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REVIEWS

Optimizing Water Use in Irrigation—A Review

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Abstract | In view of the ever increasing demand for water, every effort is directed towards increasing the efficiency of water-use including the optimal use of water for irrigation. An important long term goal of both engineering and agricultural hydrologists is to develop an improved understanding of the hydrologic processes involved in the transport of water from soil into and through vegetation. The process of root water uptake is modelled by a sink term in the equation for flow of water in unsaturated soils. Given the variation in root types, density, and structure with depth into the soil, researchers have used macroscopic models that adopt various functional forms to describe the vertical extraction of soil moisture into the root system. These models have sufficient number of parameters so that they can be fitted to data reasonably well. This paper discusses the physics of root water uptake, root uptake models and moisture extraction studies reported in the literature. Previously published work on performance evaluation of few prominent root uptake models suggests the need for a nonlinear representation of water uptake with depth. In this regard, an empirical model developed by some of the co-authors for nonlinear root uptake parameter is also discussed. Using the nonlinear root uptake model, optimal irrigation schedules may be developed to maximize irrigation water use.

1 Introduction

Growing water scarcity and misuse of available water resources are the major threats to sustainable development for most developing arid and semi-arid countries of the world. Irrigated agriculture is the main user of the available water resources. About 70% of the total water withdrawals and 60–80% of total consumptive water use are consumed in irrigation.[1] Food security can be achieved by irrigated agriculture since irrigation, on an average, doubles the crop yield compared to that usually produced under rain-fed conditions. The irrigated area would need to be increased by more than 20% and the irrigated crop yield by 40% by 2025 to secure the food for 8 billion people.[2] Given the increased stress on water to meet such crop requirements, higher irrigation efficiency would be essential. Many investigations have been conducted to gain experiences in irrigation of crops to maximize performance, efficiency and profitability. However, investigations into water saving irrigation practices are needed.[3] The amount of irrigation optimization that can be achieved is crop-dependent and generally governed by amount of water extracted by plant roots.[4]

Conventional irrigation practices in most of the world are designed to avoid crop stress in order to maximize yields. During the next few decades, as the inevitable expansion of irrigated lands for increased food production comes into conflict with accelerating competition for water and rising environmental concerns, this fundamental precept of irrigation management will probably be abandoned. The new operational rule that replaces it will be based on optimising water use in irrigation rather than yields.[5] This alternative approach, which might be referred to simply as 'optimization', is recognized as the most rational basis for irrigation management by economists and a growing number of irrigation professionals.

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A number of individual farmers, seeing the potential advantages of this approach, have attempted to develop optimum irrigation strategies on their own, but they have had little guidance from the scientific, economic or engineering communities. In fact, at present, there appear to be no educational or outreach programs providing advice on irrigation optimization for working farms in most parts of the world.

Approximately 70% of the water that is supplied to the crops as irrigation is returned to the atmosphere through evapotranspiration. Therefore, vegetated areas constitute an important part of the earth's hydrologic system, offering the most promising avenue demanding our attention for optimizing water use in irrigation. The boundary between soil and root system of the plants is a major hydrologic interface in that well over 50% of the evapotranspiration water crosses this interface. An important long term goal of both engineering and agricultural hydrologists should be to develop an improved understanding of the hydrologic processes involved in the transport of water from soil, into and through vegetation. This will lead to optimized irrigation water use and crop yield.

Water uptake by roots constitutes an important component of water balance in the field and hence understanding the root water uptake will help manage irrigation systems more efficiently. A quantitative means of describing root water uptake should be established for efficient water use. The processes of water transport within unsaturated soil layers in the root zone are controlled by physical properties of the soil, physiological characteristics of the plant and meteorological factors.[6] Generally, root water uptake from the root zone soil is modeled as a function of potential transpiration, vertical root distribution and soil water availability with or without a prescribed function of the soil moisture/pressure head accounting for the effect of reduction in moisture on uptake.

Moisture extraction from the root zone has been observed to follow different patterns, and different root water extraction models presume the uptake to be constant, linear, exponential or non-linear within the root zone. The model which predicts the moisture extraction in the root zone most accurately can help plan irrigation schedules with maximum water use efficiency. The present paper outlines various root uptake models available in literature and discusses their working efficiency. Published work on performance evaluation of few prominent root uptake models and empirical formulations to compute root uptake parameters have also been delineated. To estimate the soil moisture extraction in cropped soils, a root uptake model as a volumetric sink term may be added to the Richards equation to account for vertical accretion by plant roots.[7]

2 Physics of Plant Moisture Uptake

Root water uptake by plants is a critical process controlling energy exchange between the land surface and the atmosphere and plant growth. Root water uptake is therefore sensitive and an important building block in ecohydrological models that simulate terrestrial water, energy and carbon balances to support, crop growth or global climate models.[8,9]

Modeling the hydrological cycle requires a mathematical description of the process of the uptake of water from the soil profile by the plant root system. For many models, only a very gross description of this process is needed and the exact distribution of the water uptake over space and time is not critical. For example, the long-used rule of thumb that forty per cent of the water uptake comes from the upper quartile of the root zone, with successive zones contributing thirty, twenty, and ten per cent has been deemed adequate for many purposes.[10] were able to describe the water balance in a sandy soil with quasi-empirical representations of the evaporation and drainage processes without specifying the exact distribution of the uptake.

However, if we are to understand and model soil and plant processes and design efficient irrigations schemes, we need a quantitative means of describing the uptake process. This is especially true when dealing with questions of plant competition and other ecological questions. Only a limited review of relevant root uptake studies focussing on uptake physics has been carried out due to space constraints. Many models,[11–13] have in common the same basic premise that flow through the plant is viewed as analogous to flow through a resistance network. With the acceptance of the Richards equation for the flow of water in unsaturated soils and the development of methods for measuring the unsaturated conductivity of soils, it became possible to calculate the resistance to flow in the soil portion of the flow path.[14] The problem of coupling the flow system of the plant to that of the soil still remains unresolved.

From the popularly accepted Ohm's Law analogy, one can write equations for the steady state transport of water from a unit volume of soil to a plant leaf. It is recognized that when soil water is relatively available, flux is determined largely by atmospheric factors. At low soil water potentials, flux is determined by the stomatal resistance of the plant leaf, but this, in turn, is influenced by the rate of supply of water to the plant.

One especially important and difficult task for root water uptake models is to reflect the dynamic response of plant uptake to water stress, in which uptake increases from sparsely rooted but well-watered parts of the root zone to compensate for stress in other parts. This compensatory increase of water uptake from soil zones that are still well-watered following drying of more densely rooted layers has been repeatedly and convincingly documented for several decades.[15–18] Indeed, water uptake from deep subsoil has been shown to be critical in meeting atmospheric transpiration demand in water-limited environments,[19,20] especially where roots can reach the shallow groundwater.[21–23]

As a soil dries, plant water potentials also decrease, but the spatially (and especially vertically) distributed nature of the root system cause the hydraulic gradient between the canopy and soil layers that are still wet to increase. This feature compensates for the increased resistance to flow encountered from dry soil zones, so that transpiration can be maintained at the potential rate demanded by the atmosphere.[24] Contrasting irrigation practices can significantly alter the root biomass and vertical distribution of roots.[25,26] Soil drying in the densely rooted topsoil can induce a faster root penetration rate into the subsoil, and increased root growth in deeper, wetter soil layers at the expense of dry soil zones.[25,27–29]

One important unresolved challenge is to develop root water uptake models that are both relatively parsimonious with respect to data requirements, and can capture the complexity of the bio-physical response mechanisms underlying compensatory uptake in a realistic way.[9,30] 'Root architecture' models linked to soil water flow models[31–34] can provide extremely useful insights into the processes, but are too complex for routine use in large-scale modeling applications. Conversely, many crop growth models and land surface schemes include advanced mechanistic treatments of above-ground processes, but tend to oversimplify one or more aspects of root water uptake and cannot simulate compensatory mechanisms.

Several simple 'macroscopic' models have been proposed that can account for near-accurate root water uptake. Empirical approaches have been proposed that have been incorporated into some widely-used crop growth models and land surface schemes, and found to improve predictions of soil water contents.[35–41] A simple macroscopic root water uptake model that requires no more parameters than these empirical approaches, was also proposed.[42–44] This is a significant advantage, especially since the model parameters can be related to measurable properties of the soil and vegetation.

3 Parameters Involved in Root Water Uptake Modelling

It is usually difficult to evaluate the performance of the root water uptake models in an unambiguous manner because, in most cases, they are part of a one- or two-dimensional soil water flow formulation as a sink term. This sink term is dealt with in different ways by different authors who usually include some quantitative description of an effective root distribution and some analogy to moisture flow equation to give the dependence of the flux upon the soil water potential. In steady state root uptake models, an additional condition must be imposed, namely total daily water uptake by the plant root system must equal transpiration. In the calculations by,[45] it was found that the root distribution calculated to give the correct uptake at each depth and time interval agreed with that actually found by separating roots from the soil and measuring their actual length. However, the dominant factor in the uptake calculations was the non-linear water retention curve, and calculated patterns were not sensitive to assumptions about the actual number and distribution of roots.[46] It was further observed that uptake in the deeper portions of actual root systems was less, especially at initial times, than one would expect from the number of roots found, even after allowing for the effects of gravity.

There are a number of limitations with the approach described above. First, root distribution data are seldom available and are tedious to collect. Root systems are dynamic, and respond to many factors, including temperature, moisture, soil strength, pH, nutritional status, and plant maturity.[46] Immediately following an irrigation or rainfall event, transpiration is limited by the aerial portion of the plant and atmospheric factors. Eventually, soil water becomes limiting and uptake is then determined by the subsurface portion of the system. The transition from one regime to the other may not be readily predictable from the above model, and may have to be imposed from empirical considerations.

Many root uptake models assume that immediately following wetting of the soil profile, uptake from all portions of the root zone should be determined only by the effective root length at each depth and the gravitational component of the hydraulic head thereby ensuring some water withdrawal at all depths. However, this is often contrary to observations. Except in very confined root systems, water uptake from the lower portion of the root system does not occur for some time following a water application, and then only after significant quantities of water have been removed from the soil layers above. Even when there is considerable vertical resistance to flow within the root system, some uptake should still occur at all regions from the very beginning of a drying cycle. Nevertheless, most models have been considered reasonably satisfactory since an 'effective root distribution' can almost always be found that will provide a reasonable fit between calculations and observations for most of the root zone.

In an attempt to gain a better understanding of the uptake process, a large number of published root uptake patterns have been examined.[47] Root uptake models are often calibrated using field data such as soil moisture contents, rainfall rates or amounts, soil evaporation and plant transpiration rates.[48] The complex parameters of the root uptake terms such as root length density, root permeability and root water potential are chosen by trial error to make the overall model fit the data.[13] Root length, however, can be determined by well documented methods.[49] Evaporation and transpiration, or the evapotranspiration rate, are often estimated from the meteorological data[50,51] or by a water balance approach.[52]

Several researchers used a constant transpiration rate.[53–56] An accurate transpiration rate is required when validating Root Water Uptake (RWU) models, otherwise, errors in transpiration rate will affect the magnitude of the uptake rate and hence the reliability of the soil water predictions. Using a lysimeter setup to measure the crop evapotranspiration can help reduce uncertainty in the transpiration data. Crop evapotranspiration is partitioned into soil evaporation and plant transpiration using measured Leaf Area index (LAI) during the crop period. The procedures of obtaining various parameters involved in the RWU model are discussed by.[47]

4 Sink Term/Root Uptake Models

Moisture flow towards plant roots has been studied by a number of investigators. Some studies[13,57–61] utilized radial flow of moisture to a single root. Other studies[13,43,45,62–86] deal with the removal of moisture by the root zone as a whole, without considering explicitly the effect of individual roots. For convenience, the term microscopic is used for the flow process in the vicinity of a single root and macroscopic for the overall moisture extraction in the entire root zone. In the microscopic approach, an individual root is considered as an infinitely long cylinder of constant radius and water absorbing properties.[75] The soil moisture flow equation is written in cylindrical coordinates and solved with appropriate boundary conditions at the root surface and at some distance r_{max} from the root. In many studies, r_{max} is taken to be infinite. The appropriate form of the flow equation is:

$$\frac{\partial \theta}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rD\frac{\partial \theta}{\partial r}\right) \tag{1}$$

where D is soil moisture diffusivity, t the time and r is the radial distance from the axis of the root.[14] Solved this equation by applying appropriate boundary conditions. Based on the microscopic approach, the usual method for studying the composite soil-plant system has been to consider flow to a single root. The results are then multiplied by an average root density which incorporates the entire root-plant system.[14] Because the detailed geometry of a growing root system is time-consuming and expensive to measure, and the water permeability of a root varies with position along the root,[87] this type of approach is currently not in practice.

In the macroscopic approach, flow to individual roots is ignored and the overall root system is assumed to extract moisture from each differential volume of the root zone at some rate. At a given point, this rate depends on space, time, moisture content, water potential or a combination of these variables. The moisture removed by the roots is represented as an extraction term in the soil moisture flow equation. Boundary conditions are specified at boundaries of the composite soil-plant system, such as the soil surface and bottom of root domain or water table. By disregarding the flow towards the individual roots, this approach avoids any geometric complications involved in analyzing the distribution of the flux and the potential gradient at a micro-scale.[54,66,88] Models based on the macroscopic approach do not require complete insight into the physical processes of root water uptake and therefore eliminate the need for difficult-to-obtain soil and plant parameters. Macroscopic models have been specifically favoured in irrigation water optimization studies.

The idea of using an extraction function to represent or calculate water uptake by plant roots has been around at least since the early 1960's.[45,89] However, all of the various sink term functions proposed in literature are more or less empirical.[75]

The most important difference between the existing root extraction models is the uptake distribution pattern selected for the extraction function.

A comprehensive listing and study of extraction functions,[43,45,52,54,64,67,68,70–73,75,77–80,83,85,86,88–96] used by various researchers to represent water uptake by plant roots available in literature were carried out, few of which are given here. The symbols used are those in the original references. Some of the notations being used in these models are common wherein, k or K is unsaturated hydraulic conductivity, L the length of roots per unit soil volume, T the transpiration rate per unit soil surface area, t the time, z the depth below soil surface, z_r the root depth, v the depth of root zone, θ the soil moisture content, θ_s or θ_{sat} the saturation moisture content, ψ the pressure head, T_p the plant transpiration rate, f(h) or α(h) is prescribed function of the soil moisture pressure head, S_{max} the maximum rate of root water extraction and E_{pl} is the actual transpiration.

Gardner (1964)

$$S = B(\delta - \tau - z)kL \tag{2}$$

where B is the constant, δ the water potential of plant roots and τ is the suction potential of soil.

Molz and Remson (1970)

$$S = \frac{-1.6T}{v^2}z + \frac{1.8T}{v} \tag{3}$$

Feddes et al. (1978)

$$S_{max} = \frac{2E_{pl}}{z} = \text{maximum rate of root water extraction} \tag{4}$$

$$\begin{aligned} &S = 0 \quad 0 \geq \psi > \psi_1 \\ &S = S_{max} \psi_1 \geq \psi > \psi_2 \\ &S = S_{max}(\psi - \psi_3)/(\psi_2 - \psi_3)\ \psi_2 \geq \psi > \psi_3 \\ &S = 0 \quad \psi_3 \geq \psi \end{aligned}$$

where ψ_1 is maximum soil pressure head for which $S = S_{max}$, ψ_2 is minimum soil pressure head for which $S = S_{max}$, and ψ_3 is soil pressure head at wilting.

Prasad (1988)

$$S(h) = \alpha(h)\ S_{max}$$

$$S_{max} = \frac{2T_j}{z_{rj}}\left(1 - \frac{z}{z_{rj}}\right) \tag{5}$$

where α(h) is prescribed function of the soil moisture pressure head, T_j is transpiration on jth day and z_{rj} is root depth on jth day.

Govindaraju and Kavvas (1993)

$$S_{max} = \frac{E_{pot}}{z_r} = \text{maximum possible root extraction rate} \tag{6}$$

$$S(\psi) = \alpha(\psi)\ S_{max}$$

$$\alpha(\psi) = \exp[-\delta(\psi - \psi_b)], \quad \psi \leq \psi_b$$

$$\alpha(\psi) = 0, \quad \text{otherwise}$$

where α(ψ) is a dimensionless function which determines the proportion of the maximum possible root extraction rate for a particular value of ψ, E_{pot} is potential transpiration rate, ψ_b is the bubbling pressure and δ is an exponential decay constant reflecting the rate at which water availability to roots is reduced as the soil becomes drier.

Ojha and Rai (1996)

$$S_{max} = \alpha\left[1 - \left(\frac{z}{z_{rj}}\right)\right]^{\beta} 0 \leq z \leq z_{rj} \tag{7}$$

where α is given as

$$\alpha = \frac{T_j(\beta + 1)}{z_{rj}}$$

$$S(h) = f(h)S_{max}$$

where α and β are model parameters and z_{rj} is root depth on the jth day.

Li et al. (1999)

$$S(h) = \alpha(h)S_{max} = \frac{K_{z_1 - z_2} PT_j}{|z_1 - z_2|} \tag{8}$$

where PT_j is potential transpiration on jth day and $K_{z_1 - z_2}$ is fraction of the total root length between depths z_1 and z_2 for a given area.

Lai and Katul (2000)

$$S(\theta, z, t) = \alpha(\theta)g(z)E_p(t) \tag{9}$$

where $\alpha(\theta)$ is root efficiency function, g(z) is the root density function and $E_p(t)$ the potential transpiration.

Kang et al. (2001)

$$S(z,t) = f(\theta)T_p(t)\frac{1.80e^{-1.8z/z_r}}{(1-e^{-1.80})z_r} \tag{10}$$

where $f(\theta)$ is a dimensionless term ranging between 0 and 1, as a function of soil water content, $T_p(t)$ is potential transpiration rate, z_r is the effective root zone depth.

Dogan and Motz (2005a)

$$W_r(h,z,t) = \left(1-\left\{\frac{h_{fc}-h}{h_{fc}-h_{wp}}\right\}^{C_3/T_p}\right) \times \left(\frac{\ln C_d}{C_d^{Z_r}-1}T_p\right)C_d^z \quad \text{if } h \le h_{fc} \tag{11}$$

$$W_r(h,z,t) = 0 \quad \text{if } h > h_{fc}$$

where $W_r(h, z, t)$ is root water uptake term, h_{fc} and h_{wp} are pressure heads at field capacity and at wilting point of the soil around root zone, h is the pressure head around root zone, C_d the crop and soil coefficient ($0.1 < C_d < 1$) and C_3 the parameter which defines the shape of the water stress function.

5 Moisture Extraction Studies

Of the various detailed quantitative studies of water extraction by plant roots, many authors have developed or applied dynamic models by coupling the root uptake term as sink term with the 1-D or 2-D Richards equation. For one dimensional vertical flow in a cropped soil, the mixed form of the Richards equation with a sink term accounting for root water uptake can be written as[95]

$$\frac{\partial}{\partial z}\left[K(\psi)\left(\frac{\partial \psi}{\partial z}+1\right)\right] - S(z,t) = \frac{\partial \theta}{\partial t} \tag{12}$$

where ψ is the pressure head, θ the volumetric moisture content, K the hydraulic conductivity, S(z, t) the water uptake by roots expressed as volume of water per unit volume of soil per unit time, t is time, and z is the vertical distance measured positive upwards. Equation (1) is non-linear in nature, since the conductivity and storage properties (K and θ) are complex functions of the dependent variable ψ. This necessitates use of functional relationships for $\theta - \psi$ and $K - \theta$. Of the many empirical functional forms existing in the literature for the SMC, the most popular are Brooks-Corey[98,99] and van Genuchten[100] relationships. The[100] relationships for $\theta - \psi$ and $K - \theta$ are as follows:

$\theta - \psi$ Relationship

$$\Theta = \begin{cases} \left[\dfrac{1}{1+\|\alpha_v\,\psi\|^{n_v}}\right]^m & \text{for } \psi < 0 \\ =1 & \text{for } \psi \ge 0 \end{cases} \tag{13}$$

where α_v and n_v are unsaturated soil parameters with $m = 1 - (1/n_v)$ for ($n_v > 1$) and Θ is the effective saturation defined as

$$\Theta = \frac{\theta-\theta_r}{\theta_s-\theta_r} \tag{14}$$

θ_s is the saturated moisture content, and θ_r is the residual moisture content of the soil.

$K - \theta$ Relationship

$$K = \begin{cases} K_{sat}\Theta^{1/2}[1-(1-\Theta^{1/m})^m]^2 & \text{for } \psi < 0 \\ = K_{sat} & \text{for } \psi \ge 0 \end{cases} \tag{15}$$

where K_{sat} is the saturated hydraulic conductivity of the soil.

Over the years, different root uptake models have been used to represent plant moisture extraction. Some of the popular models are discussed here.

Molz and Remson[54] attempted to justify the use of extraction functions in the Darcy-Richards equation and compared calculations with data.[45,101] A linear model was proposed to fit an empirical rule that 40, 30, 20 and 10%, respectively, of the total transpiration requirement comes from each successively deeper quarter of root zone.[54] They also performed a sensitivity analysis.[13] The results were promising, although the particular extraction function had limitations. A water transport model of the soil-plant-atmosphere continuum (SPAC) was developed, which was able to simulate field and lysimeter data to a useful degree.[77,78] Extensive studies in this field culminated in the development of a well documented model for simulating field water use.[67,91,92] In many empirical root water extraction models, a constant rate of extraction was assumed for entire root zone.[92,102] However, these models do not satisfy the condition that root water extraction is typically maximum at the top and zero at the bottom of the root depth.

Linear models for soil moisture extraction represented the maximum extraction at the top of the roots, but they failed to represent zero extraction at the bottom of the root zone.[54,103] A linear model that satisfied the desired extraction at the root top and bottom was also proposed.[80] It was observed that this model was better in comparison to constant and linear rate models proposed earlier. However, the model did not provide a sufficient comparison with the experimental soil moisture depletion values.[104] In a comparison carried out, it was observed that the constant rate model underestimates the moisture depletion in the top layers and overestimates that in the bottom ones.[80] In contrast, the linear rate extraction model, agrees better with the experimental measurements, although, a tendency of underestimation in the top layers and overestimation in the bottom layers were still noticed.[80] These analyses postulate that introduction of an appropriate non-linearity would conceivably bring much better agreement with field measured values of moisture depletion.

Nimah and Hanks used the root water extraction function given by Feddes, by expressing soil suction-dependent reducing factor in a fundamentally different way, divided the soil profile within the root depth into k layers and introduced a weighted stress index, while Govindaraju & Kavvas introduced an exponential decay constant reflecting the rate at which water availability to roots is reduced as the soil becomes drier.[68,70,77,92] Janz and Stonier incorporated an evaporation front in the term given by Molz and Remson to account for the ineffectual roots in upper zone.[52–54]

Ojha and Rai[43] presented a nonlinear root water uptake (RWU) model that accommodated linear and constant rate extraction models as particular cases. The model satisfies the desired extraction conditions at the top and bottom of the root zone. The model also satisfies the condition that root water uptake varies non-linearly with depth because root density is a non-linear function of soil depth. This RWU model incorporates a parameter 'β', which represents the non-linearity of the moisture extraction pattern. A normalized distribution function of root density in the sink term to characterize the relative distribution of root density at various growth stages was introduced.[71] An exponential root water extraction model[95] based on an exponential root length distribution function was also developed to emphasize that root water uptake is proportional to root length density.

A model with a different root density distribution function and a root efficiency function was considered as basis for work on root water uptake.[79,94] Further it was proposed that potential transpiration be distributed across the root zone according to a weighted stress index that acts as a function of both root distribution and soil water availability.[73] In addition to one dimensional root extraction models, few two and three dimensional models have also been developed.[86,105,106] One-dimensional models are more popular compared to two and three dimensional models, due to their simplicity.

Another exponential model for water uptake by roots was developed.[72] Their simulation combined an existing soil water flow mathematical model in the unsaturated zone, a modified transpiration model considering the air pressure influence and the diurnal changes of the extinction coefficient of a crop canopy, and a new model for root water uptake. Comparisons between the outputs from simulation and field experiments validated the model. In their study authors aimed at developing a saturated-unsaturated, 3D, rainfall driven, groundwater-pumping model (SU3D), proposed an algorithmic root uptake term.[64,65] The model is built on a conceptualization of the unsaturated zone and integration with an evapotranspiration module in which evaporation and transpiration are computed separately. Experimental validation of the moisture uptake is required to comment on the performance of the model as compared to other existing models.

Until the early nineties, only constant and linear rate models have had predominance.[54,75,80,92] The reason for wide applicability of some of the constant rate[92] and linear[54,80] models is that they involve 'easy to obtain' parameters. Nonlinear, exponential and logarithmic RWU models have been shown to represent moisture extraction pattern more accurately, but such models involve parameters that are difficult to obtain in the field. Authors of RWU models acknowledge that plant moisture extraction pattern is neither constant nor linear.

6 Performance Evaluation of Root Uptake Models

Most of the root extraction functions involve parameters, which are either difficult to obtain in the field or their standard values are not available i.e., water potential of plant root,[45] root water potential,[89] internal root pressure head,[77] hydraulic head of the plant at the base of the stem,[88] soil resistance to root water uptake,[83] water potential of the root system,[75] stress index in the specific root zone layer,[70] normalized function of relative root density,[71] and empirical crop and soil coefficient.[64] Some of the moisture extraction models are simply based on previously existing extraction functions and incorporate slight changes in slight changes in the basic models.[52,54,68,79,92,94]

Root uptake models involving intricate parameters have reduced field applicability. Of the various root water uptake models, constant rate model,[92] linear rate model,[80] non-linear root water uptake model,[43] exponential root water uptake model[95] and exponential model[72] are the prominent ones. These models involve parameters that are easy to obtain in the field. All envisioned depletion patterns i.e., constant, linear, exponential and non-linear, investigated till date, are characterized by the root uptake models.

The nonlinear root water uptake model by,[43] termed as O-R model hereafter, quantifies nonlinearity in plant moisture uptake. According to O-R model, for potential transpiration conditions, the potential rate of soil water extraction S_{max} along the root length is given by the relation

$$S_{max} = \alpha\left[1-\left(\frac{z}{z_{rj}}\right)\right]^{\beta}, \quad 0 \le z \le z_{rj} \tag{16}$$

where α and β are O-R model parameters, z is the depth below soil surface and z_{rj} the root depth on the jth day. For $z = z_{rj}$, S_{max} is zero as per equation (16) and at $z = 0$, S_{max} attains a maximum value of α. Thus, equation (16) satisfies the desired conditions that extraction is maximum at the top and zero at the bottom of the root. In addition, S_{max} has to satisfy the following equation:

$$\int_0^{z_{rj}} S_{max}\,dz = T_j \tag{17}$$

where T_j is the transpiration on jth day. Substituting S_{max} from equation (16) into equation (17) yields

$$T_j = \frac{\alpha z_{rj}}{(\beta+1)} \tag{18}$$

from which α is obtained as

$$\alpha = \frac{T_j(\beta+1)}{z_{rj}} \tag{19}$$

Using equation (19) in equation (16), S_{max} can be expressed as

$$S_{max} = \left[\frac{T_j}{z_{rj}}(\beta+1)\left(1-\frac{z}{z_{rj}}\right)^{\beta} \quad 0 \le z \le z_{rj}\right] \tag{20}$$

From Eqn. (20), it is evident that β quantifies the nonlinearity in the O-R model. Apart from the simplicity of the parameters involved, meeting out the desired moisture extraction conditions at root zone boundaries is a unique feature of the model. The parameter 'β' of the O-R model represents the nonlinearity in moisture extraction with depth in the soil. For $\beta = 0$, (20) reduces to a constant rate extraction model of Feddes[92] with $S_{max} = T_j/z_{rj}$ while for $\beta = 1$, (20) reduces to linear extraction model of Prasad[80] with $S_{max} = 2T_j/z_{rj} - 2T_j\,(z/z_{rj}^2)$. The O-R model has the potential for use in optimal irrigation design.

The performance of different root water extraction models was examined using secondary data as well as data generated under controlled conditions.[42,47,104] Data pertaining to moisture uptake for two crops, wheat and maize, along with soil-water characteristics was monitored at the agricultural farm in Indian Institute of Technology Roorkee.[47] Reference evaporation was computed using the Penman-Monteith equation for the ET_0.[107] The crop evapotranspiration was computed as a product of reference evapotranspiration and corresponding crop coefficient. Further, the daily crop evapotranspiration was partitioned into plant transpiration and soil evaporation using equation proposed by Belmans[108] where soil evaporation (E_s) is calculated as a fraction of the ET_c using the LAI of the soil surface. A numerical model was formulated by incorporating different moisture extraction as a sink term in the Richards equation subjected to initial and boundary conditions, and employing soil constitutive relationships.[100] The numerical model was based on a mass conservative, fully implicit finite difference scheme.[97] The nonlinear system of equations was linearized using Picard's methods[109] and the resulting system of equations was solved using Thomas algorithm. The model yields spatial distribution of pressure head and moisture content at successive advancing times in the soil. From the model-computed moisture contents, the moisture depletion values at different root zone depths, and at different times were computed by numerical integration.[42]

The O-R model is more general than other root water extraction models.[72,80,92,95] The modeled and experimental values were compared using statistical parameters COD, ARE and COV.[42,110,111] For using the Sankar[44] model, the optimal value of non-linearity parameter 'β' denoted as $\beta_{optimal}$ is required. For a perfect fit, COD equals unity. The value of β, which gives maximum COD for a particular crop, is the optimum value of β for that crop. For every crop, a specific optimum beta value exists, which represents the nonlinear moisture

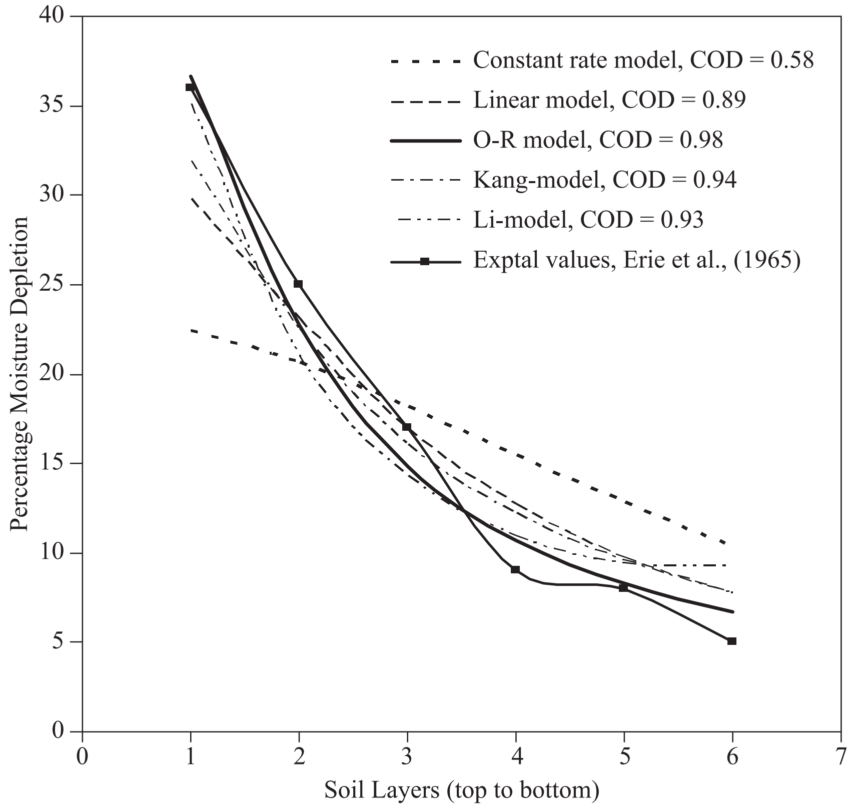

Figure 1: Comparison of percentage soil moisture depletion estimated using different root uptake models, with field observed data for wheat.

uptake pattern of that crop. Comparative evaluation of O-R model with moisture extraction terms, i.e., constant rate and linear rate (as special cases of O-R model), exponential root water uptake terms by Kang[72] and Li[95] was carried out. The percentage moisture extractions from different layers of the crop root zone predicted using the numerical model were compared with experimental values.[104] Figures 1 and 2 show the comparison of model predicted values corresponding to different root uptake models with field observed values for Wheat and Maize.[42,47]

Results of the evaluation of O-R model were substantiated with field observed soil and crop data, stressing on two aspects; one that crop specific β obtained using secondary data works well for field crops also, and secondly that the O-R model coupled with soil moisture flow simulates the soil moisture profiles in the field well. Data obtained from field crop experiments were applied to a numerical model coupled with the O-R model. Predicted soil moisture depletion patterns on discrete days and soil moisture status during the crop period were compared with the corresponding observed values. To further validate the prediction efficiency of the O-R model, observed and predicted soil moisture at depths of 0–0.15, 0.3, 0.6, 0.9, 1.2 and 1.5 m throughout the crop period were compared. A very good agreement between simulated and observed soil moisture variation at a particular depth throughout the crop period was observed.[47]

It was inferred from the study[42] that β obtained for wheat and maize on the basis of secondary data works well for the field crops too, and the O-R model incorporating β coupled with the soil moisture flow equation may be reliably used to assess moisture uptake in the field. The work postulates the suitability of the O-R model for being used in irrigation water management studies. Though β needs to be established for each crop, once its value is established, accurate prediction of soil moisture depletion can be achieved. The study highlights the need to establish the value of β for a variety of crops.

7 Emprical Formulation to Assess Uptake Parameter

An empirical relationship for the nonlinear root water uptake parameter ‘β’ in the O-R model based on easily measurable plant physiological parameters such as maximum daily

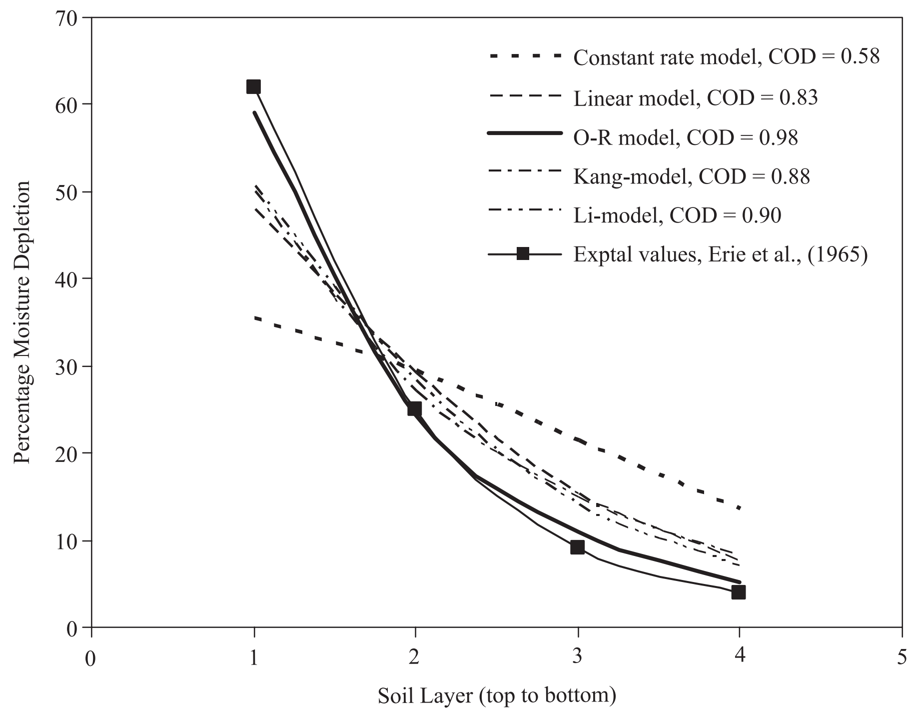

Figure 2: Comparison of percentage soil moisture depletion estimated using different root uptake models, with field observed data for Maize.

transpiration, maximum root depth, and time to attain the maximum transpiration was developed.[43,44] The nonlinearity increases with an increase in the value of β resulting in higher moisture depletions in the top layers of the crop root zone. Estimation of soil moisture depletion in different layers of the root zone is necessary for optimal scheduling of irrigation events. A non-dimensional parameter termed 'Specific Transpiration' involving the plant physiological parameters was used in this empirical relationship. Data for determining this relationship were obtained by minimizing the deviations between the field observed moisture depletions of 28 crops reported by Erie and Others[104] and Richards equation-based numerically simulated soil moisture depletions combined with O-R model accounting for root water uptake.

7.1 *Empirical relationship for β*

Crop specific nonlinear parameter of the O-R model from the field measured moisture depletions for a variety of crops was estimated. An empirical relationship for the estimation of optimal nonlinear parameter β from the easily measurable plant physiological parameters such as maximum daily transpiration T_{jmax}, maximum root depth Z_{rmax} and time to attain the maximum transpiration t_{peak}, was developed. Specific transpiration (T_s) was defined as

$$T_s = \frac{T_{j\,max}}{z_{r\,max}} \times t_{peak} \tag{21}$$

The empirical relationship between β and T_s using nonlinear regression from[28] data was obtained as

$$\beta = 5.1128\,T_s^2 - 6.117\,T_s + 3.1545 \quad 0.07 \le T_s \le 0.98 \tag{22}$$

The applicability of the proposed empirical relationship between the specific transpiration T_S and the optimal nonlinear root water uptake parameter β was studied by (i) conducting Leave-One-Out Cross Validation analysis between T_S and β for the 28 crops used for regression, (ii) determining β for Wheat, Maize and Indian Mustard using the empirical relationship from the field data and (iii) comparing the field observed and model predicted soil moisture profiles and soil moisture depletions in the root zone and the statistical analysis of the deviations.[44]

Leave-one-out cross-validation (LOOCV)[112,113] substantiated the developed empirical relationship as for a majority of the crops, and the error percentage ranged within 6.5% with few exceptions. The error percentage had an average value of 4.86% and a standard deviation of 3.56%. The three plant physiological parameters needed for the determination of the optimal nonlinear water uptake parameter β were noted from the field experiments for the three crops, Wheat, Maize and Indian mustard. For the three crops, field observed moisture profiles and soil moisture depletions in different layers of the crop root zone at various crop growth stages were compared with the model predicted soil moisture profiles and depletions.[44] The model predictions were obtained by solving Richards equation and quantifying the root water uptake with the β obtained from the empirical relationship.

The model predicted soil moisture profiles at different Days After Sowing (DAS) in the root zone compared fairly well with experimental observations for all the three crops. The COD was above 0.87 for all the three crops, indicating a good agreement between the predicted and observed moisture contents at different times. Maximum ARE of 4.6% was obtained in case of maize and a maximum COV of 0.27 for Wheat. To compare the soil moisture depletions, the root zone was divided into different layers with each layer being 15 cm thick. Soil moisture depletion in each layer was computed at various periods of crop growth and compared with the experimentally observed soil moisture depletions. The model predictions were in a good agreement with the experimental observations. It was noticed that just like the predictions of constant and linear model, the O-R model too underestimates the soil moisture depletion in the upper layers and over estimates in the deeper layers for all the three crops. The model predictions match very well with experimental observations in the middle layers. The COD varied between 0.82 and 0.94 for all the three crops indicating a good agreement between the predicted and observed moisture depletions at different times. A maximum ARE of 3.3% was obtained in case of maize and a maximum COV of 0.42 in case of Indian mustard.

Soil moisture contents were measured periodically at different depths in the root zone. Five typical depths in case of Maize and Indian mustard—15, 30, 60, 90 and 120 cm—and a sixth additional depth of 150 cm in case of Wheat were considered for the model-simulated and field-observed soil moisture contents. It may be observed from Figs. 3 and 4 that the model predicted moisture profiles and moisture contents at different depths are in close agreement with the field observed values. Apart from a cross-validation, field experiments on three Indian crops—Maize, Indian mustard and wheat were conducted to further validate the proposed empirical relationship. Comparisons of model predictions with field observations of soil moisture profiles and moisture depletions in different layers of the root zone show good agreement during different stages of crop growth. Results highlight the utility of the developed equation for modeling root water uptake and the observations of field crop experiments validate the empirical relationship.

Leave-one-out cross validation analysis suggests that the variation in regression coefficients with the variation in data is small. Comparison of model predictions with field observations and the statistical analyses indicate that the model predicted soil moisture profiles and moisture depletions in different layers of the root zone are in good agreement. Since the empirical relationship relies on easily measurable plant physiological parameters, it will prove useful for planning irrigation events for crops without the need for costly experiments. The relationship is a tool to compute nonlinear root uptake parameter of O-R model for any crop, using which moisture extraction by any crop can be estimated. The predicted moisture

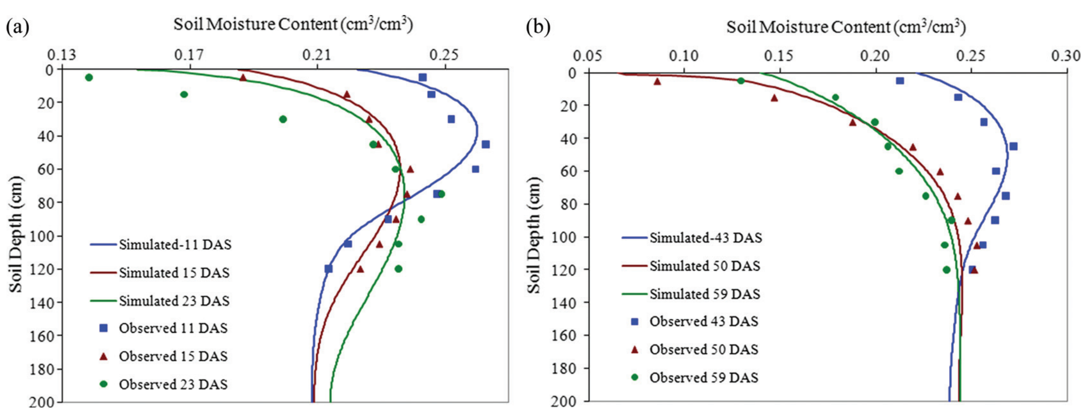

Figure 3: Comparison of model predicted and field observed soil moisture profiles on (a) 11, 15, 23 (b) 43, 50 and 59 DAS for Maize.[98]

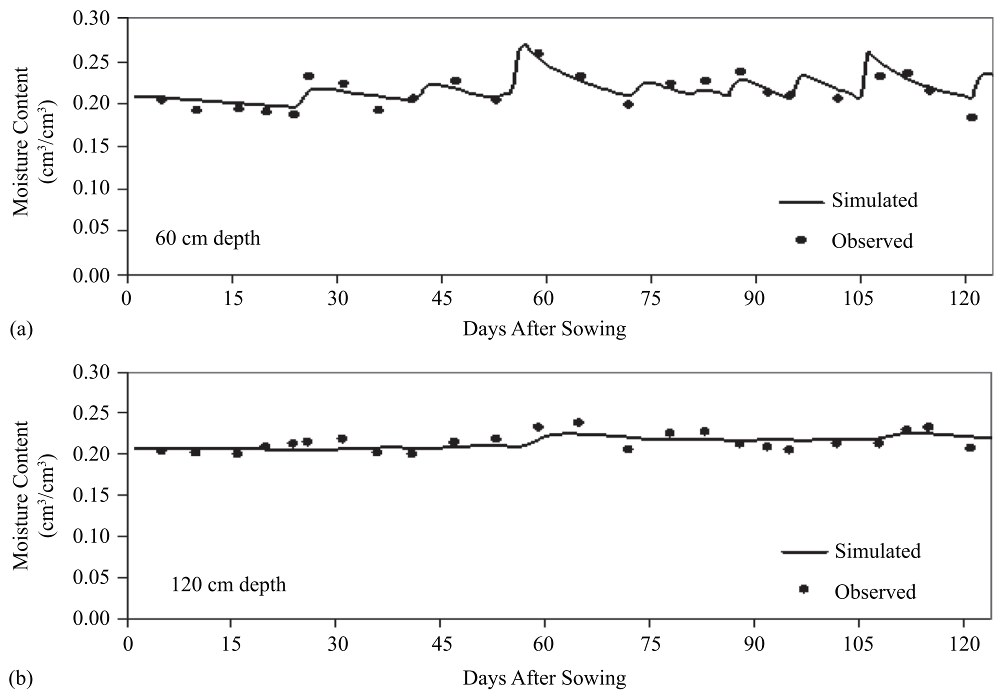

Figure 4: Comparison of model predicted and field observed soil moisture for the entire crop period for Wheat at (a) 60 and (b) 120 cm depths.[47]

extraction can be used to design optimum irrigation schedules for the crop.

8 Optimal Irrigation Schedules

Plant-Available Water (PAW) is the difference between the volume of water stored when the soil is at field capacity and the volume still remaining when the soil reaches the permanent wilting point. But the plants are unable to extract moisture below certain moisture depletion levels which lie between field capacity and permanent wilting point. Enough irrigation water should be applied to replace the depleted PAW within the root zone. About 70 percent of the water used by a crop is obtained from the upper half of the root zone. This zone is referred to as the effective root depth.[114] This depth is used to compute the volume of PAW. Irrigation amounts are computed to replace only the depleted PAW within the effective root zone. Applying only part of the scheduled amount of irrigation water will result in more efficient use of water, although this approach may require more frequent irrigation.

Generally, irrigation is practiced when the average moisture content within the root zone depth attains a certain value between the field capacity and permanent wilting point.[78] This value of moisture content is called the allowable depletion level. An adequate scheduling criterion is an important parameter in determining the frequency of irrigation events. The two parameters which contribute to assigning an adequate scheduling criterion are allowable moisture depletion level and root depth considered for accounting the average soil moisture level.

Irrigation schedules for the crops grown in the field, i.e., Maize, Indian mustard and Wheat were designed.[44] The hypothetical condition of no-rainfall was considered during the corresponding crop periods. Though, allowable moisture depletion level is dependent on the type of crop and the moisture retention capacity of the soil, 50% and 75% moisture depletion levels are not uncommon. The effective root depth considered for accounting the average soil moisture status is 0.2 m till the root depth is less than 0.2 m and half the maximum root depth when maximum root depth is more than 0.2 m with a minimum of 0.2 m always in case of all the three crops. The measured field capacity and permanent wilting point values for the soil were 0.208 and 0.068 respectively. At 50% allowable moisture depletion level, irrigation is required to be provided whenever average soil moisture in the effective root depth lowers to 0.138. Figs. 5, 6 and 7 show the irrigation schedules developed using moisture uptake prediction based on O-R model for Maize, Indian mustard and Wheat respectively. In case of Wheat, the number of irrigation events in the initial and development stage of crop growth is less due to low evapotranspiration requirements during this

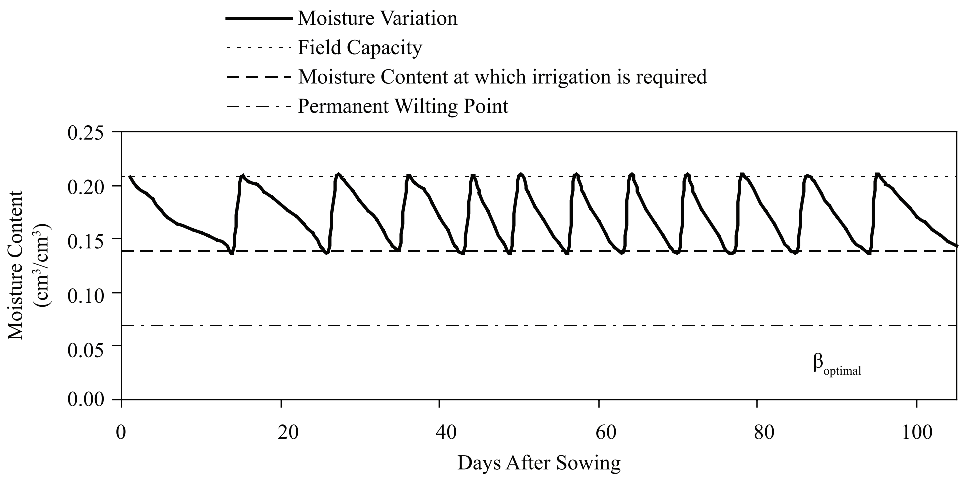

Figure 5: Irrigation schedule at 50% allowable depletion for Maize based on O-R model.

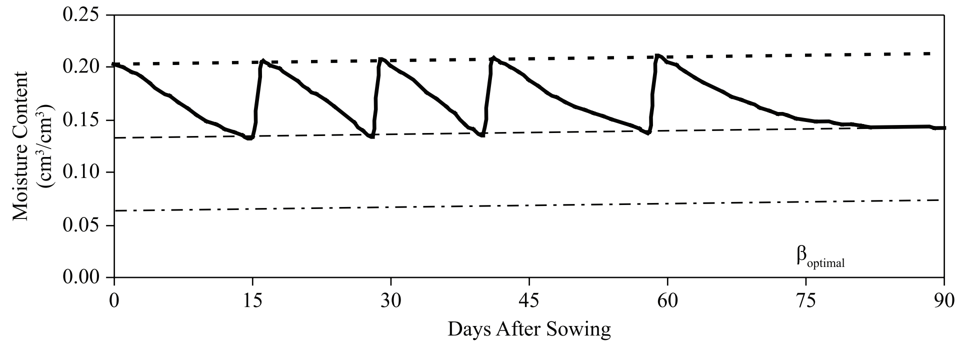

Figure 6: Irrigation schedule by O-R model at 50% allowable depletion for Indian mustard.

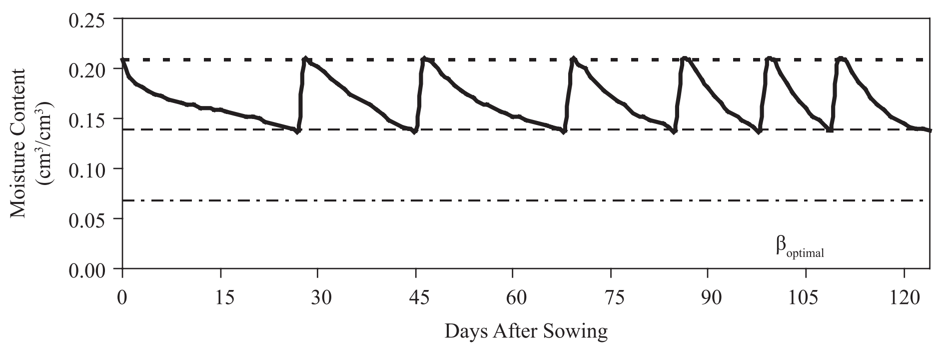

Figure 7: Irrigation schedule at 50% allowable depletion for Wheat based on O-R model.

period. However, during mid-season and late season stage, frequent irrigations are needed.

It may be concluded that if the accurate moisture extraction by the crops can be estimated, optimal irrigation schedules for the crop can be developed by using data on soil retention characteristics and plant parameters, i.e., field capacity, permanent wilting point and root depth. Also, consideration of the nonlinearity in root water uptake results in irrigation water savings. Irrigation scheduling at different allowable moisture depletion levels can be devised as per the requirement of the crop, water availability and moisture retention capacity of the soil.

Accurate prediction of the moisture uptake pattern helps in planning of optimal irrigation schedules. Crop specific nonlinearity in moisture uptake significantly differentiates, the predicted moisture use patterns being followed for accounting the crop water requirement. Irrigation scheduling with O-R model results in reduced number of irrigation events as the moisture extraction prediction efficiency of the model is established.

9 Conclusions

1. There has been an evolution in root water uptake models of increasing complexity.
2. Models, such as the O-R model that have some physical basis and allow for estimation of root uptake model parameters based on easily measured values are desirable.
3. Future work should test such models for different crops, and be used for operational use in planning irrigation operations and building crop resiliency for drought conditions.

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