with the soil beyond the root zone. Root transpiration through the plant and deep percolation into the aquifer becomes more complicated to solve because parameters turn into nonlinear functions. For hydrological and agricultural purposes the estimation of soil moisture is crucial since it controls the quantity of water available for the growth of the vegetation as well as the recharge of the deep aquifer. This article attempts to review and discuss basic concepts, strengths, weaknesses and input requirements for some of the available soil moisture models.

**Keywords—** Soil moisture, budget and dynamic models, hydraulic conductivity, suction, sink.

I. INTRODUCTION

Application of water to crops is the most important recurring aspect in water management of crop which needs careful consideration. A crop gets its water by root uptake. Irrigation is however required when the soil is incapable of supplying the water to crops. The objective of irrigation is to keep adequate water available to crops. In arid and semi-arid regions where rainfall is scarce makes irrigation system indispensable. There is no substitute for water. It is indispensable for human, animal and plant life. It is considered prime resource needed for rational development. Therefore it is necessary to develop, conserve, utilise and manage this scarce resource economically so as to meet the ever growing demand for agriculture and other human development activities.

The state and movement of moisture in the soil is a complex phenomenon since it is affected by a variety of physical, biological and chemical activities while interacting with each other [26]. The soil water (moisture) is depleted due to evaporation from soil surface, transpiration through the plant and deep percolation in to the soil beyond the root zone. Root proliferation is reduced due to high mechanical resistance of dry soil.

Irrigation provide favourable environment for higher crop growth and yield [42]. Proper soil water management for optimum crop production requires a thorough knowledge of the moisture characteristic of soil profile or medium through which the crops utilises their requirement of moisture and other nutrients for growth. The availability of moisture influences almost all the biochemical and physiological processes in plants which in turn affect the morphology of the plants. All the crop plants have an optimal moisture regime and any deviation from the optimum results in adverse effect leading to poor growth, yields and even the quality of the produce [46]. Hence an accurate quantification of moisture uptake by plants under different environmental conditions is essential for efficient irrigation scheduling and for soil moisture flow modelling in vegetative and barren soils.

II. BENEFIT OF ESTIMATING SOIL MOISTURE

The benefits of estimating soil moisture of vadoze zone or root zone depth are numerous just as:

- Efficient irrigation scheduling
- Crop selection [2] and increased crop yield through optimal soil moisture conditions at pre-planting and during the growing season [10].
- Economical and water conservation benefits through rational irrigation scheduling.
- Management of cultural practices.
- Decision about traffic-ability in the fields.
- Early drought prediction. Drought monitoring and evaluation of drought impact on agricultural production for management of rural subsidy schemes [1].
- Economical and environmental benefits from selective application of pesticides for soil moisture dependent insects and diseases.
- Improved erosion prediction can be carried out through improved hydrological modelling and the relationship between erosion and runoff producing zones can be developed.
- Design of drainage system [7] and minimizing drainage.
- Minimize leaching losses.
III. SOIL MOISTURE ESTIMATING MODELS

A number of researchers have investigated the moisture models. Literature review reveals that there are three major types of root water uptake models [10].

- Budget models
- Semi dynamic models
- Dynamic models

Mahdian and Gallichand [27] gave classification of soil moisture models into two categories.

- Water balance model (Models follow the daily budget approach)
- Numerical models (Model based on Richards partial differential equation)

3.1 Budget Models

Budget models are simplest types of soil moisture flow models. This type of models treat the soil profile as a bucket, and Soil is assumed to have fixed water capacity. The bucket is filled with application of water and emptied with evaporation or evapotranspiration. The excess water above its capacity is treated as runoff.

These types of models ignore the vertical moisture gradient. The spatial and temporal distributions of soil moisture regime calculated using budget models are not very accurate [3] [51].

The concepts of field capacity and wilting point are central to soil moisture budget models. Weakness of most budget models is that redistribution of water (except for the recharge to field capacity) is ignored [10].

One of the strength of this type of model is requirement of minimum amount of data, namely field capacity, wilting point, daily precipitation and evapotranspiration. The component parts of budget models are represented in the figure no.1.

3.2 Semi-Dynamic Models

Semi-dynamic models use a multi-layer concept. It combines budget procedures with a physically based methodology. The infiltration of this layer is first stored in the uppermost soil layer. After reaching the upper limit of the layer excess water enters in to succeeding lower layer, till the sufficient storage is available. The subsequent redistribution and drainage is estimated using a Darcy-type unsaturated flow computation. The semi-dynamic models provide a more detailed description of water movement through the soil than the budget models [5] [11] [9] [10].

3.3 Dynamic Models

The infiltration and redistribution of water are controlled by the physical factors governing water movement in soil. The amount of irrigation water for a crop field is dependent on the rooting pattern of that crop and the layer-wise distribution of soil moisture in the root zone profile. As the measurement of soil moisture at regular intervals is very costly and time consuming, there has been continuing interest in developing physical parameter based mathematical models.

3.3.1 Types of Dynamic Models

The dynamic models of moisture flow towards the roots have been classified in two major groups in the literature [34].

- Microscopic (Single Root)
- Macroscopic (Root System)

Raat [40] in his literature review considered two different types of models. These are:

- Mesoscopic scale
- Macroscopic scale

Feddes and Raat [16] in their literature considered following types.

- Local scale (microscale, mesoscale and macroscale)
- Field scale
- Regional scale to Global scale

3.3.1.1 Microscopic (Single Root) Models

Water uptake by plant root has been mathematically described by single root models where the root is assumed to be a line sink of infinite length, uniform radius and uniform absorption properties [47]. This Microscopic, bottom up approach model, deals with the radial flow of water to an individual (single) root. The driving force for the uptake of water into the root is the difference in water potential that exists between the soil and adjacent to the root and the root xylem [47] [50].
The soil moisture flow equation is written in cylindrical coordinates and solved with appropriate boundary conditions at the root surface and at some distance, \( r_{\text{max}} \) from the root. In many studies \( r_{\text{max}} \) is taken to be infinite [34]. This approach, in general, is more useful in its understanding of the root extraction process than in its interpretation of field data collected under heterogeneous condition over a period of root development [6]. As cited by [22] [23] [32] [40] [41], Phillip (1957) was the first researcher (pioneer) who developed microscopic approach. Microscopic analyses of the root extraction process have also been presented by [17] [33] [47] [21]. Raat [40] has taken critical review of this type of model in detail.

3.3.1.2 Limitation of Microscopic Models

Microscopic models are not effective due to the following reasons.

- In reality, steady-state conditions hardly exist. The living root system is a dynamic system. The detailed geometry of the root system is practically impossible to define [35] [41] [32] [50].
- The permeability of the root varies with position along the root [32].
- The root water uptake is most effective in young root material. Since the length of young root is not directly related to the total length, there will be differential absorption activities depending upon the age and location of the roots while using the microscopic approach [21] [32].
- The experimental evaluation of root properties is not practical because of the space time involved [21].
- The main limitation of the microscopic models is that they cannot be experimentally tested; boundary conditions cannot be easily defined and applied to such models [47] [32]
- Some of the microscopic studies indicate that there may be a tendency for this uniform extraction to occur even at moderate or low root densities [34].

3.3.1.3 Macroscopic (Root System) Models

The macroscopic or top-down approach eliminates the need for difficulty to obtain soil and plant parameters as discussed above. The 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 is dependent on position in a coordinate system, moisture content, time, and so forth.

Boundary conditions are specified at boundaries of the composite soil plant system such as the soil surface as upper boundary and for lower boundary two possibilities exist: one is the water table boundary condition and second is gravity flow condition [6].

IV. DEVELOPMENTS IN MACROSCOPIC MODEL

Nearly all types of macroscopic models calculate soil moisture flow by numerical solution of the Darcy- Richards equation coupled with water extraction by root system (sink). By assuming incompressible soil matrix, soil moisture continuity equation is used [6]. Gardner [18] proposed a macroscopic mathematical model to describe the water uptake by a non-uniform root system. The main thrust in his study was to determine the rooting distribution associated with each depth increment rather than integrate over the entire root zone as a continuum. In same way [49] took the surface area of the roots per unit volume of soil and some effective distance over which the water moves toward the root-a kind of root density function. Nima and Hank [36] considered the root distribution function, RDF

\[
\text{RDF} = \frac{\text{total active roots in depth increment}}{\Delta z}
\]

This RDF depends upon time as well as depth. For nine day interval they assumed it did not change with time. They determined this function by sampling the soil profile in the field. They assumed value of the effective water potential in the root depended on RDF, climatic condition and soil conditions. The root extraction per unit depth (S) was calculated from the difference between root and soil potentials multiplied by the soil hydraulic conductivity and a root distribution function estimated from measurements of root weight. As per the view of the Molz [35] macroscopic model was able to simulate field and lysimeter data to a useful degree. This model was reviewed by Rowse et al., [45] and then commented that the calculation of ‘S’ involves the improbable assumptions that the resistance to water absorption into the root is negligible compared to an assumed resistance to water conduction along the root, and that the distance between roots is always 1 cm. The Nima and Hank [36] model was later modified by Feddies et al., [13] and showed that the root effectiveness function is proportional to root mass and that both varies nearly exponentially with depth. They suggested that this function can be found by sampling the root mass with depth and determining the proportionality constant from the model calibration. They made the assumption that the potential at the root surface is constant throughout the root system.
This assumption would only be valid if the root resistance is always small compared to that in the soil. This is not always the case as per the view expressed by Rowse et al., [45]. The calculated weekly water content profiles did not agree completely with those measured in the field. Feddes et al., [14] stated that the determination of the effectiveness function takes lot of work and may need careful and expensive experimentation. For this reason different approach was proposed in which the water uptake by roots was considered to be function of the water content of the soil and introduced simpler extraction function.

The use of this macroscopic water uptake by roots category was favoured in most of the plant water uptake simulation models. Some of these models either ignore the impact of soil moisture deficit or do not consider the non-homogeneity of root density distribution throughout the soil depth. In arid and semi-arid regions, plants are subjected to varying levels of moisture stress in different parts of the root zone, which in turn results in the reduction of moisture uptake by plants. To overcome this lacuna, Feddes et al., [15] developed a model by introducing a reduction factor for plant water extraction to incorporate the impact of soil moisture availability. This modified water extraction term suggests that potential transpiration is distributed homogeneously over the rooting depth and moisture uptake is reduced during water shortage. Molz and Remson [34] proposed a linear model to fit an empirical rule that 40, 30, 20 and 10 \%, respectively, of the total transpiration requirement comes from each successively deeper quarter of the root zone. The bottom of the root zone doesn’t vanish. These models show some deviation from the result. In order to rectify this, Prasad [39] proposed models that take into account the non-homogeneous distribution of roots in the soil and also assumed that the root density, and consequently water uptake by roots decreases linearly within the root zone depth.

Marino and Tracy [30] developed model taking the root extraction term as a function of the water pressure gradient across the root-soil interface as well as soil and root parameters.

The resulting root-soil water flow model was a coupled pair of partial differential equations that describe the macroscopic movement of water through a root-soil system. Rainfall, irrigation, and evaporation were treated as sources of potential soil surface flux, and transpiration is treated as a source of potential root-surface flux. Malik et al., [29] developed model under crop condition utilizing either observed or generated root length densities incorporating factors which account for the decreased rate of water uptake by plant roots due to diminishing soil moisture during the drying cycles and due to the decreasing root effectiveness during crop growth period. The soil moisture contents simulated by the model using observed and generated root length densities were overestimated to the extent 6.0\% and 9.6\% on an overall basis, respectively in comparison to observed soil moisture contents. These variations were due to assuming soil profile was homogeneous, neglecting hysteresis effect, assumption of multiplicative nature of soil moisture dependent function and root effective function causing less water uptake by plant root. Gardner [20] developed a moving sink model to predict water uptake by roots. However, according to him, the moving sink does not explicitly explain the observed uptake patterns completely.

Ojha and Rai [37] improved the linear water uptake model proposed by Prasad [39] with nonlinear root up take model and validated this proposed model by conducting experiment and found that their model performed better[38]. The macroscopic approach can be further subdivided into two categories [48]. In the first category, the water potential and hydraulic parameters inside the plant roots which were difficult to quantify, were considered by some researcher in their model e.g. [36][22][23]. In the second category however, water uptake by plants is simulated using the potential transpiration rate, soil moisture availability, and the plant root density distribution e.g. [13][15][19][34][39][48][50][51] etc. The parameters required are relatively easy to obtain for the second category, therefore, this approach has been considered widely.

V. MODEL FORMULATION

Soil water is dynamic and moves constantly in the soil medium in the different directions. Downward and lateral movements of water occur during or after irrigation or rainfall and the upward movement take place when upper soil layer start drying up owing to evaporation or evaporotranspiration. It can be represented by following diagram no.2
The first quantitative description of water flow through a porous medium was developed by Henri Darcy in 1856, in the course of his classic investigation of seepage rates through sand filters in the city of Dijon discovered following equation \[8\] \[25\].

Where \( \Delta H/L \) is the hydraulic gradient or potential gradient, \( K \) is the hydraulic conductivity, \( q \) is specific discharge or flux density or simply flux (\( q = Q/A \) where \( Q \) is volume flowing through the column per unit time and \( A \) is cross-sectional area). Darcy’s law is useful for saturated (steady) flow. Darcy’s law is not valid for all conditions of liquid flow. It could be applied only when flow is laminar. Due to the small size of soil pores; flow through soil is generally laminar \[28\] \[12\]. The majority of the processes in the field that involve soil and water, including the flow of water and solutes below the root zone, occur when the soil is unsaturated \[24\]. Darcy’s law is not directly applicable to these circumstances. In case the flow is unsteady where the flux changes with time or soil is non uniform, hydraulic head may not decrease linearly along the direction of flow. Now the hydraulic head gradient or the conductivity is variable. In this situation localised gradient, flux and conductivity values are considered rather than overall values for the soil system as a whole \[24\].

\[ q = -K\nabla H \]  \hspace{1cm}  (1)

Where \( \nabla H \) is the hydraulic head (H) is in general the sum of the pressure and the gravitational head. Thus equation can be written as follows:

\[ \frac{\partial \theta}{\partial t} = -\nabla \cdot q \]  \hspace{1cm}  (2)

Thus

\[ \frac{\partial \theta}{\partial t} = -\nabla \cdot [K(\psi)\nabla H] \]  \hspace{1cm}  (3)

The Richards equation represents the movement of water in unsaturated soils, it is a nonlinear partial differential equation which is often difficult to approximate since it does not have a closed form analytical solution. Richards applied a continuity requirement.

The following equation is Richards’s equation with assumption of continuity.

\[ \frac{\partial \theta}{\partial t} = -\nabla \cdot [K(\psi)\nabla (\psi - g)] \]  \hspace{1cm}  (4)

Hydraulic head (H) is in general the sum of the pressure and the gravitational head. Thus equation can be written as follows:

\[ \frac{\partial \theta}{\partial t} = -\nabla \cdot [K(\psi)\nabla (\psi - g)] \]  \hspace{1cm}  (5)

Where \( g = \) gravitational head and \( \Psi \) is negative, if \( g \) is vertical in one dimensional vertical system \[24\]. In general, from a macroscopic point of view, the modified form of Richard’s equation in one dimensional form is employed to simulate movement of soil water in a vertical profile under rainfall, irrigation, infiltration and evapotranspiration. Richards’ equation is combined with a root-extraction sink term \( S \) in plant root uptake model \[14\] as follow:

\[ \frac{\partial \theta}{\partial t} = -\frac{\partial q}{\partial z} - S(\theta) \]  \hspace{1cm}  (6)

Here

\[ q = \left[ K(\psi) \frac{\partial \psi}{\partial z} + K(\psi) \right] \]  \hspace{1cm}  (7)

Used following model

\[ \frac{\partial a}{\partial t} = -\left( \frac{\delta}{\delta z} \left[ K(\psi) \frac{\partial \psi}{\partial z} + K(\psi) \right] \right) - S(z, t) \]  \hspace{1cm}  (8)

SWATRE model (Soil Water and Actual Transpiration Rate model) \[15\] \[4\] \[7\] used in their studies
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\[ \frac{C(\psi)}{\partial t} \frac{\partial \psi}{\partial t} = \left( \frac{\partial}{\partial z} \left[ K(\psi) \frac{\partial \psi}{\partial z} \right] + K(\psi) \right) + S(z,t) \quad (9) \]

Where

\[ C(\psi) = -\frac{\partial \psi}{\partial \psi} \] specific or differential water capacity and

By chain rule

\[ \frac{\partial \psi}{\partial t} = \left( \frac{\partial \psi}{\partial z} \right) \frac{\partial z}{\partial t} + \frac{\partial \psi}{\partial z} = \left( \frac{\partial \psi}{\partial z} \right) \frac{1}{c} \left( \frac{\partial \psi}{\partial z} \right) \]

SWASIM (Soil Water Simulation Model) used [7] [29]

\[ \frac{\partial \psi}{\partial t} = \left( \frac{\partial}{\partial z} \left[ K(\psi) \frac{\partial \psi}{\partial z} - K(\psi) \right] \right) - S(\psi, z, t) \quad (10) \]

\[ \frac{\partial \psi}{\partial t} = \left( \frac{\partial}{\partial z} \left[ D(\psi) \left( \frac{\partial \psi}{\partial z} - K(\psi) \right) \right] \right) - S(\psi, z, t) \quad (11) \]

Where D = diffusivity

The kinetic wave theory uses a simple approximation for solving the general governing equations of water flow. The model neglects the diffusivity factor for water flow and assumes that the only force driving the water is gravity [2].

\[ \frac{\partial \psi}{\partial t} = \frac{\partial K(\psi)}{\partial z} \frac{\partial \psi}{\partial z} - S(\psi, z, t) \quad (12) \]

Depending on sign convention and assumption like measuring the depth from surface or taking water table as datum the signs (+ or -) changes in model accordingly.

VI. CONCLUSION

Soil moisture movement is key process for vegetative growth. As the measurement of soil water at regular intervals is very costly and time consuming, there has been continuing interest in developing a physical parameter based mathematical model. From a macroscopic point of view, the modified form of Richard’s equation in one-dimensional form is employed to simulate movement of soil water in a vertical profile under rainfall and irrigation infiltration and evapotranspiration.

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