A Simple Soil Moisture Simulation Model to Address Irrigation Water Management Issues

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ABSTRACT

A simple soil moisture simulation model to use in irrigation water management issues was developed. The model employs traditional water budgeting approach, and includes mechanisms for simulating soil moisture movement, root growth and crop evapotranspiration. The model requires only a few readily available input parameters. This model was evaluated through a case study conducted at a farm in the Goulburn Irrigation Area in Victoria (Australia). The soil moisture simulation results demonstrated the effectiveness of model and revealed that the developed model was quite successful to account for the variability of evaporative demand of tested perennial pasture and the amount of rainfall received during the irrigation period. The qualitative and quantitative procedures used in model's evaluation supported its use to deal with agricultural water management issues for yielding significant water savings.

Key Wwords: **Soil Moisture, Simulation, Evapotranspiration, Irrigation Scheduling.**

1. INTRODUCTION

Water is becoming increasingly scarce. To meet the ever-increasing water demands, efficient operation of existing irrigation systems has been highly recognized. Scientific irrigation scheduling which deals with the frequency and dosage of irrigation water applications has been demonstrated as one of the potential on-farm management techniques for achieving efficient operation of these continua. Since IS (Irrigation Scheduling) deals with complex soil-plant-atmosphere continuum, the accuracy of an IS model primarily depends on how accurately this system is modelled. Comprehensive modelling of all processes involved in this continuum requires such data items which are not only costly but also laborious and time consuming to collect. Hence, comprehensive modelling of this continuum is not practically feasible under normal field conditions.

Effective irrigation scheduling requires a good knowledge of the SMC (Soil Moisture Content) of the field. Since measurement of SMC is often costly, time consuming and complicated due to endemic variability in the soil, generally two types of approaches viz. empirical and physically based models have been used to model the movement of moisture in the soil-plant-atmosphere continuum. In empirical models, simple empirical algorithms based on field observations to transfer water

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in and out of the soil profile are adopted. Although, this modelling approach has proven quite versatile, yet reliable predictions at individual site requires some calibration using observed soil moisture data. The physically based models, use the principle of continuity and Darcy's law to derive a general soil-water flow equation with water moving through the soil in response to water potential or water content gradients. Water uptake by plant roots is then simulated by adding a volumetric sink term to this soil-water flow equation. Although this approach has sound theoretical foundations, it can still only be considered as a first-order approximation to what is happening under actual field conditions [1]. In addition, the main problem with the use of physically based models is that they are data extensive. The input parameters such as unsaturated soil hydraulic conductivity, $K(\theta)$ and soil moisture diffusivity, $D(\theta)$ required by these models are either time variant or spatially variable, and need to be determined experimentally under local conditions, which are routinely not feasible in most irrigation systems. The farmer surveys conducted in Northern Victoria, Australia [2] and in USA [3] revealed that most farmers had shown interest in the use of IS models, provided that they were simple to use and compatible with their needs. However, if farmers perceive that the required input data are too difficult to obtain or that a considerable time is required to obtain and process the required data, then they are unlikely to use the irrigation scheduling programs.

While realising the limitations of aforementioned empirical and physically based models regarding accuracy and practicality under field conditions; there can be hybrid (or semi-empirical) models that can use best features of both types of empirical and physically based models. For irrigation scheduling, these hybrid models may produce reasonable accuracy (as will be shown later) while requiring less amount of data. Such a hybrid approach has been adopted in this study; and a simple soil moisture simulation model based on traditional water balance approach incorporating a dynamic moisture extraction function for modelling plant root system to mimic the actual field conditions has been developed. This model can be considered as a hybrid of empirical and physically-based mathematical models, in which the water balance components are estimated using semi-empirical methods. An effort was made to develop the model with minimum and readily available inputs, so that the model can be calibrated without the need for extensive field measurements. The developed model can play an important role in implementing irrigation sector reforms programs which are developed with the objective of improving irrigation assets' management as well as quality of service delivery through participatory management; and designing of drainage schemes such as reported by [4-5]. This paper first describes various components of the water balance model along with theoretical details and proposed estimation procedures of those components while reviewing the previous work; and then evaluates the performance of the developed model.

2. BASIC SOIL MOISTURE TERMINOLOGIES

Before discussing the proposed model, different SMC related terminologies used in this paper are briefly described. The notations SAT, FCAP and PWP have been used to refer the saturation, field capacity and permanent wilting point SMC conditions respectively. Since field capacity represents the drained upper limit of the soil after a major precipitation (i.e. irrigation and/or rainfall) event, a more recent term called DU (Drained Upper Limit) has also been synonymously used for FCAP conditions. Similarly, the term LL (Lower Limit) has been synonymously used for PWP soil moisture conditions. It is worth mentioning that in this paper the notations SAT, FCAP (or DU) and PWP (or LL) when appear in normal flow of text, represent the corresponding SMC in depth units; and when appear as subscripts with θ refer to corresponding SMC in volumetric units. The conversion of SMC from volumetric units into equivalent depth of water can be obtained as:

$$d = \theta Z \quad (1)$$

where d is depth of water per unit of soil profile depth(cm); θ is volumetric soil moisture content ($cm^3\ cm^{-3}$); and Z is depth of soil profile under interest (cm).

The term AW (Available Water) represents the amount of water stored in the soil profile between DU and PWP (or LL). Mathematically it can be expressed as:

$$AW = (\theta_{DU} - \theta_{LL})Z \quad (2)$$

where AW is available water in depth units (cm); Z is root zone depth (cm); and all other terms are as defined earlier. The average values and ranges of above SMC parameters for different soils are given in [6].

In practice, soil is never allowed to dry out to PWP (or LL), but is kept above a certain soil moisture (hereafter referred to as critical soil moisture) level to avoid yield losses. This critical soil moisture (θ_{crit}) determines when to irrigate the field, and hence, is also referred to as the refill point of the soil profile.

3. WATER BALANCE MODEL

For SMC simulations of the root zone of an irrigated crop, the traditional daily water balance can be expressed as [6]:

$$\int_0^Z \theta_{2,z}\, dz = \int_0^Z \theta_{1,z}\, dz + IR_1 + RF_1 + CR_1 - DP_1 - DR_1 - ET_1 \quad (3)$$

where $\theta_{2,z}$ is volumetric soil moisture content of root zone depth Z on day 2 ($cm^3\ cm^{-3}$); θ_1 is volumetric SMC on day 1 ($cm^3\ cm^{-3}$); Z is root zone depth (cm); IR_1, RF_1, CR_1, DP_1, DR_1 and ET_1 represent the net irrigation, effective rainfall, capillary rise, deep percolation, surface runoff /drainage out of the field and crop evapotranspiration during day 1 respectively (cm). The above water balance model (Equation 3) has been used in various irrigation studies by several [4, 7-9] researchers under various soil, crop and climatic conditions. However, in those studies the algorithms adopted for modelling various components of this water balance model varied depending on the purpose and desired degree of accuracy under respective field conditions. The proposed estimation procedures adopted in this study for each component of this model are described.

3.1 Computation of Various Components of Water Balance Model

Net Irrigation (IR): This term refers to the amount of water that is actually required to meet crops' evapotranspiration needs. This component can be estimated by multiplying gross irrigation (IR_{gross}) value with an irrigation application efficiency factor. The application efficiency values can be found in [6].

Effective Rainfall (RF): The RF term in Equation (3) refers to the amount of rain that reaches the root zone in meeting the ET requirement of the crop, after it has been intercepted and evaporated directly from the crop foliage. For a given crop, the RF can be estimated by adjusting the actual measured rainfall through the use of a rainfall correction factor. These correction factors are given in [10]. The estimated effective rainfall can then be used in the water balance model.

Capillary Rise (CR): The CR term in Equation (3) represents the amount of moisture that is contributed by the lower sub-layers to the upper adjacent sub-layers (through the capillary rise action), when there is a deficit in SMC of the upper sub-layers. Ignoring CR can result in underestimation of SMC available for plant evapotranspiration. Accurate modelling of this component is not only complicated but also data extensive, and hence requires the parameters which are seldom available in most irrigation systems. Even if they are available, the spatial variability of these parameters affects the results. For these reasons, the capillary rise aspect of soil moisture has not been included. However, this component can be indirectly accounted for through the calibration process, while considering the excess water of deep percolation, as described later in this section. The advantage of this approach is that it does not require any additional data, and is also easy to employ under local field conditions.

Deep Percolation (DP): The DP represents the amount of excess water that goes beyond the root zone and is not available for plant ET, but contributes to the sub-surface drainage. DP usually occurs when rainfall follows an adequate irrigation event where root zone is already wet, or when an irrigation event itself overfills the root zone above its water holding capacity. Since DP from an irrigated field is associated with its overfilled conditions beyond the water holding capacity, it can be estimated from the DU of the soil. Therefore, it is stipulated that DP is generated when the SMC exceeds drained upper limit θ_{DU} of the entire root zone.

It is worthwhile to note that in actual field conditions, if SMC of the root zone is already at its DU following an irrigation event, and moderate rainfall occurs subsequently, the deep percolation does not take place instantaneously soon after the rainfall [11]. In fact, field capacity is generally attained after one to four days of the irrigation/rainfall event depending upon the type of soil. In addition, some of this gradually percolating water (hereafter referred to as excess water) also becomes readily available to satisfy the crop ET requirements, before actually contributing to DP losses. However, the fraction of this excess WA for crop use depends on the prevailing crop, soil type and climatic conditions. For the same soil type, during relatively higher evaporative demand periods, this fraction is greater than during the less evaporative demand periods. During the same evaporative demand periods, a coarse soil has a higher fraction compared to that of a fine soil.

In most previous irrigation scheduling studies, the excess water was considered as "all lost" water, and hence totally discarded from the water balance calculations whenever an overfilled condition beyond the FCAP occurred. This can lead to significant discrepancies between the actual and predicted SMC in the root zone. By virtue of these under-estimated SMC predictions of the root zone, above assumption could result in more frequent and/or premature irrigation recommendations. Therefore, this component needs to be modelled carefully. In order to model this component, a simplified approximation was adopted. In this approach, the value of used in water balance model was set a few percentage points above the normal values obtained from the literature to account for the transient extra moisture available for crop use. However, this needs to be calibrated for each soil type under local field conditions. This extra allowance to be made in value was limited to 25% of total AW of the respective root zone sub-layer. Hence, any excess water above the field capacity (FCAP) was considered as loss, except the above stated extra allowance made through the θ_{DU}.

Evapotranspiration (ET): The evapotranspiration or water uptake by plants is the major 'sink' term in Equation (3), and represents the amount of soil moisture that is utilised through consumptive use of the crop. The daily potential crop evapotranspiration (ET_c) can be estimated using reference evapotranspiration (ET_o) and crop coefficient (K_c) through the following relation as:

$$ET_c = K_c ET_o \tag{4}$$

Crop coefficients for various crops and methods for estimating ET_o are given in literature [6,12]. It is important to note that the ET_c estimates obtained from Equation (4) represent the potential (or maximum) rate, which occurs only if SMC of the root zone remains close to DU moisture level. However, in real-life field conditions, this situation lasts only for a few days (following an adequate irrigation and/or heavy rainfall event) depending upon the prevalent climatic conditions. After this, the actual crop evapotranspiration (ET_a) rate decreases day by day as moisture reserve depletes from the root zone until it reaches to a minimum value. This aspect plays an important role in SMC modelling, and is discussed separately in the following section.

3.2 Modelling Water Uptake by Plants

Moisture extraction (uptake) by plant roots through ET process is one of the most difficult modelling components of the water balance model because of spatially variable and time-variant nature of the root system. In the interest of practicality and minimum input data requirements, present study employed the approach of Azhar, A.H., and Perera, B.J.C., [13] based on guidelines of [7,14] for modelling of this component. Accordingly, moisture extraction or water uptake by crop through the process of ET is considered as a diffuse volumetric "sink" controlled by a sink term specified in the water balance model. This so called sink term, S(θ,z) represents the moisture extraction (or uptake) rate by plant roots in volumetric units of moisture per unit volume of root zone profile per day ($cm^3\ cm^{-3}\ d^{-1}$); or alternatively, expressed in depth units of moisture per unit depth of root zone profile per day ($cm\ cm^{-1}\ d^{-1}$). If the entire root zone is considered in the model, it could be simply expressed in depth units of moisture per day ($cm\ d^{-1}$).

The sink term, S(θ,z) by itself is a function of maximum extraction rate (S_{max}) by plant roots ($cm\ d^{-1}$), and the soil matrix moisture content (θ), which can be described as [14]:

$$S(\theta,z) = \alpha(\theta)\, S_{max} \tag{5}$$

where α(θ) is dimensionless moisture availability reduction factor varying between 0 and 1. The proposed simplified estimation procedure for α(θ) factor is described later under Section 3.3. The simple algorithm for estimation of S_{max} is given as [13]:

$$S_{max} = 2\, T_p \left[{z_r}/{Z_e} \right] \tag{6}$$

where T_p is potential transpiration (cm); Z_e is effective root zone depth, defined as the portion of root zone which actually contributes to the evapotranspiration process (cm); and z_r is vertical distance from soil surface to depth of interest (cm). For rooting depth, while considering the dynamics of root development and compatibility with actual field conditions, a simplified approach has been adopted. As per this approach, rooting depth on a particular j-day (RD_j) is modelled in equal depth increments (ΔZ).This implies that on any day rooting depth (RD_j) would always be a multiple of ΔZ. For this, ΔZ value would be decided according to the physical characteristics of the soil profile under consideration. For simplicity, maximum of four sub-layers were considered. Hence, a value of ΔZ=15cm can be adopted for shallow rooted (i.e. RD_{max}<60 cm) crops. Similarly, ΔZ=30cm and $RD_{max}/4$ could be adopted for medium rooted (i.e. 60cm< RD_{max}<120cm) and deep rooted (i.e. RD_{max}>120cm) crops respectively.

3.2.1 Root Zone Sub-Layers

For IS studies, it is customary to divide the entire root zone depth (Z) into a number of discrete sub-layers or stratifications. While appreciating the critical aspect of heterogeneous soil profiles and the importance of minimum data requirements, entire root zone (Z) was divided into four workable sub-layers of equal thickness. For such root zone with discrete sub-layers, total SMC of entire root zone can be estimated as [13]:

$$d_z = \int_0^Z \theta_z dz = \sum_{i=1}^{n} \theta_i . z_i \tag{7}$$

where d_z is SMC of entire root zone in depth units (cm); θ_i is volumetric soil moisture content of sub-layer i ($cm^3\ cm^{-3}$); z_i is depth (or thickness) of ith sub-layer (cm); n is total number of discrete sub-layers in the entire root zone divided between 0 and Z, where Z is the entire root zone.

3.2.2 Moisture Redistribution Among Sub-Layers

To redistribute soil moisture among various sub-layers after a precipitation (rainfall and/or irrigation) event, a simple cascade type approach has been followed. According to this, any water applied to the field will be distributed among sub-layers starting from surface sub-layer to the subsequent lower sub-layers. This implies that if depth of applied water is greater than the storage capacity of surface sub-layer, firstly the surface sub-layer is recharged to its θ_{DU} level and then excess water is distributed to the second (lower) sub-layer to recharge it to its FCAP level, and so on until all applied water is distributed among all sub-layers. After having recharged all root zone sub-layers at FCAP level, if there is some excess water still left, this excess water is considered as deep percolation losses.

3.2.3 Moisture Extraction Pattern

Traditionally, when initial soil moisture content is uniform in the root zone, the root zone is divided into four equal depth sub-layers, and the moisture extraction pattern is assumed to be 40, 30, 20, and 10% per quarter of root zone depth from top to the bottom. This is satisfactory for homogeneous soil profiles in which the effective root zone of a crop is well established. However, realising the dynamic nature of the root system, the proposed time variant moisture extraction model for multiple root zone sub-layers for use in Equation (5) can be expressed as [13]:

$$\Gamma_i = 100 \times \frac{S_{\max,\,i}}{\sum_{i=1}^{n} S_{\max,\,i}} \quad \text{for} \quad \sum_{i=1}^{n} \Gamma_i = 100\,\% \tag{8}$$

and

$$S_{\max,i} = \frac{T_p}{Z_e}\left\{\frac{(2\,n - 2\,i + 1)}{n}\right\} \quad \text{for} \quad S_{\max} = \sum_{i=1}^{n} S_{\max,\,i} \tag{9}$$

where Γ_i is root density representative moisture extraction factor for i[th] sub-layer, which by definition represents the relative proportion of S_{max} from i[th] sub-layer (%); $S_{max,i}$ is partial contribution to Smax from ith sub-layer (cm d^{-1}); n is number of root zone sub-layers; and all other terms are defined earlier. It is important to note that use of Equations (5-9) models the total moisture extraction or water uptake by plant system over the entire root zone in cm cm^{-1} d^{-1} units. This water uptake by plants through roots represents the actual transpiration (T_a) on any day, which cannot exceed potential transpiration (T_p) value of the corresponding day. Therefore, it is stipulated that:

$$\sum_{i=1}^{n} S(\theta, z)_i \le T_p \quad \text{for } z < Z_e \tag{10}$$

and

$$S(\theta, z)_i = \frac{\alpha(\theta)_i\ \Gamma_i\ T_p\ \Delta z_i\ S_{\max,\,i}}{100} \tag{11}$$

where $S(\theta,z)_i$ is partial moisture extraction by plant from sub-layer i (cm d^{-1}); $\alpha(\theta)_i$ is moisture reduction factor of i[th] sub-layer; Δz_i is depth/thickness of ith sub-layer (cm); and all other terms are defined earlier. The term $\alpha(\theta)_i$ can be determined using Equations (12-14) for respective sub-layer against its current SMC level for the day under consideration (Section 3.3). In the interest of practicality and minimum data requirements, to mimic the combined effect of evaporation from the soil surface and the plant transpiration under actual field conditions, the value of ET_c computed using Equation (4) can be used in Equation (6-11) for T_p term. This is in line with the justification given by [13]. The estimates of S(θ,z) obtained from Equation (5 and 11) would in fact mirror the actual crop evapotranspiration (ET_a) estimates under prevailing climatic conditions.

As can be observed, computation of S(θ,z) component using Equation (11) requires a few, but readily available input data items. They include reference crop evapotranspiration, physical characteristics of soil (e.g. saturation, field capacity and permanent wilting points etc.), maximum root-depth, time required to attain maximum root-depth, and the crop coefficient relevant to the growth stage of the crop. The advantage of this proposed approach over previous approaches is that it accounts for the dynamic root water extraction process by using simple functions for which only rooting depth information (as a major input) is required.

3.3 Evapotranspiration Rate After Precipitation Event

When a field is recharged through precipitation (irrigation and/or rainfall) event, it takes a few (1-3) days for the root zone to reach its DU level depending upon the prevailing crop, soil and climatic conditions. During this transient period, transpiration and surface evaporation components of ET are highly variable in time and space due to the interactions of many soil, crop and climate related variables. While realising the complexity of these interactions, following assumptions have been used to compute the evapotranspiration rate after the precipitation event:

(i) SMC of the entire root zone reaches its SAT level (e.g. if a heavy rainfall occurs), or DU level (e.g. if a normal irrigation is applied to recharge the root zone just up to DU) by the end of the same day on which precipitation (i.e. irrigation and/or rainfall) event occurs.

(ii) Water uptake by crop through ET process attains its potential rate on the next day after precipitation event, unless specified by the user ET as zero for certain number of days (hereafter referred to as Anerobic days) to model anaerobic conditions after a heavy precipitation event. In case of heavy precipitation, potential rate of ET is attained after Anerobic days. The water uptake then remains at its potential rate until soil moisture level reaches a certain pre-specified DU level. Then, it starts to decline linearly and subsequently approaching to almost zero at LL soil moisture level.

(iii) If SMC<θ_{LL}, only the soil evaporation (E_s) component of ET continues and it is supported by the surface sub-layer (z_1) of the root zone alone. It also virtually ceases when SMC of surface sub-layer (SMC_{z1}) approaches a certain air-dried limiting value. For convenience, it was assumed that E_s component ceases completely when SMC_{z1} falls below $0.5\theta_{LL(zl)}$. This implies that when SMCzl<$0.5\theta_{LL(zl)}$, then ET is zero.

It is important to note that the above assumptions may cause some discrepancies between the actual and computed SMC estimates soon after the precipitation event. However, this problem would ultimately be settled down by itself (as will be shown later) after a few days after the precipitation event when a steady state is reached. Based on the above assumptions, the variation of $\alpha(\theta)$ factor (for use in Equation 5) adopted in this study is graphically shown in Fig. 1 and mathematically expressed as:

$$\alpha(\theta) = 0 \quad \text{for } \theta_t > \theta_{SAT};\ SMC_{=1} < 0.5\theta LL_{(zl)} \tag{12}$$

$$\alpha(\theta) = 1 \quad \text{for } \theta_{DU}\ \theta_t < \theta_{SAT} \tag{13}$$

$$\alpha(\theta) = (\theta_, - \theta_{LL})/(\theta_{DU} - \theta_{LL}) \quad \text{for } \theta_{LL}\ \theta_t < \theta_{DU} \tag{14}$$

where θ is volumetric SMC on a particular day (%); and all other terms are defined earlier. This completes the proposed algorithms for modelling various components of the water balance model employed in this study to simulate the SMC of the root zone of an irrigated crop. The evaluation aspect of this model is discussed in the next section.

4. MATERIALS AND METHOD

4.1 Model Execution and Input Parameters

The proposed model employs the traditional water budgeting approach, and includes mechanisms for simulating soil moisture movement, root growth and crop evapotranspiration. The model requires only a few input parameters that are readily available. They include: daily rainfall, previous irrigation (i.e. time and amount), reference crop evapotranspiration, maximum root-depth, time required to attain maximum root-depth, crop coefficients relevant to the growth stages of crop, and physical characteristics of the soil e.g. saturation, field capacity, and permanent wilting points etc. For execution, the algorithms of model were translated into a computer program using FORTRAN-77. The model calculates components of the water balance on a daily basis including actual evapotranspiration, deep percolation and the soil moisture depletion at different depths of the soil profile, to facilitate the decision of an irrigation application. The advantage of developed model over previous [16-19] models is that ET component of the model accounts for dynamic root water extraction process by using simple functions for which only rooting depth information (as a major input) is required.

4.2 Study Site and Data Collection

The validity of soil moisture simulation model was tested against the field measured SMC data of a farm at Tongala in the GIA (Goulburn Irrigation Area) in Victoria (Australia), located approximately 200 km north of the Melbourne capital city of Victoria. The daily SMC data were available for the 1997-1998 irrigation season from 8th October 1997 to 27th March 1998 for the flood irrigated perennial pasture grazed by dairy cattle for milk production [20]. The soil at the site was fine sandy loam with 40cm top soil overlying a dense red clay of 25cm thickness. This clay layer restricts downward water movement as well as rooting activity beyond the top profile. The climatic data for this analysis were obtained from a station situated 15 km to the south west of Tongala. In-situ rainfall measurements were available for the Tongala. The other required crop and soil related information were obtained from literature [20]. As per this reference, the SAT, DU and LL values were 46, 41 and 15% respectively. The rooting depth used in the soil moisture simulation model was 40cm. A value of 3 for Anerobic days (the number of days followed by a heavy precipitation event during which the root zone remains at anerobic conditions) parameter was used, which was an approximate time required to reach from SAT level to the DU level, after a heavy precipitation event.

5. MODEL VALIDATION

5.1 Evaluation Strategy

The model evaluation was based on testing of daily SMC data series simulated by the model against measured SMC data. For evaluation of SMC simulations, fifteen irrigation application events during the 82-day period from 8th October to 28th December 1997 were selected, because of

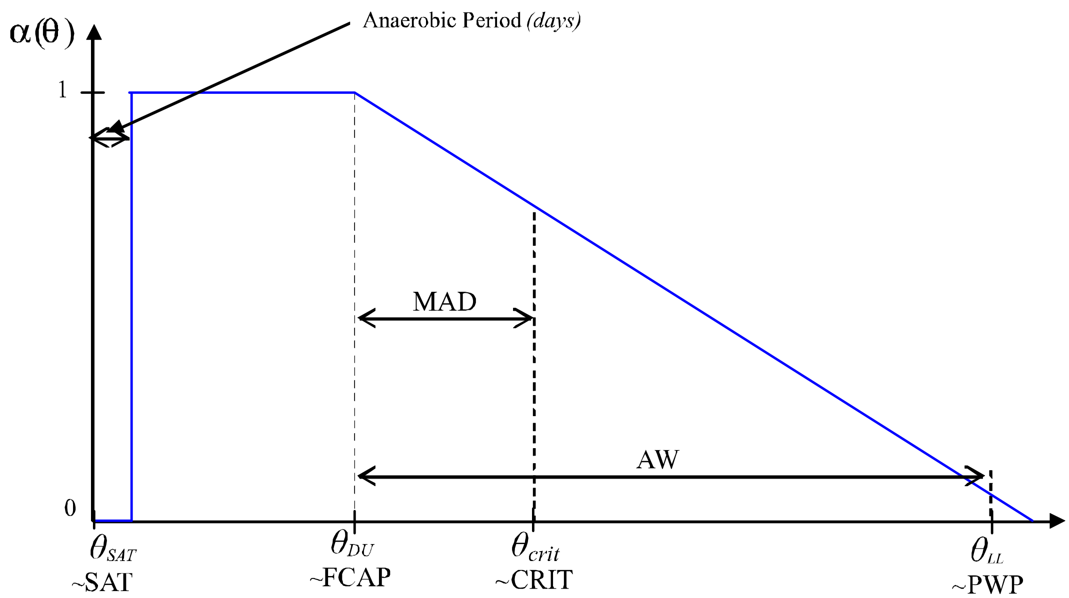

FIG. 1. SCHEMATIC OF MOISTURE AVAILABILITY REDUCTION FACTOR AS A FUNCTION OF SMC

daily measured SMC and climatic data availability (as shown later in Fig. 2). The irrigation interval between selected irrigation events ranged from 9-17 days. After having entered the required input data items, the model produced SMC values on a daily basis for each of the fifteen irrigation events. The model evaluation strategy for SMC simulations was based on both qualitative and quantitative procedures. The qualitative procedures visually compared the measured and simulated SMC time series over the given period of analysis. The quantitative procedure used statistical analysis to calculate the coefficient of determination (R^2), AE (Average Error), AAE (Absolute Average Error), RMSE (Root Mean Square Error), EF (Modelling Efficiency) and CRM (Coefficient of Residual Mass) between the measured and model-simulated SMC values. These statistical parameters were computed as described by [21-24]:

$$AAE = \frac{1}{n}\sum_{i=1}^{n}\left|\theta_p - \theta_m\right| \tag{15}$$

$$RMSE = 100 * \frac{\left\{\frac{1}{n}\sum_{i=1}^{n}(\theta_p - \theta_m)^2\right\}^{0.5}}{\bar{\theta}_m} \tag{16}$$

$$EF = 1 - \left(\frac{\sum_{i=1}^{n}\left(\theta_p - \theta_m\right)^2}{\sum_{i=1}^{n}\left(\theta_p - \bar{\theta}_m\right)^2}\right) \tag{17}$$

$$CRM = \frac{\left(\sum_{i=1}^{n}\theta_p - \sum_{i=1}^{n}\theta_m\right)}{\sum_{i=1}^{n}\theta_m} \tag{18}$$

where θ_p is simulated volumetric SMC (%); θ_m is measured volumetric SMC (%); $\bar{\theta}_m$ is mean of measured SMC (%); n is number of SMC data points. The R^2 parameter indicates the degree of general agreement between the measured and model-simulated SMC values. The AE statistical parameter represents the average difference (in % volume SMC) between the measured and model-simulated SMC values. It indicates whether the model has a tendency to over-estimate or under-estimate the observed SMC. A negative AE value indicates that the model generally under-estimates the measured SMC and vice versa. The AAE

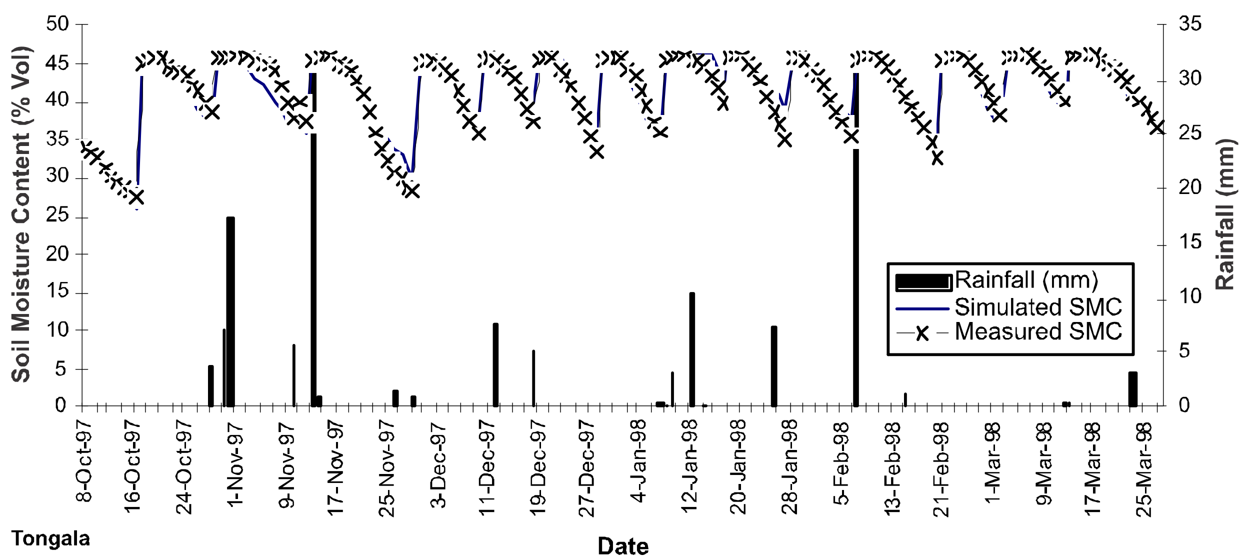

FIG. 2. MEASURED AND MODEL-SIMULATED SOIL MOISTURE CONTENTS AT TONGALA SITE

parameter represents the average absolute difference between the measured and simulated SMC values of the trialled irrigation period. RMSE describes the average percentage difference between the measured and simulated SMC values relative to the measured value, for the irrigation period under consideration. The EF parameter indicates the capability of the model to simulate actual field conditions. The CRM parameter is equivalent to that of AE, except that it indicates the over/under estimation characteristic of model in a non-dimensional form in the soil moisture simulation study [25].

The 'ideal' values of R^2, AE, AAE, RMSE, EF and CRM parameters are 1, 0, 0, 0, 1, and 0 respectively. The values of AAE less than 2% (in volumetric SMC units) are acceptable for irrigation scheduling purposes [22]. The value of EF varies between   for total lack of fit and 1 for exact fit; a value less than 0 indicates that the model simulations are worse than simply using the observed mean. Positive value of CRM means that the model over-estimates the measurements and vice versa [21].

6. RESULTS AND DISCUSSION

6.1 Quantitative Evaluation

The error statistics computed for the study period of irrigation season at Tongala site are given in Table 1. As shown in Table 1, the values of these parameters were computed for 15 data sets (ranging from 9-17 SMC observations per data set). A summary of these statistics (i.e. minimum, maximum, and average values) is presented in Table 2. The precision achieved with the model developed by the authors was also compared with that reported in the literature for other models.

The ideal value of coefficient of determination (R^2) is 1. As can be seen from Table 2, their average value is indeed very close to 1. The range of variation, when considering individual data set, also indicates that R^2 is generally close to one. When comparing this average value of R^2 with other studies, it could be observed that these R^2 values are acceptable as per [21] who

TABLE 1. STATISTICS FOR COMPARISON BETWEEN MODEL-SIMULATED AND MEASURED SMC (% VOLUME)

Data Set	R^2	AE (%vol)	AAE (%vol)	RMSE (%vol)	EF	CRM
1.	0.99	-0.66	0.66	2.81	0.85	-0.02
2.	0.97	-0.45	1.01	2.80	0.71	-0.01
3.	0.91	-1.73	1.83	5.32	0.43	-0.04
4.	0.99	1.02	1.29	4.46	0.93	0.03
5.	0.98	0.67	0.85	2.39	0.91	0.02
6.	0.98	1.05	1.05	2.91	0.81	0.02
7.	0.99	1.22	1.22	3.52	0.88	0.03
8.	0.97	-0.87	1.15	3.30	0.84	-0.02
9.	0.93	1.04	1.05	3.11	0.51	0.02
10.	0.96	1.24	1.26	4.60	0.74	0.03
11.	0.99	1.19	1.19	3.28	0.85	0.03
12.	0.99	-0.27	0.42	1.47	0.98	-0.01
13.	0.99	-0.71	0.89	2.71	0.80	-0.02
14.	0.98	-0.77	0.83	2.49	0.70	-0.02
15.	0.99	-0.86	0.88	2.42	0.90	-0.02

suggested a value of R^2>0.80 for comparisons between model simulations and observations. De Faria, et. al., [26] using VB4 and SWACROP models for wheat crops, reported that AE ranged from 2.4-3.3% and 2.4-3.6% respectively for these models. Mahdian and Gallichand [27] using the SUBTOR model in Canada, achieved AE and AAE values ranging from -3.3-0.7% and 3.3-4.2% respectively. Antonopoulos [25] in Greece, while testing a soil moisture simulation model using three different Smax functions obtained the maximum values of AE, RMSE and EF parameters as 1.4, 12.52 and 0.67 respectively. The CRM values in his study ranged from -0.05-0.02. For a loamy soil in China, Liu, et. al. [22] used ISAREG model for maize and wheat crops, and achieved the average AAE values less than 2% for both crops. In their study, the maximum value of average relative error parameter (an equivalent term to that of RMSE parameter of present study) obtained was equal to 10%. As can be observed from Table 2, for the developed model of this study all error statistics compared well with the above reported literature values. Hence, based on these error statistics, it can be concluded that the developed SMC simulation model is of acceptable accuracy for simulating SMC in the soil profile of pasture crops.

6.2 Qualitative Evaluation

Fig. 2 shows the simulated and measured SMC values during the 1997-1998 irrigation season for pasture at Tongala study site. From Fig. 2, it is also clear that developed model simulates the effects of soil-plant-atmosphere interactions reasonably well. However, some over and under-estimation by the model can be noted. For example, from 2nd November onwards the model under-estimated SMC measurements. This can be explained due to the simple fact that SMC of root zone was already at its SAT level (due to previous irrigation event of 29th October) when the rainfall on 31st October occurred, and hence this rainfall was totally treated as deep percolation loss by the model due to the assumption incorporated in it for such events. Nevertheless, as could be observed from Fig. 2 it settled down itself after a few days, while the SMC was still reasonably above the refill point. With regards to over-estimation, the three significant over-estimation events i.e. 25th November, 12th January and 24th January can be attributed to the combined effect of model inaccuracy, rainfall recording as well as SMC measurement errors that are not unusual during field data measurements. Also, it is interesting to note that the average CRM value in this case was positive which indicated an overall tendency of the model to over-estimate SMC measurements. Notwithstanding this, the error statistics described above indicated that the developed soil moisture simulation model easily satisfied the acceptance criterion for SMC simulations, and hence can safely be employed as an irrigation scheduling as well as a planning tool at farm level.

7. CONCLUSIONS

A semi-empirical soil moisture simulation model for use in irrigation water management was developed. The model employs the traditional water budgeting approach, and includes mechanisms for simulating soil moisture movement, root growth and crop evapotranspiration. The

TABLE 2. SUMMARY STATISTICS OF 15-DATA SETS FOR SMC COMPARISON AT TONGALA SITE

Statistical Parameters	Average	Range
Coefficient of Determination, R^2	0.97	0.91-0.99
AE (SMC %vol.)	0.07	-1.73-1.24
AAE (SMC %vol.)	1.04	0.42-1.84
RMSE (%)	3.17	1.47-5.32
EF	0.790	0.43-0.98
CRM	0.002	-0.04-0.03

model requires only a few input parameters that are readily available. The model calculates components of the water balance on a daily basis including actual evapotranspiration, deep percolation and the soil moisture depletion at different depths of the soil profile, to facilitate the decision of an irrigation application. The advantage of developed model over previous models is that this model accounts for dynamic root water extraction process using simple functions for which only the rooting depth information is required as the major input.

The validity of developed model was tested against field measured SMC data of a farm at Tongala in Goulburn Irrigation Area, Victoria (Australia). The SMC simulation analysis indicated that the developed model was quite successful to consider the variability of evaporative demand of perennial pasture crop and also to account for exactly the rainfall received during the irrigation period. It is important to appreciate that at Tongala study site, SMC simulations of the developed model showed an excellent agreement with the daily measured SMC data without the need for any significant calibration. The only parameter that required to be adjusted was the anaerobic days (i.e. the number of days followed by a heavy precipitation event during which the root zone remains at anaerobic conditions), which in this case was set to 3 days based on the visual observation of plotted graph of daily measured SMC data values. Although the performance of this model was found to be quite satisfactory at the Tongala site, yet for use under different soil and environmental conditions the model needs to be calibrated against measured SMC data under local conditions. The calibration aspect of this model is described.

The developed model easily satisfied the acceptance criterion for SMC simulations,and hence can be safely employed as an irrigation scheduling as well as a planning tool at farm level. The model has flexibility for its use under a wide range of soil, crop and climatic conditions, given the relevant soil, crop and climatic data are provided. This model can also play an important role in implementing irrigation sector reforms programs developed with the objective of improving irrigation assets' management as well as quality of service delivery through participatory management, and designing of drainage schemes.

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