Effect of Shallow Groundwater Table on the Moisture Depletion Pattern in Crop Root Zone

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Abstract—Different techniques for estimating seasonal water use from soil profile water depletion frequently do not account for flux below the root zone. Shallow water table contribution to supply crop water use may be important in arid and semi-arid regions. Development of predictive root uptake models, under influence of shallow water table makes it possible for planners to incorporate interaction between water table and root zone into design of irrigation projects. A model for obtaining soil moisture depletion from root zone and water movement below it is discussed with the objective to determine impact of shallow water table on seasonal moisture depletion patterns under water table depth variation, up to the bottom of root zone. The role of different boundary conditions has also been considered. Three crops: Wheat (Triticum aestivum), Corn (Zea mays) and Potato (Solanum tuberosum), common in arid & semi-arid regions, are chosen for the study. Using experimentally obtained soil moisture depletion values for potential soil moisture conditions, moisture depletion patterns using a non linear root uptake model have been obtained for different water table depths. Comparative analysis of the moisture depletion patterns under these conditions show a wide difference in percent depletion from different layers of root zone particularly top and bottom layers with middle layers showing insignificant variation in moisture depletion values. Moisture depletion in top layer, when the water table rises to root zone increases by 19.7%, 22.9% & 28.2%, whereas decrease in bottom layer is 68.8%, 61.6% & 64.9% in case of wheat, corn & potato respectively. The paper also discusses the causes and consequences of increase in moisture depletion from top layers and exceptionally high reduction in bottom layer, and the possible remedies for the same. The numerical model developed for the study can be used to help formulating irrigation strategies for areas where shallow groundwater of questionable quality is an option for crop production.

Keywords—Moisture Depletion, crop root zone, ground water table, irrigation.

I. INTRODUCTION

MOSTLY it is being observed that, as the water becomes scarce in arid and semi-arid regions, use of shallow water table developed in many areas plays an important role in crop water supply.

Several factors have developed which have changed the thinking regarding the management of irrigation systems. As water supplies become scarce, all available water supplies are evaluated as potential sources of irrigation water. Recent research has indicated that most crops have higher salt tolerance values than previously thought [18], which means

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that many ground waters of tolerable quality are suitable for supplemental irrigation purposes. Many researchers [14], [12] and [3] have shown in field and lysimeter studies that crops will extract significant quantities of water from the shallow groundwater. The limitation has been using these data to manage an irrigation system to insure the groundwater use by a crop [2]. [1] Developed a modification for a cotton crop coefficient to explicitly account for shallow groundwater use by the crop. This modification provides a positive means of developing the passive groundwater management potential in a given irrigation system.

Studies in California and Texas (USA) have shown that salt tolerant crops (cotton, alfalfa, barley) are capable of extracting significant quantities of water from a saline water table [3]. [9] reported that under arid conditions, water table can supply as much as 60-70 % of a crop's water requirements. [21] found that cotton extracted up to 60 % of its evapotranspiration (ET) from a saline (6 dS/m) water table. [3] reported that cotton extracted up to 49 % ET from a saline (10 dS/m) water table depending on the amount of non saline water applied. The maximum use of saline groundwater occurred, when, only one irrigation was applied after pre-plantation irrigation for cotton as reported by [3]. Despite these advantages, irrigation management system has usually not taken into account the effects of high water table on the moisture uptake and consequent moisture depletion from the crop root zone. Successful incorporation these effects into the irrigation scheduling and into performance models requires determination of the effects of water table on the percentage of crop water demand satisfied by the water table. Successful use of the water table also depends on the soil's water retention and transmitting properties, evapotranspiration demand, distribution of the plant root systems, and salinity and toxic ion effects on crop growth. Therefore, different crops may respond differently to various soil, weather and water table conditions. The objective of the present study is to determine seasonal shallow groundwater contributions to wheat, corn and potato water use, with water table depth variation up to the root zone and consequent effect of rising water table on the moisture depletion pattern in crop root zone. Causes of severe reduction in the moisture uptake from the bottom layers of the root zone, and utilizable consequences of the increase in the moisture uptake from the top layers have also been discussed.

II. MATERIALS AND METHODS

A. Water Movement in Soil

Three standard forms of unsaturated flow equation may be identified: the ψ based form; the θ based form and mixed

form. [5], concluded that mass conserving approximation based on the mixed form of Richards equation combines the benefits inherent in both the θ based and the ψ based forms of the equation while circumventing major problems associated with each. These problems include poor mass balance and associated poor accuracy in ψ based solutions and restricted applicability of θ based models. Hence in the present work the mass balance equation for water flow in one dimensional [19] incompressible unsaturated soil in its mixed form with root water extraction term has been used

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

where θ is the volumetric moisture content of soil, ψ is the soil matric potential, t is the time, z is the vertical distance from reference level directed positive upwards, K is hydraulic conductivity (a function of soil matric potential ψ), and S(z, t) is the water uptake by roots expressed as volume of water per unit volume of soil per unit time.

Richards equation is highly non linear due to pressure head dependencies in the soil moisture capacity and relative hydraulic conductivity terms [16], the latter term contributing a non linearity to both the diffusion type component $\partial / \partial z\left(K(\psi)\partial \psi / \partial z\right)$ and the gravitational gradient term $\partial K(\psi)/\partial z$. In order to solve Richards equation, it is required to specify constitutive relations between the dependent variable (moisture content in this case) and the non linear terms (soil matric potential and hydraulic conductivity). [20] closed form equation for the soil water retention curve and [13] unsaturated hydraulic conductivity function are used to describe the soil hydraulic properties. The relation between water content and pressure head is given by [20]

$$\Theta = \left[\frac{1}{1 + \|\alpha \psi\|^n}\right]^m \quad \text{For } \psi \leq 0 \qquad (2)$$

$$= 1 \qquad\qquad \text{for } \psi > 0$$

$$m = 1-(1/n)$$

where Θ= effective saturation; ψ= Soil matric potential; n, m= Van Genuchten's parameters

$$\theta = \Theta(\theta_s - \theta_r) + \theta_r \qquad (3)$$

where θ_s= saturated moisture content; θ_r= residual moisture content

Based on [13] model the relation between water content and hydraulic conductivity is given by [20]

$$K_r = K/K_{sat}$$

$$K_r = \Theta^{1/2}(1-(1-\Theta^{1/m})^m)^2 \qquad (4)$$

where K_r=relative hydraulic conductivity of soil; K_{sat}= saturated hydraulic conductivity of soil

B. Root Water Uptake

According to [15], for potential transpiration conditions, the potential rate of soil water extraction S_{max} is given by the relation

$$S_{max} = \alpha\left[1-\left(\frac{Z}{Z_{rj}}\right)\right]^{\beta} \quad 0 \leq Z \leq Z_{rj} \qquad (5)$$

where α, β=model parameters; Z=depth below soil surface; and Z_{rj}=root depth on the jth day.

For $Z = Z_{rj}$, S_{max} is zero as per (5) and at Z=0, S_{max} attains a maximum value. Thus (5) satisfies the desired extraction conditions that extraction is maximum at the top and zero at the bottom of the root. Also S_{max} has to satisfy the following equation:

$$\int_0^{Z_{rj}} S_{max}\, dZ = T_j \qquad (6)$$

Substituting for S_{max} from (5) into (6) yields the following equation for T_j:

$$T_j = \frac{\alpha Z_{rj}}{(\beta + 1)} \qquad (7)$$

From which α is obtained as

$$\alpha = \frac{T_j(\beta + 1)}{Z_{rj}} \qquad (8)$$

Using (8) in (5), S_{max} is obtained as

$$S_{max} = \left[\frac{T_j}{Z_{rj}}(\beta + 1)\left(1 - \frac{Z}{Z_{rj}}\right)^{\beta}\right] \qquad (9)$$

It is noted that for β=0, (9) converts to constant rate extraction model of [8]: $S_{max} = T_j/Z_{rj}$ and for β=1, (9) converts to linear extraction model of [17]: $S_{max} = 2T_j/Z_{rj} - 2T_j (Z/Z_{rj}^2)$. Since linear and constant rate extraction models are particular cases of it, so its use is preferable. The model satisfies the desired extraction conditions at the top and bottom of the root. 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.

C. Simulation when Soil Moisture is Limiting

When the moisture content is below the Available Moisture Content (AMC), actual transpiration is lower than the potential value. [8] proposed a model to describe the sink term under the limiting moisture condition, where

$$S(\psi) = f(\psi)\, S_{max} \qquad (10)$$

where f(ψ) is the prescribed function of the soil moisture pressure head. The root water uptake is zero above the anaerobiosis point ψ_1, as well as below the wilting point ψ_4 and is constant at its maximum value between ψ_2 and ψ_3, where soil moisture pressure head ψ_2 and ψ_3, represent field capacity of soil and available moisture content (AMC: moisture content below which moisture to plant root is not readily available and irrigation needs to be provided to avoid reduction of moisture content to permanent wilting point). The value of ψ_3 is dependent on the evaporative demand of atmosphere. Definition sketch of f(ψ) [17] assumes a linear variation of f(ψ) with ψ when the latter is less than ψ_3 or greater than ψ_2. [17] illustrate the following change in Equation (9), when limiting soil moisture exists and root depth has attained its maximum value

$$S(\psi, Z) = \frac{T_j}{Z_{r\,max}}(\beta + 1)\left(\frac{\psi - \psi_4}{\psi_3 - \psi_4}\right)$$
$$\left(1 - \frac{Z}{Z_{r\,max}}\right)^\beta \text{ for } \psi < \psi_2 \tag{11}$$

D. The Initial and Boundary Conditions

Length L of the soil column is divided into n nodes; distance between each node is denoted by delz. Initially, it is assumed that the head throughout the soil column of length L, in the model is defined by

$$\psi(Z,0) = \psi_0(Z,0) \text{ for } 0 \le Z \le L \tag{12}$$

The upper boundary condition is a prescribed flux boundary condition accounting for the evapotranspiration taking place from the top soil. Thus

$$\psi(0,t) = \psi_1(t) \qquad \text{for } 0 \le t \le t_i \tag{13}$$

$$-K(\psi)\left(\frac{\partial \psi}{\partial z} - 1\right) = ET \quad \text{for } t_i \le t \le t_p \tag{14}$$

where $\psi_i(t)$ is the applied water (head), t_i is the irrigation application time, ET is the potential evapotranspiration from the top soil, t_p is the duration of evapotranspiration.
When groundwater table is deep, at lower boundary gravity drainage type condition has been assumed, where a unit hydraulic head is considered.

$$K(\psi)\left(\frac{\partial \psi}{\partial z} - 1\right) = -K(\psi) \quad \text{for } t \ge 0 \tag{15}$$

Whereas when groundwater table is within the root zone, the lower boundary is at water table, at which the pressure head is considered to be at atmospheric pressure i.e. $\psi=0$. Thus

$$\psi(Z,t) = 0 \qquad \text{for } t \ge 0 \tag{16}$$

E. Soil Parameters

Evapotranspiration and soil moisture depletion data for different layers of root zone, reported by [7] has been used to compare the results of the present root water uptake model. The experiments have been conducted over duration of 6-7 years at Agricultural Experiment Station, Tucson, Arizona to obtain this data. The soil in this area is coarse soil of type sandy clay loam. The soil moisture parameters required for assessment of moisture flow in unsaturated media in different classes of soil proposed by [4] has been used for present study. The value of saturated hydraulic conductivity (K_s), saturated moisture content (θ_s), residual moisture content (θ_r) and Van Genuchten' parameters α & n for sandy clay loam are 0.0002183 (m/minute), 0.39 ($m^3 m^{-3}$), 0.1($m^3 m^{-3}$), and 5.9 & 1.48 respectively.

F. Numerical Procedure

Several numerical models have been developed for simulating the movement of water in unsaturated zone. Finite difference approximations have been widely used in several studies solving one dimensional (vertical), unsaturated flow problems. In the present work a mixed form of unsaturated flow equation using sink term given by [15], for root water uptake has been developed using Fully Implicit finite difference scheme and solved by employing the Picard iteration scheme as described in [5].
For solving the differential equation (1), a finite difference grid is superposed over the solution domain. The grid comprises of n number of nodes, with spacing between each node equal to Δz. Time increment is denoted by Δt. Iteration number is denoted by m. Due to high nonlinear nature of Richard's equation, very small time steps are needed to have mass conserving solution [5]. However number of iterations will continue until the convergence criteria is not met with.
For larger time steps the error in the solution increases, although the solutions are still convergent and unconditionally stable with Picards iteration scheme [16]. However if the time steps used in the simulation are small, changes in the pressure head during each time step are generally quite gradual [6]. As a result the solution for a given time step is usually an excellent starting value for the next time step. So the solution converges quickly within a few iterations, minimizing the computational effort but maximizing the total computational time.

G. Field Data and Model Input

The three crops which have been used for simulation are wheat, corn and potato. The daily evapotranspiration data have been taken from [7], [15]. Consumptive use was computed from gravimetric soil moisture measurements on soil samples taken at depths and locations that could be expected to evaluate the average soil moisture distribution and depletion by the plants under study. The consumptive-use curves [7] are averages of several years and do not show short time fluctuations in water use. All the experiments were conducted in optimal soil moisture conditions. [7], shows the data for various crops, representing the mean of values measured over several years by monitoring soil moisture depletion. Data for other all the three crops run on the same lines. The crops chosen show a wide range in the length of growing season,

seasonal consumptive use and the length of vegetative phases. Wheat has a root depth of 1.83 m, while all other crops have 1.23 m. Percentage moisture depletion for different layers is also available.

The root depth increases steadily till midseason, and thereafter remains constant. It has generally been found that during the growing stage, the ratio of consumptive use to the root depth is remarkably constant [11]. [11], [17] and [15] used equation (17) to obtain the root depth during the crop period.

$$\frac{T_j}{Z_{rj}} = \text{Constant} \tag{17}$$

It is assumed that maximum root depth is attained on the day when the daily consumptive use is the maximum [17]. Equation (17) is valid from the sowing day until the day of maximum consumptive use. The value of the constant can be found from the maximum consumptive use and maximum root depth. Once it is known root depth on any day can be calculated from equation (17).

III. RESULTS AND DISCUSSION

To observe the effect of the rising water table on the moisture uptake pattern of the plants the lower boundary condition of the unsaturated flow domain requires modification depending on the depth of the ground water table. For the deep GWT gravity drainage has been assumed at the bottom, whereas for water table approaching the root zone dirichilet boundary condition has been employed while running the simulation. The root zone has been divided into layers of thickness 0.3m each. The main stress for moisture depletion pattern has been put on the topmost layer which is vital from irrigation point of view and bottommost layer which is significant due to its vicinity to groundwater table. Here it is very important to note that, the topmost and bottommost layers are important from plant moisture uptake point of view too. The maximum root density and hence the maximum moisture uptake by plants corresponds to the topmost part of the root zone, where as bottommost part of root zone acts as a store of moisture and as the time elapses, moisture is transmitted upwards through continuous capillary action. The non linear coefficient for the sink term has been used as the values of the coefficient which gave closest matching moisture uptake values with the experimental data, for different crops. Based on a statistical approach the value of coefficient β thus comes out to be 2 for wheat & potato and 1.5 for corn. These coefficients are representative of the non linear distribution of the moisture depletion pattern from the root zone. It is clear from the analysis that these coefficients are crop specific.

Simulation initially has been run for potential moisture condition assuming deep groundwater table in case of all the crops keeping gravity drainage at bottom. This resembles the field conditions of the area, from which the data base has been used for the study. For the hypothesis carried out in the present study, to assess the effect of rising groundwater table on the moisture uptake, groundwater table has been varied from 4.5 m below the ground level to within the root zone.

Fig. 1 shows the effect of rising water table on the moisture uptake of wheat crop.
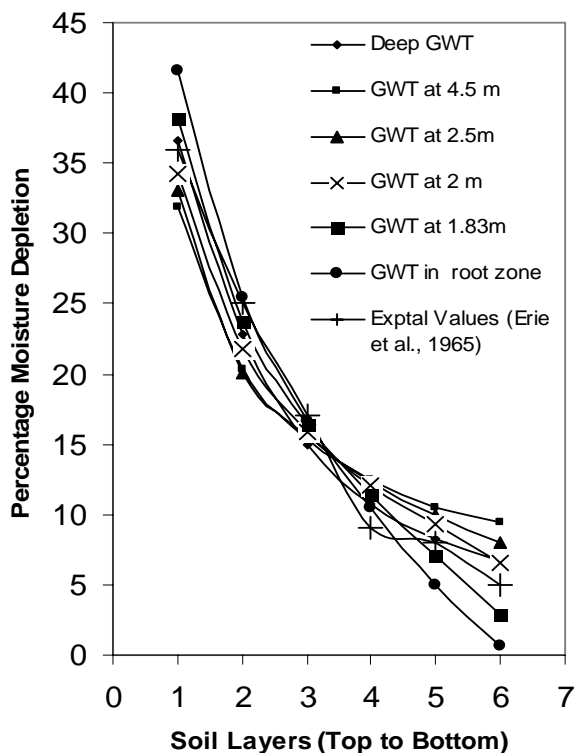

Fig. 1 Comparison of Moisture Depletion at Different Stages of Rising Water Table, with Experimental and Simulated Values, when GWT is Deep. (Results for Wheat)

It is evident from Fig. 1 that simulated moisture depletion patterns under potential moisture conditions and deep ground water table (GWT) match closely with the experimental values, which reflects the precision of the simulation developed. With the groundwater table at a depth of 4.5 m, moisture depletion from the topmost layer is less, whereas from bottommost layers it is more. As the water table rises from 4.5m to 2.5 m the change in the moisture depletion pattern is mild but it increases from the top layer and reduces from the bottom layer. The change is severe, when water table reaches the root zone. It has been observed that from top layer the moisture depletion increases by 19.7 % and from bottom most layer it decreases by 68.8 % as compared to the situation when GWT is well below the root zone. The intermediate layers follow the trend of the layers in vicinity, but the variation in the moisture depletion from these layers is not very significant. Fig. 2 shows the influence of rising water table on the moisture depletion pattern of corn.
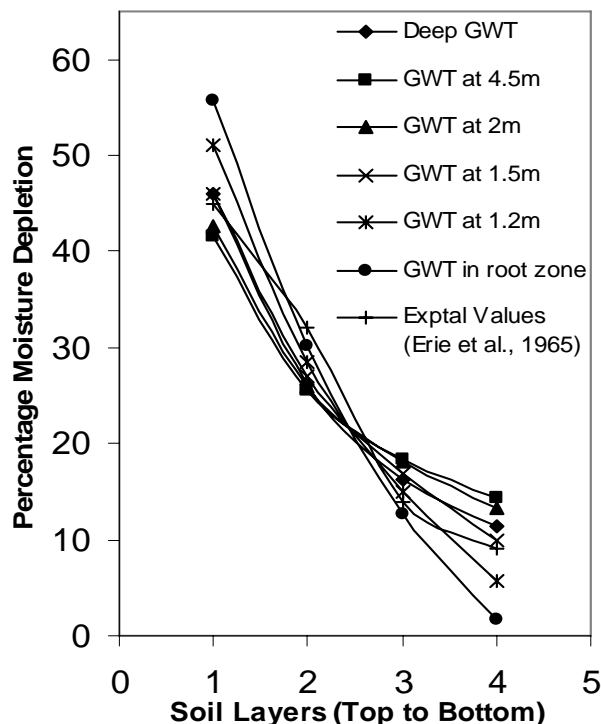
Fig. 2 Comparison of Moisture Depletion at Different Stages of Rising Water Table, with Experimental and Simulated Values, when GWT is deep. (Results for Corn)

Results of the comparison for corn run on the similar pattern as wheat, with a difference that in case of corn the effective root zone depth is 1.23m (Fig. 2). When the water table raises from deep to a depth of 2.5m the variation in moisture depletion pattern is insignificant till it reaches 2 m below ground. The increase in the moisture depletion when water table rises from deep to bottom of root zone is 22.9% and respective decrease in the bottom layer is 61.6%. Fig. 3 shows the results of study for potato.

Being a shallow rooted crop, potato also follows the similar pattern of deviation in the moisture depletion when GWT rises from deeper zone to immediate vicinity of the root zone. Moisture depletion from the top layer increases by 28.2% and decreases by 64.9% from bottom layer, when GWT ascends from deeper layers to bottom of the root zone. Intermediate layers again show trivial variation. The causes and consequences of increase in the moisture uptake from top layers and decrease from the bottom layers due to rise of GWT needs to be discussed.

The problem of how to manage irrigation systems to best utilize the shallow groundwater resource is an important question in arid irrigation areas. [10], suggested a systems approach to irrigation water management. In this approach, the irrigation system is operated to promote groundwater uptake by the crop through better irrigation scheduling. When groundwater use by the crop is included in the irrigation water balance, the estimated rate at which water is depleted from stored soil water is reduced and the irrigation interval is increased, thus reducing the total number of irrigations and total required depth of applied water. [22] states; "Improved

irrigation scheduling techniques need to be developed that allow the farmer to utilize a portion of the high water table to meet the crop *ET* while minimizing the upward flow of salt in the root zone". An irrigation schedule that includes direct plant use of saline groundwater requires both the time of application and the depth of application to be specified.
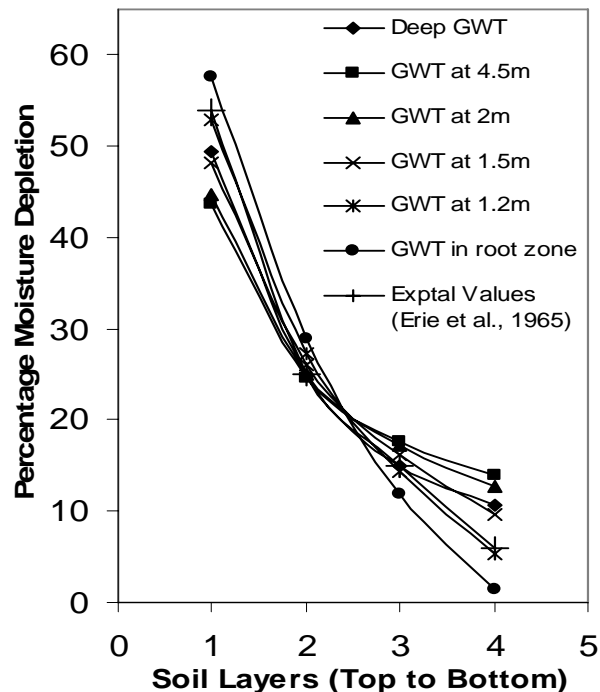

Fig. 3 Comparison of Moisture Depletion at Different Stages of Rising Water Table, with Experimental and Simulated Values, when GWT is deep. (Results for Potato)

The results of the present study clearly indicate that there is significant increase in the moisture uptake when GWT rises towards the root zone. The reason for this increased moisture accessibility is the upward flow of water from the shallow water table by capillarity. It is interesting to note that the major increase in moisture uptake is in the top layer which is the vital from the root moisture uptake consideration, as the maximum root density is concentrated in the top layer resulting in maximum moisture uptake from this zone. Hence increased availability of moisture in this zone due to rise in GWT can be utilized to meet the crop water requirements. As for as the reduction in the moisture uptake from the bottom layer is concerned, it is evidently a case of anaerobic conditions developed at the bottom of the root zone due to presence of water. These conditions hinder the process of water uptake by the roots. The bottom layer being inconsequential from the water uptake point of view due scanty root density in this zone does not pose much danger to the plant growth. But the situation needs to be addressed with proper irrigation scheduling and other management measures particularly if the groundwater is of poor quality.

Salinity of irrigated agricultural soils can be managed satisfactorily for salt tolerant and moderately salt-tolerant crops when using saline water for irrigation. Due to the

continuous use of saline or poor quality water over a period there is a progressive buildup of salinity which must be controlled to make continued use of saline water viable. The results of present study indicate that a deep rooted crop like wheat can utilize the shallow water table as compared to small root crops, as in case of wheat the moisture uptake has been enhanced even when water table is sufficiently below root zone, thus having the benefit of increased moisture availability, as well as less reduction in moisture uptake from the bottom layers, whereas as in case of shallow rooted crops e.g. corn and potato, the increase is significant only when water table is very near to the root zone, thus increasing the moisture accessibility at top layer but reducing the water uptake from bottom layer severely.

IV. CONCLUSION

In the presence of a shallow groundwater table, plants appear to derive much of water from the watertable directly, thus saving much of the irrigation water, which is generally scarce in arid and semiarid areas. Root water extraction patterns change as a result of an increase in moisture accessibility. The process of ET causes upward capillary flow of groundwater, and can have a significant impact on groundwater levels in the short term with a negative impact that capillary up-flow causes salt to be brought into the soil and root zones, if this process operates without some irrigation management.

On the basis of simulated moisture uptake pattern of different crops under the influence of rising GWT and its comparison with uptake, when water table is deep, present work demonstrates that there is significant increase in the moisture uptake from the top layer in case of water table moving to the vicinity of root zone. This can be utilized as a means of fulfilling a part of crop water demand through this process. Bottom layer suffers from the severe depletion of moisture uptake owing to occurrence of anaerobic conditions in this zone. The benefits of shallow water table can be drawn as supplementation of a part of crop water demand and disadvantage as continued build up of salt in root zone if water is of poor quality. Subsequently it can be concluded that shallow water table can be utilized beneficially, but proper irrigation management measures are needed to be implemented to marginalize the adverse effects of poor quality waters. Further work in this direction can be carried out to see the impact of shallow water table on moisture uptake pattern of other crops with different rooting characteristics, and in case of different soil types. Influence of water quality on uptake can also be studied.

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