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CROP WATER REQUIREMENT, FIELD EFFICIENCIES AND IRRIGATION PLANNING

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PREFACE

Under its work plan National Institute of Hydrology, an autonomous society under Ministry of Irrigation, Government of India, has to carry out research works in different areas of Hydrology. The areas of consumptive use, field efficiencies and irrigation planning are some of these areas. The preparation of status report by the scientists who are to proceed abroad for training under UNDP Project, has been recommended by the sub-committee of Technical Advisory Committee of NIH. This status report has been prepared by referring various research developments at national and international levels in the areas of crop water requirement, field efficiencies and irrigation planning.

The report contains six sections. An introduction to various aspects of irrigation planning and development in India has been given in section one. Section two deals with description of various concepts related to soil water, soil moisture movement, plant water relationships, evapotranspiration, field efficiencies etc. A compilation of available research works done at national and international levels in the fields of crop water requirement, effective rainfall, moisture extraction pattern, dynamics of soil water, irrigation scheduling, irrigation efficiencies etc. has been done in section three. Determination of water requirement of crops is an important aspect of irrigation planning which has been dealt in section four.

Experiments on irrigation requirement of field crops have been done at different research centres of India. Some of the results of such experiments are given in section five. On the basis of review work done, the following specific aspects for carrying out research have been identified in section six.

(i) To find appropriate formula of ET computation by doing comparison between experimental methods and empirical formulae of ET determination.

(ii) Irrigation scheduling for various crops based on solution of Richards equation.

(iii) Determination of water application points in a field to minimise problem of non-uniform distribution of irrigation water.

(iv) Selection of cropping pattern for a particular region depending upon then carrying capacities of canals in that region.

(v) Development of easier techniques of irrigation scheduling.

(vi) Selection of irrigation method for a particular crop to get maximum irrigation efficiency.

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ABSTRACT

Design of irrigation systems and judicious application of irrigation water need reliable information on the consumptve use of various crops grown in the command area. In recent past, studies on scheduling of irrigation based on soil water status, plant water status,irrigation water availability etc. have been done to develop irrigation scheduling model for different crops under varying climatic conditions. The basic idea behind all such studies is to minimise various water losses involved in an irrigation process so as to increase irrigation efficiency.

A review of different research works done at national and international levels in the fields of crop water requirement, field efficiency and irrigation planning is presented in this report. On the basis of the present review work the following research aspects have been identified in the report :

(i) To find appropriate formula of evapotranspiration computation for an area by doing comparison between experimental methods and empirical formulae.

(ii) Irrigation scheduling for various crops based on solution of Richards equation.

(iii) Determination of water application points in a field to minimise problem of non-uniform distribution of

irrigation water.

(iv) Selection of cropping pattern for a particular region depending upon the carrying capacities of canals in that region.

(v) Development of instrumentation for irrigation scheduling.

(vi) Selection of irrigation method for a particular crop to get maximum irrigation efficiency.

1.0 INTRODUCTION

The appropriate design of irrigation systems and the judicious application of irrigation water in the field demand reliable information on consumptive use of the various crops grown in a command area. Irrigation may be defined as the artificial supply of water to the soil for the purpose of increased crop production. The demand for water in various sectors is increasing day by day and water is no longer an unlimited resource, so its efficient utilisation in agriculture needs careful study.

Rural development and prosperity through irrigation have been given priority in Indian planning since the beginning of the era of five-year plans. The first quarter century of independent India has witnessed a near doubling of the area under irrigation. A report of Ministry of Irrigation (82-83) describes that since 1951 an average 1 million ha. annual increase in irrigation potential has been achieved upto end of the 4th plan in 1974. Thereafter, the tempo of increase in irrigation potential was almost doubled i.e. about 2 million ha.per annum.

On a broad assessment made by the states, it is estimated that it will be possible to extend irrigation to a gross area of 113 million ha. by 2000 A.D. from all sources including ground water. Upto the end of 5th five year plan

(1979-80), a gross potential of 56.6 million ha. was created through major, medium, and minor irrigation projects. This means the progress so far achieved amounts to 50% of the ultimate potential of 113 million ha. and to achieve this target, an annual irrigation potential of about 3 million ha. will have to be created in coming years. The 6th five year plan (1980-85) aims a target of 13.7 million ha. out of which 2.30 m.ha. and 2.47 m.ha. have been created in years 80-81 and 81-82 respectively. The target for year 82-83 was 2.35 m.ha. (Annual Report, M.O.I.,1982-83).

The table given below gives some idea about the progress of irrigation and use of agriculture inputs in past few decades in our country.

Item	Unit	Level in 1949-50 1950-51	Level in latest year	Year
Net area sown	m.ha	118.8	143.0*	1978-79
Gross cropped area	"	131.9	175.2*	1978-79
Intensity of cropping	%	111.0	122.5*	1978-79
Net irrigated area	m.ha	20.9	39.8	1979-80
Gross irrigated area	"	22.6	50.4	1979-80
Percentage of gross		17.1	28.8	1979-80
Irrigated cropped area	%	1.5	6.4	1982-83
Fertiliser consumption	m.ton	(1967-68)		
High-yielding area in	m.ha	6.0	47.7	1982-83
Varieties		(1967-68)		
Pesticides	Ton	NA	61.0	1982-83
Electricity	GWH	1103 (1962-63)	13189	1979-80
Credit for Agriculture				
Short-term	Crore	Rs.488(69-70)	1922	1982-83
Medium & long-term	"	Rs.205(69-70)	634	1982-83
Total	"	Rs.693(69-70)	2556	1982-83

* Latest information is available for 1979-80 but because of widespread drought the cropped area was abnormally low.

Ref: The Hindustan Times dt. 16th September,1983

As seen from the table, there is wide difference between gross cropped area and gross irrigated area. Therefore, it is quite evident that the water which is available for irrigation is insufficient for assured irrigation to the available gross cultivable area in our country. Knowledge of water requirements of crops is essential even under unirrigated conditions for planning cropping patterns in commensurate with available water supplies.

A forecast model which takes care of daily hydrometeorological data and soil moisture status, should be developed for different regions to find irrigation scheduling. As far as water use management is concerned priority need be given for development of such model for various crops at national planning level.

2.0 SCIENTIFIC SYSTEM DISCUSSION

It is necessary to understand the physics of soil moisture before the solutions of irrigation problems are attempted. Soil serves as a storage reservoir for water by virtue of its porosity. Only the water stored in the root zone of a crop can be utilised by the crop for its transpiration.

2.1 Soil Water

When water is added to a dry soil either by rain or irrigation, it is distributed around the soil particles where it is held by adhesive and cohesive forces; it displaces air from the pore spaces and eventually fills the pores.

The following are three main classes of soil water:

i) Hygroscopic water : Water held tightly to the surface of soil particles by adsorption forces, which can not be utilized by plant.

ii) Capillary water : Water held by forces of surface tension as continuous film around soil particles and in the pore spaces, most of which is used by plants.

iii) Gravitational Water : Water that moves freely in response to gravity and drains out of the soil, while being drained it may be used for plant growth.

As shown in figure 1 the moisture occuring on a thin layer at surface is called soil water. This is basically responsible for the sustenance of plant life. Water draining into lower layers is held in the intermediate zone. This is not readily available for plants because the roots do not extend upto this zone. This is followed by a capillary zone very near the water table. Water moves down these zones in sequence and due to gravity drains into the water-table.

Figure 2 shows the illustration of vadose water held at contact points of particles in the unsaturated zone.

It is also necessary to look into various equilibrium points for water in soil. The depth scale in figure 3. corresponds to moisture content.

When all the air space is filled up by water, the soil is saturated. This condition may exist during rainfall. At this stage soil is said to be saturated. The tension of water' at saturation capacity is almost zero. As the soil is flooded with water, gravitational drainage of water starts and once the drainage rate becomes relatively stable, the moisture content of soil is referred as field capacity. At field capacity, the large soil pores are filled with air the micro pores are filled with water and gravitational drainage has ceased. The soil moisture tension at field capacity varies from soil to soil, but it generally ranges from 1/10 to 1/3 atmosphere.

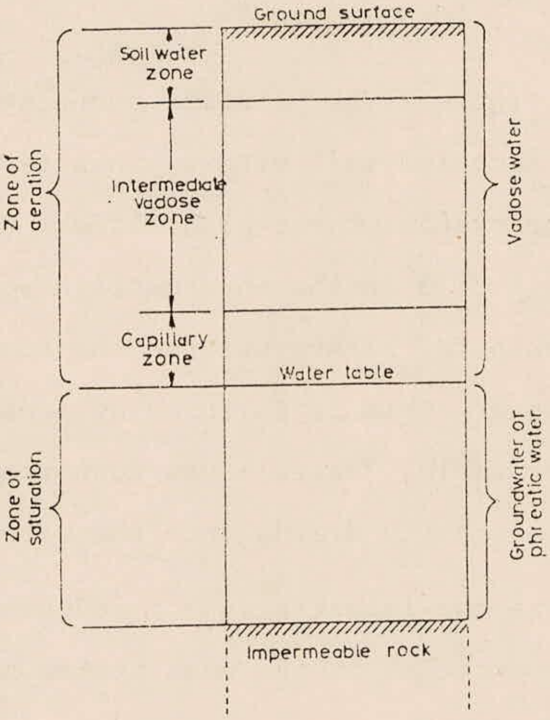


FIGURE 1 - DIVISIONS OF SUB-SURFACE WATER

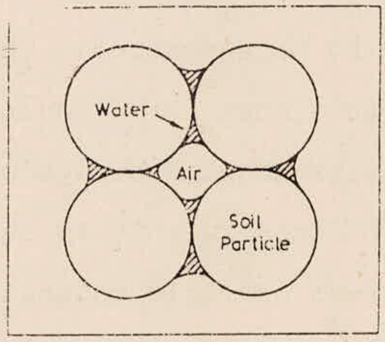


FIGURE 2 - ILLUSTRATION OF VADOSE WATER HELD AT CONTACT POINTS OF PARTICLES IN UNSATURATED ZONE

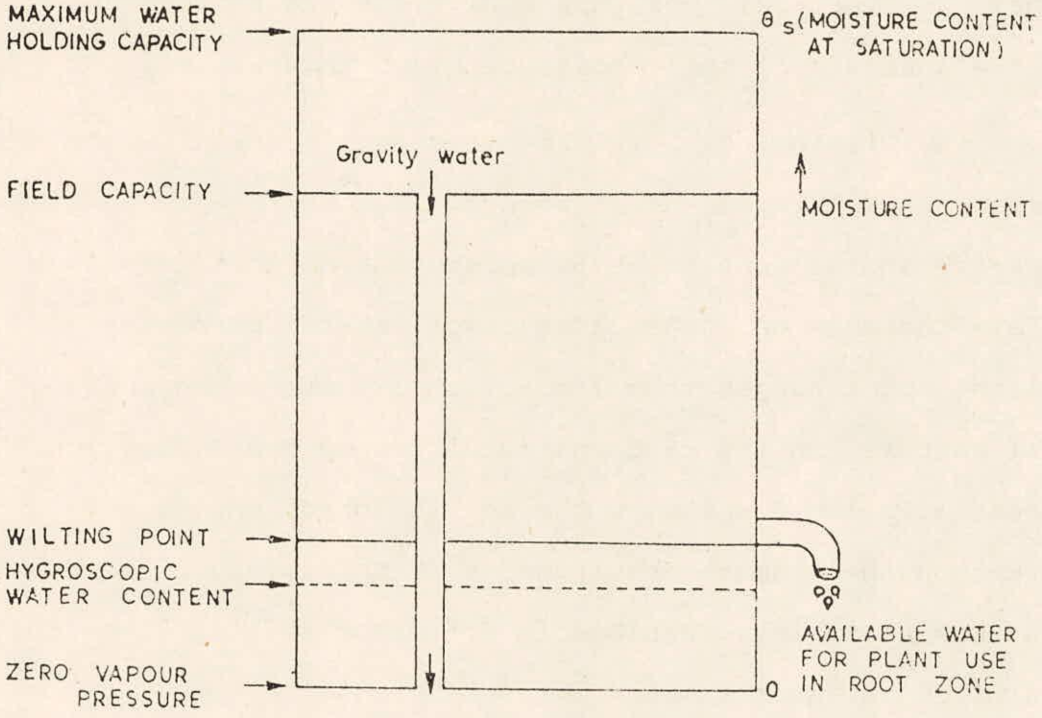


FIGURE 3 - SOIL MOISTURE EQUILIBRIUM POINTS

Moisture equivalent is defined as the amount of water retained by a sample of initially saturated soil material after being subjected to a centrifuge force of 1000 times that of gravity for a definite period of time, usually half an hour. For sands, the field capacity is higher than moisture equivalent. For clays both are approximately the same. However, soil moisture equivalent has no relevance in the analysis of soil moisture plant interaction.

The wilting point is the moisture content at which permanent wilting of plant occurs. The difference in field capacity and wilting point is moisture available for plant life. The moisture tension of a soil at the permanent wilting point ranges from 7 to 32 atmosphere depending upon soil texture, on the kind and condition of the plants, on the amount of soluble salts in the soil solution and to some extent on the climatic environment (Michael,1978). Moisture contents at various tensions in different soil types of India are given in table 1.

2.2 Plant - Water Relationship

Almost every plant process is affected directly or indirectly by the water supply. Water constitutes about 80 to 90 percent of most plant cells and tissues in which there is active metabolism. Plant roots take up water and transfer it through the root tissues to the conducting vessels of the plant. These conducting vessels pass it on to the

Table 1 - Moisture at Various Tensions in Different Soil Types in India

(Ali et al.1966)

Soil	Atmosphere				Available moisture,%
	0	1/10	1/3	15	
1	2	3	4	5	6
Alluvial					
Delhi	A 34.0	27.2	10.7	4.4	6.3
(Delhi)	B 37.4	29.9	17.7	7.7	10.0
Lucknow	A 47.0	42.1	29.2	8.1	21.1
(U.P.)	B 41.2	34.6	25.8	6.0	19.8
Pusa	A 32.1	31.6	15.5	1.9	13.6
(Bihar)	B 36.6	34.6	23.8	2.8	21.0
Black					
Padegaon	A 83.8	68.3	43.5	25.7	16.8
(M.S.)	B 76.3	68.8	43.3	27.2	16.1
Nagpur	A 58.1	54.4	38.9	21.1	17.8
(M.S.)	B 54.5	51.3	34.8	20.5	14.3
Red					
Cheruvukomimupalem	A 33.8	30.2	17.5	8.5	9.0
(A.P.)	B 41.4	34.9	23.0	12.3	10.7
Yemmiganur	A 34.5	31.4	19.8	8.2	11.6
(A.P.)	B 44.3	38.7	24.9	13.6	11.3
Raichur	A 31.4	26.2	13.7	7.4	6.3
(Karnataka)	B 32.2	24.3	14.0	7.5	6.5
LATERITE AND LATERITIC					
Midnapore	A 27.6	21.8	13.7	5.2	8.5
(W.B.)	B 37.3	27.9	18.2	9.1	9.1
Suri	A 24.0	22.5	14.2	4.3	9.9
(W.B.)	B 23.0	20.5	13.3	4.4	8.9
MOUNTAIN AND FOREST					
Ootacamand	A 49.7	42.0	30.5	18.7	11.8
(T.N.)	B 45.2	34.9	26.7	17.3	9.4
Dehradun	A 41.3	37.0	29.1	8.4	20.7
(U.P.)	B 43.7	35.0	26.8	9.8	16.9

Table 1 contd...

1	2	3	4	5	6
Bhowali (U.P.)	A 56.2 B 50.3	44.9 36.4	32.3 27.2	9.1 10.4	22.9 16.8
DESERT					
Pali (Rajasthan)	A 40.1 B 48.2	29.8 36.5	19.3 29.5	8.0 10.7	11.0 9.3

A and B represent surface (0-15 cm) and sub-surface (15-30 cm) samples, respectively.

mesophyll tissues of the leaves. After moving through these tissues, the water reaches the evaporation sites which are primarily the walls of the sub-stomatal cavities. The final transfer of water from the sub-stomatal cavities through the stomata of the leaves is a process of molecular diffusion of water vapour.

Out of the total quantity of water abosorbed by plant, five percent is used for its physiological function and the rest 95 percent is lost back to atmosphere by the process of transpiration. Reduction in the rate of transpiration in the loss of turgidity, cessation of growth, and eventual death of plant from dehydration.

The main areas of plant-water relationships are:

i) water absorption

ii) water conduction and translocation, and

iii) water loss or transpiratioin

Hence, in determining the importance of water in crop productivity, clear understanding of three processes viz., absorption, translocation, and transpiration is necessary.

The amount of water varies in different plant parts. The apical portion of the root and stem contain 90 percent or more water. Leaves and young fruits are other organs which are rich in water. When the organs mature their water content decreases. Crops like wheat, barley, and sorghum contain 50-60 percent at harvest. Freshly harvested grains of most crops contain 10 - 15 percent of water (Michael, 1978).

2.3 Soil Water Potential

Soil water, like other bodies in nature, contain energy in different quantities and forms. Two principal forms are kinetic and potential energy. As the movement of water in the soil is quite slow, its kinetic engery, which is proportional to the velocity squared, is generally considered negligible. The potential energy, which is due to position or internal condition, is of primary importance in determining the state and movement of water in the soil. Differences in potential energy of water between one point and another give rise to the tendency of water to flow within the soil. The rate of decrease of potential energy with distance is in fact the moving force causing flow. Since potential energy is a measure of the amount of work a body can perform by virtue of the energy stored in it, knowledge of the potential energy state of water in the soil and in the plant growing in that soil can help in estimating how much work the plant must expend to extract a unit amount of water.

When the soil is saturated and its water is at a hydrostatic pressure greater than the atmospheric pressure(as for instance, under a water table) the potential energy level of that water may be greater than that of the reference reservoir (a hypothetical reservoir of pure water, at atmospheric pressure, at the same temperature as that of soil water, and at a given and constant elevation). In such case water will tend to move spontaneously from the soil into such reference reservoir. If, on the other hand, the soil is moist but unsaturated, water will no longer be free to flow out toward a reservoir at atmospheric pressure. On the contrary , the spontaneous tendency will be for the soil to draw water from such a reservoir.

A soil physics terminology committee of the International Soil Science Society (Aslyng,1963 in Hillel,1982) defined the total potential of soil water as the amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure to the soil water (at the point under consideration).

Soil water is subject to a number of force fields, which cause its potential to differ from that of pure, free water. Such force fields result from the attraction of the soil matrix for water as well as from the presence of solutes and the action of external gas pressure and gravitation.

Accordingly, the total potential of soil water can be thought of as the sum of the separate contributions of various factors as follows:

$$\phi t = \phi g + \phi p + \phi o \qquad \ldots(1)$$

where,

ϕt = total potential

ϕg = gravitational potential

ϕp =(pressure) matric potential

ϕo = osmotic potential

To raise a body against gravitational force, work must be expended, and this work is stored by the raised body in the form of gravitation potential energy. The gravitational potential of soil water at each point is determined by the elevation of the point relative to some arbitrary reference level.

When soil water is at hydrostatic pressure greater than atmospheric, its pressure potential is considered positive. When it is at a pressure lower than atmospheric (tension or suction) the pressure potential is considered negative. Thus water under a free water surface is at positive pressure potential, while water at such a surface is at zero pressure potential, and water which has risen in a capillary tube above that surface is characterised by a negative pressure potential. A negative pressure potential has often been termed as capillary potential and more recently matric potential. This potential of soil water results from the capillary and adsorptive forces due to the soil matrix. These forces attract and bind water in the soil and lower its potential energy below that of bulk water.

The presence of solutes in soil water affects its thermodynamic properties and lowers its potential energy. In particular, solutes lower the vapor pressure of soil water. The osmotic effect is important in the interaction between plant roots and soil, as well as in processes involving vapor diffusion. For understanding osmotic potential it is necessary to understand osmosis process. A schematic representation of a pure solvent separated from a solution by a semi-permeable membrance is shown in figure 4. As there is semi-permeable membrane in between two fluids so it will not allow the molecules present in solution to pass to solvent area but in stead, the solvent (pure water) molecules will pass through the membrance to dilute the concentration of the solution. Consequently, the solution level will be driven up in the left hand tube until the hydrostatic pressure of the column of the dilute solution on the left is sufficient to counter the diffusion pressure of the solvent molecules drawn into solution through the membrane . The hydrostatic pressure at equilibrium, when solvent molecules are crosssing the membrane in both directions at equal rates, is the osmotic pressure of the solution. The expression osmotic pressure of a solution can be misleading. What a solution exhibits relative to the pure solvent (say,water) is not an excess pressure but, on the contrary, a 'suction' such that will draw water from a reservoir of pure water brought into contact with the solution across a semi-permeable boundary. Hence, it will be more justified to speak of an osmotic suction as the characteristic property of a solution rather than of osmotic pressure which,however, is the conventional term. The actual process of osmosis will take place only in the presence of a semi-permeable membrance separating a solution from its pure solvent, or from another solution of different concentration. In principle,however, the property of the solution which includes the process of osmosis exists whether or not a membrane happens

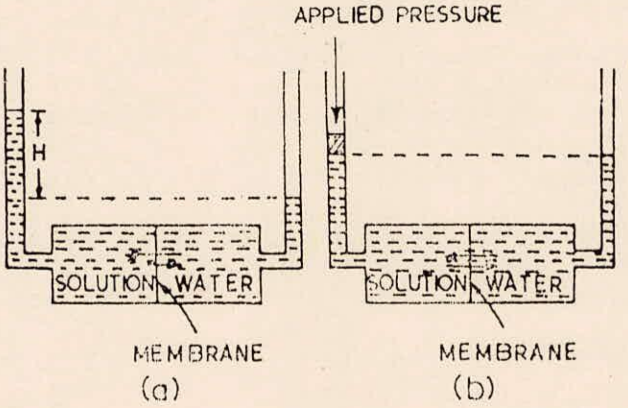


FIGURE 4 - OSMOSIS AND OSMOTIC PRESSURE

(a) Osmosis: the flow of water molecules through the membrane into the solution is at first greater than the reverse flow from the solution into the water compartment. The hydrostatic pressure due to the column of expanded solution increases the rate of water flow from the solution to the water compartment until at equilibrium, the opposite flows are equal.

(b) The osmotic pressure of the solution is equal to the hydrostatic pressure which must be applied to the solution to equalise the rate of flow to and from the solution and produce a net flow of zero(Hillel,1982).

to be present as it derives fundamentally from the decrease of potential energy of water in solution relative to that of pure water. Osmotic potential differences have little effect on liquid movement in the soil but strongly affect flow of water from soil to plant.

Not all the separate potentials described above act in the same way and their separate gradients may not be equally effective in causing flow (for example, the osmotic potential gradient requires a semi-permeable membrane to induce liquid flow). The main advantage of the total potential concept is that it provides a unified measure by which the state of water can be evaluated at any time and any where within the soil-plant-atmosphere continuum.

The following table shows the approximate magnitudes of water potential in the soil-plant-atmosphere system. This is diagramatically represented in figure 5.

Approximate magnitudes of water potential in the soil-plant-atmosphere system:

Component	Water Potential (bars)
Soil	-0.1 - -20
Leaf	-5.0 - -50
Atmosphere	-1000 - -2000

From above table it is obvious that the total difference in total water potential in the soil-atmosphere system could generate a driving force for water movement from the soil through the plant to atmosphere.

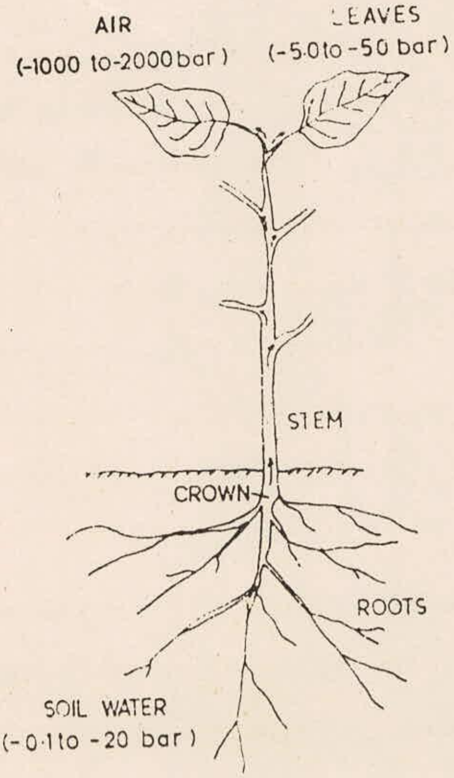


FIGURE 5 - SCHEMATIC ILLUSTRATION OF THE VARIATION OF WATER POTENTIAL ALONG THE TRANSPIRATION STREAM

In attempting to express the negative pressure potential of soil water (relative to atmospheric pressure) in terms of an equivalent hydraulic head, one must agree with the fact that this head may be of the order of -10,000 or even -100,000 cm of water. To avoid use of such cumbersome large numbers, Schofield(1935) (In Hillel,1982) suggested the use of pF which he defined as the logarithm of the negative pressure head in cms. of water. A pF of 1 is,thus, a tension head of 10 cm H_2O, a pF of 3 is a tension head of 1000 cm H_2O, and so forth.

In the process of water movement through plants, conditions are often such that the rate of water loss exceeds the rate of absorpition, cuasing an internal water deficit to develop in the plant. It is this internal water deficit, through its influence on many of the physiological processes in the plant, that is directly responsible for the growth and yield of a crop under the prevailing conditions.

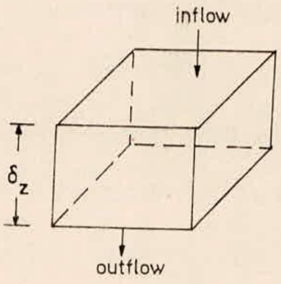
2.4 Soil Water Flow Equation

Most cf the processes involving soil-water interactions in the field, and particularly the flow of water in the rooting zone of most crop plants, occur while the soil is in an unsaturated condition. Unsaturated flow processes are in general complicated and difficult to describe quantitatively since they often ental changes in the state and content of soil water during flow. As in case of saturated soils,in unsaturated soils the rate of flow is proportional to the potential gradient and is affected by the geometric properties of the pore channels through which flow takes place. The most important difference between unsaturated and saturated flow is in the hydraulic conductivity. When the soil is saturated, all the pores are water filled and conducting, so that continuity and hence conductivity are maximal. When the soil desaturates, some of the pores become air filled and the conductive portion of the soil's cross sectional area decreases correspondingly. Furthermore, as suction develops, the first pores to empty are the largest one, which are the most conductive, thus leaving water to flow only in the smaller pores. A saturated sandy soil conducts water more rapidly than a clayey soil. However, the very opposite may be true when the soils are unsaturated.

Richards (1931) extended Darcy's equation for unsaturated flow conditions with a provision that conductivity is a function of the moisture content.

One-dimensional vertical flow in unsaturated soil can be understood as follows:

Assuming an elementary soil bulk volume as shown below:



X-Sec. Area perpendicular to flow is unity.

Let, θ_t = initial moisture content (vol.basis)of soil volume.

$\theta_{t+\delta t}$ = moisture content(vol.basis) of soil volume after time δ_t

So, $\theta_t\,\delta_z$ = volume of water initially contained in soil volume

$\theta_{t+\delta t}\,\delta_z$ = volume of water finally contained in soil volume.

Assuming, water enters soil volume with an average velocity of V_w in time interval δ_t. Hence,

total inflow in time $\delta_t = V_w . \delta_t$

total outflow in time $\delta_t = (V_w + \frac{\partial V_w}{\partial z}\,\delta_z)\,\delta_t$

Initial moisture present in the soil volume + total inflow in time δ_t = total outflow in time δt + Final moisture content at the end of time interval δt.

or,

$$\theta_t\;\delta_z + V_w\;\delta_t = (V_w + \frac{\partial V_w}{\partial z}\;\delta_z)\,\delta_t + \theta_{t+\delta_t} . \delta z$$

or,

$$\frac{\partial V_w}{\partial z} + \frac{\partial \theta}{\partial t} = 0 \qquad \text{...(2)}$$

According to Darcy's law,

$$V_w = - K(\theta)\frac{d_{h_w}}{d_z} + K(\theta) \qquad \text{...(3)}$$

putting value of V_w in equation (2) from Eqn.(3)

$$-\frac{\partial}{\partial z}(-K(\theta)\frac{d_{h_w}}{d_z} + K(\theta))\;\frac{\partial \theta}{\partial t} = 0 \qquad \text{...(4)}$$

now, capillary pressure (p_c) = atmospheric pressure(p_a) - water pressure (p_w)

or,

$$p_c = p_a - p_w$$

or,

$$\frac{p_c}{\gamma_w} = \frac{p_a}{\gamma_w} - \frac{p_w}{\gamma_w}$$

or,

$$h_c = h_{aw} - h_w$$

Assuming air pressure is same throughout and is atmospheric. (hence it can be taken zero).

or,

$$h_o = - h_w$$

or,

$$\frac{dh_c}{d\theta} = - \frac{dh_w}{d\theta} \qquad \ldots(5)$$

putting $\frac{dh_w}{d}$ value in equation (4)

$$\frac{\partial}{\partial z}(K(\theta)\frac{dh_c}{d\theta} \cdot \frac{\partial}{\partial z} + \frac{\partial}{\partial z} K(\theta)) + \frac{\partial\theta}{\partial t} = 0$$

or, $$\frac{\partial\theta}{\partial t} + \frac{\partial}{\partial z}(K(\theta) \frac{dh_c}{d\theta} \cdot \frac{\partial\theta}{\partial z}) + \frac{\partial}{\partial z} K(\theta) = 0 \qquad \ldots(6)$$

Equation(6) is basic differential equation for soil water flow in vertical direction. This is the governing equation where there is no sink or source term present. The amount of water absorbed by roots, which varies with root density and soil moisture content, can be introduced into equation(6) as a sink term.

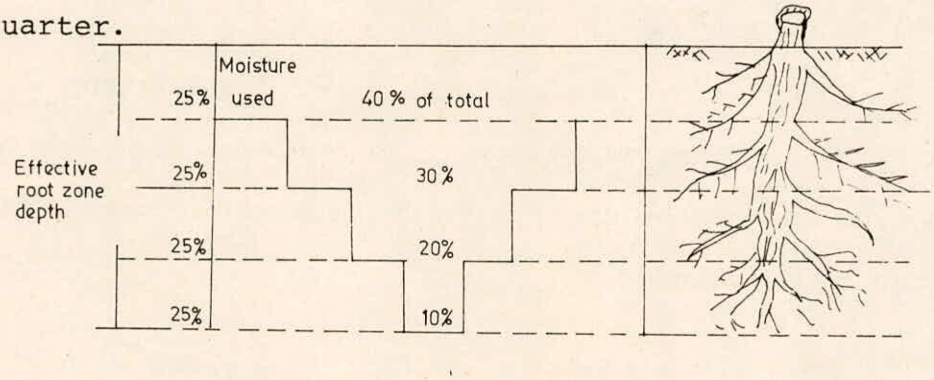
Let s(z,t) represents the sink term per unit length in the root zone. Hence, the governing equation for non-steady flow of water in soil-olant system can be wrriten as:

$$\frac{\partial\theta}{\partial t} + \frac{\partial}{\partial z}(K(\theta \frac{dh_c}{d\theta} \cdot \frac{\partial\theta}{\partial z}) + \frac{\partial}{\partial z} K(\theta) + S(z,t) = 0 \qquad \ldots(7)$$

2.5 Soil Moisture Removal by Plant Roots

When to irrigate and how much to apply are affected considerably by where and when water is removed from the soil by the plant roots Shallow rooted crop require more frequent irrigation than deep rooted crop. Soil moisture characteristics, such as field capacity and wilting percentage depend on type of soil and little can be done to alter these limits to any great extent. Greater possibilities lie in changing the characteristics of the plant, enabling it to extend its rooting system deeper into the soil, thereby enlarging its reservoir of water. Where a good root system has developed during favourable growing periods, a plant can draw its moisture supply from deeper soil layers.

The moisture extraction pattern shows the relative amounts of moisture extracted from different depths within the crop root zone. Following figure shows the moisture extraction pattern of average crop plants growing in deep uniform soils. It may be seen that about 40 percent of the total moisture used is extracted from the first quarter of the root zone, 30% from the second, 20% from the third and only 10% from the last quarter.



The above figure shows the average moisture extraction pattern of plants growing in a soil without restrictive layers and with an adequate supply of soil moisture (Michael,1978).

2.6 Evaporation,Transpiration and Consumptive Use

For estimating irrigation requirement and planning irrigation systems the important factors are evaporation,transpiration and consumptive use.

Evaporation is a process during which a liquid changes into a gas. This is the only form of moisture transfer from land and oceans into the atmosphere.

Transpiration is a process by which water vapour leaves the living plant body and enters the atmosphere.

Consumptive use of water involves problems of water supply, as well as problems of management and economics of irrigation projects. Consumptive use, or evapotranspiration is sum of two terms ;(i) transpiration, which is water entering plant roots and used to build plant tissue or being passed through leaves of the plant into the atmosphere (ii) evaporation, which is water evaporating from adjacent soil, water surfaces, or from the surfaces of leaves of the plant.

Consumptive use can apply to water requirements of a crop,a field, a farm, a project, or a valley. When the consumptive use of the crop is known, the water use of larger units can be calculated.

Three major considerations influence the time of irrigation and how much water should be applied, namely (a) water needs of the crop, (b) availability of water with which to irrigate, and (c) capacity of the root zone soil to store water.

Among various factors, water needs of the crop are of paramount importance in determining the time of irrigation during the crop growing season on irrigation projects which obtain their water supplies from storage reservoirs or from other dependable sources of water. Irrigation farmers can't always apply water when the crop is most in need ; sometimes to save water they must apply it even though the crop does not need it, provided the soil has capacity to store additional water. Therefore, crop needs, available water apply, and storage capacity of the soil must be considered before irrigation water is applied.

Though both terms consumptive use and evapotranspiration are interchangeably used but in reality consumptive use includes water used by plant for its metabolic activities in addition to evaporation and transpiration losses. But as the water used in actual metabolic processes is insignificant(less than 1% of ET)the term consumptive use is taken equivalent to ET.

2.7 Measurement of Evapotranspiration

To have an idea about total water requirement of the crop, it is necessary to know the ET rate of the crop. This can be determined either by conducting experiments or by using empirical relations. Generally lysimeter is used to find ET rate of crop under field conditions.

Several empirical equations have been developed to estimate ET rate of crop. Generally, with the help of such equations, potential evapotranspiration is determined. Potential ET is defined as 'the rate of evapotranspiration from an extensive surface of 8 - 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water' (Doorenbos & Pruitt,1977). Actual evapotranspiration rates can be found by multiplying potential ET by appropriate crop factor which depends on type of crop, crop stage etc.

2.8 Water Requirement

The estimation of the water requirement of crops is one of the basic needs for crop planning on the farm and for the planning of any irrigation project. Water requirement may be defined as the quantity of water,regardless of its source, required by a crop or diversified pattern of crops in a given period of time for its normal growth under field conditions at a place. Water requirement may be formulated as follows:

WR = ET + application losses + Special needs.

Application losses include the loss of water during water application. These losses are unavoidable losses. Special needs include water required for land preparation, transplanting, leaching etc. Some part of the total water requirements of a crop may be met by rainfall and also some portion may be shared by contribution from soil profile. Hence irrigation requirement will be calculated as follows:

$$IR = WR - (ER + S) \quad \ldots(8)$$

Where,

IR = Irrigation requirements

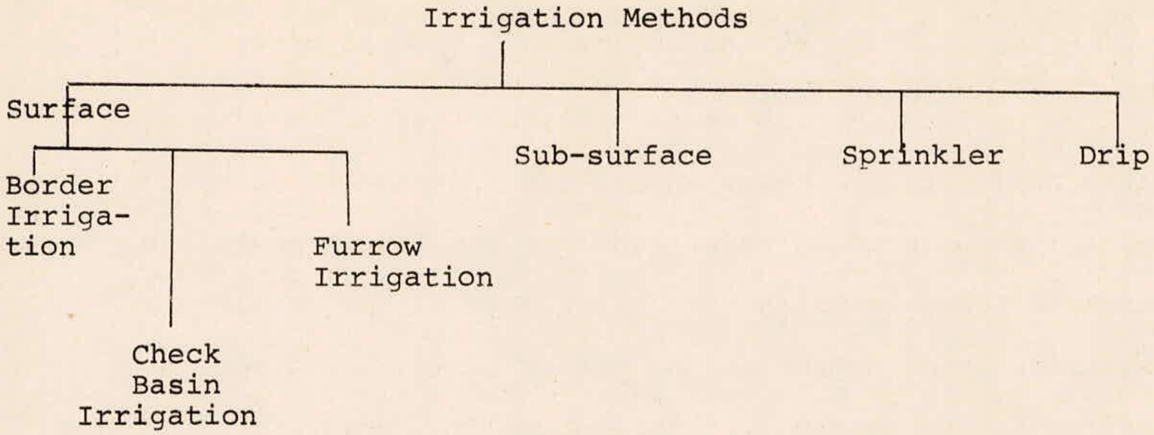
WR = Water requirements

ER = Effective rainfall

S = Soil profile contribution

Once irrigation requirements of a crop are known, various methods can be employed to irrigate the crop depending on the water supply, the type of soil, the topography of land, and the crop to be irrigated.

Irrigation water may be applied to crops by flooding it on the field surface, by applying it beneath the soil surface, by sparaying it under pressure and by applying it in drops. The common methods of irrigation are indicated schematically as follows:



2.9 Surface Irrigation Methods

In these methods water is applied directly to the soil surface from a channel located at the upper reach of the field. Water may be distributed to the crops by border strips, check basin and furrows.

In border irrigation method the water moves in sheet form down the slope along long parallel strips called borders. Check basin irrigation is the most common method of irrigation in our country. This method consists of dividing the field into smaller unit areas (basins) so that each has a nearly level surface. The basins are filled to a desired depth and the water is retained until it infiltrates into the soil. The furrow method of irrigation is used in the irrigation of row crops with furrows developed between the crop row in the planting and cultivating processes. As water is applied to furrows, it infiltrates into the soil and spreads laterally to irrigate the area between the furrows.

2.10 Sub Irrigation

In sub-irrigation water is applied below the ground surface by maintaining an artificial water table at some depths depending on soil texture and the depth of the plant roots.

2.11 Sprinkler Irrigation

In this method of irrigation, water is sprayed into the air and allowed to fall on the ground surface somewhat resembling rainfall.

2.12 Drip Irrigation

It is one of the latest methods of irrigation which is becoming increasingly popular in areas with water scarcity and salt problem. In this method the water is applied slowly to keep the soil moisture within the desired range for plant growth.

2.13 Irrigation Efficiencies

In planning and designing an irrigation system, a major problem is to decide what water use efficiency to apply in calculations. Since basic knowledge on this subject is lacking, it is common practice that this efficiency is either conjectured or derived from existing irrigation systems. Obviously, the efficiency thus obtained is unlikely to suit the conditions of the project area in its future state. Because water use efficiency is usually the 'Guess' factor in the design of an irrigation system, engineers are facing the problem of uncertainty in their calculations. To cover this uncertainty, canals, structures, and reservoirs are being given a greater capacity than would be necessary if objective efficiency standards were available and could be applied. Apart from harmful side-effects, this way of doing things leads to investments that may be considerably higher than would otherwise be necessary.

Obviously, there is an urgent need for more basic knowledge of irrigation efficiencies under different climatological, topographical, soil,agricultural, and socio-economic conditions.

Basically, irrigation efficiency indicates how efficiently the available water supply is being used. Loss of irrigation water occurs in the conveyance and distribution system, non-uniform distribution of water over the field, percolation below crop root zone etc. The losses can be held to a minimum by adequate planning of the irrigation system, proper design of the irrigation method, adequate land preparation and efficient operation of the system.

The system of water distribution can be split up into the following successive stages:

- conveyance by main, branch, distributory, minor canal to the farm inlet (irrigation outlet)
- conveyance by field channels to the field
- application to and distribution over the field from the field inlet (irrigation outlet)

Accordingly, following various kinds of efficiencies are defined:

2.13.1 Conveyance efficiency(e_c)

It is the efficiency of canal and conduit networks from the reservoir, river diversion, or pumping station to the off-takes of the distributory system. It can be expressed as:

$$e_c = \frac{V_d}{V_c} \qquad \ldots(9)$$

Where,

V_c = volume diverted or pumped from the river (m^3)

V_d = volume diverted to the distributioin system(m^3)

2.13.2 Distribution efficiency (e_d)

This is the efficiency of the water distribution canals and conduits supplying water from the conveyance network to individual fields. It can be expressed as :

$$e_d = \frac{V_f}{V_d} \qquad \ldots(10)$$

Where,

V_d = volume diverted to the distribution system(m^3)

V_f = volume of water furnished to the fields (m^3)

2.13.3 Field application efficiency(e_a)

It is the relation between the quantity of water furnished at the field inlet and the quantity of water stored in the soil root zone during irrigation . It can be expressed as:

$$e_a = \frac{V_m}{V_f} \qquad \ldots(11)$$

Where,

V_f = volume of water furnished to the fields (m^3)

V_m = volume of water stored in the soil root zone during irrigation (m^3)

2.13.4 Tertiary unit efficiency(e_u)

It is the combined efficiency of the water distribution system and of the water application process. In other words, it is the efficiency with which water is distributed and consumptively used within the tertiary unit. It is expressed as :

$$e_u = \frac{V_m}{V_d} \qquad \ldots(12)$$

or

$$e_u = e_d \cdot e_a$$

2.13.5 Irrigation system efficiency (e_s)

It is the combined efficiency of the systems of water conveyance and distribution, or :

$$e_s = \frac{V_f}{V_c} \qquad \ldots(13)$$

or,

$$e_s = e_c \cdot e_d$$

2.13.6 Overall or project efficiency (e_p)

The separate assessments of conveyance, distribution, and field application efficiencies will indicate if and where remedial measures are required to improve the efficiency of water use in the project as a whole. The data used to assess the separate efficiencies can also be used to assess a project's overall irrigation efficiency. It can be expresses as:

$$e_p = \frac{V_m}{V_c} \qquad \ldots(14)$$

This value represents the efficiency of the entire operation between river diversion or source of water and the root zone of the crops :

or,

$$e_p = e_c \cdot e_d \cdot e_a \qquad \ldots(15)$$

2.14 Water Use Efficiency

Efficiency in utilisation of water is finally determined in the field where the ultimate aim of irrigation meets either with success or failure. This implies two aspects, the first is technical and relates to water application with minimum wastage by avoiding unnecessary runoff and evaporation losses which has been discussed earlier and the second deals with the agronomic aspects of water use by crops which is generally described as water use efficiency.

Singh and Sinha (1977) defined water use efficiency in two ways :

2.14.1 Crop water use efficiency or consumptive water use efficiency (EC_u)

It is ratio of crop yield (Y) to the sum of the amount of water taken up and used by the crop in growth(G), transpired through foliage (T) and evaporated directly from the soil surface (E_s) or consumptively used (C_u) ;

$$EC_u = Y/ (G+T+E_s) = Y/C_u \qquad ...(16)$$

2.14.2 Field water use efficiency(E_u)

This is the ratio of crop yield(Y) to the amount of water used in the field (WR) including growth (G), transpiration (T), direct evaporation from soil surface (Es) and deep percolation loss (D) ;

$$E_u = Y/ (G+T+E_s+D) = Y/WR \qquad ...(17)$$

Of the two indices defined above, crop water use efficiency is of more fundamental interest to research workers, but field water use efficiency is of greater practical importance for planners and farmers.

3.0 REVIEW OF SCIENTIFIC WORK

Various criteria have been developed for scheduling irrigations for different crops. These criteria have been based on factors like plant water status, soil water status, irrigation water availability, crop growth state etc. Surveys have been done at internatioinal level to study the various irrigation practices popular in different countries and ways of reducing irrigation water loss have been suggested. A brief description of research work done on various aspects of crop water requirement, field efficiency is given in this chapter.

3.1 Water Requirement of Crops

The estimation of the water requirement(WR) of crops is one of the basic needs for crop planning on a farm and for planning of any irrigation project. Water requirement may be defined as the quantity of water, regardless of its sources, required by a crop in a given period of time for its normal growth under field conditions at a place. Water is needed mainly to meet the demands of evapotranspiration(ET) and the metabolic activities of plant, both together knwon as consumption use (C_u). Since the water used in the metabolic processes of plant is practically negligible, ET is practically considered equal to C_u. Water requirement, includes the losses during the application of irrigation water(unavoidable losses) and the quantity of water required for special operations such as land preparations, transplanting, leaching etc. It may thus be formulated as follows :

$$WR = ET \text{ or } C_u + \text{application losses} + \text{Special needs.}$$

Water will generally be supplied either by irrigation water or by rainfall and some may be by soil profile contribution.

Evapotranspiration measurements are based on water balance methods accounting for all inflow and outflow of water. A generalised water balance equation is expressed as:

$$RA + IR + Cr = ET + SP + R + W \qquad \text{...(18)}$$

Where,

RA = rainfall in mm

IR = net irrigation in mm

Cr = capillary rise in mm

ET = evapotranspiration in mm

SP = percolation in mm

R = runoff in mm

W = change in moisture of the soil expressed in mm

The techniques for determining water requirements of different crops can be grouped as follows: (Dastane et.al.1970).

i) Depth-interval yield approach

ii) Soil moisture deficit approach

iii) Climatological approach

iv) Drum culture technique for rice.

The details are described in section 4. Generally, Lysimeters are used in the field for evapotranspiration meaurement.

In climatological approach, the climatic variables are combined to give an estimate of evapotranspiration need of various crops. Some of the empirical relations developed to estimate ET are summarised below:

Penman (1948) proposed an equation for evaporation estimation from a free water surface and evapotranspiration estimates for crops can be done by multiplying the estimated evaporation by the crop coefficient. Blaney and Criddle(1950) developed an empirical equation which correlates evapotranspiration values with monthly temperature, percent of daytime hours, and length of growing season.

Wendell (1960) proposed the P.E.(Precipitation-Evaporation) index method. The monthly precipitation - evaporation ratio is computed and the sum is determined on annual basis. He gave a set of P/E values applicable for most crops. In a given month, knowing temperature, and the needed P/E index, the amount of precipitation can be determined from a nomograph.

Russel (1961) gave a simple expression for potential evapotranspiration.

$$PE = C\,D^2\,P_t \qquad \ldots(19)$$

where,

PE = potential evapotranspiration

C = a constant

D = possible hours of sunshine, 12 hr.unit.

P_t = saturated water vapour density

Hendricks(1962) approached the problem on micro scale and concluded that actual evaporation depends on one of the three conditions that predominates i.e. the heat available for transpiration, the capacity of the soil to supply moisture, and the moisture carrying capacity of the plant xylem.

Jensen and Haise (1963,1966) have presented an energy balance approach to estimate evapotranspiration. The Jensen-Haise method for potential ET for well watered alfalfa (30 -50 cm.ht.) developed in the western U.S. is :

$$ET = Ct\ (tc - tx)\ Rs = 0.025\ (tc + 3)\ Rs \qquad \ldots(20)$$

where,

ET = potential ET in mm/d

Ct = temperature coefficient

tc = mean air temperature in ^{o}C

tx = intercept of ET/Rs Vs. t regression line with the temperature axis

Rs = solar radiation as equivalent depth of evaporation in mm/d

Christiansen (1968) proposed a revised empirical formula, originally developed in 1966 to estimate pan evaporation from climatic data when reliable measured pan evaporation data are not available for estimation of evapotranspiration. The equation given is as follows :

$$EV = Kev.\ R.Ct.Cw.Ch.Cs.Ce.Cm \quad \ldots(21)$$

where,

EV = computed pan evaporation equivalent to class A pan evaporation,

Kev = empirically developed dimensionless constant

R = extra-terrestrial radiation,

Ct, Cw, Ch, Cs, and Ce are coefficients for temperature, wind velocity, relative humidity, percent of possible sun shine and elevation, respectively. Cm is a monthly coefficient

Doorenbos and Pruitt (1977) have suggested radiation method for ET estimation. This method is based on Makkink formula (1957). The relationship recommended is as follows:

$$ET_o = C\ (W.R_s)\ \text{mm/day} \quad \ldots(22)$$

Where,

ET_o = reference crop evapotranspiration in mm/day

W = weighing factor which depends upon temperature and altitude

C = adjustment factor which depends on mean humidity and daytime wind conditions

Other who have contributed to this area are Kohler et al. (1962), Van Bavel (1966), Ivanov (1968), Ostromecki (1965), Papadakis (1966), Behnke and Maxey (1969), Oliver (1961), Stephens and Stewart (1963), Turc (1961) etc.

All above mentioned empirical relations are based on correlating climatic variables with crop evapotranpiration

Table 2 gives the classification of various methods and principal references. Further, Table 3 gives details of type of estimate each method makes.

3.2 Effective Rainfall

In its simplest sense, the term effective rainfall indicates the proportion of total rainfall which is useful or utilisable for productive purposes. From the point of the water requirements of crops, the Food and Agricultural Organisation (FAO) of the United Nations has defined the effective rainfall as that part of the total annual or seasonal rainfall which is useful directly and/or indirectly for crop production at the site where it falls, but without pumping(Dastane,1974). The ineffective rainfall is that portion of the total annual or seasonal rainfall which is lost by surface runoff, deep percolation beyond root zone, the moisture remaining in the soil after the harvest of the crops and is not useful for the next crop.

Several methods and criteria have been adopted to measure the effective rainfall in different countries (Dastane,1974).

In Japan, a daily amount less than 5 mm is treated as non-effective for the paddy crop and also daily rainfall over 50 mm is taken as 50 mm assuming the rainfall amount of more than 50 mm will cause an overflow over the earthern bank of paddy field.

In Thailand, the percentage of effective rainfall

Table 2 - Classification of estimating ET Methods and Principal References

Classification	Method	References
Combination	Kohler, Nordenson and Fox	Weather Bur.Res.Paper 38,1955 and Monthly Weather Rev.90,1962
	Penman	Proc.Roy.Soc.A193,1948 and Tech. Comm.No.53,Commonwealth Bur. of Soils,Eng.,1963.
	Van Bavel-Businger	Water Resources Res.Vo.2(3), 1966 and Neth.J.Agr.Sci.4,1956
Humidity	Ivanov	WMO Tech.Note No.97,1968
	Ostromecki	Prace 1, Studia,Komitetu,Vol.7 No.1,1965 (USDI TT 67-56052)
	Papadakis	Climates of the World Buenos Aires,1966
Miscellaneous	Behnke-Maxey	J.of Hydrol.,8,1969
	Christiansen	Trans.Int'l,Comm.on Irrig. and Drain.,Vol.III,1969 and J. Irrig. and Drain.Div.Am.Soc. Civ.Engr.,94,1968
	Olivier	Irrig.and Climate,Edward Arnold Ltd., London,1961
Radiation	Jensen-Haise	Trans.Am.Soc.Agr.Engr.,14,1971 and J.Irrig. and Drain.Div. AmSoc.Civ.Engr.,89,1963
	Makkink	J.Inst.Water Eng.,11,1957, and Am.Soc.Agr.Engr.ET Symposium, 1966
	Stephens-Stewart	J.Hydr.Div.,Am.Soc.Civ.Engr. 1965 and Publ.62,Int'l Assoc. Sci.Hydrol.,1963
	Turc	An.Agron.,12,1961, and Am.Soc. Agr.Engr.ET,Symposium 1966
Temperature	Blaney-Criddle	USDA SCS Tech.Rel.21,1967 (Rev.Sept.1970)
	Thornthwaite	The Geographical Rev.,38,1947, and Public. in Climat.,8 Lab. of Climat., Centerton,N. Jersey,USA,1955

Table 3 - Type of Estimate Intended by the Various Methods

Method	Type of Estimate	Remarks
Kohlerm et al.	Lake evaporation	Data from 4 lakes in U.S.A.
Penman	Potential evapotranspiration	Short green crop completely shading the ground never short of water
Van Bavel-Businger	Potential evaporation	Evaporation when water is available at the surface, applicable to various surfaces
Ivanov	Potential evapotranspiration	Surface or crop not specified
Ostromecki	Evapotranspiration	Clover with timothy,E.Europe,coefficient based on one cutting period
Papadakis	Potential evapotranspiration	Surface condition or crop not specified
Behnke-Maxey	Potential evapotranspiration	Evapotranspiration with no moisture deficiency. Varies with crop,but no reference crop indicated
Christiansen	Potential evapotranspiration	Coefficients derived from clipped ryegrass,(8-15 cm) Davis,California
Olivier	'Basic water requirements for a crop-soil unit'	Crop or surface condition not specified
Jensen-Haise	Evapotranspiration from a reference crop (E_{tp})	Reference crop is alfalfa(lucerne),well-watered, with 30-50 cm of growth. Coefficients derived from U.S.A.' data
Makkink	Same as for Penman	

Table 3 ....Contd.

Method	Type of estimate	Remarks
Stephens-Stewart	Potential evapotranspiration	Single surface or crop not specified. Coefficients derived from St.Augustine grass in Florida, ryegrass at Davis,California,grass in North Carolina, and alfalfa,cotton,oats and wheat in Western USA
Turc	Potential evapotranspiration	Crop factor-70, derived from western Europe data
Blaney-Criddle	Evapotranspiration from a specific crop	Evaluated for alfalfa using SCS crop coefficients
Thornthwaite	Potential evapotranspiration for a standard surface	Grass, solid cover, with no moisture deficiency. Application essentially restricted to conditions similar to those in New Jersey, U.S.A.

varies with the months. During the wet season 75% of the monthly rainfall figures is considered effective for April to September. For October the effective percentage reduces to 65% due to heavier intensity of rainfall. During the dry season, for November, 80% of the month's total rainfall is considered usable by plants ; and for the period December to March, 90% of each month's total rainfall is taken effective. In Burma,80% of the amount greater than 12.7 mm is considered effective for rice plants during the wet season. For farm crops the effective percentage reduces to 65% during the same season. In the dry season 65% of the amount greater than 25.4 mm is considered as effective for farm crops.

In India, among various methods of estimation of effective rainfall, the common one is to take 70% of the average monthly figures as the effective rainfall. In some states, rainfall amount more than 6.35 mm and less than 76.2 mm is considered effective during the transplanting period of the rice crop (June - August). For the maturation period (Sept.-Nov.) rainfall from 25.4 to 50.8 mm in one day is taken to be effective.

Ramdas (1960) suggested the use of a small percolating filled in soil type cylinder for direct measurement of percolation losses in the field. This does not provide day-to-day information of effective rainfall and the soil conditions in the container may vary from that in the field.

Stanhill (1958) used an integrating gauge consisting of a rainfall receiver which is connected to a water collecting reservoir and this in turn is connected to an evaporating surface (plate) to represent crop evapotranspiration. The reservoir is also provided with an overflow device which is simple, practical, useful and can easily be set up in the field and moisture balance can be recorded at any time.

Dastane et al.(1966) used set of three cylindrical drums to determine effective rainfall. The details have been given elsewhere in this report.

Empirical relations have also been developed for estimating effective rainfall. A rough guide for estimating effective rainfall has been developed by U.S.Bureau of Reclamation (Stamm,1967) for arid and semi-arid regions in which the mean seasonal precipitation of the five driest consecutive years is used as the basis. The effectiveness of increments of monthly rainfall range from more than or 90% of the first 25 mm to 0% for precipitation greather than 150 mm. The same has been modified and given as below by Doorenbos & Pruitt (1975) to account for the effectiveness of rainfall.

Monthly rainfall increments,mm	25	50	75	100	125	150	150
Effective (%)	90	85	75	50	30	10	0

A simple semi-empirical method, used in some projects in India, has been described by Dastane (1974). A ratio of PET, taken as 0.8 of the U.S.W.B. Standard class A pan data, to the total rainfall for the certain group of days (excluding the rainless period) during the growing season is computed. The number of days in the group is based on moisture properties of soil type as well as evapotranspiration rates. The ratios are expressed as percentage for each period and hence these can't exceed 100. The simple monthly means and grand mean from monthly means are computed for the entire growing season. There can be, however, some under or over estimation of effective rainfall depending upon the distribution of rainfall, but error involved is small when seasonal and annual values are computed. This method is rapid and inexpensive and is good only for broad planning.

3.3 Leaf - Area Index

In a developing canopy, leaf area index (L_{ai}) which is the ratio of leaf to ground area, is an important parameter for estimating intercepted light, photosynthesis, crop water requirements etc. Leaf area index mainly depends on plant variety, plant population, row spacing, fertilizer, and water applied. In the early stages of growth, L_{ai} is linearly related to population (Fowler, 1966). For Corn, Splinter and Beeman (1968) developed the following relationship between Leaf area and stem diameter :

$$LA = m\ D^{n} = 550\ D^{2.905} \qquad \ldots(23)$$

where,

LA = Total Leaf area (inch^2) per plant

D = Stem Diameter (inch)

m and n are constants.

Acevedo (1975) conducted experiments with maize crop at Experiment Station of the University of California at Davis, U.S. and gave following relationship for total Leaf area:

$$LA = 0.759 \sum_{i=1}^{n} L_i W_i \qquad ...(24)$$

where,

LA = Total Leaf area (cm^2)

L_i = Length of i^{th} Leaf

W_i = Maximum width of i^{th} Leaf'

n = Total number of leaves in each plant.

He further gave graphical relationship between Leaf area index and days after planting.

3.4 Root Length and Distribution

Root growth and water absorption by plants are processes that are closely associated. Water abosorption enhances root growth, which in turn favours water absorption by exploring new soil and/or shortening the distance that water has to move to reach root surface. Simulation results on soil moisture distribution in a given soil profile under a given crop,time, and environmental conditions are largely a function of effective root length distribution.

Because of the difficulties of field measurements and the complexity of the root growth process, limited field data are available on root growth process, Newman (1974) dealt with root and soil water relations, and Head (1973) has reviewed the chracteristic of root growth development. Lungley(1973) proposed a numerical simulation model for root growth. Hillel and Talpaz (1976) have also proposed a theoretical root development model using three parameters of proliferation, death, and extension rate, recognising the difficulties of assigning actual numbers for each process for a given crop and soil condition.

There is considerable uncertainty about the fraction of total root length that is effective in water uptake by field crops. For water-uptake studies, Walter and Barley(1974) and Ponsana (1975) proposed using the length of hair-bearing roots per unit volume of soil, LH, rather than the total length of roots per unit volume of soil, LV. They obtained values of LH ranging from 0.1 to 0.3 LV.

As investigation into the description of effective root length continues, interpretation and evaluation of the RDF(Z) (so called root-effectiveness function) is handled differently by researchers. Gardner (1964) and Whisler et al. (1968) considered the root density function as reflecting the surface area of the roots per unit bulk volume of soil and some effective distance over which water moves to the root. Feddes (1971) considered RDF as a parameter which accounts for the length and geometry of the roots and derived it experimentally with lysimeter measurements of vertical flow together with the assumption that the rate of flow from roots through plants is linearly proportional to the corresponding difference between plant and roots. Feddes et al. (1974) also report that the root effectiveness function is proportional to the root mass, with both varying more or less exponentially with depth. Acevedo (1975) described following relationship to find root length density

$$LV = AA\ (1 - B_1 \exp(-B_2 t)) \qquad \ldots(25)$$

where,

LV = root length density (cm root cm^{-3}soil)

AA = coefficient that determines the value of the asymptote

B_1 = coefficient that determines the intersection of the curve with the abscissa at $t = 0$

B_2 = coefficient that determines the degree of the curve

t = time in days after root penetrates to the given depth.

While sufficient information on the hydraulics of growing root systems is not available, yet the limited data already available (e.g. Taylor and Klepper,1975) suggest that the distribution of roots in the profile can change rather markedly within a period of weeks or even days, particularly in the case of an annual crop. It is,therefore, of interest to attempt to devise a logical frame work for the dynamic simulation of root growth within the context of an overall model of soil water extraction by variously distributed root systems. Such a model might serve as a better criterion for the evaluation of soil moisture availability to different types of plants and different stages of growth (Hillel,1980).

3.5 Moisture Extraction Pattern

The fundamental requirement in soil moisture profile prediction is to find pattern of soil moisture extraction.

In fact, the rate of water uptake from a given volume of soil depends on rooting density (the effective length of roots per unit volume of soil), soil conductivity and the difference between average soil water suction and root suction. If the initial soil-water suction is uniform throughout all depths of the rooting zone, but the active roots are not uniformly distributed, the rate of water uptake should be highest where the density of roots is greatest (Hillel,1980).

Aldreich (1935) showed that the rate of moisture extraction is maximum at soil surface and decreases towards the bottom of root zone.

Shockley (1953) proposed that the amounts of moisture extraction in each quarter of root zone from top were equal to 40%, 30%, 20% and 10% which was also reported by Micahel (1978).

Furr and Taylor (1939) reported that the rate of water extraction from one part of the soil in the root zone was influenced by the moisture content of the soil in other parts of the zone.

Beckett et al.(1930) concluded that soil moisture extraction rate is not affected by content of soil moisture as long as it is above wilting point.

Wadleigh(1946) concluded that with the removal of water from soil by roots, the water stress upon the root system keeps increasing.

Ogata et al.(1960) have reported non-uniformity of water uptake from different soil depths in field. In a non-uniform root system, sunction gradients can form which may induce water movement from one layer to another in the soil profile itself. In general, the magnitude of this movement is likely to be small relative to the water uptake rate by plants, but in some cases it will be considerable.

Mustonen (1967) related evapotranspiration losses from lysimeter with soil moisture and stated that ET loss varied as the one-fourth of soil moisture. Rice (1975) studied ET losses with respect to soil moisture patterns and concluded that moisture extraction is maximum at the surface where soil moisture is high. The moisture extraction pattern changes as moisture at surface gets depleted.

A mature root system occupies a more or less constant soil volume of fixed depth so that uptake should depend mainly upon the size of this volume, its water conrent and hydraulic properties, and the density of the roots. On the other hand in young plants, root extention and advance into deeper and moisture layers can play an important part in supplying plant water requirements. (Kramer and Coile,1940), Wolf,1968).

Wind (1955) stated that the roots of the deeper layers may offer greater resistance to water movement within the plant than the roots of the upper layer.

Rose and Stern (1967) presented an analysis of the time rate of water withdrawal from different soil depth zones in relation to soil wetness and hydraulic properties, and to the rate of plant-root uptake.

A detailed field study of water extraction by a root system was carried out by Van Bavel et al. (1968 a,b) using the instantaneous profile method of obtaining the hydraulic properties of a complete profile in situ (Watson,1966 ; Hillel et al. 1972). The calculated root extraction rates agreed reasonably well with separate measurements of transpiration obtained with lysimeters.

Denmead and Shaw (1962) did experimental confirmation of the effect of different meteorological conditions on water uptake and transpiration of corn plants. The transpiration rate was reported almost constant with the change in soil moisture under cloudy and humid conditions. Under partly cloudy condition the rate of increase of transpiration was found less than under warm and dry conditions.

In recent years there have been development of numerous models aimed at quantitative formulation and prediction of the sequential and simultaneous processes involved in the movement of soil moisture and its extraction by plants. More specifically, the available models vary in principle, depending on whether they are based on empirical or mechanistic approaches to the complex soil-plant-water-atmoshpere system.

Mainly the modelling of soil moisture extraction by roots has been done by Cowen,1965 ; Feddes et al., 1974,1976; Hansen,1975; Hillel et al., 1975, 1976; Lamber and Penning de Vries, 1973; Molz and Remson, 1970,1971; Molz 1976 ; Nimah and Hanks,1973 ; Rose et.al., 1976; Van Bavel and Ahmad,1976. All these authors have differed widely in their quantitative assessment of the relative importance of the root versus soil resistance terms at various stages of the extraction process. Theoretical and experimental studies conducted by Gardner, 1960,1964; Greasen et al.,1976; Herkelrath,1975; Newman,1969, 1974; Reicosky and Ritchie,1976; So et al.1976; Taylor and Klepper,1976; Young and DeJong,1971 have suggested that both resistance terms i.e. soil resistance and root resistance can be important: the root resistance term most probably tending to predominate in situations of low soil moisture tension, i.e. high soil hydraulic conductivity, and the soil's hydraulic resistance tending to gain importance as the extraction process continues and causes progressive depletion of soil moisture.

In principle, two approaches can be taken to modelling the uptake of soil water by roots. These are :

i) MICROSCOPIC MODEL OR SINGLE ROOT MODEL

This approach considers the convergent radial flow of soil water toward and into a representative individual root, taken to be a line or narrow-tube sink uniform along its length. This approach involves casting the flow equation in cylindrical co-ordinates and solving it for the distribution of potentials, water contents, and fluxes from the root outward. The solutions can be attempted by analytical means (e.g., Philip, 1975; Gardner,1960 ; Cowan,1965), which usually require rather restrictive assumptions, or by numerical means (e.g. Molz and Remson,1970; Lambert and

Penning de Vries, 1973; Hillel et al.,1975), which require use of digital computer.

ii) MACROSCOPIC SCALE OR ROOT SYSTEM MODEL

This approach regards the root system entirely as a diffuse sink which permeates each depth layer of soil uniformly, though not necessarily with a constant strength through out the root. These macroscopic approaches were taken by Ogata et al.(1960), Gardner (1964), Whisler et al. (1968), Molz and Remson (1970,1971), Nimak and Hanks (1973), Hillel et al.(1976), and others.

Gupta et al.(1978) carried out study on field simulation of soil-water movement with crop water extraction. The basic objectives of the study were to develop a soil water-flow model which can predict soil moisture contents at specified depths, soil water flux in each depth increment, and root water extraction and surface evaporation. This study was a part of main study aimed at predicting nitrogen leaching losses from the crop root zone as a function of sprinkler irrigation and N- fertilizer application rates. A computer model was developed to simulate natural physical process in the crop root zOne as they affect soil water movement and plant uptake.

Sarma et al.(1982) developed a computer based procedure for calculation of water balance in the crop root zone at W.T.C., I.A.R.I., New Delhi. This computer programme could compute the moisture profile from field observations of soil moisture tensions and could also evaluate the daily evapotranspiration as a residue from the water balance equation. The programme can also evaluate the effects of rainfall on irrigation during the periods of observation in addition to give an estimation of loss of water due to deep percolation. It has a provision to take care of the limitation in the availability of data due to occasional skipping of records for two or more days at a stretch. The special features of this programme include the procedures for the computation of infiltration and moisture flow. The model was applied to actual field data and results were taken out.

3.6 Dynamics of Soil Water

Movement of water in the crop root zone mostly occurs through pores partially filled with water, or under unsaturated conditions. In recent decades, unsaturated flow has become one of the most important and active topics of research in soil-water-plant interaction area.

It has been found that for unsaturated flow conditions, Darcy's law is applicable if hydraulic conductivity (K) is regarded as a function of moisture content (θ). The argument of this was first given by Buckinghams (1907) and was later discussed explicitly by Richards (1931). Richards gave the equation for unsaturated flow as follow :

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z} \left(K(\theta) \frac{\partial H}{\partial z} \right) + A(z,t) \qquad \ldots(26)$$

where,

θ = volumetric water content

Z = depth

t = time

K = hydraulic conductivity

H = hydraulic head

$A(z,t)$ = root extraction term

Klute (1952) attempted to solve this equation for soils in which diffusivity varied with moisture content. He considered only horizontal moisture movement where no gravity effect operates.

Philip (1957) found the following expression for depth to moisture front after solving Richards equation.

$$Z\ (\theta,t) = \emptyset_1 t^{\frac{1}{2}} + \emptyset_2 t + \emptyset_3 t^{3/2} + \emptyset_4 t^2 + \ldots\ldots \ldots\ldots \emptyset_m t^{m/2} \qquad \ldots(27)$$

where,

$Z(\theta,t)$ = depth to moisture front dependent on moisture content and time

$\emptyset_1, \emptyset_2, \emptyset_3 \ldots\ldots \emptyset_m$ are solutions of ordinary differential equations and depend on soil moisture properties and are functions of moisture content. Philip made use of Boltzman transformation to get the solution.

Gardner and Mayhugh (1958) made an experimental verification of solution of Richards equation. The diffusivity was assumed to be an exponential function of the moisture content. The diffusivity can be related to moisture content in the following form :

$$D(\emptyset) = a\ e^{b\theta} \qquad \ldots(28)$$

To simplify the mathematical and experimental treatment of unsaturated flow processes, it is often advantageous to change the flow equations into a form analogous to the equations of diffusion and heat conduction, for which ready solutions are available. (e.g., Carslaw and Jaeger,1959 ; Crank,1956). To transform the flow equation, it is sometimes possible to relate the flux to the water content(wetness) gradient rather than to suction gradient.

The matric suction gradient $\frac{\partial\psi}{\partial x}$ can be expanded by the chain rule as follows :

$$\frac{\partial\psi}{\partial x} = \frac{d\psi}{dQ} \cdot \frac{\partial Q}{\partial x}$$

where , $\frac{\partial\theta}{\partial x}$ is the wetness gradient and

$\frac{d\psi}{d\theta}$ is the reciprocal of the specific water capacity $C(\theta)$ as :

$$C(\theta) = d\theta/d\psi$$

Which is slope of soil-moisture characteristic curve at any particular value of wetness θ. So now the Darcy Equation can be written as :

$$q = -K(\theta)\,\frac{\partial\psi}{\partial x} = -K(\theta)/C(\theta)\,\frac{\partial\theta}{\partial x} \qquad \ldots(30)$$

To cast this equation into a form analogous to Fick's law of diffusion, a function was introduced (Child and Collis-George,1950), originally called the diffusivity(D), where:

$$D(\theta) = K(\theta)/C(\theta) = K(\theta)\,d\psi\,/d\theta \qquad \ldots(31)$$

D is thus defined as the ratio of the hydraulic conductivity K to the specific water capacity C, and since both of these are functions of soil wetness, D must also be so.

Hanks and Bowers (1962) solved the Richards equation for two layered soil since a homogeneous and isotropic soil is normally not met in practice. This was the first attempt to make use of the digital computers in the solution of the partial differential equation adopting method of finite differences. Their results show that where a less permeable soil overlies a more permeable soil, the infiltration is controlled by the less pervious soil. In case of a more pervious soil, the finding was that till such time the moisture front reaches the interface, infiltration is governed by top soil and later by the less pervious soil.

Rubin and Steinhardt (1963-64) defined for the first time the term 'ponding time'. They considered a constant flux and for these conditions solved the partial differential equation.

Whisler and Klute (1965) considered a column of soil well drained after saturation with water-table-maintained at a given depth. A solution was found for the position of moisture front, the depth vs. moisture content at different time periods after supplying a thin layer of ponded water. It was found that form of moisture front is a direct reflection of the soil properties.

Remson et al.(1967) considered one dimensional drainage of a soil column subject to evaporation and hysteresis. Evaporation was seen to affect only a limited layer at the surface. Hysteresis introduces a discontinuity in the values of soil moisture at the depth where the change from inhibition to drainage occurs.

Ibrahim and Brutsaert (1968) solved the one dimensional infiltration into a hysteresis affected soil.

Whisler et al.,(1968) are the first to consider evapotranspiration as a negative source term in the general equation.

Hanks et al.(1969) solved numerically the problem of infiltration, redistribution, drainage and evaporation from soil. It was assumed that the relationship between moisture content and conductivity is unique. Hysteresis in the soil is accounted for.

Bhuiyan et al.(1971) attempted the Philip's infiltration problem. They adopted a CSMP digital simulation model and found that the results obtained agreed well with those of Philip's four term solution with small differences.

Smith (1972) made use of the numerical method to solve for ponding time for five soils subject to constant flux. He determined infiltration rate subsequent to ponding also. Ponding time varied inversely as the rainfall flux raised to a negative power.

$$t_p = a_1 R^{-a2} \qquad \ldots(32)$$

where

t_p = ponding time

R = constant rainfall flux

a_1 and a_2 constant for a given soil.

The post ponding infiltration rate is given as

$$F = f \alpha + A (t-t_o)^{-\infty} \qquad \ldots(33)$$

where

F = post ponding infiltration rate

f_{α} = saturated conductivity of soil

A, α and t_o are constant for a given soil.

t is time from start of rainfall flux. Smith also gave a method to determine time to ponding for a varying rainfall as obtained in nature.

Whisler et al. (1972) solved the flow equation for a heterogeneous soil. This is the situation normally found in field.

Jean-Yves Parlange (1972) contributed a series of eleven papers. The problem consisted of solving the flow equation for various boundary conditions. Parlange recognised that constant rainfall flux conditions arise most generally. The following equation, for finding time required to attain a given moisture concentration at the surface in a dry soil, is given by him.

$$t = \int_{0}^{\theta} \frac{D(B)\ B.d\beta}{Q\ (\ Q - K\ (\ \beta\ ))} \qquad \ldots(34)$$

where

t = time to raise surface moisture content from 0 to θ

$D(\beta)$ = diffusivity, a function of moisture content

Q = constant flux

$K(\beta)$ = capillary conductivity, a function of β

By this equation the ponding time can be calculated if the upper limit is the soil porosity corresponding to maximum soil moisture content. He also gave an equation for the soil moisture profile for a given moisture content at surface.

Van Bavel et al. (1973) adopted the CSMP language and simulated the soil moisture at different depths based on the fundamental Darcy and continuity equations. For purpose of subirrigation, they tried the position of supply pipe at different depths. Water loss by surface evaporation and root uptake was taken into consideration. The limits of soil moisture fluctuations were laid down such that irrigation was turned on at the lower moisture content and turned off at higher moisture content. This program could account for soil non-homogeneity and hysteresis.

Morel-Seytoux and Khanji (1974) considered that ignoring pressure variations of air contained between the infiltrating moisture sheet and the water table will introduce large errors where water tables are high. The predicted errors might vary between 10 to 70 percent. From viscous and capillary considerations they derived the mean suction at moisture front for five soils.

Hanks and Nimah (1973) gave a model to find soil-plant-interrelations. The flow equation for unsaturated conditions was modifi3d for the presence of roots. It was done along the lines of Whisler (1968) and Molz and Remson (1970), a plant root term S (z,t) (sink term) is included giving.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left(K(\theta) \frac{\partial H}{\partial z} \right) + S(z,t) \qquad \ldots(35)$$

This root extraction term depends on water potential flow coefficient, osmotic potential, active roots etc.

Gupta et al.(1978) described macroscopic approach to describe Sink term (S (z,t)).

In macroscopic approach, Sink term as described by **Nimah** and Hanks (1973 a) and Feddes et al.(1974) are **described** as:

$$S = -K(h_r - h_{loss} . Z - h(z,t) - h_o(z,t)).b' \qquad \ldots(36)$$

$$S = -K(h_r - (1 + C_r).Z - h_s(Z) - h_o(z,t)).b' \qquad \ldots(37)$$

where,

h_r = effective water pressure in the root at the soil surface where Z is considered zero (cm.)

C_r = coefficient representing pressure head loss in water movement per unit depth

$h_o(z,t)$ = osmotic pressure in equivalent head units (cm.)

b' = coefficient of proportionality describing root-effectiveness functions (cm^{-2})

h_{loss} = pressure head loss in water movement per unit depth (cm.)

Nimah and Hanks (1973 a) defined b' as :

$$b' = \frac{R\ D\ F(Z)}{X\ \Delta Z} \qquad \ldots(38)$$

where,

RDF(Z) = proportion of total active roots in the ΔZ depth.

x = horizontal distance between the plant roots at the given point where the sink is estimated

Z = depth increment (cm.)

Nimah and Hanks (1973 a) took ΔX value to be one.

Equation (37) considers the resistance of flow as being primarily that of soil and results obtained by such simplified description compare reasonably well with field measurements.

Feddes et al.(1975) also proposed an alternative method for expressing the sink term :

$$S(\theta) = \alpha(\theta) \frac{2E_t}{L} \qquad \ldots (39)$$

where,

E_t = actual transpiration

L = rooting depth

(θ) = variable depending on soil moisture content (refer Figure 6)

The above expression is based on the assumption that sink term varies linearly with depth and thus can be approximated by the surface of the triangle (Figure 7) given below:

$$E_t = \int_0^L S(z,t)dz = \tfrac{1}{2} L.S._{max} \qquad \ldots (40)$$

or,

$$S_{max} = \alpha(\theta) \frac{2E_t}{L}$$

(θ) is taken as linear function between moisture contents at wilting point θ_w and field capacity θ_d.

3.7 Redistribution

In the study of soil moisture next to infiltration study, the redistribution study is also very important. Once infiltration ceases, the moisture in the soil begins readjusting itself in a soil column due to gravity and pressure gradient. This process is known as redistribution. High conductive soils drain very fast and are not suitable for plants while soils with low conductivity can retain water for

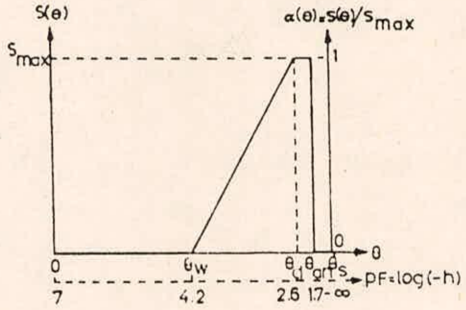


FIGURE 6 - GENERAL SHAPE OF THE SINK TERM AS A FUNCTION OF THE SOIL WATER CONTENT (FEDDES et al,1975)

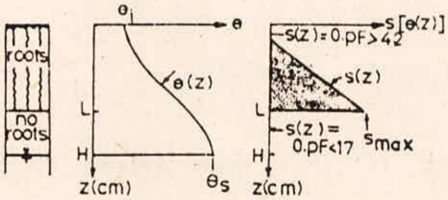


FIGURE 7 - GENERAL PATTERN FOR THE VARIATION OF SOIL WATER CONTENT AND THAT OF THE SINK TERM WITH DEPTH (FEDDES et al.1975)

more time because of slower readjusting nature and hence are more conducive for plant life.

Biswas et al.(1966) studied problem of redistribution for three agricultural soils. In this process the top layers lose moisture while the bottom ones gain moisture. This aspect can be studied only when hysteresis is considered. The authors studied the problem experimentally and compared the results with predicted profiles.

Feodoroff (1969) presented a paper on Infiltration and redistribution of soil moisture following precipitation and its influence on groundwater flow' at Wageningen conference on " Water in the unsaturated 'One'. In this paper he has described experiences in which the water movement during redistribution had to proceed either downwards or upwards. It is shown that the orientation of the soil column has no influence on moisture distribution after 24 hours , except in coarse sandy soils. It was finally concluded that redistribution is mainly due to atrractive forces of the dry soil.

Canarache et al (1969) presented paper on ' Infiltration rate as related to hydraulic conductivity, moisture deficit and other soil properties' at Wageningen conference on ' Water in the unsaturated zone'. They reported that water infiltration into the soil takes place through the non-capillary pore space being directly porportional to its volume; positive correlations exist between infiltration rate and percent of water-free pores at field capacity(r = + 0.364 and + 0.541), as well as between infiltration rate and log hydraulic conductivity (r = +0.520 and + 0.509). At the same time, water penetrating into the soil encounters a resistance provided by the air compressed within pores ranging in size from the those filled at field capacity to those filled at moisture content at the beginning of the determination. No correlations were observed between infiltration rate and the total percent of water-free pores at that time.

3.8 Irrigation Scheduling

This is a decision making process of irrigating a field depending upon the water needs of the crop. Researchers have developed several techniques for scheduling irrigation for different crops. These schedules are based on different criteria like plant water status, soil water status etc. Various research works differ in the degree of sophistication and complexity in the number of input variables.

Jensen et al.(1969) developed a user oriented USDA irrigation scheduling computer program which estimates daily ET for a crop. When this is combined with experimental data on allowable soil moisture depletion for the crop and the soil, the date of next irrigation is estimated following each irrigation, the optimum water required is computed as well.

Brosz (1971) developed a method for irrigation scheduling using the data of mean evapotranspiration rates. A procedure, which was suggested to be used in conjunction with experience and judgement of an irrigator, was developed whereby an irrigator could use the evapotranspiration values to schedule irrigation and to determine the quantity of water to apply. Hiler et al.(1971) introduced a concept of 'Stress Day Index (SDI)' for determining irrigation timing.

Busch and Rochester (1975) developed an irrigation scheduling programme and considerations of when to irrigate were taken to be dependent on soil moisture content and soil moisture tension. When the moisture values fell below the critical moisture level, irrigation was needed and this was indicated by computer.

Doorenbos and Pruitt (1977) have recommended a method of irrigation scheduling based on the soil water balance. The monthly soil water balance was expressed as :

$$We = Wb + Ge + Pe - ET\ crop\ \text{(mm/month)} \qquad \ldots(41)$$

where,

We = soil water available at the end of each month

Wb = stored soil water use

Ge = ground water contribution

Pe = effective rainfall

ET crop = crop evapotranspiration

In December,1981 ASAE held a conference on irrigation scheduling for water and energy conservation in the 80's. The main research papers discussed are reviewed below:

Hat-field (1981) presented a research paper on irrigation scheduling with thermal infrared and spectral remote sensing inputs. Field studies on grain sorghum have been conducted to evaluate use of spectral reflectance and thermal infrared to the crop water use and crop water stress. The data collected showed that stress-degree-day provides a valid indicator of crop stress, and the leaf-air temperature difference increases rapidly above zero when more than 65% of the available water is depeleted and it was concluded that change in leaf-air temperature is closely related to the availability of water under the climatic condition of a region which suggests a critical soil water content when stress becomes detrimental to crop growth.

Crough et al.(1981) have developed a program for a desk top data processing system which allows irrigations to be scheduled by an operator with no technical knowledge of computer operation or irrigation scheduling. Simplicitly of operation combined with built-in sophisticated irrigation scheduling techniques allow the desktop data processing system' to be successfully applied to situations where previous irrigation scheduling approaches have failed.

English et al.(1981) described an approach for optimum water use. The approach involves the use of a crop stress indicator as an index of water requirements, combined with the use of mathematical filtering techniques to detect critical stress values. According to them, rather than calling for an irrigation when moisture depletion is approaching a critical point, the goal should be to recognise when it has reached a critical point. In addition, the critical point may not be that point at which yields begin to be affected but rather some later point at which yields are reduced by a specified amount.

Cary (1981) described a method of scheduling irrigation with the help of soil instruments. Gypsum resistance blocks were suggested to be used for scheduling purposes. It was further suggested that representative field sites would be instrumented with three to four blocks connected in series to a resistance measuring device that could, upon demand, transmit by wire or radio the resistance to a microprocessor in the manager's office. The manager would only required to be able to estimate soil temperature by ± 3°C and the water potential at which irrigation is sought and rest scheduling is done automatically.

Phene et al. (1981) developed an electronic sensor which has ability to monitor the matric potential of soil water and control high-frequency irrigation systems.

Rhoades et al. (1981) presented a research paper on scheduling and controlling irrigations from measurements of soil electrical conductivity. According to their view, when salinity is significant, mesurements of soil water content or matric potential are not sufficient for scheduing irrigations. In this paper the concept and principle of using measurements of bulk soil electrical conductivity, σ_a , to schedule irrigations to control the depth of water penetration and to obtain a desired leaching fraction are introduced and supporting evidences are presented. It is suggested that some irrigation systems could be automated with burial type four electrode probes to initiate an irrigation when σ_a at a shallow depth declines to a predetermined set point value and to terminate when the wetting front arrives at a desired lower depth sensor location and that irrigation amount can be adjusted overtime to achieve a desired leaching fraction from feed back information of σ_a. in the lower region of the root zone.

Slack et al.(1981) described a method irrigation scheduling in subhumid areas with infrared thermometry. Small, hand-held, relatively inexpensive infrared thermometers can measure canopy temperature which is used as tool for irrigation scheduling. Canopy temperature or canopy air temperature difference was taken to be an indicator of crop-water stress and this paper described the factors influencing canopy air temperature. In addition, it also described the irrigation scheduling procedure by using canopy air temperature and presented results of experimental evaluation of such scheduling procedure.

Lamber et al.(1981) gave irrigation scheduling methods for humid areas of U.S. They described four irrigation scheduling methods which are :

i) scheduling via personal computer and water budget
ii) scheduling via screened pan evaporation,
iii) scheduling via tensiometers,and
iv) scheduling via calculated risk.

Employing the principle of calculated risk to make irrigation decisions involves calculations of an expected loss and comparing it with the cost that would be necessary to prevent the loss.

In India, Warabandi system of distribution of irrigation water is in current practice. Under this system, the irrigation water is supplied to the farmers and they are left free to choose their own cropping patterns. In this system the water requirement of the crop and exact time of irrigation are not considered and water is supplied to the farmers at fixed schedules if it is available(Malhotra,1982).

In our country Department of Agriculture, Government of India has brought out a manual on Irrigation Water Management prepared by Pai and Hukkeri (1979). The manual describes two general approaches for irrigation scheduling vis-a-vis availability of water resources and cultivated land which can be stated as follows:

i) where water resources are in excess in comparison to land resource, the aim should be to obtain maximum yield per unit area of land ;

ii) where water resources are deficient compared with land resource, the objective should be to obtain maximum production per unit of water used.

Under case (i) irrigations may be scheduled to meet the full water needs of crops. Intensive irrigation practices may be followed to realise maximum production per unit area of land. High cropping intensity, crops requiring more water and grown even on ligher and shallower soils should be supplied with irrigation water. The areas which can be covered under this category are, however, limited.

In arid and semi-arid regions as in case (ii) instead of intensive irrigation over a limited area, the approach should be to serve maximum area with reduced irrigation intensity in order to increase the overall production and the irrigation water use efficiency per unit amount of water. In such areas, irrigation water can be applied at critical physiological stages of crops. Under such conditions soil and water conservation practices should also be adopted.

The manual further describes the irrigation scheduling criteria based on available soil moisture. The depth of soil layers to be considered can be for conveience the suface 0-60 cm as most of the roots are concentrated in these layers. Generally for forage and other vegetatively used crops around 25-30% of soil moisture is allowed to be depleted and for grains around 50-60% of available soil moisture may be allowed to be depleted.

Another criterion for scheduling irrigation is depending on plant factors. Certain growth states are more critical than others in their demand for water. Such stages which can be easily identified by the farmers can be used as criterion for irrigation scheduling.

It has been found that at some places the optimum irrigation requirement of the crop coincides with certain physiological stages and irrigations could be scheduled based on these. For instance, at Delhi, a wheat crop requires 5-6 irrigation and these coincide with crown root initiation, tillering, jointing, flowering, milk and dough stages. However, this does not hold good at Jobner in Rajasthan where wheat requires about 9-10 irrigations. It is not possible to identify 10 distinct stages of crop growth in case of wheat.

The manual further suggests that when criterion of critical stage is followed, it is very important to remember that irrigation must be applied sufficiently before the particular 'Stage of growth' is reached so that the optimum moisture conditions prevail during that stage.

Another criteria for irrigation scheduling is based on climatic factors. If the value of ET is directly obtained from properly maintained lysimeters, it can serve as a best criteria to know the soil water balance in the field. India meteorological department has installed many small weighing lysimeters at several locations for such purposes. In the absence of such data the ET could be estimated by PET values obtained with the help of suitable formulae such as the ones given in Table 2. The other indirect method of ET estimation is by use of evaporimeters which are exposed to same environmental conditions as that of a crop. Proper correlation could be established between crop ET and Evaporation (E) from evaporimeters for scheduling irrigation. Several types of evaporimters like open pan, sunken pan, screened pans and small cans can be used to determine E values. But USWB class A pan is recommended as its values are available now from many meteorological observatories in the country. The ratio of the amount of irrigation water (IW) to cummulative pan evaporation

(CPE) can also be used for scheduling irrigation. The depth of irrigation water in this case is decided by the available water holding capacity of the soil and the probable deficit before irrigation and the irrigation efficiency that can be achieved.

3.9 Irrigation Efficiencies

International Commission on Irrigation and Drainage (ICID), New Delhi, the University of Agriculture, Wageningen, and the International Institute for Land Reclamation and Improvement (ILRI), Wageningen, these three organisations colloborated to collect information on irrigation practices in areas where small farms prevail. The basic aim of this joint venture was to gain knowledge of irrigation efficiencies under different climatological, topographical, soil,agricultural and socio-economic conditions. A total of 29 National Committees of the ICID cooperated in this venture by submitting 91 sets of data covering as many irrigated areas. Bos and Nugteren (1978) have prepared a report title ' On Irrigation Efficiencies' based on the informations collected from various countries which participated in this venture. The conclusions drawn in this report can be used as a guide in planning and designing new irrigation systems and in studying deficiencies in existing system.

On the basis of climate and socio-economic conditions the countries, which were studied, were grouped into four major categories. Some general results on irrigation efficiencies given for category one in which India was grouped are as follows:–

The graphical relationship between irrigable surface (ha.) and conveyance efficiency (e_c) indicated that maximum e_c value of 0.88 was found for irrigable areas between 4000 and 6000 ha. For smaller areas, e_c values may be as low as 0.50 and it was interpreted that this reduction in e_c value is due to reduction in management staff. Also it was found that if irrigable area is large (more than 10,000 ha.), the conveyance efficiency decreases sharply.

After the irrigation water has been conveyed to the farm or group inlet through the main, lateral, and sometimes sub-lateral canals, the subsequent stage is its distribution to the various fields. The distribution efficiency (e_d) is affected by possible seepage losses from the distributaries, by the method of water distribution, and by the size of the farms which are served by the distribution system. It was found that for smaller farms (less than 3 ha.), served by a rotational water supply, the e_d value is lower than the large farms (over 10 ha.). The reasons for this are that for small farms the water supply must be adjusted at shorter intervals (accuracy of timing) and that the relatively heavy losses at the beinning and end of each irrigation turn can't be avoided. To improve distribution efficiency, it was recommended that the farm cansls should be lined, especially those that have a low flow capacity and are used for short periods of time.

After the water is conveyed through a canal system to the (tertiary) off take where the farmer (or farmers) distributes the flow to the field inlet, the ultimate goal is to apply it as uniformly as possible over the field at an application depth which matches the water depeletion of the root zone. The average value of application efficiency (e_a) was reported as 0.53. Separately for basin, furrow, and borders the values reported were 0.56,0.54, and 0.47 respectively. It was also reported that no definite correlation exists between farm size and the application efficiency. Also nor did the type of soil on which the farm is situated seem to have any independent influence on the field application efficiency.

Once control of water is turned over from the water supply organisation to the farmers, the efficiency of water use is expressed by tertiary unit efficiency (e_u). Tertiary unit efficiency can be regarded as a product dependent on two factors e_a and e_d . After analysis, it was concluded that e_u value is more influenced by socio-economic conditions in the irrigated area, water use method, irrigation practices, etc., than the often low charges for irrigation water.

The ultimate goal of any irrigation project is to convey and distribute a quantity of water over the project area and to the fields within it, so that the water can be applied to the crops. As irrigation system efficiency (e_s) is multiplication of e_c and e_d, hence, those factors that influence e_c and e_d also have their influence on e_s values.

When an irrigation project is designed, there will usually be a water source at the upstream end of the project and water consuming crops at the downstream end, with in between a rather dense system of canals, pipelines, ditches, and related structures that will serve to convey and distribute the available water over the area. As described earlier overall project efficiency (e_p) is product of e_c,e_d and e_a. Hence all factors affecting e_c, e_d and e_a will also affect e_p.

Further, Bos and Nugteren (1978) gave following conclusions and recommendations in their report.

i) A method to estimate efficiency of water use in existing or future irrigation projects was described in this report. This method consists of estimating separately the application, distribution, conveyance, tertiary unit, and irrigation system efficiencies which when combined, give the project efficiency.

ii) In an irrigable area where the entire canal and ditch system operates at a near constant flow rate so that no division structures have to be manipulated, the only water losses will be due to seepage. In such areas conveyance efficiency decreases slightly as the irrigable area increases.

iii) In all irrigated areas where either one main crop (other than rice) or a certain combination of crops is cultivated, the water supply must be adjusted, sometimes even frequently. A maximum conveyance efficiency with an average of about 0.88 can be attained if the size of the irrigable area is between approximately 4000 and 6000 ha. For smaller areas the conveyance efficiencies decrease significantly, probably because of difficulties encountered by the project management in making the rather frequently needed adjustments in the discharge measuring/regulating structures in the relatively small capacity canals ; moreover, small areas are less likely to be managed by an adequate operational staff. If the area served by one canal system is larger than about 10,000 ha., the conveyance efficiency also decreases significantly. The reason for this is that the project management apparently faces the problem of controlling the water supply and is not able to balance the specific requirements of the various sub-areas.

iv) To achieve a favourable water conveyance efficiency in large irrigation projects, it is recommended that the projects be managed as follows:

a) GENERAL PROJECT MANAGEMENT : It operates the dam-site or diversion and main canal. The main canal should have a flow rate that can be adjusted to meet the water requirements of the various lateral units.

b) LOCAL IRRIGATION MANAGEMENT: Depending on topography and local conditions, the irrigation project should be divided into a number of lateral units, each having an area of between 2000 and 6000 ha. (mean 4000 ha.). Each lateral unit should receive its water at one point from the main canal and should have its own skilled local irrigation management staff who will be responsible for the water supply within that lateral unit only.

v) From the view point of conveyance efficiency, the optimum size of a rotational unit (i.e. and irrigated unit commanded by a canal on intermittent flow) lies between 70 and 300 ha.

vi) It was further recommended that the main, lateral and sublateral canals be operated on a schedule of continuous flow and that the area not be divided into sub-rotational units. During the entire season the flow rate in each of these canals should be solely a function of the water requirement of the commanded area.

Each lateral unit should contain a number of rational units whose size should be between 70 and 300 ha. depending on topography and local farm size, within each rotational unit the water distribution should be organised independent of the overall conveyance and should be based on the requirements of the farms in that unit.

3.10 Water Use Efficiency

Efforts have been made by several workers to determine the water use efficiency for crops under different growing conditions and have been summarised time to time (Berg et al. 1973 ; Black,1966 , Hagan et al.,1973 ; Pandey et al.,1970 ; Shmueli,1971,1973 ; Viets,1962,1966 in I.A.R.I. Monograph No.4).

Water use efficiency, being a ratio, is influenced by changes in both the numerator and denominator. The numerator is the plant production which depends on such factors that affect gains in the form of dry matter production and losses due to diseases, pests and other environmental factors. It means that water use efficiency can be increased by genetic environmental manipulations of crops. The denominator i.e. water supply under field conditions is also to some extent subjected to manipulations and control and thus it also influences the water use efficiency (Singh & Sinha,1977 in I.A.R.I. monograph 4).

Climatic conditions affect both the numerator or crop yield and denominator or water need of a crop in water use efficiency equation and are the main causes of variations in water requirement of crops (Dastane, 1972 in I.A.R.I. monograph 4). Water use efficiency has almost an inverse relationship to relative humidity. Factors such as sunglight and temperature that normally affect both evapotranspiration of the crop and the rate of photosynthesis or dry matter production, will either increase or decrease water use efficiency, depending upon the predominance of one of the two processes in a particular condition.

Water use efficiency varies with crop species. For example, maize , sorghum, sugarcane and ragi show high water use efficiency while moong,arhar,soyabean and peas show poor water use efficiency (IARI monograph No.4,1977).

Water use efficiency can be increased by reducing transpiration which can be achieved by use of antitranspirants. These antitranspirants increase the stomatal resistance to water diffusion and hence reduce transpiration. Ray (1969) observed an increase in water use efficiency of 30 to 78 percent when beans, citrus and wheat leaves were white washed without any adverse effect on photosynthesis and yield. Similarly, Reddy and Shah (1973) noted that a 2 percent spray of Kaolin on plotted wheat plants reduced transpiration from 11 to 21 percent under wet and dry regimes for a period of 25 days.

Water use efficiency can also be bettered by using mulches. Field experiments using mulches have shown beneficial effects of mulches in conserving and economising water use by crops ranging from 10-50 percent, depending upon the crop in which it is used, type and colour of mulches, type of soil, rainfall and amount of water added, wind velocity and temperature of both air and soil(I ARI monograph-4). Bansal et al.(1971) working on a sandy loam soil at Hissar observed that different kinds of mulches influenced the consumptive use of irrigated maize, but not irrigated pearl millet. Patil et al.(1972) attributed beneficial effect of straw mulching on swelling black soil to better moisture conservation and higher intake rate under irrigated conditions. Generally, finer the plant residues (rice husk, saw dust etc.), the more effective they are in water conservation.

Irrigated crops in semi-arid and arid climates extract large quantities of energy from the air brought in from the nearby uncropped area in the form of sensible heat that tends to equalize the differences in micro-climates, at least between adjacent small areas. This results in measurable differences in sensible heat transfer between upwind and down wind points. Greatest evapotranspirational loss of water occurs near the upwind edge because of drier air (Pruitt & McMillan,1962 ; Rider et al.,1963) and decrease with distance downwind (Millar,1964) due to progressive decrease in evaporative demand with leading distance, depending upon micro-climatic parameters (Davenport and Hudson,1967 a, 1967 b).

Other factors which influence crop water use efficiency are soil moisture supply and irrigation, fertilizer application, weeds and their control, insect, pests and diseases. Extensive research has been conducted to evaluate the effect of moisture stress by withholding irrigation at different stages of crop growth of wheat, barley,sorghum, and millets under the All India Coordinated Crop Improvement Projects and the All India Coordinated Project for Research on Water Management and Soil salinity. Results obtained from these experiments indicate that grain yield and crop water use efficiency are significantly affected by the timing of waterings under limited water supply (Dastane et al.,1970).

Influence of fertilizer application in relation to soil moisture supply on crop growth, yield and water use efficiency has been described by several workers from time to time (Arnon, 1972,1974,1975 ; Black,1966 ; Hillel,1968 ; Pendleton, 1966 : Viets, 1962, 1966 in IARI Monograph-4). In India, Singh and Gandhi (1964) have reviewed the work done on the fertilizer-irrigation relationship and Pandey et al.(1970) on water use efficiency and the various concepts used. Water use efficiency invariably increases with the application of fertilizers on deficient soils under adequate soil moisture conditions. This is because fertilisers increase crop growth which results in higher yield.

Weeds are another important factor which reduces water use efficiency. They rob off crop plants of their soil nutrients, water and intercept light and cause reduced crop growth, yield and quality. It is reported from IRRI(1973) that weeds reduced grain yield of rice in Phillippines by 26% of the total produce on farmer's fields in the wet season whereas the corresponding reduction in dry season was only 9 percent. Hence, controlling of weeds is essential for growing a good crop and to harvest high and quality yields as well as for obtaining high water use efficiency.

Insect, pests and diseases reduce crop yield or quality or both as well as water use efficiency to varying degrees, depending upon degree of infestation, because evapotranspiration or water requirement of crops would not change to a significant level except in cases where pre-mature death of plants results. It has been reported from IRRI,Philippines (1973) that during wet season which is favourable for the growth of rice plant, grain yield on farmer's field was reduced to the extent of 70 percent by diseases and pests. Chaudhury and Sharma (1960) observed an increase in infestation of wheat stem borer with the increase in irrigation.

It is,therefore, imperative that to harvest good yields and to increase water use efficiency by crops adequate moisture, maintenance of good drainage and judicious use of chemicals alongwith other management practices are essential. In summary, water use efficiency can be increased by increasing the crop yield and/or by decreasing the evapotranspiration and other losses of water. Crop yields can be increased, without significant increase in water need, by selecting suitable crops and varieties adopted to climatic conditions of the locality and through agronomic managements such as using good quality seeds, sowing at appropriate time and depth, placing balanced fertilizers in soil in adequate quantity and at right time as well as protecting the crops from infestation of weeds, pests and diseases.

4.0 VARIOUS METHODS OF DETERMINATION OF WATER REQUIREMENT OF CROPS IN INDIA

Techniques used to determine water requirement of different crops in the country are by and large similar and can be grouped into following classes :

1. Depth-interval-yield approach,
2. Soil moisture deficit approach,
3. Climatological approach- Use of empirical and semi-empirical formulae and use of open pan evaporimeters, and
4. Drum culture technique for rice

4.1 Depth-Interval - Yield Approach

Several workers in the Irrigation and Agricultural Department in the country have carried out field trials to find out optimum water requirement of crops. Different depths of irrigation were applied at different intervals. These depths and intervals were fixed arbitrarily without taking cognizance of soil characteristics and weather conditions. The irrigation treatment which gave the maximum yield with the minimum delta of water was taken as the optimum water requirement of that particular crop. Bulk of the work, conducted in the field of irrigation in India, falls in this category.

The limitations of this approach are as follows :

i) the arbitrarily fixed depth caused either under irrigation or over irrigation.

ii) the arbitrarily fixed intervals also resulted either in premature irrigations or delayed irrigations and thus the crop was affected by excess water at one stage and lack of water at the other.

iii) the evaporative demand and the soil moisture status were not taken into consideration.

Based on the data collected by this approach, the Irrigation Depts. worked out value of duty of water for different crops. Further, these values were applied not only in the same tract but elsewhere also for planning water delivery practices. Consequently, faulty irrigation schedules have developed on many irrigation projects (Dastane et al, 1970).

4.2 Soil Moisture Deficit Approach

The depth-interval yield approach was further improved by fixing the treatments of depth of irrigation on the basis of soil moisture deficit. Values of field capacity and bulk density were determined layer-wise of a soil profile to work out the moisture deficit using the formula :

$$d = \frac{FC - A}{100} \times BD \times D \qquad \ldots(42)$$

where,

d = moisture deficit in a soil layer,

FC = field capacity, in percentage,

A = actual moisture content, in percentage,

BD = bulk density of soil, and

D = depth of soil layer.

The net amount of water that should be diverted from the source to the field is found by dividing net deficit in the root zone by irrigation efficiency.

As described in Section 2 the moisture in excess of wilting point upto field capacity is available for plant growth. However, it has been realised that as the available soil moisture decreases the plant growth i.e. dry matter yield also decreases.

The degree of depletion of soil moisture was measured with different criteria such as percentage availability, tensions, resistance etc. The crop was irrigated when the moisture in the root zone reached the desired degree of dryness. The typical treatments in such experiments were as follows :

Criteria	Moisture regime
1) Percentage availability FC = 100 , WP = 0	100-75 ; 100-50 ;100-25
2) Tension (atm.) FC = 0.10 to .33 WP = 15.0	FC to 0.4 atm.; FC to 0.6 atm; FC to 0.8 atm.
3) Resistance (ohms) ; FC = 400 ohms ; WP = 60,000 ohms.	FC to 5000 ohms ; FC to 1000 ohms ; FC to 50,000 ohms

Experiments of this nature have been in progress from 1956 onwares at the IARI,New Delhi and at certain agricultural colleges, where trained staff and necessary equipment were available.

This technique is satisfactory for all practical purposes. Precise scheduling, depths of irrigation and water requirements can be worked out by this technique.

4.3 Climatological Approach

Consumptive use of water by a crop, which is the main part of water requirement in most field crops, is governed primarily by meteorological parameters (e.g. temp., humidity etc.) when plant canopy is adequate and moisture supply is not limiting. Several empirical equations have been developed correlating climatic variables with evapotranspiration losses. Generally equations given by Penman (1944), Thornthwaite(1948) and Blaney and Criddle (1950) are used in India to find evapotranspiration losses. Use of open pan evaporimeters is also in extensive use to find ET requirements. Dastane and Singh (1964) found that climatological approach is relatively simpler than soil moisture deficit approach. Experiments at IARI, New Delhi showed best correlation of open pan evaporimeter values with consumptive use values as compared to any other formula. Dastane and Patil (1967) prepared a broad map showing isolines of annual consumptive use based on the U.S. open pan evaporimeter data in India (Figure 8). Sharma and Dastane (1966) have designed sunken screened open pan evaporimeters for direct determination of consumptive use of water by an irrigated crop. The device is simple and cheap and has been tested at New Delhi for winter and summer crops.

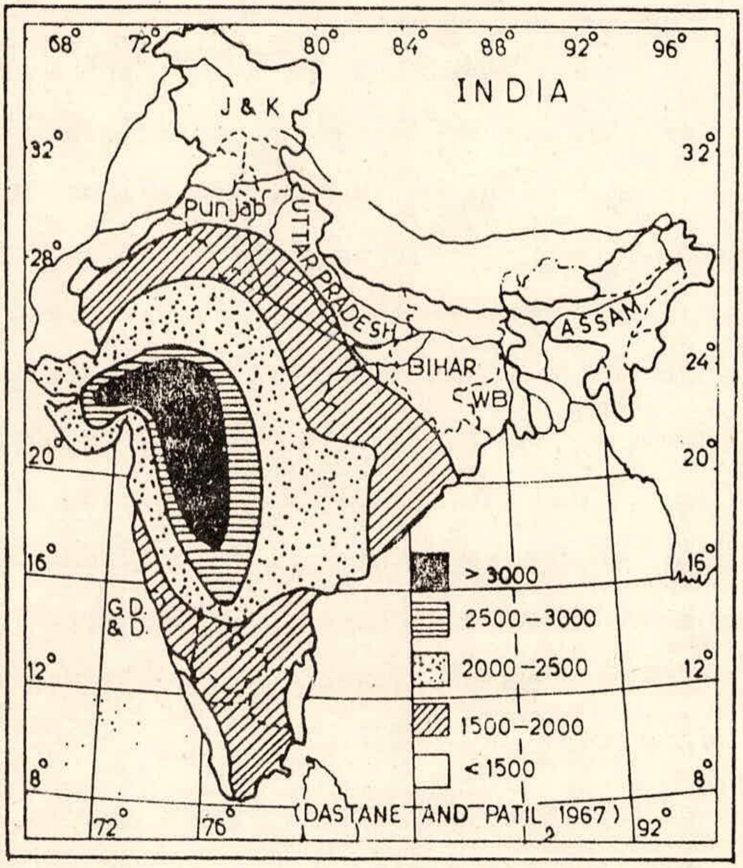


FIGURE 8 - ISOLINES SHOWING ANNUAL CONSUMPTIVE USE OF WATER (mm) IN INDIA

4.4 Drum Culture Technique for Rice

In case of rice field, percolation losses form a substantial amount in water requirement of this crop.

Dastane et el.(1966) have reviewed techniques employed in the case of rice and suggested that different components of water requirement must be assessed separately to have greater applicability of results to other areas. They stated that rice requires water to meet percolation needs of soil and evaporative demands of atmosphere. The latter are much less than former in which water is just lost by percolation serving no useful purpose in following practice of land submergence. They evolved a simple drum culture technique for assessment of consumptive use of water, percolation loss and ineffective rainfall and worked out water requirement of rice.

In this technique, three containers (drums)A,B and C of 40 gallons capacity and 100 cm in height are installed with 20-25 cm protruding above the soil level in a rice field as shown in Figure 9. Drum 'A' is with bottom intact while drums 'B' and 'C' are bottom less. The drum 'C' is fitted with an overflow device at a suitable height. Water levels are recorded daily. Daily differences between water levels in containers A and B furnish percolation values. Difference between two consecutive readings in container A gives the values of consumptive use. Ineffective rainfall is determined

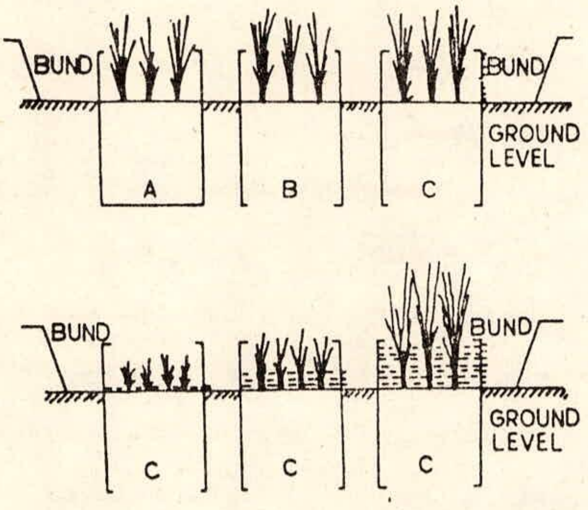


FIGURE 9 - DRUM CULTURE TECHNIQUE FOR DETERMINATION OF WATER REQUIREMENT OF RICE (Dastane et al,1966)

from the difference in values of total rainfall and water level in container C.

In the case of rice, any rainfall submergences beyond a certain critical height is harmful. This critical height varies with the stage of growth as well as variety. It varies from 5 to 30 cm. Similarly rainfall in excess of that which can be stored as a free standing water is also a waste. The height of bunds in rice field will decide the amount of water that can be stored as free standing water. The height of bunds may vary from 15 to 60 cm. Out of these two factors, namely, critical crop height and bund height, one of which is lower value at a given time governs the optimum depth of submergence. If the critical crop height at a particular stage is 8 cm and bund height is 30 cm, any rainfall causing submergence exceeding 8 cm is waste. Similarly if critical crop height is 20 cm and bunds are 15 cm, any rainfall resulting in submergence exceeding 15 cm is ineffective.

In these studies with increase in crop height, the outlets from the drum 'C' were plugged up from the soil surface level progressively upwards to the optimum level as shown in Figure 9. Difference in water level in drums B and C furnishes the value of ineffective rainfall during the growth period. The technique is simple, rapid and reliable for determination of water requirement of rice. With this technique, Vamadevan and Dastane (1968) at Delhi found that on sandy loam soil, out of 1680 mm of water applied to rice, 1190 mm i.e. 70% was lost by percolation.

5.0 IRRIGATION REQUIREMENT OF FIELD CROPS IN INDIA

Experiments on Water requirement of several crops have been conducted at different Research Centres belonging to Agricultural Universities, ICAR, Research Institutes, and all India Coordinated Projects. Based on available information, the irrigation requirements of crops are described as follows:

5.1 Rice

Rice crop occupies about 40% of the irrigated area in the country. Rice is grown under varied soil and climatic conditions and one to three crops per annum are taken in one or the other part of the country. Its water requirements are many times more than other food crops. This requirement is further amplified due to increased losses in deep percolation on light textured soils. With a view to reduce the irrigation requirement, studies were undertaken at Cuttack, Chiplima, Jorhat, Kharagpur, Madhipura, Jabalpur, Pantnagar, Hyderabad, Bikramganj, and Ludhiana centres.

Rice is grown mostly under low land conditions. Under low land conditions rice is generally transplanted on puddled soil and land is kept under submerged conditions by rain or irrigation water. The puddling and transplanting operation require nearly 200-300 mm of water. In addition about 300-500 ha.mm of water are required for growing seedlings in wet nursery. For low land rice the practice of keeping the soil under shallow submergence of about 50 ± 20 mm water throughout the crop growth period is conducive for higher yield. When continuous land submergence is practised, it is necessary to drain the soil once or twice during the growth period especially when water is ponded and not kept flowing from the field on poorly drained clayey soils. Drainage helps to remove toxic substance like sulphides and regulates oxygen supply to roots. Water requirement and irrigation requirement of rice in some of the major rice growing areas are given in Table 4.

Major portion of water (50-70%) delivered to the rice crop is lost rhrough deep percolation depending upon season and the soil type.

5.2 Wheat

This crop occupies about 27% of the total irrigated area. Moist and warm atmospheric conditions are not suitable for this crop. Dwarf varieties of wheat which are highly responsive to irrigation and fertilizer application have gained popularity in the country. Taller varieties are liable for lodging when irrigated during grain formation stage.

In the northern wheat growing belt, good yield of wheat was found when the soil moisture in the top 60 cm of soil was not allowed to deplete below 50% of maximum available soil water. This required 4-6 irrigation on sandy loam to loam soils and 8-10 irrigations on sandy soils. The water requirement of wheat varies from 350-460 mm. Irrigation requirement

Table 4 - Water and Irrigation Requirements of Rice at Different Locations

Place	Soil Type	Water requirements (mm)	Irrigation* requirements (mm)	Season
1	2	3	4	5
Kharagpur (West Bengal)	Sandy-clay-loam	1850 1890 2150	N.A. 1440 N.A.	May/April-June/July July/Aug-Nov/Dec Dec/Jan-March/April
Cuttack (Orissa)	Clay-loam	1300 1190	790 980	June-September Jan-April
Chakuli (Orissa)	Sandy-loam	N.A. N.A.	1100 330	Jan-May July-October
Bhubaneshwar (Orissa)	Clay-loam	1440 1650	780 1630	June-September Sept-December
Pantnagar (U.P.)	Loam	N.A.	500	June-October
Roorkee (U.P.)	Loam	1620	750	June-October
Hyderabad (A.P.)	Clay-Loam	N.A.	780	March-June
Coimbatore (T.N.)	Clay-loam	1680	N.A.	July/Aug-Dec/Jan.
Madurai (T.N.)		N.A. N.A.	900 830	July-November July/October
Pattukottai	Sandy-loam	2006	N.A.	June-September
Chalakudy (Kerala)	Sandy-loam	N.A.	1620	Feb - May
Delhi	Sandy-loam	2400	1600	June-October
Ludhiana (Pb.)	Sandy-loam	N.A.	1240	June-October

N.A.-Not available

* Actual number and interval of irrigation will depend on rainfall distribution and water table situation.

for wheat at various places in the country is given in Table 5.

The yield of wheat usually does not increase in proportion to the frequency of irrigation. It, therefore, pays to irrigate more area with the available water resources in order to increase the overall production of the region.

5.3 Maize

It is grown all over the country though it grows best in warm and humid climate.

The optimum soil moisture range for maize is from field capacity to 50% of maximum available soil moisture within 30 cm depth of soil layer for sandy laom to loam soils. The irrigation requirements varies from place to place depending on the rainfall pattern and the season. In the North, maize is grown mostly in Kharif (June-Oct) while in the South it could be grown in all the three seasons (June-Sept., Oct.-Jan, and Feb.-May) because of favourable weather conditions.

5.4 Sorghum

It grows best in semi-arid areas with a well distributed rainfall of about 300-1000 mm. The crop is mainly grown in Kharif (June-Sept.).

The grain Sorghum can withstand upto 75% depeletion of available soil moisture on black clay soils and upto 50% depletion on medium type of soils (loams) in surface

Table 5 - Irrigation Requirement of Wheat After sowing at Different Places in India

Place	State/ Union Territory	Sowing	Harvesting	Soil Type	Optimum regime	Irrigation Requirement	
						No.	Amount (mm)
Jobner	Rajasthan	2nd week of Nov.	2nd week of April	Sandy to loamy sand	0.9 IW/CPE (4.5 cm)	9	405
Hissar	Haryana	-do-	Ist week of April	Sandy loam	0.9 IW/CPE (6 cm)	5	300
Ludhiana	Punjab	Ist week of Nov.	-do-	-do-	0.9 IW/CPE (7.5 cm)	5	360
Karnal	Haryana	-do-	-do-	-do-	0.9 IW/CPE (6 cm)	5	300
Delhi	Delhi	-do-	-do-	-do-	0.9 IW/CPE (6 cm)	5	300
Roorkee	U.P.	-do-	-do-	-do-	0.9 IW/CPE (6 cm)	6	360
Bikramganj	Bihar	2nd week of Nov.	-do-	Loam	0.9 IW/CPE (6 cm)	5	300
Ranaghat	West Bengal	4th week of Nov.	Mid March	Clay loam	0.8 IW/CPE (7 cm)	3-4	210-280
Kharagpur	-do-	-do-	3rd week of March	Sandy-clay-loam	0.9 IW/CPE (8 cm)	5	400
Chakuli	Orissa	2nd week of Nov.	Ist week of March	Sandy-loam	0.9 IW/CPE (8 cm)	5	400
Hyderabad	Andhra Pradesh	Mid November	End of Feb.	Sandy-clay-loam	0.9 IW/CPE (6 cm)	5	300
Jabalapur	Madhya Preadesh	2nd week of Oct.	2nd week of March	Clay to clay loam	1.0 IW/CPE (7.5 cm)	5	375

Table 5 contd...

Place	State/ Union Territory	Sowing	Harvesting	Soil Type	Optimum regime	Irrigation Requirement	
						No.	Amount (mm)
Indore	Madhya Pradesh	2nd week of Oct.	End March	Medium black clay	1.05 IW/CPE (8 cm)	6	480
Navasari	Gujarat	--do-	Mid March	Black clay	0.8 IW/CPE	6	480
Dharwar	Karnataka	Ist week of Nov.	Ist week of March	Loam to clay	6 Stages	6	300
Sirugu-ppa	-do-	-do-	-do-	Clay	1.05 IW/CPE (6.5 cm)	7	450

IW - Amount of irrigation water (given in parenthesis)

CPE - Cumulative pan evaporation

ASM - Available soil moisture

30 cm soil depth.

5.5 Bajra

It is preferred when the rainfall is inadequate for maize and sorghum as it can escape drought because it takes less time to mature (85-90) days. The crop can tolerate 75% of depletion of maximum available soil moisture upto 30 cm depth of soil in clay type of soils and depletion of 50% in sandy loam soils.

Table 6 gives irrigation requirements after sowing of maize, sorghum, and bajra at different places in India.

5.6 Pulses or Grain Legumes

Legumes by virtue of their tap root system utilise soil moisture from deeper soil layers and hence require less number of irrigations as compared to many other cereal crops. These crops are,therefore, recommended for places having limited water resources. Additionally, these crops also improve soil fertility. The important legumes grown in Kharif are cowpeas, green gram (Mung), black grain (urad), Soyabean and pigeon pea (arher). The prominent grain legumes grown in winter (rabi) are gram, lentil, and pea.

Most of the legumes do not require irrigation at early vegetative state as it may do more harm than good by interfering with the nodulation and oxygen requirement of roots.

Table 6 - Irrigation Requirements After Sowing of Maize, Sorghum and Bajra at Different Places in India

Crop	Place	Soil type	Season	* Irrigation requirements	
				Nos.	Amount (mm)
Maize	Delhi	Sandy loam	Kharif	2-3	100-150
	Hissar (Haryana)	Sandy loam	Kharif	5-6	300-360
	Pantnagar (UP)	Loam	Kharif	4	225-275
	Udaipur (Raj.)	Sandy loam	Kharif	4	300
	Arabhavi (Karnataka)	Clay loam	Kharif	3	150
	Siruguppa (Karnatakka)	Black clay	Summer	10	510
	Bhubaneshwar (Orissa)	Loam	Kharif	2	100-150
			Rabi	11	500-600
	Madurai (TN)	Sandy clay loam	Summer	18	900
			Kharif	6	860
	Bhavanisagar Tamilnadu	Loamy	Summer	25	1250
	Hyderabad (AP)	Black Clay	Kharif	2	120
	Ludhiana (Pb)	Loamy sand	Kharif	2	150
Sorghum	Dharwar (Karnataka)	Loam to clay	Kharif	5	360
	Sirguppa (Karnataka)	Black Clay	Summer	1-2	75-150
	Hyderabad (A.P.)	Sandy loam	Rabi	4	300
	Coimbatore (TN)	Clay loam	Summer	4	300
	Madurai (TN)	Sandy clay loam	Summer	8	600
	Delhi	Sandy loam	Kharif	4	250
Bajra	Siruguppa (Karnataka)	Black clay	Kharif	2	250
	Hissar (Haryana)	Sandy loam	Kharif	3-4	225-300
	Delhi	Sandy loam	Kharif	2	150
	Anand (Gujrat)	Sandy loam	Kharif	10	500
	Jobner (Raj.)	Sand	Kharif	2	180

* Pre-sowing irrigation not included.

5.7 Oilseeds

The main oilseeds are groundnut, sesamum, soyabean and niger during Kharif and safflower, mustard , and linseed during rabi season. In Kharif, these crops are generally grown as rainfed but these crops profit from irrigations. Rabi oilseeds need presowing irrigation if moisutre at sowing is insufficient. After sowing the soil moisture should be maintained within 50% of availability in the active root zone of the crops

5.8 Cotton

It is a sub-tropical crop. It is grown in areas receiving 750 to 2500 mm of well distributed rainfall. It tolerates high temperature upto 45-50°C but temperature below 21°C are not condusive to good growth of this crop.

In the North, cotton is mostly sown in the month of May. In central and South India, sowing of cotton coincides mostly with the onset of monsoon in the month of June.

Cotton can withstand 75% depletion of available soil moisture in the active root zone in clay soils and about 50% depletion in sandy loam soils. Irrigations may continue upto first picking but if soils are light, irrigations may be needed upto second picking.

5.9 Sugarcane

About 5% of total irrigated area in the country is under sugarcane cultivation. This crop occupies the land for about 10 to 18 months and thus necessitates the irrigation application for realising good yields. Sugarcane grows best tropical weather (warm and humid).

In the North, planting is mostly done with the commencement of spring season (Feb-March). In Tamilnadu and Andhra Pradesh, planting is done from December to February.

The optimum soil moisture range for sugarcane has been reported as 50% depletion of available water from 30-60 cm depth of soil layer in Tamilnadu. A tension of 0.7 bar at 22 cm soil depth was recommended at Delhi on sandy loam soil.

The crop entirely depends on irrigation except in parts of Bengal,Assam, North Bihar, and Eastern U.P. Irrigations are normally withheld 25-30 days before harvesting of canes.

Irrigation requirements for gram, groundnut, mustard and cotton in different parts of India are given Table 7 through 10 respectively.

5.10 Vegetables and Fodder Crops

The important Kharif and summer vegetable crops are lady finger, tomato, cowpeas, brinjal, sweet potato, pumpkin

Table 7 - Irrigation Requirement After Sowing Gram in Different Parts of the Country

Place	State/ Union Territory	Season		Soil type	Optimum regime	Irrigation requirements	
		Sowing	Harvesting			Nos.	Amount (m.m.)
Indore	M.P.	Mid October	Ist week of March	Clay loam	Stages*	3-4	180-420
Prabhani	Maharashtra	-do-	End of Feb.	Clay loam	Stages*	2	150
Siruguppa	Karnataka	-do-	3rd week of Feb.	Medium Heavy Black clay	0.8 IW/CPE (6 cm)	6-7	360-420
Dharwar	-d0-	-d0-	-do-	Clay	0.8 IW/CPE (6 cm)	6	360
Kota	Rajasthan	Mid November	Ist week of April	Clay	Stages*	1	100
Delhi	Delhi	Ist week of October	2nd week of March	Sandy loam	Stages*	1	75
Hissar	Haryana	Mid October	Ist week of April	Sandy loam	States*	2	140
Jabalpur	M.P.	Ist week of October	4th week of Feb.	Clay loam	States*	3	225
Navsari	Gujarat	Ist week of	Mid March	Clay	Stages*	4	300
Chikhli	-do-	Ist week of Dec.	3rd week of March	Clay	Stages*	2	150

* Based on the stage of growth, 1,2,3, and 4 irrigation are given at initiation of flowering, initiation of podding, active branching and pod development in that order of priority.

Table 8- Irrigation Requirement After sowing of Groundnut in Different Parts of India

Place	State/ Union Territory	Season		Soil type	Optimum Regime	Irrigation requirement	
		Sowing	Harvesting			No.	Amount (mm)
Bhavanisagar	T.N.	(Kh.)Mid of Aug.	Ist week of December	Red sandy loam	75% depletion of ASM	7	280
		(Rabi)Mid of Feb.	Ist week of June	-do-	50% depletion of ASM	15	475
Hyderabad	A.P.	Mid of Jan.	Mid of May	-d0-	25% depletion of ASM	10	650
Yeminiganur	Karnataka	Mid of Oct.	Mid of March	-do-	50% depletion of ASM	6-7	300-350
Parbhani	Maharashtra	Mid of Feb.	Mid of May	Clay loam	100 mm CPE	8	500
Kanpur	U.P.	July	October	Sandy loam	50% depletion of ASM	2	150
Hissar	Haryana	July	October	-do-	75% depletion of ASM	4	300
Ludhiana	Punjab	June to early July	October to November	Loamy sand	50% depletion of ASM	5-6	250-300
Chakuli	Orissa	Mid of Nov.	Ist week of April	Loamy sand	25% depletion of ASM	10	690
Dharwar	Karnataka	Ist week of July	3rd week of October	Black clay	50% depletion of ASM	5	360
Kharagpur	West Bengal	Ist week of Feb.	4th week of June	Sandy clay loam	0.8 IW/CPE (8 cm)	6	440

Table 8 (contd...)

Place	State/ Union Terriroty	Season		Soil type	Optimum regime	Irrigation requirement	
		Sowing	Harvesting			No.	Amount (mm)
Madurai	T.N.	Ist week of Feb.	4th week of June	Sandy loam	0.9IW/CPE (6 cm)	7	420
Jabalpur	M.P.	4th week of June	4th week of October	Black clay	50% depletion of ASM	3	225

IW - Amount of irrigation water (given in parenthesis)

CPE - Cumulative pan evaporation

ASM - Available soil moisture

Table 9 - Irrigation Requirement After Sowing of Mustard in Different Parts of India

Place	State/ Union Territory	Season		Soil type	Optimum Regime	Irrigation Requirement	
		Sowing	Harvesting			NO.	Amount (mm)
Jobner	Rajasthan	2nd week of September	End of March	Sandy to loamy sand	0.55 IW/CPE	4	180
Ludhiana	Punjab	2nd week of October	4th week of March	Loamy sand	3-4 weeks after sowing	1	80
Karnal	Haryana	Ist week of October	2nd week of March	Sandy loam	75% depletion of ASM	1	60
Hissar	Haryana	Ist week of October	3rd week of March	Sandy loam	0.2 IW/CPE (8 cm)	1	80
Chakuli	Orissa	3rd week of October	4th week of January	Sandy loam	0.9 IW/CPE (6 cm)	3	180
Kharagpur	W.B.	Ist week of December	Ist week of February	Sandy loam	0.4 IW/CPE of ASM	1	80
Phulia	W.B.	2nd week of October	2nd week of February	Sandy loam	75% depletion of ASM	2-3	130-195
Pantnagar	U.P.	2nd week of October	Ist week of March	Sandy loam	80% depletion of ASM	2	160
Kota	Rajasthan	2nd week of October	Ist week of March	Black clay	Branching and pod formation stages	2	150
Madhipur	Bihar	3rd week of October	3rd week of January	Sandy loam	3rd week of after sowing	1	75

Table 9 (contd....)

Place	State/ Union Territory	Season		Soil type	Optimum regime	Irrigation requirement	
		Sowing	Harvesting			No.	Amount (mm)
Navasari	Gujarat	Mid Oct.	End March	Clay	40% depletion of ASM	6	420
Cuttack	Orissa	4th week of October	Ist week of Oct	Sandly loam	Branching and flowering	2	100

IW = Amount of irrigation (given in parenthesis)

CPE = Cumulative pan evaporation

ASM = Available soil moisture

Table - 10 Irrigation Requirement After Sowing of Cotton in Different Parts of India

Place	State/ Union Territory	Season		Soil Type	Optimum regime	Irrigation Requirement	
		Sowing	Picking Period			No.	Amount (mm)
Hissar	Haryana	May	Sept.-Oct.	Sandy loam	25% depletion of ASM	4	350
Ludhiana	Punjab	May	Sept.-Oct.	Sandy loam	* Stage	5	300
Delhi	Delhi	May	Sept.-Oct.	Sandy loam	50% depletion of ASM	3	210
Bhavanisagar	T.N.	Feb	June	Red Sandy loam	-do-	11	725
Coimbatore	T.N.	i) 3rd week of August	February	Clay loam	75% depletion of ASM	5	300
		ii) February	June	Clay loam	80% depletion of ASM	6	360
Sirguppa	Karnataka	Mid of August	March	Clay	75% depletion of ASM	6	640
Dharwar	-do-	August	March	Clay	75% depletion of ASM	5	150
Rahuri	Mahrashtra	July	February	Clay	75% depletion of ASM	2	150
Akola	-do-	July	January	Clay	-	2	200
Hyderabad	A.P.	Sept.	April	Black clay	0.8 IW/CPE	11	640

ASM - Available soil moisture
IW - Amount of irrigation water (given in parenthesis)
CPE - Cumulative pan evaporation
*Stage- 2 Irrigation during pre-flowering, 2 during flowering and 1 during post flowering

beans etc. The important rabi vegetables are cabbage, cauliflower, radish, turnip,peas,potato,leafy vegetables etc. The important summer and kharif fodder are maize, cowpeas, bajra, sorghum etc. The important rabi fodder are oats and berseem.

These crops require frequent supply of water for good growth. The soil moisture should be maintained at or above 75% of availability in the active root zone. Water requirement will directly depend upon the soil and the season in which the crops are grown.

5.11 Spices ,Condiments,Fruit and Plantation Crops

Very limited information is available on the irrigation requirement of spices , condiments, fruits and plantation crops.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Present review work describes various aspects of soil-plant-water interactions and some of the research works done in this field at national and international levels.

National Institute of Hydrology includes research in the fields of evaporation, consumptive use, soil moisture movement, and irrigation efficiencies in its work plan.

On the basis of review work given in this report research on following aspects of irrigation planning may be carried out :

(i) Hitherto several empirical formulae and experimental methods have been developed to estimate evapotranspiration need of crops. Study may be carried out to identify appropriate formula/method out of all formulae/methods available for ET estimation for different crops under varied climatic conditions in India.

(ii) The optimal irrigation frequency and the amount of each irrigation should be found such that percolation loss in the field is minimum subject to the conditions that plants are not put under moisture stress. For this purpose solution of Richards equation is to be found for the boundary condition pertaining to prevailing hydrometeorological conditions and various irrigation practices in India.

Solution of Richards equation for above conditions will be used as a subroutine to find the optimal dose and timing of irrigation.

(iii) When water is applied at field level, the application of water is done at one end of the field and subsequently it is allowed to distribute over the entire field. In this process the area in the vicinity of application point gets over orrigated and area at the tail end remains under irrigated which results in non-uniform distribution of irrigation water and hence dissimilar growth of crop in the same field. Study may be caried out to find required number of water application points to minimise problem of non-uniform distribution of irrigation water which will increase distribution efficiency. For such study field experiments are necessary.

(iv) In areas where ground water resources are not available, irrigation has to be done by irrigation canals. A particular canal has a specific capacity of carrying irrigation water and depending upon availability of water, it feeds water to agricultural land. Attempts can be made to design cropping pattern for a particular region as per the available capacity of irrigation canals in that region.

(iv) Study may be carried out to evolve easier techniques for irrigation forecasting. For this purposes soil moisture sensors having ability to monitor soil moisture can be developed. A suitable index such as soil moisture tension, capillary pressure can be identified to correlate soil moisture values. For various crops a critical value of so developed index can be found out at various stages and if the index value at any stage in the field condition falls below the critical value of that stage, irrigation will be applied.

(vi) Among the various methods of irrigation, study is required to be done to identify appropriate method of irrigation for different crops under various hydrometeorological conditions. The ultimate aim of this study should be to select that irrigation method which will result in maximum possible irrigation efficiency.

All above mentioned aspects are proposed to be studied with the help of necessary data.

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