            |         |      |     |            |         |      |     |            |         |      |     |
|                | 26–41      | 0.67    | 0.68 | 0.14  | 27–43      | 0.70    | 0.71 | 0.14  |
|                | 57–72      | 0.68    | 0.71 | 0.16  | 45–55      | 0.73    | 0.73 | 0.13  |
|                | 97–105     | 0.73    | 0.74 | −0.19 | 57–79      | 0.75    | 0.70 | −0.15 |
| Indian mustard |            |         |      |     |            |         |      |     |            |         |      |     |
|                | 24–42      | 0.72    | 0.70 | 0.13  | 32–46      | 0.69    | 0.72 | 0.18  |
|                | 65–84      | 0.69    | 0.74 | −0.14 | 52–70      | 0.73    | 0.74 | −0.14 |

$R^2$, coefficient of determination; NSE, Nash–Sutcliffe efficiency; MBE, Mean bias error.
Field-observed and model-predicted soil moisture status for the entire crop period for maize at 60 cm depth for different agro-climate zones. The $R^2$ and NSE values are found above 0.65, which shows the good agreement between model-predicted and field-observed profiles, referring to the satisfactory consideration of O-R model for practical applications in various agro-climates. Also, the range of MBE values in the three agro-climates is low. Hence all three agro-climates considered in this study, gave satisfactory results.

Soil moisture status at various root zone depths

Soil moisture variation at different depths of CRZ elaborates the accessibility of moisture for plant moisture uptake which indicates the part of CRZ, most susceptible to moisture depletion. The moisture status at various root zone depths at which soil moisture measurement sensors were embedded was compared with the corresponding model-predicted soil moisture status of maize, wheat and Indian mustard for three agro-climates. Generally, in the upper parts of the root zone having high root density, moisture depletes comparatively faster than deeper parts of the root zone. The model-predicted and field-observed soil moisture variation for 60 and 30 cm depths of maize and wheat respectively are shown in Figures 13 and 14. It is evident from Figures 13 and 14 that model-predicted soil moisture variation at a particular depth throughout the crop period shows good agreement with the field-observed soil moisture content values during the crop period of both crops for three agro-climates. Table 6 shows the comparative error statistics for model-predicted and field-observed values. The $R^2$ value for various root zone depths were above 0.65 which depicts good agreement between model-predicted and field-observed values. It was observed that the other two performance parameters, NSE and MBE gave satisfactory values too. These observations on the values of statistical parameters $R^2$, NSE, and MBE for the soil moisture status at particular depth for three agro-climates indicate that the non-linearity of RWU is well predicted using O-R model.
Figure 14. Field-observed and model-predicted soil moisture status for the entire crop period for wheat at 30 cm depth for different agro-climate zones.

Table 6. Comparison of field observed and model-predicted error statistics for soil moisture status at different depths of maize and wheat and mustard for different agro climatic zone

| Location      | Crop name | Soil depth | R² | NSE | MBE | R² | NSE | MBE | R² | NSE | MBE |
|---------------|-----------|------------|----|-----|-----|----|-----|-----|----|-----|-----|
| Roorkee       | Maize     | 0–0.2      | 0.68 | 0.66 | -0.15 | 0.67 | 0.66 | 0.23 | 0.67 | 0.65 | 0.19 |
|               |           | 0.2–0.4    | 0.70 | 0.68 | -0.19 | 0.70 | 0.69 | 0.14 | 0.65 | 0.67 | 0.16 |
|               |           | 0.4–0.6    | 0.72 | 0.69 | 0.16  | 0.72 | 0.68 | 0.13 | 0.69 | 0.66 | 0.14 |
|               |           | 0.6–0.8    | 0.73 | 0.72 | 0.15  | 0.70 | 0.71 | 0.14 | 0.70 | 0.69 | 0.15 |
|               | Wheat     | 0–0.2      | 0.68 | 0.67 | -0.14 | 0.65 | 0.67 | 0.18 | 0.66 | 0.67 | 0.16 |
|               |           | 0.2–0.4    | 0.70 | 0.69 | -0.16 | 0.69 | 0.66 | 0.14 | 0.67 | 0.71 | 0.21 |
|               |           | 0.4–0.6    | 0.67 | 0.66 | 0.14  | 0.71 | 0.69 | 0.16 | 0.69 | 0.72 | 0.237|
|               |           | 0.6–0.8    | 0.72 | 0.71 | 0.17  | 0.69 | 0.70 | 0.15 | 0.70 | 0.69 | 0.143|
|               | Indian mustard | 0–0.2 | 0.66 | 0.67 | -0.21 | 0.68 | 0.66 | 0.23 | 0.67 | 0.65 | 0.13 |
|               |           | 0.2–0.4    | 0.67 | 0.66 | 0.23  | 0.67 | 0.69 | 0.19 | 0.69 | 0.68 | 0.15 |
|               |           | 0.4–0.6    | 0.68 | 0.65 | 0.14  | 0.70 | 0.67 | 0.16 | 0.73 | 0.72 | 0.19 |

Conclusion

In present study, the moisture prediction efficiency of non-linear O-R model was evaluated for semi-arid (Roorkee), sub-temperate sub-humid (Solan) and humid sub-tropical (Hamirpur) agro-climates. A numerical code was developed for computing RWU and simulating soil moisture dynamics in the CRZ. Field crop experiments on maize, wheat and Indian mustard were performed in humid sub-tropical agro-climate and secondary data for other two agro-climates were considered. Graphical comparisons and error statistics provide reliable agreement between percentage SMD (between two wetting events), soil moisture profile (along depth) and soil moisture variation.
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