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ORIGINAL ARTICLE

Investigating the effect of limited climatic data on evapotranspiration-based numerical modeling of soil moisture dynamics in the unsaturated root zone: a case study for potato crop

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Abstract

Root water uptake (RWU)-based numerical modeling was employed for simulating the moisture dynamics in the unsaturated root zone of potato (*Solanum Tuberosum L.*) crop, wherein crop evapotranspiration (ET_c) is an important input parameter. Richard's equation incorporating a nonlinear RWU model was considered in the study. Reference evapotranspiration (ET_0) was computed using full climatic data (combination-based methods) and limited climatic data (radiation, temperature and pan-evaporation-based methods). The crop coefficients (K_c) during different stages of the crop growth were adjusted for the local agro-climate (humid subtropical) following the FAO-56 K_c modification procedure. ET_c estimated from different ET_0 methods using the FAO-56 crop coefficient approach was compared with the field ET_c obtained through the water balance approach. The methods Penman–Monteith (PEN–M) (combination-based), FAO-24 radiation (RAD) (radiation-based), Hargreaves-Samani (HAR) (temperature-based) and Snyder (SD) (pan-evaporation based) performed better in their respective categories. Soil moisture values simulated using the numerical model (considering ET_c computed from PEN-M, HAR, RAD and SD) were graphically and statistically compared with the field observed soil moisture. Results indicate that a field soil moisture depletion of 30% corresponds to the simulated soil moisture depletion of 15%, 25%, 28% and 40%, based on ET_c inputs from SD, HAR, PEN-M and RAD, respectively. The results augment the investigations on the influence of limited climatic data on the simulated irrigation schedules of the potato crop. The study has significance in effective irrigation scheduling in water deficit areas having different scenarios of climatic data availability.

Keywords Crop coefficient · Soil moisture · Water balance · Evapotranspiration · Irrigation

Introduction

After maize, wheat and rice, potato ranks fourth in terms of global production (Bruinsma 2017). Potato (*Solanum Tuberosum L.*) crop is extremely sensitive to the deficit or surplus moisture and requires an optimum amount of irrigation at frequent intervals for its proper growth (Van Loon 1981; Doorenbos and Kassam 1986; Kashyap and Panda 2003). In water-scarce areas, frequent irrigation to the crops is difficult owing to the stressed water resources and increased demand for other purposes. This necessitates an improvement in the water use efficiency to fulfill the water requirement of the crops (Satchithanantham et al. 2014; Poddar et al. 2018b). Several investigators used the water balance approach to study the crop water requirements, soil moisture dynamics, crop coefficients and irrigation schedules for potato crop (Curwen and Massie 1984; Vitosh 1984; Kashyap and Panda 2001; Yuan et al. 2003; Stalham and Allen 2004; Kumar et al. 2020). Climatic variables, i.e., radiation, temperature, humidity, wind speed and precipitation have been used to develop a model for simulating the soil moisture depletion in root zone of potato crop (Singh et al. 1993). Geremew et al. (2008) compared traditional and scientific methods for scheduling irrigation in potato and

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concluded that the traditional methods did not meet the crop water requirements to obtain the acceptable yield.

The effective way of scheduling irrigation necessitates a proper understanding of moisture uptake by the roots and variation of the moisture in the unsaturated crop root zone (Shankar et al. 2017; Goel et al. 2019). The root water uptake (RWU) and soil moisture dynamics are complex processes. Field investigations and estimation of the parameters involved in these processes require expensive instrumentation (Kumar et al. 2019). Hence, numerical modeling is generally employed for studying such processes (Feddes et al. 1988; Šimunek and Hopmans 2009). The approach involves numerical simulation of the soil moisture flow equation containing a sink term representing RWU (Richards 1931; Govindraju et al. 1992). Numerous RWU models considering different root moisture extraction patterns, i.e., constant (Feddes and Zaradny 1978), linear (Molz and Remson 1970; Prasad 1988), nonlinear (Ojha and Rai 1996) and exponential (Li et al. 1999; Kang et al. 2001) are available in the literature. The efficacy of the RWU-based numerical model for simulating the dynamics of soil moisture in the root zone of different crops was investigated previously (Shankar et al. 2012; Kumar et al. 2013a). RWU-based numerical modeling has been utilized for scheduling irrigation events of the potato crop (Poddar et al. 2018b).

Sensitivity analysis of the model parameters involved in the numerical simulation indicated that the simulated soil moisture is highly sensitive to the RWU parameters (Kumar et al. 2013b). It has been observed that, in nearly all the models, RWU is primarily governed by plant transpiration and root depth. The root depth can be determined using field methods, but the estimation of actual transpiration from the plant is difficult, and usually expressed as a partitioned component of crop evapotranspiration (Ritchie 1972; Belmans et al. 1983).

Crop evapotranspiration (ET_c) represents the evaporation and the transpiration occurring through a soil-crop-air system. ET_c changes with the variation in the crop canopy and the meteorological conditions. ET_c is estimated by conducting water balance studies using a lysimeter, which is expensive and involves extensive data computations (Kosugi and Katsuyama 2004; Shankar 2007; Devatha et al. 2016). An alternate and widely accepted method for estimating ET_c is the FAO-56 crop coefficient approach, in which ET_c is computed as a product of the crop coefficient (K_c) and the reference evapotranspiration (ET_0) (Allen et al. 1998).

ET_0 is the evapotranspiration rate from a well-watered, disease-free reference crop growing under the optimal conditions (Pereira et al. 2015). Several investigators developed methods for ET_0 estimation, which include the methods based on temperature, radiation, evaporation and combination of all (Samani 2000; Irmak et al. 2003; Paredes and Pereira 2019). The precise estimation of ET_0 is governed by the availability of quality climatic data. Generally, the combination type methods are found to give better results when compared with the lysimetric data (Kashyap and Panda 2001; Hargreaves and Allen 2003; Itenfisu et al. 2003; Cai et al. 2007); however, if only limited climatic data are available, other methods are employed to estimate the ET_0 (Koudahe et al. 2018; Yirga 2019). Before using any particular ET_0 method, its performance must be evaluated for the local agro-climate (Nandagiri and Kovoor 2006; Tabari et al. 2013; Poddar et al. 2018a). The standard values of K_c for various crops are given by Allen et al. (1998); however, a local calibration of the K_c values is essential before utilizing them for estimating ET_c (Shankar et al. 2009).

The accuracy and reliability of the ET_0 depend on the climatic data availability, which is a major concern in most of the regions worldwide. The present study area is characterized by a hilly terrain, where scarce availability of the quality climatic data and costly augmentation of the irrigation facilities hinder the optimal supply of irrigation water. Potato being a major cash crop in the area, the present study is focused on optimal water application to potato crop through the soil moisture simulation and efficient irrigation scheduling through RWU-based numerical modeling, considering the crop, soil and climatic variables. The effect of climatic data availability is incorporated in the numerical model by computing ET_c values using the FAO-56 crop coefficient approach based on full climatic data (combination type methods) and limited climatic data (radiation, temperature and pan-evaporation methods). The objectives of the study are:

(i) To evaluate the performance of ET_0 methods in different scenarios of climatic data availability based on a comparative analysis between empirical (crop coefficient approach) and field observed (water balance approach), ET_c.
(ii) To simulate the soil moisture dynamics using a numerical model, considering empirical ET_c computed from the best performing ET_0 method in each category of climatic data.
(iii) To study the influence of limited climatic data on the irrigation schedule of the potato crop obtained using the numerical model.

Materials and methods

Details of experimental station and climatic data

Field experiments were conducted in the agricultural experimental station of the National Institute of Technology Hamirpur, Himachal Pradesh (India) from 2014 to 2017. The co-ordinates of the experimental station are 31°42′32″

N latitude and 76°31′36″ E longitude, and the mean elevation is 872 m. The agro-climate of study area is humid subtropical and falls under the western Himalayan region. The climatic variables were monitored daily by an all-weather station located at the agricultural experimental station. Daily evaporation was measured using a Class A evaporation pan installed in an open space near the experimental station. Table 1 summarizes the details of climatic parameters recorded during the study period.

Field experiments were performed to estimate the crop evapotranspiration (ET_c) and observe the soil moisture in the unsaturated crop root zone. Field ET_c values were estimated by conducting water balance study using the lysimeters. For this purpose, two drainage lysimeters were installed in the experimental plot. The dimensions of the lysimeters were 1.5 m × 1.5 m × 2 m. The lysimeter rim was kept 0.10 m above the ground level to prevent surface runoff. A 0.3-m-thick filter arrangement was provided at the bottom of the lysimeter to facilitate the collection of the percolated water through drains ($\phi = 0.04$ m) in a calibrated bucket. An elevated water tank was used to provide irrigation to the field in measured amounts using water hose (surface irrigation) with a meter installed at the inlet. The irrigation was supplied at a moisture depletion of 30%. The soil moisture was recorded at every 0.1 m (max. depth 1.6 m) with a soil moisture capacitance probe (M/S Sentek Sensor Technologies, Australia).

Details of crop and soil parameters

Potato (*Solanum Tuberosum* L.) was uniformly grown in the lysimeters and the surrounding field during the crop season (January–May). The experiments were conducted in 2014 and repeated in 2015, 2016 and 2017. The entire crop duration was divided into initial, crop development, mid-season and late-season stages (Doorenbos and Pruitt 1977). Table 2 gives the details of the growth stages and the irrigation events for potato during each repetition. The irrigation was provided at a soil moisture depletion of 30%.

The soil texture was classified based on the USDA classification system, which involved a detailed particle size analysis using a set of standard sieves and a calibrated hydrometer (Trout et al. 1982). Results of the sieve and hydrometer analysis indicated the soil texture to be sandy loam with the percentages of sand, silt and clay equal to 54.98, 23.83 and 21.19 respectively. The saturated hydraulic conductivity (K_s) was estimated using an automated dual-head infiltrometer (Meter Group Inc., USA). A pressure plate apparatus (Soil Moisture Equipment Corp., USA) was used to measure the corresponding soil moisture and matric potential values for the determination of soil moisture characteristics (SMC) curve. The SMC was well described by the Van Genuchten model (Van Genuchten 1980). The values of soil hydraulic parameters α_v, n_v, K_s, θ_r and θ_s were 5.9 m^{-1}, 1.83, 2.96 cm h^{-1}, 0.056 cm^3 cm^{-3} and 0.36 cm^3 cm^{-3}, respectively. Experimentally obtained field capacity (θ_{fc}) and permanent wilting point (θ_{pwp}) using the pressure plate apparatus were 0.22 cm^3 cm^{-3} and 0.07 cm^3 cm^{-3}, respectively.

Three relevant crop parameters, i.e., leaf area index (LAI), root depth (R_d) and plant height (H_p) were obtained at regular intervals during the crop period. The trench profile method was employed to determine the root depth (Boehm 1979). Plant height was measured using a measuring tape. LAI was measured using a plant canopy analyzer (LAI-2200C, LI-COR Biosciences, Lincoln USA). Figure 1 shows the variation of LAI, R_d and H_p with the days after sowing (DAS) the crop. The values shown in Fig. 1 are the mean of four cropping seasons.

Evapotranspiration

The evapotranspiration which represents plant transpiration (T_p) and soil evaporation (E_s) occurring simultaneously from a vegetative surface depends on several meteorological (humidity, radiation, wind speed, temperature) and crop (type and growth stage) parameters.

Computation of reference evapotranspiration

The methods for computing reference evapotranspiration (ET_0) are mentioned in Table 3. Present study employs thirteen ET_0 methods which are classified based on the full

Table 1 Monthly average of meteorological parameters for the study period (2014-2017)

Month	T_{max} (°C)	T_{min} (°C)	T_{mean} (°C)	P (mm)	RH (%)	U (ms^{-1})	R_s (MJ m^{-2} day^{-1})	E_{pan} (mm day^{-1})
January	18.03	4.09	9.13	73.03	58.43	1.23	7.73	1.59
February	19.89	4.41	10.49	15.54	62.03	1.45	10.03	2.48
March	26.84	8.94	15.21	14.65	51.64	2.06	13.87	2.88
April	35.89	14.54	21.21	42.43	48.87	2.32	18.11	5.61
May	38.71	17.32	27.77	16.54	31.21	2.56	20.13	7.02

T_{max}, T_{min} and T_{mean} are maximum, minimum and mean air temperatures, respectively; P is precipitation; RH is relative humidity; U is wind speed; R_s is solar radiation; E_{pan} is pan evaporation

Table 2 Details of the growth stages, crop duration and irrigation events for potato crop

Crop	Variety sown	Date of sowing	Date of harvesting	Duration (days)	Growth stages (days)				Irrigation provided (day)	Spacing (cm)
					I	II	III	IV		
Potato (*Solanum tuberosum* L.)	Kufri Himsona	January 25th, 2014	May 24th, 2014	120	24	32	35	30	22nd, 42nd, 54th, 65th, 88th and 104th	45 × 20
		January 24th, 2015	May 27th, 2015	124	25	32	35	32	19th, 38th, 55th, 68th, 92nd and 108th	45 × 20
		January 29th, 2016	May 27th, 2016	120	25	30	36	30	20th, 40th, 56th, 68th, 90nd and 108th	45 × 20
		January 25th, 2017	May 28th, 2017	124	24	32	38	30	22nd, 38th, 54th, 66th, 88th and 106th	45 × 20

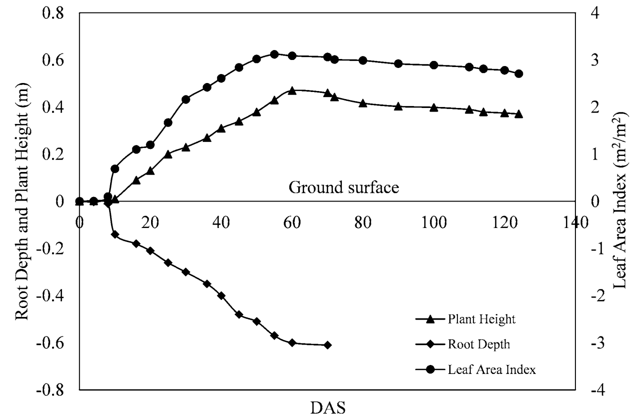

Fig. 1 Mean variation of crop parameters during the growth period of potato

climate data (combination-based methods) and limited climate data (temperature, solar radiation and pan-evaporation based). A thorough description of these methods can be referred to in the publications cited in Table 3.

Crop coefficients calibration

A crop coefficient (K_c) represents the crop-specific water use and is necessary for estimating ET_c using the crop coefficient approach. K_c for a crop varies throughout the growing season, is governed predominantly by the crop parameters, and to a limited extent by the climatic parameters (Allen et al. 1998). A comprehensive list of K_c values for various crops under different growth stages is provided in FAO-56 (Allen et al. 1998).

FAO-56 outlines the numerical procedure for modification of the K_c values for local agro-climatic conditions. Modification of initial stage K_c ($K_{c\ ini}$) considers the magnitude of the wetting events, the duration between the wetting events and the evaporative power of the atmosphere. The modification procedure of mid-season K_c ($K_{c\ mid}$) and end-season K_c ($K_{c\ end}$) involves climatic parameters (relative humidity and wind speed) and plant height. The daily K_c during development and late-season stages is computed using a graphical linear interpolation technique. In the present study, the following equations are used to modify $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ values.

$$K_{cini} = K_{cini(FAO)} + \frac{(I - 10)}{(40 - 10)}\left[K_{cini\ (heavywetting)} - K_{cini\ (lightwetting)}\right] \tag{1}$$

$$K_{cmid/end} = K_{cmid/end(FAO)} + \left[0.04\left(u_2 - 2\right) - 0.004\left(\mathrm{RH}_{\min} - 45\right)\right]\left(\frac{h}{3}\right)^{0.3} \tag{2}$$

Table 3 Different reference evapotranspiration computation methods and governing equations

Type	Method	Equation	Acronym	References
Combination-type methods (*full climate data*)	FAO-56 Penman–Monteith	$\mathrm{ET}_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u(e_s - e_0)}{\Delta + \gamma(1 + 0.34u)}$	PEN-M	Allen et al. (1998)
	FAO-24 corrected penman	$\mathrm{ET}_0 = c\left[\mathrm{WR}_n' + (1 - W)0.27(1 + 0.01U)(e_a - e_d)\right]$	C-PEN	Doorenbos and Pruitt (1977)
Radiation-based methods (*limited climate data*)	FAO-24 radiation	$\mathrm{ET}_0 = C(\mathrm{WR}_s)$	RAD	Doorenbos and Pruitt (1977)
	Priestley-Taylor	$\mathrm{ET}_0 = \beta \frac{\Delta}{\Delta+\gamma}(R_n')$	PT	Priestley and Taylor (1972)
	Turc	$\mathrm{ET}_0 = 0.31\left(\frac{\overline{T}}{\overline{T}+15}\right)(R_s' + 2.09)\left(1 + \frac{50 - \mathrm{RH}_{\mathrm{mean}}}{70}\right)$ $\mathrm{ET}_0 = 0.31\left(\frac{\overline{T}}{\overline{T}+15}\right)(R_s' + 2.09)$	TC	Turc (1961)
Temperature-based methods (*Limited climate data*)	Hargreaves-Samani	$\mathrm{ET}_0 = 0.0023(\overline{T} + 17.8)(T_{\max} - T_{\min})^{0.5} R_a'$	HAR	Hargreaves and Samani (1985)
	Blaney and Criddle	$\mathrm{ET}_0 = a_b + b_b\left[p(0.46\overline{T} + 8.13)\right]$	BC	Blaney and Criddle (1950)
	Thornthwaite	$\mathrm{ET}_0 = 16\left(10\frac{\overline{T}}{I}\right)^a$	TH	Thornthwaite (1948)
Pan-evaporation-based methods (*limited climate data*)	Frevert	$\mathrm{ET}_0 = \begin{pmatrix} 0.475 - (2.4 \times 10^{-4} \times U) + (5.16 \times 10^{-3} \times \mathrm{RH}) \\ +(1.18 \times 10^{-3} \times F) - (1.6 \times 10^{-5} \times \mathrm{RH}^2) - (1.01 \times 10^{-6} \times F^2) \\ -(8 \times 10^{-9} \times \mathrm{RH}^2 \times U) - (1 \times 10^{-8} \times \mathrm{RH}^2 \times F) \end{pmatrix} \times E_{\mathrm{pan}}$	FV	Frevert et al. (1983) and Cuenca (1989)
	Allen and Pruitt	$\mathrm{ET}_0 = \begin{pmatrix} 0.108 - (3.1 \times 10^{-4} \times U) + (14.34 \times 10^{-2} \times \ln \mathrm{RH}) + \\ (4.22 \times 10^{-2} \times \ln F) - (6.3 \times 10^{-4} \times \ln F^2 \times \ln \mathrm{RH}) \end{pmatrix} \times E_{\mathrm{pan}}$	AP	Allen and Pruitt (1991)
	Snyder	$\mathrm{ET}_0 = \begin{pmatrix} 0.482 - (3.76 \times 10^{-4} \times U) + (4.5 \times 10^{-3} \times \mathrm{RH}) + \\ (2.4 \times 10^{-2} \times \ln F) \end{pmatrix} \times E_{\mathrm{pan}}$	SD	Snyder (1992)
	Modified Snyder	$\mathrm{ET}_0 = \begin{pmatrix} 0.5321 - (3.21 \times 10^{-4} \times U) + (2.5 \times 10^{-3} \times \mathrm{RH}) + \\ (2.49 \times 10^{-2} \times \ln F) \end{pmatrix} \times E_{\mathrm{pan}}$	MS	Grismer et al. (2002)
	Orang	$\mathrm{ET}_0 = \begin{pmatrix} 0.51206 - (3.21 \times 10^{-4} \times U) + (2.889 \times 10^{-3} \times \mathrm{RH}) + \\ (31.886 \times 10^{-3} \times \ln F) - (1.07 \times 10^{-4} \times \mathrm{RH} \times \ln F) \end{pmatrix} \times E_{\mathrm{pan}}$	OG	Orang (1998)

where I is the average infiltration depth (mm); RH_{min} is the mean daily minimum relative humidity (%); u_2 is the mean daily wind speed at 2 m height (m s^{-1}); and h is the mean plant height (m) during the corresponding crop growth stage (Fig. 1). Subscripts FAO, light wetting and heavy wetting represent the FAO recommended value, $K_{c\ ini}$ obtained from the FAO-curve corresponding to the light wetting and $K_{c\ ini}$ obtained from FAO-curve corresponding to heavy wetting.

Crop evapotranspiration

Empirical ET_c (crop coefficient approach) The empirical ET_c was calculated as the product of ET_0 and the corresponding value of K_c (Eq. 3). This approach is independent of the field crop experiments for computing ET_c values.

$$ET_c = K_c \times ET_0 \tag{3}$$

The daily ET_0 value computed from the 13 methods considered in the present study was multiplied with the corresponding daily K_c value. The performance of the methods under different scenarios of climatic data availability was evaluated before their implementation in the numerical model. This evaluation was based on a qualitative and quantitative comparison with field ET_c obtained from water balance studies. Daily empirical ET_c thus obtained was converted into seasonal empirical ET_c for comparison with the field ET_c.

Field ET_c (water balance approach) Field crop experiments using the lysimeters were conducted to estimate the field ET_c. The change in the soil moisture at different depths in the lysimeter was measured using the capacitance probe. The percolation to the groundwater was represented by drainage from the lysimeter. Field ET_c was computed using the following water balance equation (Bandyopadhyay and Mallick 2003),

$$ET_c = I + P - RO - D \pm \Delta S \tag{4}$$

where P = Precipitation in mm (recorded daily); I = Irrigation in mm (recorded when applied); D = Drainage from the lysimeter in mm (recorded weekly); RO = Runoff in mm; and ΔS = Change in soil moisture storage in mm (recorded daily). The change in the soil moisture for a specific period at a specific depth (d_z) was computed as:

$$\left(\Delta S_z\right) = \left(\theta_{z,\text{final}} - \theta_{z,\text{initial}}\right) \times d_z \tag{5}$$

where $\theta_{z,\ \text{initial}}$ and $\theta_{z,\ \text{final}}$ are the initial and final water content in the soil profile in a discrete-time interval.

Partitioning of crop evapotranspiration

The estimation of plant transpiration is imperative for modeling the RWU through the active crop root zone. There exists a considerable interaction between soil evaporation and plant transpiration which is governed by the changing plant cover (Stanhill 1973). E_s and T_p are generally obtained as the partitioned components of the ET_c using various numerical relationships (Campbell and Norman 1998; Merta 2002; Liu et al. 2002; Zhang et al. 2004; Eberbach and Pala 2005). The relationship proposed by Eberbach and Pala (2005) was used in the present study (Eq. 6). The values of E_s and T_p thus obtained were used as inputs to the numerical model.

$$\frac{E_s}{ET_c} = e^{(-0.39\times \text{LAI})} \tag{6}$$

Numerical model

The numerical model is based on the solution of the soil moisture flow equation and involves a set of governing equations comprising constitutive relationships, relevant boundary conditions and a RWU model.

Governing equations

The Richards equation (Richards 1931) assimilates the mechanism of moisture redistribution within a soil. The mixed form of the Richards equation (Eq. 7) governing water flow in an unsaturated crop root zone incorporating a sink term is given by (Celia et al. 1990):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[\left(\frac{\partial \psi}{\partial z} + 1\right)K(\psi)\right] - S(z,t) \tag{7}$$

where θ is the volumetric soil moisture content (mm^3 mm^{-3}); t represents time; ψ is the pressure head (m); z represents the vertical coordinate (negative upwards); k is the hydraulic conductivity (m day^{-1}); S (z, t) represents the root water uptake expressed as volume of water per unit volume of soil per unit time.

Constitutive relations

Van Genuchten's (1980) $\theta - \psi$ and $K - \theta$ constitutive relationships are used in the present study to obtain the solution for Eq. (7), which are as follows:

$$\Theta = \left[\frac{1}{1 + \alpha_v \psi^{n_v}}\right]^m = 1 \quad \text{for}\psi 0, \tag{8}$$

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad \text{for}\ \psi > 0 \tag{9}$$

$$\begin{aligned} K &= K_s \Theta^{1/2}[1 - (1 - \Theta^{1/m})^m]^2 && \text{for}\ \psi < 0 \\ K &= K_s && \text{for}\ \psi \geq 0 \end{aligned} \tag{10}$$

where α_v and n_v are the unsaturated soil hydraulic parameters; m is given by $1-(1/n_v)$; Θ is defined as the effective saturation, θ_s is the saturated moisture content (mm^3 mm^{-3}), θ_r is the residual moisture content of the soil (mm^3 mm^{-3}) and K_s represents the saturated hydraulic conductivity of the soil.

Initial and boundary conditions

In the present study, the initial condition of the solution domain, i.e., soil profile, is the measured value of pressure heads in the field.

$$\psi = \psi_{\text{measured}}(z) \quad \text{for } 0 \le z \le L, \quad t = 0 \tag{11}$$

where $\psi_{\text{measured}}(z)$ represents the measured pressure head in the field and L represents the length of solution domain.

The upper boundary condition is a flux-type boundary that accounts soil evaporation (E_s), taking place from the topsoil and a Dirichlet-type boundary during irrigation/rainfall, i.e.,

$$\psi = \psi_{i/r} \quad \text{z} = \text{L, during irrigation / rainfall}$$
$$-K(\psi)\left(\frac{\partial\psi}{\partial z} + 1\right) = E_s \quad \text{z} = \text{L, in absence of irrigation} \tag{12}$$

where $\psi_{i/r}$ represents the pressure head corresponding to saturated moisture content, prevalent during irrigation or rainfall and E_s is the soil evaporation.

The lower boundary condition is a gravity drainage type since water table is present at a considerably deeper depth compared to the root zone, i.e.,

$$-K(\psi)\left(\frac{\partial\psi}{\partial z} + 1\right) = -K(\psi) \quad \begin{matrix} z = 0, \text{ free drainage} \\ t \ge 0, \end{matrix} \tag{13}$$

Root water uptake model

In the present study, the nonlinear O–R model (Ojha et al. 2009) was used as the RWU model because the model can incorporate the crop-specific nonlinearity in the moisture uptake (Kumar et al. 2015). The model performed better than linear, constant and exponential RWU models (Ojha et al. 2009). The mathematical expression for the potential soil water extraction, i.e., O–R model, is given as,

$$S_{\max} = \left[\frac{T_{pj}}{z_{rj}}(\beta+1)\left(1-\frac{z}{z_{rj}}\right)^{\beta}\right] \quad \text{For } 0 \le z \le z_{rj} \tag{14}$$

where β is the model parameter; T_{pj} is the transpiration on the jth day; z represents the depth below soil surface; z_{rj} is the root depth on the jth day.

The crop-specific nonlinearity model parameter 'β' is computed using an empirical relationship (Eq. 15) developed by Shankar et al. (2012). The relationship is based on a non-dimensional parameter called specific transpiration 'T_s'.

$$\beta = 5.1128T_s^2 - 6.117T_s + 3.1545$$
$$T_s = \frac{T_{pj}\max}{Z_r\max \times t_{\text{peak}}} \quad \text{For} \quad 0.07 \le T_s \le 0.98 \tag{15}$$

where $T_{\text{pj max}}$ is the maximum daily transpiration; $Z_{\text{r max}}$, the maximum root depth; and t_{peak} the time to attain peak transpiration.

Numerical simulation

A code was written in FORTRAN-95 programming language to implement the numerical model. The soil moisture flow equation incorporating the sink term, i.e., O–R model, subjected to initial and boundary conditions is solved using the numerical model. The constitutive relationships described above are used for converting pressure head values into corresponding moisture content values. The numerical model is based on a fully implicit, mass conservative, central finite difference scheme proposed by Celia et al. (1990). The solution involved numerical approximation of the spatial and temporal derivatives in the equation by finite differences. The system of nonlinear equations obtained was linearized by Picard's iterative method, and the resulting equation was solved using the Thomas algorithm (Paniconi et al. 1991; Remson et al. 1971). The iteration continues until a specific convergence value is obtained. The model generates a temporal and spatial distribution of soil moisture in the unsaturated root zone. From the model simulated soil moisture content, the moisture depletion values were computed. The flowchart depicting the numerical simulation process is shown in Fig. 2.

Statistical analysis

Two sets of comparisons were performed in the study, one for the ET_c values and other for the soil moisture values. In the case of ET_c, the empirical ET_c was compared with the field ET_c for evaluating the performance of empirical ETc methods. Whereas in the case of the soil moisture, field observed soil moisture was compared with the simulated soil moisture to evaluate the efficiency of numerical model simulations and visualize the resulting differences to understand the irrigation schedules under different scenarios of climatic data. The comparison was based on graphical plots and error statistics. The error statistics used in the present study are mean bias error (MBE), root mean square error (RMSE), percent error (PE), coefficient of determination (COD) and mean absolute error (MAE). MBE, RMSE, PE, MAE and COD are defined as (Willmott 1982; Tabari et al. 2013):

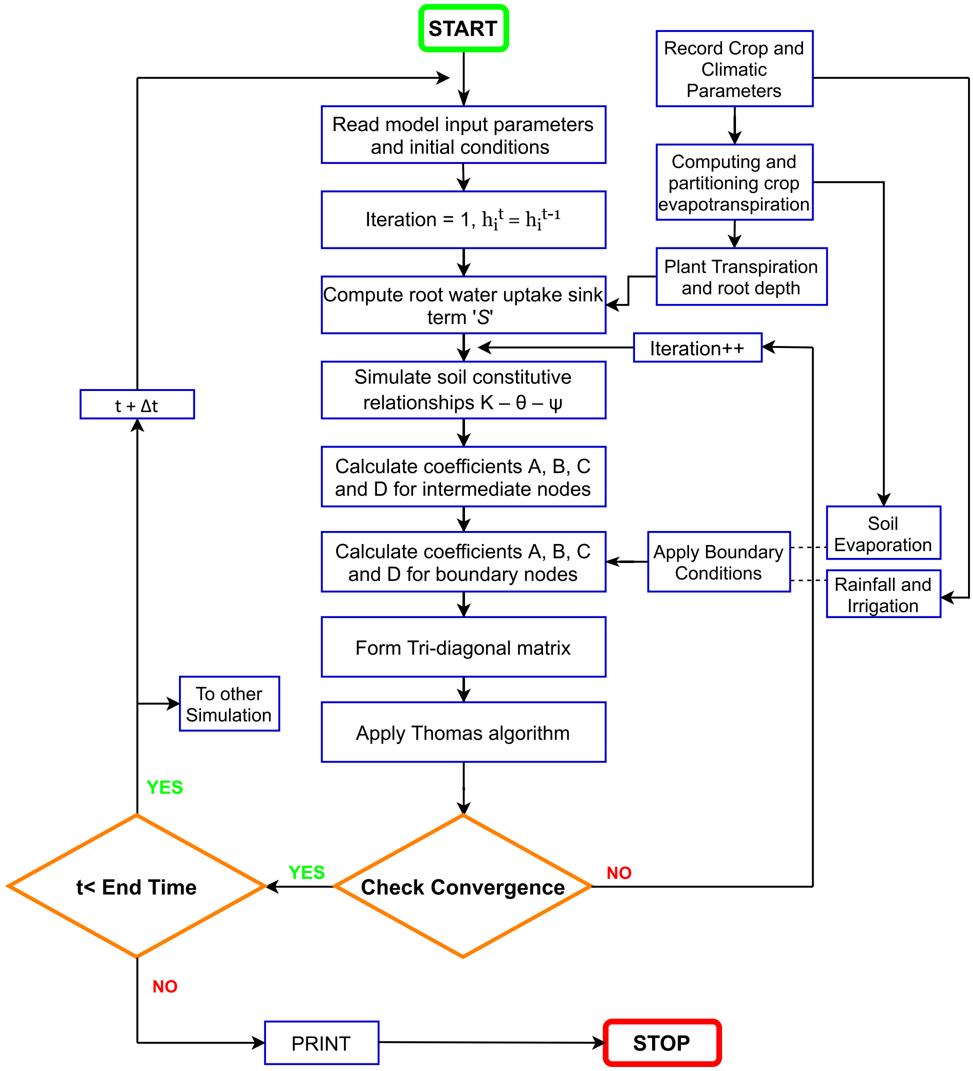

Fig. 2 Flowchart representing the numerical simulation model

Table 4 Mean daily ET_0 estimates during the crop period from different methods in the study area

Season (Jan–May)	Mean daily ET_0 values (mm day^{-1})												
	Combination methods		Radiation-based methods			Temperature-based methods			Pan-evaporation-based methods				
	PEN-M	C-PEN	RAD	PT	TC	HAR	BC	TH	FV	AP	SD	MS	OG
2014	3.94	4.01	4.33	4.64	4.26	3.88	3.74	3.68	2.58	3.02	3.18	3.01	2.93
2015	3.71	3.83	4.02	4.43	4.69	3.65	3.68	3.58	2.36	2.71	2.98	2.97	2.52
2016	3.84	3.96	4.12	4.48	4.36	3.85	3.71	3.43	2.46	2.84	3.01	3.02	2.68
2017	3.92	4.04	4.41	4.56	4.26	3.82	3.64	3.54	2.59	2.86	3.14	2.94	2.83

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(X_i - Y_i\right)^2} \tag{16}$$

$$\mathrm{MBE} = \frac{1}{n}\sum_{i=1}^{n}\left(X_i - Y_i\right) \tag{17}$$

$$\mathrm{PE} = \frac{1}{n}\sum_{i=1}^{n}\left(\left|\frac{X_i - Y_i}{Y_i}\right| \times 100\right) \tag{18}$$

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}\left|X_i - Y_i\right| \tag{19}$$

$$\mathrm{COD} = 1 - \left[\frac{\sum_{i=1}^{n} \left(X_i - Y_i\right)^2}{\sum_{i=1}^{n} \left(X_i - \bar{Y}\right)^2} \right] \tag{20}$$

where X = Empirical ET_c/modeled values of the soil moisture; Y = Field ET_c/field soil moisture; $\bar{Y}$ = Average value of field ET_c/average value of field soil moisture; n refers to the total number of observations; subscript i denotes the ith observation when soil moisture/ET_c was measured/computed.

Results and discussion

Computed reference evapotranspiration

The daily reference evapotranspiration (ET_0) is computed by substituting the climatic data in the ET_0 methods mentioned in Table 3. The values of the mean daily ET_0 computed from all the methods for the study period are shown in Table 4. It was observed that the temperature-based and the radiation-based methods gave higher values of ET_0, whereas the pan-evaporation-based methods gave lower values of ET_0 when compared with the combination-based methods. The minimum and maximum daily ET_0 was given by PAN and RAD methods, respectively.

Modified crop coefficients

FAO crop coefficient (K_c) values for the potato crop were modified for the local agro-climate. Equation 1 was used to modify the value of $K_{c\ ini}$. The values of $K_{c\ mid}$ and $K_{c\ end}$ are modified using Eq. 2. Due to low LAI (< 0.5) during the initial stage, crop factors were insignificant and climatic factors were dominant. Hence, the modification of $K_{c\ ini}$ was highly dependent on the value of ET_0 resulting in different $K_{c\ ini}$ values for each ET_0 method. However, this was not the case during the mid-season and the end-season, wherein the crop factors were dominant than the climatic factors. Table 5 shows the modified values of $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ for the potato crop averaged over four growing seasons, i.e., 2014–2017. The value of $K_{c\ ini}$ shown in Table 5 is for the PEN-M method. The mean values of $K_{c\ ini}$ for C-PEN, RAD, PT, TC, HAR, BC, TH, FV, AP, SD, MS and OG are 0.53, 0.53, 0.51, 0.56, 0.52, 0.57, 0.56, 0.49, 0.51, 0.51, 0.49 and 0.52, respectively.

Estimated crop evapotranspiration

Field ET_c (water balance approach)

The actual water requirement of the potato crop was estimated by performing the water balance studies using

Table 5 Mean value of modified crop coefficients for potato along with modification parameters

	Crop coefficients								
	$K_{c\ ini}$			$K_{c\ mid}$			$K_{c\ end}$		
	FAO value	Modifying parameters	Modified value	FAO value	Modifying parameters	Modified value	FAO value	Modifying parameters	Modified value
Crop season (Jan–May)	0.5	Wetting frequency = 10 days Avg. ET_0 = 1.2 mm/day (PEN-M)	0.51	1.15	u_2 = 2.45 ms^{-1} RH_{min} = 35.64 H = 0.35 m	1.18	0.75	u_2 = 2.01 ms^{-1} RH_{min} = 32.21 H = 0.38 m	0.77

Table 6 Water balance components for field ET_c computation of potato crop

Season (Jan–May)	Crop growth stage	Components (mm)				ET_c
		P	I_r	D_r	S	
2016	Initial	10.45	20	7.82	−8.54	31.17
	Development	26.22	100	20.56	13.58	92.08
	Mid-season	45.65	200	44.64	−7.55	208.56
	Late-season	11.56	50	6.52	−11.23	66.27
	Total	93.88	370	79.54	−13.74	398.08
2017	Initial	5.65	20	5.65	−9.67	29.67
	Development	12.64	100	17.21	9.54	85.89
	Mid-season	56.45	200	41.23	−9.43	224.65
	Late-season	15.02	50	5.36	−10.65	70.31
	Total	89.76	370	69.45	−20.21	410.52

Table 7 Mean daily ET_c estimates from different methods using the FAO-56 crop coefficient approach for potato crop in the study area

Season (Jan–May)	Mean daily ET_c values (mm day^{-1})												
	Combination methods		Radiation-based method			Temperature-based methods			Pan-evaporation-based methods				
	PEN-M	C-PEN	RAD	PT	TC	HAR	BC	TH	FV	AP	SD	MS	OG
2014	3.84	3.92	4.21	4.48	4.16	3.79	3.59	3.57	2.48	2.94	3.07	2.90	2.83
2015	3.62	3.73	3.91	4.32	4.57	3.54	3.60	3.54	2.24	2.61	2.88	2.86	2.40
2016	3.73	3.85	4.05	4.39	4.28	3.72	3.62	3.32	2.37	2.69	2.92	2.94	2.58
2017	3.81	3.91	4.23	4.42	4.17	3.73	3.51	3.47	2.48	2.78	3.05	2.86	2.75

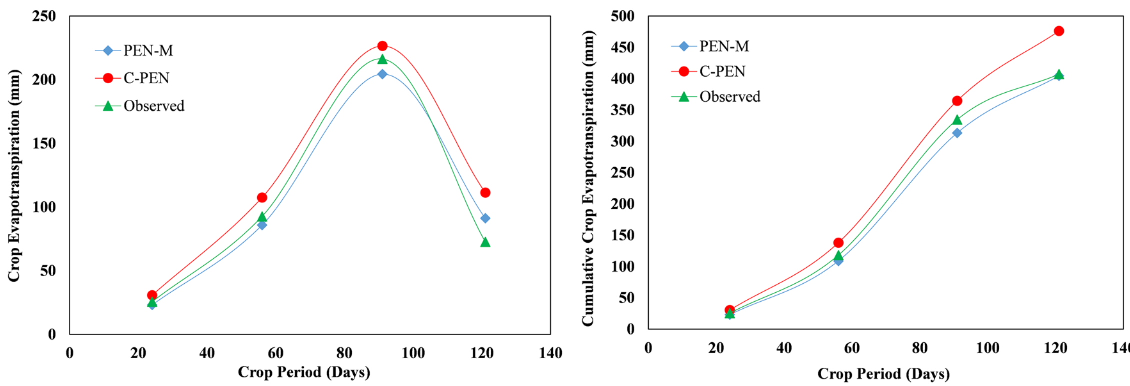

Fig. 3 Comparison of seasonal mean estimates of empirical ET_c based on combination-type methods and field ET_c

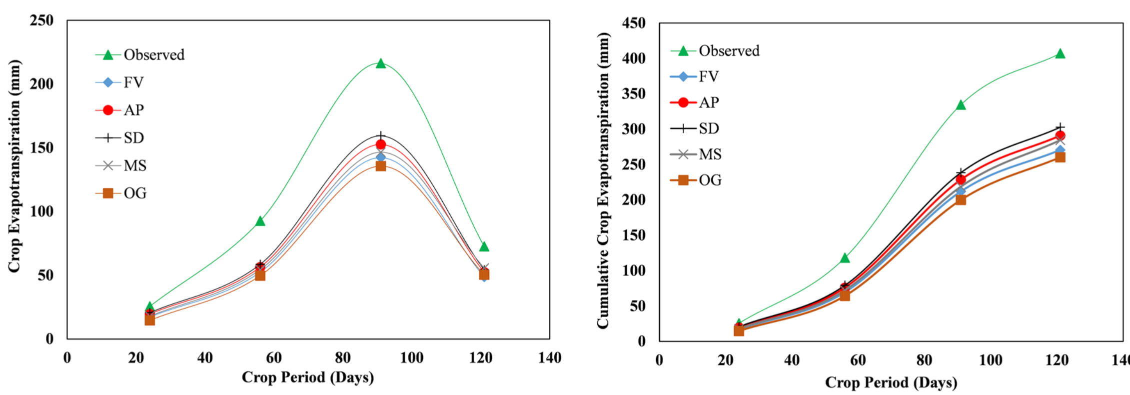

Fig. 4 Comparison of seasonal mean estimates of empirical ET_c based on pan-evaporation methods and field ET_c

lysimeter. The components of water balance were recorded throughout the crop period. Table 6 presents the total and stage-wise irrigation (I), precipitation (P), change in soil moisture storage (ΔS) and deep percolation (D) along with the computed field ET_c for 2016 and 2017 growth seasons. The corresponding values for 2014 and 2015 follow similar pattern to those of 2016 and 2017.

Empirical ET_c (crop coefficient approach)

The maximum and minimum values of the empirical ET_c were given by C-PEN and RAD methods, respectively. The mean values of daily ET_c computed from different ET_0 methods considered in the study are shown in Table 7. The daily values of the empirical ET_c obtained from different methods were converted into seasonal empirical ET_c for the statistical comparison and evaluation with the field ET_c.

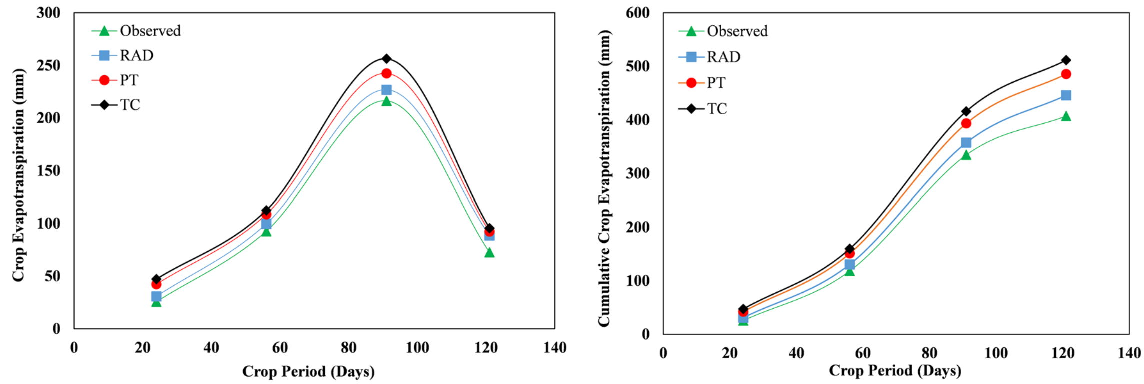

Fig. 5 Comparison of seasonal mean estimates of empirical ET_c based on radiation methods and field ET_c

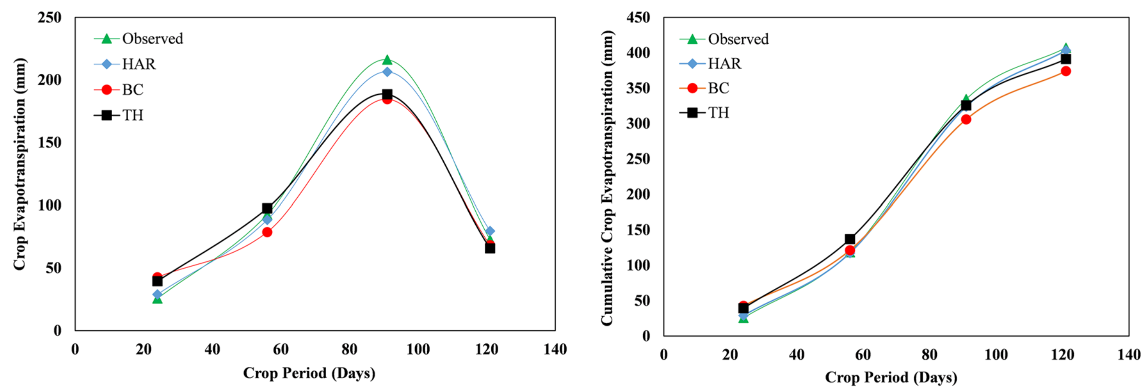

Fig. 6 Comparison of seasonal mean estimates of empirical ET_c based on temperature methods and field ET_c

Table 8 Error statistics for comparison between empirical ET_c computed using crop coefficient approach and field ET_c estimated using lysimeter

Type	Method	RMSE (mm/day)	MAE (mm/day)	R^2	MBE (mm/day)	PE (%)	Overall rank
Combination-type method	PEN-M	0.54 (1)	0.32 (1)	0.95 (1)	0.08 (1)	2.02 (1)	1.0
	C-PEN	0.78 (3)	0.56 (2)	0.88 (2)	0.12 (3)	4.15 (3)	2.6
Radiation-based methods	RAD	0.72 (2)	0.71 (4)	0.86 (3)	0.19 (4)	7.85 (4)	3.4
	PT	1.06 (7)	0.84 (6)	0.72 (5)	0.25 (5)	11.35 (5)	5.6
	TC	1.11 (8)	0.92 (8)	0.69 (7)	0.51 (9)	11.72 (7)	7.8
Temperature-based methods	HAR	0.90 (4)	0.66 (3)	0.78 (4)	−0.08 (2)	3.19 (2)	2.8
	BC	1.02 (6)	0.87 (7)	0.64 (8)	−0.28 (6)	11.66 (6)	6.6
	TH	0.96 (5)	0.79 (5)	0.73 (6)	−0.31 (7)	11.97 (8)	6.2
Pan-evaporation-based methods	FV	1.44 (12)	1.04 (11)	0.46 (13)	−0.78 (11)	23.25 (12)	11.8
	AP	1.32 (10)	0.99 (10)	0.60 (10)	−0.64 (10)	15.76 (10)	10.0
	SD	1.26 (9)	0.96 (9)	0.61 (9)	−0.43 (8)	12.31 (9)	8.8
	MS	1.38 (11)	1.17 (13)	0.54 (11)	−0.96 (13)	18.52 (11)	11.8
	OG	1.51 (13)	1.08 (12)	0.51 (12)	−0.91 (12)	26.38 (13)	12.4

Number inside brackets represent the rank

Evaluation of ET_c

A comparison between the empirical ET_c and the field ET_c was carried out to evaluate the most reliable alternative for estimating ET_c in the absence of expensive and laborious lysimetric measurements. The evaluation was based on quantitative and qualitative comparison of the seasonal ET_c values. The qualitative procedure involved a graphical comparison between seasonal and cumulative values of the empirical ET_c and field ET_c (Figs. 3, 4, 5 and 6), whereas the quantitative procedure involved the use of error statistics explained in Sect. 2.5. The results of the quantitative evaluation for all the methods are shown in Table 8. Rankings were assigned to the methods based on the value of error statistics for ease of selecting the alternative method to estimate the ET_c using the empirical approach depending upon the available climatic data.

Methods based on full climatic data

The ET_c values estimated using PEN-M were relatively close to the field ET_c values as compared to C-PEN. The graphical comparison between the empirical ET_c and the field ET_c is shown in Fig. 3. The results of the statistical analysis are shown in Table 8. A strong correlation exists between ET_c values computed using PEN-M and C-PEN with field ET_c and the same is indicated by low values of error statistics and high value of COD. The performance of C-PEN and PEN-M was almost similar since the climatic requirements are nearly the same for both methods.

Methods based on limited climatic data

Pan-evaporation-based methods The values of pan coefficients (K_{pan}) are calculated using the pan-evaporation-based methods given in Table 3. The K_{pan} values were found to be in the range of 0.57–0.95. The highest K_{pan} values (mean = 0.84) and the lowest K_{pan} values (mean = 0.71) were given by SD and OG methods, respectively. The mean values of the K_{pan} estimated from AP, FV and MS methods were 0.78, 0.76 and 0.72, respectively. ET_c values obtained from these methods were compared with the field ET_c. In general, the pan-evaporation-based ET_c underestimates the field ET_c values. This underestimation was also observed in the earlier studies (Grismer et al. 2002; Nandagiri and Kovoor 2006; Poddar et al. 2018a). As evident from Fig. 4, ET_c computed using the SD method was relatively closer to the field ET_c when compared to the other evaporation-based methods and is consistent with earlier studies (Xing et al. 2008; Tabari et al. 2013). Table 8 shows the details of error statistics. ET_c values estimated using the SD method gave the least values of MAE (0.96 mm day^{-1}), RMSE (1.26 mm day^{-1}), PE (12.31%) and MBE (0.43 mm day^{-1}).

Radiation-based methods The ET_c values computed from the radiation-based methods and the field ET_c are plotted as shown in Fig. 5. It was observed that the empirical ET_c from radiation-based methods overestimates the field ET_c values for the potato crop. Table 8 presents the error statistics of the empirical ET_c with the field observed ET_c. The overestimation was least for the RAD method (MBE = 0.19 mm day^{-1}), while the overestimation was maximum for the TC method (MBE = 0.51 mm day^{-1}). The ET_c estimated by the RAD method presented a reliable agreement with the field ET_c and was substantiated by the low error statistics (MAE = 0.71 mm day^{-1}, RMSE = 0.72 mm day^{-1}).

Temperature-based methods Figure 6 shows the comparison of seasonal field ET_c with the empirical ET_c computed from the temperature-based methods. It was observed that the temperature-based empirical ET_c values underestimate the field ET_c values. The results of the statistical evaluation are given in Table 8. HAR-based empirical ET_c presents reliable agreement with the field ET_c. The underestimation

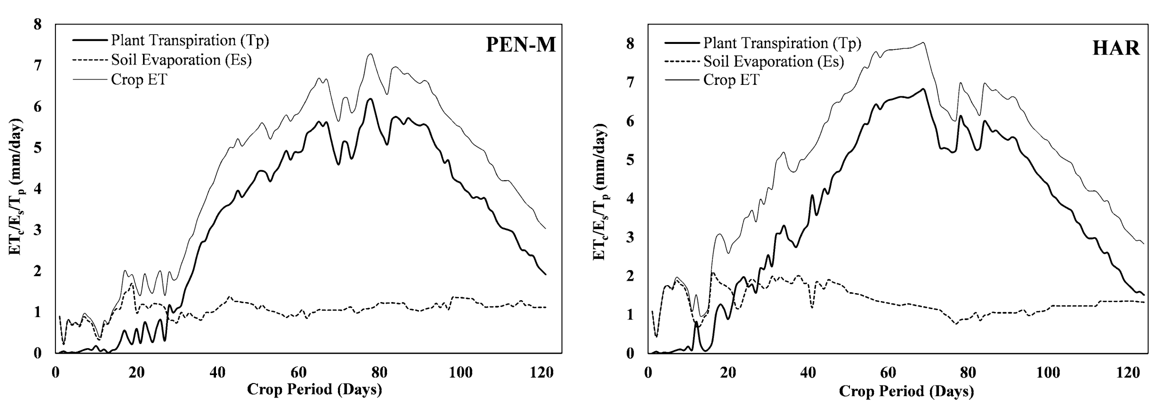

Fig. 7 Daily crop evapotranspiration, plant transpiration and soil evaporation for potato estimated from (**a**) PEN-M (**b**) HAR

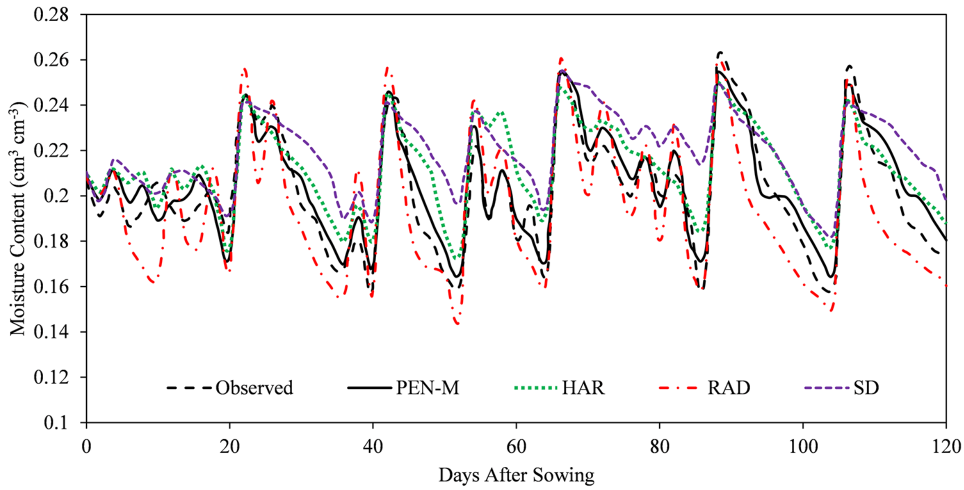

Fig. 8 Comparison of daily estimates of simulated soil moisture based on ET_c values of PEN-M, HAR, RAD, SD methods and field observed soil moisture at 10 cm depth

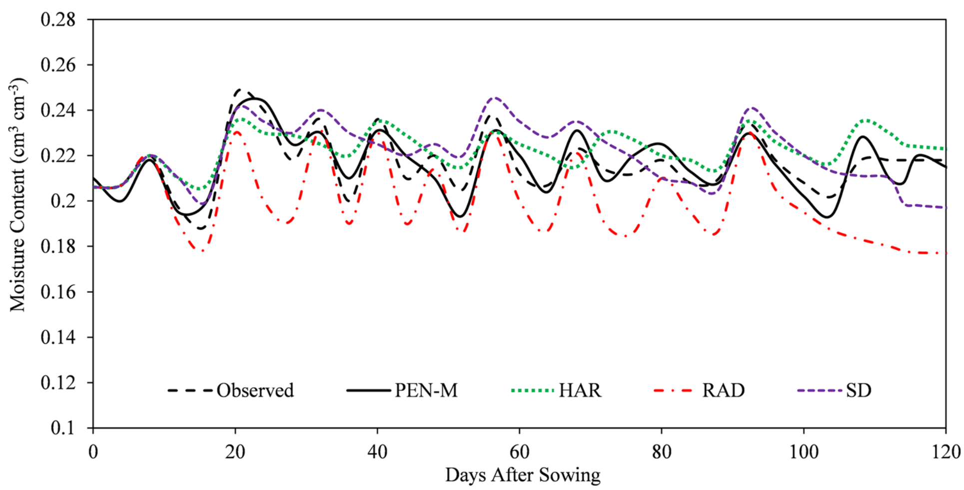

Fig. 9 Comparison of daily estimates of simulated soil moisture based on ET_c values of PEN-M, HAR, RAD, SD methods and field observed soil moisture at 40 cm depth

was maximum for BC and minimum for HAR-based ET_c. The HAR method as an alternative to the combination-based methods for different agro-climates has been previously suggested (Hargreaves and Allen 2003).

Evaluation of the ET_0 methods

Based on overall evaluation, PEN-M attained the highest rank followed by C-PEN (Table 8); however, both require the complete climatic dataset. Considering the methods based on limited climatic data, the performance of temperature and radiation-based methods was reliable, but pan-evaporation-based methods presented unsatisfactory results for estimating the empirical ET_c in potato crop. HAR, RAD and SD methods attained the highest rank in their respective categories indicating their suitability to be used as an alternative for estimating ET_c in the absence of the field ET_c and under limited climatic data availability. Other methods were less reliable for potato crop under the agro-climate of study area.

Partitioned crop evapotranspiration

In the present study, ET_c estimates from PEN-M, RAD, HAR AND SD methods were considered to incorporate the effect of climatic data availability on soil moisture simulation. Of these methods, PEN-M required full climatic data whereas other methods were based on limited climatic data. The empirical ET_c values estimated from these methods were partitioned into plant transpiration (T_p) and soil evaporation (E_s) using the partitioning equation (Eq. 6). The partitioned components of the ET_c based on PEN-M and HAR methods are shown in Fig. 7a, b. The values of T_p and E_s obtained were used as inputs to the numerical model wherein E_s was used as a boundary condition and T_p was used for computing the sink term. The maximum value of T_p during the crop growth period was used for computing the nonlinear RWU model parameter "β" (Eq. 15).

Table 9 Results of error statistics between field observed and model simulated soil moisture at different depths

Depth (m)	Method	RMSE (cm^3 cm^{-3})	MAE (cm^3 cm^{-3})	R^2	MBE (cm^3 cm^{-3})	PE (%)
0.10	PEN-M	0.032	0.021	0.78	0.013	8.11
	RAD	0.058	0.039	0.71	− 0.027	12.14
	HAR	0.041	0.032	0.75	0.018	11.68
	SD	0.082	0.067	0.59	0.039	25.56
0.20	PEN-M	0.028	0.018	0.81	0.011	6.23
	RAD	0.049	0.038	0.74	− 0.018	8.44
	HAR	0.040	0.029	0.77	0.015	9.56
	SD	0.066	0.054	0.67	0.029	20.16
0.40	PEN-M	0.012	0.008	0.92	− 0.004	3.65
	RAD	0.032	0.014	0.81	− 0.009	5.96
	HAR	0.028	0.015	0.88	0.006	4.68
	SD	0.068	0.052	0.68	0.027	15.68
0.60	PEN-M	0.014	0.010	0.91	0.005	3.88
	RAD	0.031	0.012	0.82	− 0.008	6.24
	HAR	0.025	0.018	0.86	0.008	4.21
	SD	0.056	0.042	0.72	0.023	13.56

Soil moisture dynamics

Field observed soil moisture

The soil moisture content at every 0.1 m depth (up to 1.6 m) in the crop root zone was recorded daily using the soil moisture probe throughout the crop period. The variation in the field soil moisture was observed during each repetition. Figures 8 and 9 present the variation of soil moisture at 0.10 m and 0.40 m depth, respectively. The rise in the moisture indicates wetting events (rainfall/irrigation). The irrigation was provided as soon as the moisture in the crop root zone depletes to 30%. Field observed soil moisture was used for comparing and evaluating the model simulated soil moisture based on empirical ET_c computed under different scenarios of climatic data availability.

Simulated soil moisture

The soil moisture in the crop root zone of potato was simulated using the RWU-based numerical model. The inputs to model consist of soil parameters (α_v, n_v, K_s, θ_s, θ_r, θ_{fc}, θ_{pwp}), crop parameters (T_p, Z_r), climatic parameters (P, E_s) and the initial and relevant boundary conditions. The RWU was estimated using the nonlinear O-R model which is based on the values of T_p and Z_r. The model simulated soil moisture was obtained under the scenarios of full (PEN-M) and limited climatic data (RAD, HAR, and SD). For each method, separate simulation was run, in which all other parameters were identical except T_p and E_s. A time series plot of the simulated soil moisture considering the above-mentioned methods at 0.10 m and 0.40 m is shown in Figs. 8 and 9, respectively. The simulated soil moisture was then compared with the field observed soil moisture and subsequently employed to study the effect of limited climatic data on the irrigation schedules of the potato crop.

Graphical and statistical comparison

The qualitative comparison between the field observed and the model simulated soil moisture was performed using the graphical plots. The comparison was made at every 0.1 m depth for the entire crop growth period. Figures 8 and 9 show the comparison of the simulated soil moisture with the field soil moisture at 0.10 m and 0.40 m, respectively. The simulated soil moisture considering the PEN-M method presents strong agreement with field soil moisture, which is further substantiated by the values of error statistics mentioned in Table 9.

Simulated soil moisture considering the empirical ET_c from HAR, RAD and PAN was of more relevance for the present study, since they represented the scenario of limited climatic data availability. HAR-based soil moisture simulation presented a reliable agreement with the field soil moisture. The moisture variation closely followed the trend of PEN-M simulated and field observed soil moisture throughout the crop period. This was essentially because the ET_c estimates from HAR and PEN-M were found to be close. However, such was not the case with RAD and PAN simulated soil moisture values. In the case of RAD, the simulated soil moisture shows more depletion as compared to the field observed values. This was due to the overestimation of ET_c by RAD, which resulted in a higher RWU and faster depletion of the soil moisture for potato crop. In the case of PAN, there was a poor agreement between the field observed and model simulated soil moisture values. The depletion levels were too small to represent actual field moisture dynamics owing to the underestimation of the field ET_c by PAN. Depletion of 30% in the field observed soil moisture corresponds to 28%, 25%, 40% and 15% depletion in simulated soil moisture using PEN-M, HAR, RAD and PAN-based empirical ET_c, respectively.

Irrigation scheduling

Irrigation is generally applied when the soil moisture reaches a certain pre-defined allowable depletion. However, optimal irrigation scheduling improves the water use efficiency of crops which necessitates precise information on the RWU and the soil moisture dynamics in the crop root zone. For the present study, the maximum depletion level was allowed at 30%. This value was selected based on the results of the earlier studies and current irrigation practices followed in the study area. The results obtained from the numerical model were utilized for scheduling the irrigation of potato and assess its variation under different scenarios of climatic data availability. The schedules were based on the condition of three rainfall events of 30 mm each during the period of crop growth (based on rainfall data) and can be adjusted depending on the frequency and amount of actual rainfall events. The corresponding levels of soil moisture depletion as mentioned previously were used as the scheduling criterion for irrigation events. The number of irrigation events for potato crop based on the simulated soil moisture was six. This means, while using limited climatic data in a RWU-based numerical model for scheduling the irrigation of potato in a humid subtropical climate, one needs to supply the field with six irrigation events. The irrigation should be applied as soon as the model simulated soil moisture depletion reaches 25% in the case of temperature-based ET_c, i.e., HAR; 40% in the case of radiation-based ET_c, i.e., RAD; and 15% in case of pan-evaporation-based ET_c, i.e., SD. In the case of the PEN-M-based ET_c, the potato crop should be irrigated at 28% model simulated soil moisture depletion. However, the duration between successive irrigations will vary throughout the growth period of potato depending on the crop water requirements (ET_c).

Conclusion

The present study evaluated thirteen ET_0 methods in a humid subtropical agro-climate and subsequently employed a root water uptake (RWU)-based numerical model to simulate the soil moisture dynamics in the crop root zone of potato. Based on the findings of the study, the following conclusions were drawn:

- PEN-M, HAR, RAD and SD methods can be used as suitable alternatives for estimating the field ET_c using the FAO-56 crop coefficient approach in the absence of the lysimetric measurements, under different scenarios of climatic data availability.
- Under limited climatic data scenario, simulated soil moisture based on HAR (temperature method) and RAD (radiation method) present a satisfactory agreement with observed soil moisture. However, SD (pan-evaporation method)-based simulated soil moisture shows poor agreement.
- While using limited climatic data, irrigation is required to be supplied at the simulated soil moisture depletion of 15% (in case of pan-evaporation-based ET_c, i.e., SD), 25% (in case of temperature-based ET_c, i.e., HAR), and 40% (in case of radiation-based ET_c, i.e., RAD).

The study can be extended for investigating the soil moisture dynamics and scheduling irrigation of other crops involving scenarios of limited climatic data availability. This will supplement the existing knowledge on decision making and irrigation planning for optimizing water use for irrigation in the absence of expensive instrumentation.

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Data availability statement Some data, models or code used during the study are available from the corresponding author by request.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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