TN - 11

WATER REQUIREMENT OF CROPS

SATISH CHANDRA
DIRECTOR

STUDY GROUP

V K LOHANI

P V SEETHAPATHI

NATIONAL INSTITUTE OF HYDROLOGY
JAL VIGYAN BHAVAN
ROORKEE-247667,(U.P.)
INDIA

1984-85

LIST OF FIGURES

CONTENTS

ACKNOWLEDGEMENT

The authors are grateful to Shri R S Saksena, S.E., UPIRI for giving constructive criticims on the present technical note. The implementation of FAO Program on VAX-11/780 system of the NIH by Sri A T Jeyaseelan, SRA, NIH is duly acknowledged. The climatological data were provided by the Irrigation Research Institute, Roorkee for which the authors express sincere thanks to the concerned officer.

ABSTRACT

It has become essential to make effective use of the available water resources allocated for agricultural purposes. Besides better methods of land preparation, proper management of irrigation water and improved cultural practices, it is necessary to improve the estimates of crop water requirements based on climatic data. Procedures for estimating crop water requirements should provide consistent and reliable results, and require minimum of data and computation. A reliable estimation of crop water requirements will help planning, design and execution of an irrigation project.

The present technical note describes various methods of estimating crop water requirements. A review of various empirical relations for determining evapotranspiration has been presented. Application of various empirical relations has also been discussed giving details of data requirement. The various instruments required to collect the necessary data have also been mentioned. The F.A.O., in its Irrigation and Drainage paper No.24, described four methods viz., Blaney Criddle, Radiation, Modified Penman, and Pan evaporation for estimating reference evapotranspiration and listed a computer program using these methods for computing evapotranspiration. The program has been implemented on VAX-11/780 computer system of the institute and the results for a set of data are given. An exhaustive bibliography is given at the end of the note.

1.0 INTRODUCTION

Water is essential for plant growth. Water is needed for seeds to germinate, seedings to emerge, and for the many plant growth functions. Water prevents the dehydration of plants, and provides the transport mechanism for plant nutrients and the products of photosynthesis. Crop yields under controlled irrigation are higher than rainfed conditions under similar climatic conditions. Because yields on irrigated lands are higher and more consistent, irrigation plays an important role in stabilizing food and fibre production. The main objective of irrigation is to provide plants with sufficient water to prevent stress that may cause reduced yield or poor quality of harvest. The required timing and amount of irrigation is governed by the prevailing climatic conditions, type of crop and its stage of growth, soil moisture holding capacity, and the extent of root development.

In order to find out 'when' and 'how much' amount of irrigation is needed, it is necessary to know the consumption of water by various crops in the field. One way to find 'when' is to observe crop indicators such as change of color or leaf angle, but this information may be too late to avoid reduction in crop yield and quality. The scientific approach to find 'when' and 'how much' would be to estimate water requirements of crops and then based on soil water balance predict 'when' and 'how much'. Researchers have investigated various ways of estimating crop water requirements by conducting experiments or developing empirical relations.

The work on water requirements of crops was started as early as 1850 at Rothamsted but the term was actually defined by Hellregal, who conducted investigations in pots to determine the water requirements of the crops in 1883 (Saksena et al.,1984).

Initial investigations on water requirements of crops were conducted in pots. It was soon realised that the information thus made available was not in toto applicable to field conditions, as the water requirements worked out in pots had a limited applicability. Therefore, it was realisted that more importance should be given to experiments conducted with more scientific basis of irrigation. With due course of time various experimental techniques and empirical relations were developed to assess the crop water requirements. The empirical relations were developed correlating climatic variables with crop water requirements. In the present technical note various experimental methods and empirical relations developed in different parts of world are described to find out crop water requirements.

Based on the empirical relations, the FAO Irrigation and Drainage paper no.24 has listed a computer program to estimate reference crop evapotranspiration. This program has been implemented on VAX-11/780 computer system of the NIH and the results obtained for a set of climatic data are given in the note.

2.0 DEFINITION OF IMPORTANT TERMS

Some of the important terms which have been used frequently in following chapters are defined as follows:

2.1 Evapotranspiration (ET)

It is a combined process by which water is transferred from earth's surface to the atmosphere. It includes evaporation of liquid or solid water from soil and plant surfaces plus transpiration of liquid water through plant tissues expressed as the latent heat transfer per unit area or its equivalent depth of water per unit area(Jensen,1983).

2.2 Consumptive Use(Cu)

Plant need water for meeting the demands of evapotranspiration (ET) and the metabolic activities, both together known as consumptive use. Since the water use in the metabolic activities of the plant is almost negligible, Cu is considered practically equal to ET.

2.3 Potential Evapotranspiration

The rate at which water, if available, would be removed from the soil and plant surface expressed as the latent heat transfer per unit area or its equivalent depth of water per unit area (Jensen, 1983). There have been ambiguities in defining potential ET as various researchers have interpreted it in different ways. Doorenbos and Pruitt (1977) have defined a similar term called reference ET as 'the rate of evapotranspiration from an extensive surface of 8-15 cm, green grass of uniform height, actively growing, completely shading the ground, and not short of water.

2.4 Crop Water Requirements

It is defined as the depth of water needed to meet the water loss through evapotranspiration of a disease free crop growing in large fields under non-restricting soil conditions including soil water and fertility and achieving full production potential under the given growing environments (Doorenbos and Pruitt, 1977). The water requirements (WR) of a crop may be formulated as follows:

$$WR = ET + \text{application losses} + \text{special needs}$$

Application losses include the unavoidable losses of water during water application. Special needs include water required for land preparation, transplanting, leaching etc.

2.5 Effective Rainfall (Pe)

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 FAO has defined 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).

2.6 Evaporation

It is the process during which a liquid changes into a gas. The process of evaporation of water is one of the basic components of the hydrologic cycle by which water changes to vapour through the absorption of heat energy. The essential requirements for evaporation process are the source of heat to vaporise the liquid water and the presence of a concentration gradient of water vapour between the evaporating surface and the surrounding air.

2.7 Transpiration

It is the process by which water vapour leaves the living plant body and enters the atmosphere. It involves continuous movement of water from the soil into the roots, through the stem and out through the leaves to the atmosphere.

2.8 Crop Coefficient (Kc)

In order to compute actual ET(ET crop) from potential or reference ET, the values of crop coefficient are needed at various stages of crop growth or,

ET_{crop} = Kc.Potential or Reference ET

The effect of the crop characteristics on crop water requirements is accounted for by multiplying the potential or reference ET by the crop coefficient. The Kc value relates to evapotranspiration of a disease-free crop grown in large fields under optimum soil water and fertility conditions and achieving full production potential under the given growing environment (Doorenbos and Pruitt, 1977).

3.0 REVIEW

The main objective of irrigation is to provide plants with sufficient water to prevent stress that may cause reduced yield or poor quality of harvest. The required amount of irrigation water and its timing is governed by the prevailing climatic conditions, type of crop, crop growth stage, and type of soil. In order to plan an irrigation project it is essential to estimate water requirements of crops that are proposed to be grown in the project area. Plants need water mainly to meet their evapotranspiration requirements and for metabolic activities however the latter requirement is negligible as compared to the former one. In the following paras the history of development of consumptive use computation, various methods of computing evapotranspiration etc. will be discussed.

3.1 History of Development

The term consumptive use was probably not applied to water consumption prior to 1900 (Jensen, 1973). During first two decades of twentieth century extensive plot and field studies using soil sampling techniques were initiated to determine seasonal consumptive use. In 1927 in the USA a committee of A.S.C.E.named as Duty of Water Committee prepared an excellent summary of seasonal consumptive use of water and has later published (Anonymous, 1930). One of the different definitions of consumptive use as suggested by this committee is that the consumptive use is defined as the quantity of water in acre-feet per cropped acre per year, absorbed by a crop and transpired or used directly in the building of plant tissue, together with that, evaporated from the crop-producing land. Consumptive use was defined as the sum of water used by the vegetative growth of a given area in transpiration or building of plant tissue and that evaporated from the area, in a report published in 1930 by state of California (Blaney et al.,1930). In 1934, the committee on Absorption and Transpiration of the HYdrology Section, American Geophysical Union, proposed the definition of consumptive use as the quantity of water per annum used by either cropped or natural vegetation in transpiration or in the building of plant-tissue, together with water evaporated from the adjacent soil, snow or from intercepted precipitation (Anonymous, 1934). In 1935, ASCE adopted definitions of consumptive use and evapotranspiration as the quantity of water transpired and evaporated from a cropped area and combined loss of water from soils by evaporation and plant transpiration respectively (Anonymous, 1935). In 1938, the National Resources Committee in the U.S.published the definition of consumptive use (evapotranspiration) as the sum of volumes of water used by the vegetative growth of a given area in transpiration and building of plant tissue, snow, or intercepted precipitation on the area in any specified time, divided by the given area (Blaney et al, 1938). In 1942, the National Resources Planning Board in the U.S.defined consumptive water requirement as the annual quantity of water, regardless of its source, required by vegetation for its normal growth under field conditions, expressed in acre-feet per acre.

3.2 Evaporation

It is the process during which a liquid changes into a gas. The process of evaporation of water in nature is one of the basic components of the hydrologic cycle by which water changes to vapour through the absorption of heat energy. This is the only form of moisture transfer from land and oceans into the atmosphere. The essential requirements for evaporation process are the source of heat to vaporize the liquid water and the presence of a concentration gradient of water vapour between the evaporating surface and the surrounding air. The source of energy for evaporation may be in solar energy, in the air blowing over the surface or in the underlying surface itself. The unavoidable energy required for evaporation of water regardless of the surface water evaporation is taking place is 590 calories per gram of water at 20°C. Evaporation can, however, occur only when the vapour concentration at the evaporating surface exceeds that in the overlying air. Dalton(1882) stated that evaporation is a function of the difference in the vapour pressure of the water and the vapour pressure of the air which may be written as follows:

$$E = (e_s - e_d).F\ (u) \qquad \ldots (1)$$

where,

E = evaporation

e_s = saturation vapour pressure at the temperature of evaporating surface, mm Hg.

e_d = saturation vapour pressure at the dew point temperature, mm Hg

$F(u)$ = a function of the horizontal wind velocity.

The total heat content of a given mass of air can be described by its temperature and vapour pressure. The total heat content is the sum of its sensible heat, depending on temperature, and latent heat, depending on vapour pressure. If water is allowed to evaporate in an isolated mass of unsaturated air, its latent heat content increases and its sensible heat content decreases. The process will stop when the air becomes saturated at the wet bulb temperature, T_w. Although there is always continuous exchange of water molecules to and from the atmosphere, the hydrologic definition of evaporfation is restricted to the net rate of vapour transport to the atmosphere. This process certainly consumes energy and if the temperature of the surface is to be maintained, these large quantities of the heat must be supplied by radiation and conduction from the overlying air or at the expense of energy stored below the surface. Evaporation from land surface is affected mainly by meteorological factors and nature of evaporating surface. If natural evaporation is viewed as an energy exchange process, the radiation is by far most important single factor and that the term solar evaporation is basically applicable. On the other hand theory and wind tunnel experiments have shown that the rate of evaporation from water of specified temperature is proportional to wind speed and is highly dependent on the vapour pressure of the overlying air. If radiation exchange and all other meteorological elements were to remain constant over a shallow lake for an appreciable time, the water temperature and the evaporation rate would become constant. If the wind speed is then suddenly doubled, the evaporation would also double momentarily. This increased rate of evaporation would immediately begin to extract heat from the water at a more rapid rate than it should be replaced by radiation and conduction. The water temperature would approach a new, low equilibrium value and evaporation would diminish accordingly. On a long term basis, a change of 10 percent in wind speed will change evaporation only 1 to 3 percent, depending on other meteorological factors. In order to evaluate the relative importance of meteorological factors the consideration of energy budget and mass transfer equations is required. However, it can be stated that the rate of evaporation is influenced by solar radiation, air temperature, vapour pressure, wind and possibly by atmospheric pressure. Since solar radiation is an important factor, evaporation varies with latitude, season, time of day and sky condition (Linsley et al.,1975). All surfaces exposed to precipitation such as vegetation, buildings, and paved streets , are potentially evaporation surfaces, Since the rate of evaporation during rainly periods is small, the quantity of storm rainfall disposed of in this manner is essentially limited to that required to saturate the surface. The rate of evaporation from a saturated soil surface is approximately the same as that from an adjacent water surface of the same temperature. As the soil begins to dry, evaporation decreases and its temperature rises to maintain the energy balance. Eventually, evaporation virtually ceases since there is no effective mechanism for transporting water from appreciable depths. Thus the rate of evaporation from soil surfaces is limited by the availability of water, or evaporation opportunity. Mulches are effective in decreasing evaporation for a few days after a rain or irrigation. The mulch restricts air movement, maintains a high vapour pressure near the soil surface, and shields the soil from solar energy, all of which reduce evaporation. The description of evaporation from the land surface in terms of the energy budget is an alternative concept to the view that evaporative flow proceeds in response to a gradient of water vapour concentration. It recognises that the latent heat flux, LE, away from the land surface, where L is the latent heat of vaporisation of water, can carry much energy that has to be supplied mostly be the radiation received at the land surface. The complete energy balance can be written as:

$$R = H + LE \qquad \ldots (2)$$

where,

R = energy available for maintaining fluxes of sensible heat (H) and latent heat

The available energy is derived essentially from the radiant energy of the sun and sky falling upon and being absorbed at the land surfaces. It can be represented by following equation:

$$R = (1 - \alpha) R_s - R_1 \pm G \pm Q \qquad \ldots(3)$$

where,

G and Q are the energy fluxes going into or out of the heat storages in the soil and the plant biomass respectively, R_l is the net longwave radiation from the land surface and R_s is the short-wave radiation from the sun and sky. The reflection, α , often termed as albedo, is an important natural coefficient that can vary so widely and greatly influences the energy budget. The first two terms on the right hand side of the above equation are usually referred to as the net radiation, RN, which can be measured conveniently with one radiometer sensitive in the whole of the wave-length spectrum of interest in this connection (Funk, 1959). Some representative values of albedo as given by Marshall and Holmes (1981) are given in the following table:

Some values of Albedo (α) of the earth

Surface	Albedo (α)
Sand(dry)	0.30-0.40
Dark clay soil (dry)	0.14-0.20
Wet soil	0.18-0.25
Grass land	0.22-0.28
Green cereal crop	0.20-0.26
Evergreen forest	0.17-0.23
Shallow water	0.08-0.15
Deep,clear water	0.04-0.07

The soil moisture status can influence, to some degree, all the quantities specified in equations 2 and 3, with the exception of R_s. The flux of sensitive heat can be described by the following equation:

$$H = - K_H d\ (\rho\ C_p\ T)/dZ \qquad \ldots (4)$$

where, T is the temperature at height Z and K_H is a transfer coefficient that depends upon the horizontal wind velocity, aerodynamic roughness of the land surface, height of measurement and stability or instability of the atmospheric air column. The density of the air, ρ, and the heat capacity at constant pressure,

C_P, (Joules $Kg^{-1}K^{-1}$) are substantially constant so that equation 4 becomes:

$$H = -K_H \rho C_P \frac{dT}{dZ} \qquad \ldots (5)$$

The flux of evaporation can also be described by an equation similar to equation 5 as follows :

$$E = -K_W \rho \; d\,q/\,dz \qquad \ldots (6)$$

where, K_W is the transfer coefficient for water vapour, analogous to K_H and influenced by the same physical conditions of the atmosphere, and q is the specific humidity. In 1926 Bowen established a ratio called Bowen ratio, β , which he defined as ratio of sensible heat to latent heat or,

$$\beta = H/LE = \frac{K_H \; C_P \; dT/dZ}{K_w \; L \; dq/dZ} \qquad \ldots (7)$$

When the lowest layer of the atmosphere which is of concern here, is in stable equilibrium, implying that there is no tendency for air to rise or sink because buoyancy is absent the transfer coefficients are equal to each other i.e.

$$K_H = K_W,$$

Therefore,

$$\beta = \frac{\gamma \; dT/dZ}{dq/dz} = \frac{\gamma \partial T}{\partial q} \qquad \ldots (8)$$

where $\gamma = C_p/L$

The partial differenciation term in eq.8 can be replaced by differences that are appropriate for the analysis of measurements of specific humidity and temperature, thus

$$\beta = \frac{(T_1 - T_2)}{q_1 - q_2} \qquad \ldots (9)$$

where the subscripts mean that the temperature and the specific humidity are measured at the same two heights, Z_1 and Z_2. The combination of equation 9 with equation 2 suggests that the evaporation and sensible heat fluxes can be derived, if the available energy, R, can be measured. In equation 9 it can be seen that β will be negative if $T_2 > T_1$ or temperature at Z_1 is less than it is at Z_2 $(Z_2 > Z_1)$. Then the sensible heat flux is directed downwards and is negative. The evaporative flux may also be negative, and if H and E are both negative, β becomes positive again. Occasions when one or both of the fluxes are negative occur when energy budget is relatively small, during night time when R is negative. The combination of energy budget and the Bowen ratio method is not possible to derive the evaporation and sensible heat fluxes for short intervals of time because the conduction of energy into or out of the heat storage of the ground, G and the biomass, Q, can not be estimated with the required accuracy. Priestley and Taylor (1972) expressed eq.7 in following way:

$$\frac{LE}{H} = \frac{L}{C_p} \left(\frac{\partial q_s}{\partial T} \right)_{T = \bar{T}} \qquad \ldots (10)$$

If the specific humidity is that appropriate to saturate air, q_s, at the temperature, T_o, of the evaporating surface, then $\partial q_s(T_o) / \partial T$ could be a useful partition function. Suppose a mean temperature, $\bar{T}$ is measured at a height α little above the surface, Priestley and Taylor (1972) suggest that the relation

$$\frac{LE}{H} = \frac{L}{C_p} \left(\frac{\partial q_s}{\partial T} \right)_{T = \bar{T}} \qquad \ldots (11)$$

is approximately correct when the evaporating surface is so wet that the specific humidity of the air very close to the evaporating sites is the saturated value at the surface temperature. In that case equation 11 would be appropriate to foliage recently wet by rain; probably it would be applicable to dry canopies of plant communities adequately supplied with soil moisture, and it is likely to deviate from the observed partitioning of available energy when the plant communities of a landscape are subject to drought. Equation 11 can be written as:

$$\frac{LE}{H} = S/\gamma \qquad \text{... (12)}$$

where, S is the slope of the saturated specific humidity versus temperature relationship, evaluated at T. Then an exact relation can be defined as

$$LE = \alpha\, SR/\,(S+\gamma) \qquad \text{. . . (13)}$$

where α is a quantity that can be examined by comparing the predictions of equation 3 with observed data of latent heat flux. Penman (1948) pulished first of his numerous papers about combination of the energy budget and the aerial relative humidity in a theory of evaporation. He gave expression for evaporation from shallow water such as a closed pond as:

$$LE = \frac{SR}{S+\gamma} + \gamma\,\frac{F\,(\,q_s\text{-}d)}{S+\gamma} \qquad \text{. . . (14)}$$

Here F is a transfer coefficient similar to F(u) in Dalton's equation. Many combination formulae have followed upon Penman's initiative, the purpose of which is to enable potential evaporation to be calculated from weather data that are commonly observed at regular meteorological stations. There is, as yet, no proven method of obtaining actual evaporation if it is less than the potential rate given by equation 14, except by direct measurement (Marshal and Holmes, 1984). The effect of salinity, or dissolved solids, to evaporation is brought about by the reduced vapour pressure of the solution. The vapour pressure of sea water (35,000 ppm dissolved salts) is about 2 percent less than that of pure water at the same temperature (Linsley et al, 1975). The reduction in evaporation is less than that indicated by the change in vapour pressure because with reduced evaporation there is an increase in water temperature-which partially offsets the vapour pressure reduction. Any foreign material which tends to seal the water surface or change its vapour pressure or albedo will affect the evaporation.

Atmospheric environmental conditions that affect evaporation from a free-water surface also affect that from soils. In case of evaporation from soil surface, the water molecules have to overcome greater resistance to escape from soils than from a free water surface. In addition to the factors that affect the escaping of water molecules from water bodies, the water molecules have to overcome the resistance due to attraction of the soil particles towards them. With the decrease in moisture content of soil, the resistance increases and so, the loss of moisture by surface evaporation reduces. The vapour pressure of the water in the soil in relation to that of pure free water at the same temperature can be used to determine the free energy, or thermodynamic potential, of the water. The total free energy is composed of several components, including those due to hydrostatic pressure, to osmotic value given by the dissolved material, to force field such as adsorption, and to surface tension if the water is in an interface. At high soil moisture content, the adsorptive field force probably plays minor role, but as the soil moisture decreases, it becomes increasingly important. If the moisture of the whole system is in equilibrium, the total free energy is a constant, but the magnitude of each component generally varies from point to point in the system. In the graphical relation between free energy and soil moisture, no points of sudden change can be seen on the curves to indicate that the water at one level is in a condition different from that at another. At the permanent wilting point, however, there is a rapid change in the energy and soil moisture relations. This lends support to the selection of free energy as a reference for the measurement of soil moisture. Evaporation from the soil surface will continue as long as the shallow surface layer, about 4 inch for clays and about 8 inch for sands remains moist. Veinmeyer and Brooks (1954) reported the results of measurements of evaporation from soils in contact with free water. They showed that evaporation rates do not bear a linear relation to the depth of the water table from the soil surface. If a water table is within one foot of the bare surface, the soil evaporation loss is comparable with the transpiration loss for an irrigated crop.

3.3 Transpiration

Only a small portion of the water absorbed by the root system of a plant remains in the plant tissue; virtually all is discharged to the atmosphere as vapour by a process which is called transpiration. This process constitutes an important phase of the hydrologic cycle since it is the principal mechanism by which the precipitation falling on land surface is returned to the atmosphere. In studying water balance of a drainage basin, it is required to find out evapotranspiration, a component which is combination of evaporation and transpiration. Transpiration is basically an evaporation process. However, unlike evaporation from a water surface, transpiration is modified by plant structure, and stomatal behaviour operating in conjunction with the physical principles governing evaporation. Transpiration is the dominant factor in plant-water relations because evaporation of water produces the energy gradient which causes the movement of water into and through plants. The difference in concentration between the sap in the root cells of a plant and the soil water causes an osmotic pressure which moves soil water through the root membranes into the root cells. Once inside the root, the water is transferred through the plant to the intercellur space within the leaves. Air enters the leaf through the stomata, openings in the leaf surface, and the chloroplasts within the leaf use carbon dioxide from the air and a small portion of the available water to manufacture corbohydrates for plant growth (photosynthesis). As air enters the leaf, water escapes through the open stomata; this is the process of transpiration. The factors affecting transpiration may be physiological or environmental. Important physiological factors are density and behaviour of stomata, extent and character of protective coverings, leaf structure, and plant diseases. The essential environmental factors include temperature, solar radiation, wind, and soil moisture when the permanent wilting percentage is reached. Plant type becomes an important factor in controlling transpiration when available soil moisture is limited. As the upper layersof the soil dryout, shallow-rooted species can no longer obtain water and wilt, while deep rooted species continue to transpire until the soil moisture at greater depths is reduced to the wilting point. Rainfall intercepted by vegetation is subsequently evaporated and thereby utilizes some of the energy otherwise available for transpiration. Since it is not possible to measure transpiration loss from an appreciable area under natural conditions, determinations are restricted to studies for small samples under laboratory conditions. Most measurements are made with a phytometer, a large vessel filled with soil in which one or more plants are rooted. The only escape of moisture is by transpiration, which can be determined by weighing the plant and container at desired intervals of time. The precise determination of transpiration cannot be easily obtained as the amount of transpiration depends on many variables.

3.4 Evapotranspiration and Potential Evapotranspiration

Evapotranspairation is a combined process by which water is transferred forom the earth's surface to the atmosphere. It includes evaporation of liquid or soil water forom soil and plant surfaces plus transpiration of liquid water through plant tissues expressed as the latent heat transfer per unit area or its equivalent depth of water per unit area (Jensen,1983). Thornthwaite (1948) thought soil moisture may have an effect upon evapotranspiration and suggested a term potential evapaotranspiration to define the transpiration that would occur were there an adequate supply at all times. Jensen (1983) defined potential evapotranspiration as the rate at which water, if available, would be removed from the soil and plant surface, expressed as the latent heat transfer per unit area or its equivalent depth of water per unit area. It has been found that evapotranspiration depends on the density of cover and its stage of development. It is, therefore, potential ET needs to be defined with reference to a particular surface cover. Some investigators in western USA have used the ET from a well-watered crop like alfalfa with 30-50 cm of top growth and at least 100 m of fetch as representing potential ET(Jensen, 1974). Penman (1956) suggested that the original definition be modified to include the stipulation that the surface be fully covered by green vegetation. Van Bavel(1966) defined potential ET as the evapotranspiration that occurs when the vapour pressure at the evaporating surface is at the saturation point. Doorenbos and Pruitt (1977) defined the effect of climate on crop water requirements by the reference crop evapotranspiration (ET_o) which they 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.

3.4.1 Methods of measuring and calculating evapotranspiration

There are numerous approaches for estimation or measurement of evapotranspiration, none of which is generally applicable for all purposes. The common methods used in engineering investigations are as follows:

a. Soil moisture sampling

This method is usually suitable for irrigated field plots where soil is fairly uniform and the depth to ground water is such that is will not influence soil moisture fluctuations within the root zone. The soil is usually sampled two to four days after an irrigation and again 7-15 later or just before the next irrigation. The average rate of ET between sampling dates is calculated using following equation:

$$ET = \frac{Wet}{\Delta t} = \frac{\Sigma_{i=1}^{M_r} (\phi_1 - \phi_2) \Delta S_i + R_e - W_d}{\Delta t} \qquad \ldots (15)$$

where,

M_r = number of layers to the depth of the effective zone

ΔS = thickness of each layer

ϕ_1 & ϕ_2 = volumetric water content on the first and second date of sampling respectively

R_e = rainfall that does not runoff the area

W_d = drainage from zone sampled

b. Lysimeter determination of ET

Lysimeter are tanks filled with soil in which crops are grown under natural conditions to measure the amount of water lost by evapotranspiration. Soil conditions inside the lysimeter must be essentially the same as those outside. It is necessary that the root development should not be inhibited by the limited dimensions of the lysimeter, and cover characteristics (density, height and vigor) must be the same over and adjacent to the lysimeter. Lysimeters are grouped in three categories: (i) non-weighting, constant water-table type, which provides reliable data in areas where a high water table normally exists, (ii) non weighing percolation type, in which changes in water stored in the soil are determined by sampling or neutron probe methods and the rainfall and percolation are measured, and (iii) weighing type, in which changes in soil water are determined either by weighing entire unit with a mechanical scale, counterbalanced load cell, or by supporting the lysimeter hydraulically.

c. Water balance technique

Assuming that storage and all items of inflow and outflow except ET can be measured, the volume of water required to balance the continuity equation for a basin represents evapotranspiration. Among other things, the reliability of a water-budget computation hinges largely on the time increments considered. As a rule, normal annual evapotranspiration can be reliably computed as the difference between long-time averages of precipitation and streamflow, since the change in storage over a long period is inconsequential(Knox and Nordenson, undated). As in this method measurements of inflows to and outflows from an area are involved,the usual difficulty arises in determining the flow quantities accurately.

d. Integration method

If unit evapotranspairation and the areas of various classes of agricultural crops, natural vegetation, bare land, and water surfaces are known, the total evapotranspiration loss from the total land area can be computed by summing the products of evapotranspiration/evaporation for each type of land use times the respective areas (Chow, 1964).

e. Energy balance method

This method can be used to determine ET for short periods because the components of energy balance such as energy for heating the soil and the advective energy can be neglected for short durations. This method is generally more accurate when soil moisture is not limiting ET. Tanner (1960) and Fritschen (1965) have discussed this method thoroughly with the instrumentation requirements for measurement of various components of energy balance.

In addition, there are other methods which are based on principles of mass transfer and combination of energy balance and heat and mass transfer. The observations of daily rise and fall of the water table may also be used to compute evapotranspiration of overlying vegetation.

3.4.2 Estimating and predicting potential evapotranspiration

The lack of basic data and difficulties in measurement required in the field methods have accounted for the great efforts made to develop evapotranspiration equations that can relate evapotranspiration with some readily available climatic data. Various researchers have suggested a number of equations for this purpose and some typical ones are as follows:

Hedke(1930) gave an equation which describes estimation of evapotranspiration based on cumulative values of available heat for the growing season expressed in degree-days above the germinating or minimum growing temperature. The relationship is expressed as:

$$U = K\ H \quad \ldots (16)$$

where U = annual evapotranspiration in feet

K = annual consumptive use coefficient

H = accumulated degree days above minimum growing temperature for growing season.

The Lowry-Johnson equation proposed in 1942 assumes a linear relationship between the effective heat and evapotranspiration. The relationship is expressed as:

$$U = 0.000156\ H + 0.8 \quad \ldots (17)$$

where U = annual evapotranspiration in feet

H = accumulated degree-days of maximum daily temperature above 32°F for growing season.

Blaney-Morin(1942)gave following relationship to estimate monthly evapotranspiration:

$$E = K\ T\ P\ (114\text{-}RH) \quad \ldots (18)$$

where E = monthly ET(inches)

T = mean monthly temperature ($^{\circ}$F)

K = monthly coefficient

P = monthly percent of yearly day time hours

RH= annual mean relative humidity in percent

Thornthwaite (1944) gave the following relationship to estimate potential ET based on mean monthly temperature as follows:

$$PET = C\ t^{a} \qquad \ldots (19)$$

PET = potential ET (cm./month)

t = mean monthly temperature (^{o}C)

C and a are coefficients varying with temperature

$$a = 0.000000\ 675\ I^{3} - 0.0000771\ I^{2} + 0.017921\ I + 0.49239 \qquad \ldots (20)$$

I = annual heat index $= \Sigma\ i$ $= \Sigma$ monthly heat index

$$i = (t/5)^{1.514} \qquad \ldots (21)$$

where t = mean monthly temperature (^{o}C)

Penman(1948) first introduced for an initial estimate of evaporation from a hypothetical open water surface and then its conversion to potential ET. The Penman equation (1963) modified for estimating alfalfa based reference ET in Cal./cm^{2}-day is as follows:

$$\text{Reference ET} = \frac{\Delta}{\Delta + \gamma}(R_n + G) + \frac{\gamma}{\Delta + \gamma}\ 15.36\ W_f(e_a - e_d) \qquad \ldots (22)$$

Δ = slope of vap-pr.-temp.curve in m.bar/o_c

γ = psychrometric constant (mb/o_c)

R_n = net radiation in Cal./cm^{2}-day

G = soil heat flux in cal./cm^{2}-day

$e_a - e_d$ =mean daily vapour pressure deficit in m.bar

W_f = wind function = $(1.0 + 0.0062\ u_2)$

u_2 = wind speed at 2 m.height in km./day

Blaney-Criddle (1945, 1950, 1962) gave an equation to estimate evapotranspiration based on the assumption that ET varies directly with the sum of the products of mean monthly air temperature and monthly percentage of day-time hours with an actively-growing crop with adequate soil moisture. The relationship is expressed as :

$$U = KF = \Sigma\ k\ f \qquad \ldots (23)$$

where,

U = estimated evapotranspiration in inches for the growing period or season.

F = sum of monthly consumptive use factors, f, for the season or growing period.

$f = \frac{tp}{100}$ where, t = mean monthly air temperature in ^{o}F.

p = mean monthly percentage of annual day time hours

k = monthly consumptive use coefficient

Doorenbos and Pruitt (1977) have given a modified version of Blaney-Criddle method as follows:

$$ET_o = C\ [P\ (0.46\ T + 8)]\ \text{mm/day} \qquad \ldots (24)$$

where,

ET_o = reference crop evapotranspiration in mm/day for the month considered

T = mean daily temperature in 0_C over the month considered

P = mean daily percentage of total annual daytime hours.

C= adjustment factor which depends on minimum relative humidity, sunshine hours and daytime wind estimates.

As in above equation only a single weather factor i.e.temperature is involved in predicting ET, this method should be used when temperature data are the only measured weather data available.

Ivanov (1954) proposed an equation to estimate potential evapotranspiration as follows:

$$Et = 0.0018\ (25 + T)^2\ (100\text{-r.h.}) \qquad \ldots (25)$$

where,

T = mean air temperature (^{o}C)

r.h.=relative humidity in percentage

Et=potential ET in mm/month

Makkink(1957) presented the following equation for estimating potential ET for grass over 10 day period under cool climatic conditions of the Netherlands:

$$Et = 0.61 \frac{\Delta}{\Delta + \gamma} \frac{R_s}{58.5} - 0.12 \qquad \ldots (26)$$

where,

ET=potential ET in mm/day

Δ = slope of vap.pr.-temp.curve in m bar/ ^{o}C

γ = psychrometric constant (m b/^{o}C)

R_s = solar radiation (langlay/day)

Turc (1961) gave following two equations to estimate potential ET based on radiation data for two conditions of relative humidity,

for r.h. > 50%

$$Et = 0.013 \frac{T}{T+15} (R_s + 50) \qquad \ldots (27)$$

for r.h.< 50%

$$Et = 0/013 \frac{T}{T+15} (R_s + 50) (1 + \frac{50\text{-r.h.}}{70}) \qquad \ldots (28)$$

where,

T = average temperature (^{o}C)

R_s=solar radiation (ly./day)

Olivier (1961) proposed an equation for monthly potential evapotranspiration based on average depression of the wet bulb temperature and a radiation-latitude factor on clear sky values of solar radiation by latitudes and months. The equation proposed is as follows:

$$Et_{\phi} = DW_{\phi} \qquad \ldots (29)$$

where,

Et_{ϕ} = basic water requirement (mm/day) at latitude ϕ

D = mean monthly depression of the wet bulb in O_C

W_{ϕ} = water requirement constant for months and latitude available in tabular form.

Jensen and Haise (1963) gave an equation that used solar radiation (R_s) and temperature data for estimating potential evapotransiration as follows:

$$Et = (0.00043\ T + 0.00\ 133)\ Rs \quad \ldots (30)$$

where,

Et = potential Et(mm/day)

T = mean daily temperature (^oC)

R_s = solar radiation at land surface (ly./day)

Hamon (1963) gave a relation to estimate potential evapotranspiration as follows:

$$Et = CD^2\ P_t \quad \ldots (31)$$

where,

C = constant (0.55)

D = possible hours of sunshine in units of 12 hours

P_t= saturated water vapour density (abs.humidity) at mean daily temp.(g./$m^3 \times 10^{-2}$)

Ostromecki (1965) described an equation which was actually developed by Alpat'ev in 1954. The equation is as follows:

$$Et = B_H d_a \quad \ldots (32)$$

where,

Et= potential ET(mm/day)

d_a=average daily vapour pressure deficit in m.bars

B_H=hydrometric coefficient(B_H = 0.56 for clover)..

Stephens (1965) proposed an equation for estimating potential ET based on radiation data as follows:

$$Et = (o.014\ T - 0.37)\frac{Rs}{1500} \quad \ldots (33)$$

where,

Et = potential ET (inches/day)

T = mean air temperature (^oF)

R_s=solar radiation (langlay/day)

Papadakis (1966) proposed following equation for estimating monthly potential ET.

$$Et = 0.5625\ (e^{o}max - e_z) \qquad \ldots (34)$$

where,

Et= monthly potoential ET in cm.

$e^{o}max$ = saturation vapor pressure corresponding to average daily maximum temperature in mb.

E_z = average vapour pressure for the month in m.bar.

Behnke-Maxey(1969) gave an equation for potential ET as follows:

$$Et = \frac{T}{1.9}\ W_{\phi} \qquad \ldots (35)$$

where, $\frac{T}{1.9}$ = simulated wet bulb depression in °C.

T = mean air temp. (°C)

W_{ϕ} = water requirement constant for months and latitude and available in tabular form.

Et = potential ET in mm/day

Christiansen (1968) and Christiansen and Hargreaves (1969) developed an equation for estimating USWB class A pan evaporation from which potential ET can be estimated. The equation using solar radiation is as follows:

$$ET_p = 0.492\ Rs\ C_{TT}\ C_{WT}\ C_{HT} \qquad \ldots (36)$$

where,

Rs = solar radiation (ly./day)

$C_{TT} = 0.463 + 0.425\ (T_c/T_{co}) + 0.112\ (T_c/T_{co})^2$

T_c = mean temperature °C

$T_{co} = 20^{o}C$

$C_{WT} = 0.672 + 0.406\ (W/W_o) - 0.0780(W/W_o)^2$

W = mean wind velocity 2 meters above ground (miles/day)

W_o = 100 miles/day

$C_{HT} = 1.035 + .240 (H_m/H_{mo})^2 - .275 (H_m/H_{mo})^3$

H_m = mean relative humidity expressed decimally

H_{mo} = 0.60

ET_p = potential ET in equivalent radiation (ly./day)

Studies during past several decades have suggested use of pan evaporation data for estimating potential evapotranspiration. Various authors have studied this aspect and published papers. Some of the important ones are by Stanhill (1961, 1962), Fuchs and Stanhill (1963), Pruitt and Jensen (1965), Pruitt (1960), Jensen, et al.(1961), Campbell et.al (1959), Chang et al.(1963) and Thompson et al. (1963). Doorenbos and Pruitt (1977) have described pan evaporation method to estimate reference crop evapotranspiration as follows:

$$ET_o = K_p \cdot E_{pan} \qquad \ldots (37)$$

where,

ET_o = reference crop ET (mm/day)

K_p = pan coefficient

E_{pan} = pan evaporation in mm/day

Values of pan coefficient depend upon ground cover around the pan, mean relative humidity, wind velocity and type of pans. Tables have been given to find K_p for class A pan and Colorado Sunken pan for different ground cover and levels of mean relative humidity. The literature in general, provides ample evidence of the extreme care needed in interpreting pan evaporation data to obtain reliable estimates of potential ET. Studies done by Ramdas (1957) and Pruitt (1966) are evidence to the same.

Dooresbos and Pruitt (1977) have described radiation method of estimating reference crop evapotranspiration which is essentially an adaption of Makkink formula (1957). The relationship given is as follows:

$$ET_o = C\ (w.Rs) \qquad \ldots (38)$$

where,

ET_o = reference crop ET in mm/day

Rs = solar radiation in equivalent evaporation in mm/day

w= weighing factor which depends on temperature and altitude

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

A slightly modified Panman equation is also suggested by Doorenbos and Pruitt (1977) for estimating reference crop ET. The equation given is as follows:-

$$ET_o = C\,[w\,R_n + (1-w)\,F(u)(e_a - e_d)] \qquad \ldots (39)$$

where,

ET_o = reference crop ET in mm/day

w = temperature related weighing factor

R_n = net radiation in equivalent evaporation in mm/day

f(u)= wind-related function

(e_a-e_d) = difference between the saturation vapour pressure at mean air temperature and the mean actual vapour pressure of the air,both in m.bar.

C = adjustment factor to compensate for the effect of day and night weather conditions.

The water management division of the Ministry of Irrigation, Govt. of India has brought out a guide in May,1984 for estimating irrigation water requirements. The guide discusses use of modified Penman equation to estimate reference crop ET. Computation of evapotranspiration based on Pan evaporation data is also described in the guide. The measured or computed pan evaporation data are multiplied by same factor to compute ET. This factor κ depends on type of crops and their growth stages. Various crops have been divided into seven groups i.e. Group A to Group G and rice has been assigned values of k ranging from 0.80 to 1.30. The guide has given tables to list values of k for various groups of crops varying with the percent of crop growing season (Saksena et.al.,1984),Hargreaves (1984) has suggested a new method for estimating reference crop ET based on temperature and radiation data. The relationship suggested is as follows:

$$ET_o = 0.00\ 75 \times Rs \times T \qquad \ldots (40)$$

where,

ET_o and Rs are in equivalent units of water evaporation (usually mm per unit of time)

T = mean temperature in degrees Fahrenheit

An equation has been developed by Hargreaves and Samani(1982) to estimate Rs from extraterrestrial radiation RA and the temperature range as follows:

$$Rs = K x RA x\ T_D^{0.5} \qquad \ldots (41)$$

where,

K is a coefficient

T_D is mean maximum minus mean minimum temperature.

Rs and RA are in equivalent units of water evaporation. By substituting Rs value in equation 40, the ET_o can be estimated by

$$ET_o = a + b\ (R_A \times T^oC \times T_D^{0.50}) \qquad \ldots (42)$$

The values of coefficients a and b can be obtained by local calibration. The author has found values for a and b for Davis, California based on Lysimetric results.

3.5 Estimating Evapotranspiration for Crops

The crop evapotranspiration depends on several crop and environmental conditions such as climate, soil moisture, the type of crop, stage of growth and the extent to which plants cover the soil. Hence, in order to have accurate estimates of crop ET it is necessary to take into account these factors. If estimates of potential ET for a reference crop are available, the estimates of ET for specific crops can be made using:

$$ET = Kc.\ E_t \qquad \ldots(43)$$

where,

K_c = crop coefficient determined experimentally

ET = actual evapotranspiration

Et = potential or reference evapotranspiration

Experimentally developed crop coefficients reflect the physiology of the crop, the degree of the crop cover, and the reference ET. Factors affecting the values of crop coefficient (K_c) are mainly the crop characteristics, crop planting or sowing date, rate of crop development, length of growing season and climatic conditions. In the experimental determination of crop coefficients, ideally, both crop ET and reference ET are measured concurrently. The crop coefficient is then calculated as the dimensionless ratio of the two measurements. Crop coefficients may either be based on alfalfa or green grass which will depend on method of ET estimation. Alfalfa is selected for reference ET because it has relatively high ET rates in arid areas where there is considerable advective sensible heat input from the air. The procedure for establishing alfalfa based crop coefficient is described in detail by Jensen (1974) and Jensen et al.(1971). Doorenbos and Pruitt (1977) have described grass based crop coefficients in F.A.O.Irrigation and Drainage paper 24. They have divided the growth period of field and vegetable crops into four stages viz.,i) initial stage ii) crop development stage iii) mid-season stage and iv) late season state. A procedure has been described to develop crop curve i.e.distribution of crop coefficients with time for various field and vegetable crops. FAO paper No.33 on Yield response to water has listed crop coefficient values for different crops at different growth stages which are given in Appendix B.

A lot of work has been done on water requirement of field crops in India. For principal crops like paddy, wheat, maize, bajra ,barley, groundnut, mustard, linseed, cotton and sugarcane, the suggested values of water requirement/ irrigation requirement for different parts of country are given in Appendix C.

3.6 Irrigation Water Losses and Irrigation Efficiency

As the water flows from the head end of the irrigation canal to the field, considerable amount of water is lost through evaporation and seepage in the canal system. These losses are termed as conveyance losses. According to a study of Central Water and Power Commission (1967) it is observed that in any unlined canal system from head works down to the field the loss of water is to the extent of 71 percent(canals 15%, distributories 7%, water courses or field channels 22%,field losses 27%) and only 29% is effective for utilization. A major portion of conveyance losses occur because of seepage through sides and bed of canal,evapotranspiration losses caused by weeds or plants in the channel bed, and evaporation losses from exposed water surface.There could also occur operational water losses during the delivery of water by sluicing, breaks in the conduits and diversions on deliveries in excess of demands. Out of all major conveyance losses seepage losses are the major ones and should be assessed carefully.As the theoretical solution for estimating seepage losses is not easy, it is general practice to estimate the average losses over a length of canal based on experimental data. The observed value is usually the combined figure for evaporation and seepage losses expressed as cumec per million square meter of wetted area perimeter or cubic meters per square meter for wetted perimeter per 24 hours. Data on actual observations of canal losses are limited but even the limited data have shown that actual losses are generally much higher than those assumed in design calculation. A considerable amount of water may get lost if the water loving plants(Phreatophytes and Hydrophytes) grow along the banks of canal. Measurement of consumptive use indicate that some water loving natural vegetation uses 50-100 percent more water than most field crops. In order to account for losses of water incurred during conveyance and application to the field and efficiency factor should be included while calculating project irrigation requirement. The project efficiency is normally divided into three stages each of which is affected by a different set of conditions. Conveyance efficiency (Ec) is defined as the ratio between water received at inlet to a block of fields and that released at the project headworks. Bos and Nugteran (1978) have reported that maximum value of conveyance efficiency as 0.88 for irrigable areas between 4000 to 6000 ha. For smaller areas, the conveyance efficiency gets reduced because of reduction in management staff. Field canal efficiency (Eb) is defined as the ratio between water received at the field inlet and that received at the inlet of the block of fields. Field application efficiency (Ea) is defined as the ratio between water directly available to the crop and that received at the field inlet. Project efficiency is the ratio between the water made available to the crop and that released at headworks, or $E_p = Ea.Eb.Ec$.

3.7 Net Irrigation Requirements (In)

Once the water requirements of a crop is assessed, the net irrigation requirement can be calculated as follows:

$$I_n = ET - P_e - G_e - W_b + \text{application losses} + \text{special needs} \qquad \ldots (44)$$

where,

I_n = net irrigation requirements

ET = crop evapotranspiration

P_e = effective rainfall

G_e = ground water contribution

W_b = stored soil moisture

In addition to meeting the net irrigation requirements, water may be required in the field for leaching the accummulated salts from the root zone and for cultural practices. The leaching requirement (LR) is the portion of the irrigation water applied that must drain through the active root zone to remove accummulated salts. Doorenbos and Pruitt (1979) have given a relationship to calculate leaching requirements (LR) for sandy loam to clay loam soils with good drainage in low rainfall conditions as follows:

For surface irrigation methods (including sprinklers)

$$LR = \frac{EC_W}{EC_e - EC_w} \qquad \text{... (45)}$$

For drip and high frequency sprinkler

$$LR = \frac{EC_W}{2 \, MaxEC_e} \qquad \text{. . . (46)}$$

where,

EC_w = electrical conduitvity of the irrigation water mmhos/cm

ECe = electrical conductivity of the soil saturation extract for a given crop appropriate to the tolerable degree of yield reduction

Max EC_e = Max.tolerable electrical conductivity of the soil saturation extract.

The project irrigation supply requirements(V) can be obtained by the relationship given by Doorenbos and Pruitt (1977) as follows:

$$V = \frac{10}{EP} \sum_i \left[\frac{A.I_n}{1 - LR}\right]_i \; m^3/\text{month} \qquad \text{... (47)}$$

where,

Ep = project irrigation efficiency (fraction)

A = area under a given crop (ha)

In = net irrigation requirements of given crop (mm/month)

LR=leaching requirement, fraction

In order to design the capacity of engineering works, the requirements during peak water use period (V_{max}) may be taken.

4.0 INSTRUMENTS FOR RECORDING/MEASURING CLIMATIC VARIABLES

In studies concerning determination of crop water requirements and related aspects, the weather phenomena to be observed should preferably include temperature, humidity, wind, rainfall, sunshine duration and evaporation. The site of the observation station should, where possible, be within a cultivated area with a crop cover as large as possible upwind. In close proximity of station there should be no road. There should not be any obstructions like houses, trees etc. close to observation site and the ground should be levelled. In order to have better standards of punctuality and reliability of observations, the observer should be provided accommodation close to the observation site. The station ground should be covered with green grass. The site of the station itself should be at least 10 m by 10 m and preferably be installed in the centre of an open space of at least 50 m by 50 m which is covered by grass or a short crop. As per layout of the station, there is no standard layout of the station, however, it should be ensured that instruments do not affect the exposure of other instruments. Errors which can be expected on instrument design, reading accuracy and exposure are as follows:

Observation	Instrument error	Exposure error	Observer error	WMO Standard
Temperature	0.5°C	2°C	5°C	±0.1°C
Min.temperature	0.5°C	3°C	5°C	±0.5°C
Relative humidity	5%	5%	10%	±0.1°C
Hygrometer	2-5%	5%	2%	±1%
Wind	2-5%	20%	2%	±10 %
Sunshine	5-10%	10%	10%	±0.1 h/h
Rainfall	2-5%	10%	5%	±2%
Evaporation pans	2-5%	15%	5%	±0.1 mm

Source: Agro-meteorological field stations, FAO paper 27, Rome.

The description of various instruments required to record/measure different climatic variables are as follows:

4.1 Temperature

The station temperature commonly refers to the air temperature measured inside the thermometer shelter at a height between 1.5 m and 2 m. Thermometers most commonly used in agro-meteorological field stations are:

instantaneous data - mercury-in-glass thermometer

chart recording - mercury-in-steel or bimetallic thermograph

maximum temperature - mercury-in-glass thermometer and thermograph, if any.

wet/dry bulb temperature - mercury-in-glass thermometers

4.2 Air Humidity

It is difficult to obtain in the field a direct measurement of vapour pressure. Most common instruments for field use are the dry and wet bulb thermometers, the mercury-in-steel recording psychrometer, and the hair hydrograph. The aspirated dry and wet bulb thermometers, commonly called the aspirated psychrometer Assmann type consisting of two mercury-in-glass thermometers, one of which has the bulb covered with a wet wick, are used to measure dry and wet bulb temperatures. The temperature data are converted to humidity data with the help of tables. In field, sling psychrometer can also be used to measure dry and wet bulb temperatures. Sling psychrometer consists of wet and dry bulb thermometers placed in a frame with a handle. After wetting the wet bulb the framework is rotated and temperature readings of both the thermometers are recorded. Recording psychrometer and hair hydrograph are other instruments generally used to measure air humidity.

4.3 Wind

Wind is expressed in velocity or wind run, and direction. Generally, anemometer or wind run meter is used to measure wind speed. Wind direction is indicated by installing wind vane. For measurement of instantaneous wind velocity recording anemometers are used. Woelfle anemograph can be used for recording wind velocity and direction.

4.4 Sunshine and Radiation

Two types of instruments are required: one for measuring sunshine duration and another for intensity of sunshine. The Cambell Stokes sunshine recorder is used to measure sunshine duration. A rough measure of sun brightness can be made by observing degree of cloud cover in the sky. The instruments used for measuring solar radiation are sophisticated for routine use in the field. Some of the most common types of instrument are Bimetalic Actinograph Bellani Pyronometer, Thermo-Electric-Solarimeter etc.

4.5 Precipitation

Measurements of precipitation are done to estimate total depth of rainfall and intensity of rainfall. Raingauges are used to measure the depth of precipitation. The duration and intensity of precipitation are measured with the help of rainfall recorders. The most common recorders are the tilting siphon, the tipping bucket and the weighing type. The non-recording totalizing rain gauge having a large capacity container is used to record long-term rainfall data.

4.6 Evaporation

Measurement of evaporation has been done using open water pans for many years. Developmemt of empirical relations for evaporation computation in recent years have to some extent replaced pan measurements. Most commonly used evaporation pan is class A evaporation pan. Another type of evaporation pan is called as Sunken or Colorado pan. Estimation of evaporation power of the air can be made by atmometers. In this water evaporates from a constantly wet filter paper or thin porous ceramic disc which is in contact with a water reservoir.

5.0 F.A.O. COMPUTER PROGRAM FOR ESTIMATING REFERENCE CROP EVAPOTRANSPIRATION

F.A.O.Irrigation and Drainage paper 24 has listed a computer program for estimation of reference crop ET. The program estimates the reference crop ET based on Blaney criddle, Radiation, modified Penman and Pan evaporation methods which have also been discussed in there. The program can be used on a routine basis the daily, weekly or monthly reference ET data for several locations in development projects. Estimates of reference crop ET can be made using daily, weekly, 10-day or monthly average values of climatological data. The programme is designed to handle the input climatological data regardless of units used, with the programme handling the necessary conversions.

5.1 Program Description

The program consists of one main program, five subroutines. The subroutines are : BLANEY, RADIAT, PENMAN, CORPEN and ETPAN. In CORPEN, the correction factor (c)of the modified Penman equation is found by interpolation while for PENMAN the correction factor(c) is assumed to be unity. The salient features of the program are as given below:

(i) Through variable 'NPRINT' following three levels of outputs can be obtained:

NPRINT=0 prints only station name and reference ET estimates.
= 1 prints as above in addition to converted data
= 2 prints as above plus the input data without conversion

(ii) If neither measured sunshine (or cloudiness) solar radiation, nor net radiation data are available,calculation by RADIAT is omitted.

(iii) Similarly, if neither measured relative humidity, sunshine data nor solar radiation data are available, calculation by PENMAN and CORPEN is omitted.

(iv) The program used the relationship developed by W.O.Pruitt for calculating mean average pressure (PMB) for the year if it is not defined for the station. The relationship is:

$$PMB = 1013 - (0.1152 \times ALTITUDE) + (5.44 \times 10^{-6} \times (ALTITUDE)^2)$$

(v) The program assumes U day/U night ratio as 2 if no data of this type is given. The program reads two out of three elements of wind data i.e.24 hour wind, day time wind and day/night ratio and calculates the missing parameter.

(vi) If from the three humidity terms ($T_{dew\ point}$ vapor pressure and relative humidity) only one parameter is given, the programme approximates the others from known physical and mathematical relationships.

(vii) The equation used in the program to estimate solar radiation is:

$$Rs = (0.25 + 0.50\ n/N\ )\ RA$$

where

Rs = solar radiation

RA = extra terrestrial radiation

n/N = ratio of actual to maximum possible bright sunshine hours.

(viii) The macro flow chart of computation of reference ET is given in Figure 1.

5.2 Results

The program was implemented on VAX-11/780 computer system of the Institute. The climatic data for year 1971 recorded at climatic station at Bahadrabad, a field station of I.R.I.,Roorkee were used for computing Reference ET. The data are given in Appendix A. Results of ET estimation by various methods as covered in the program are given in the following table:

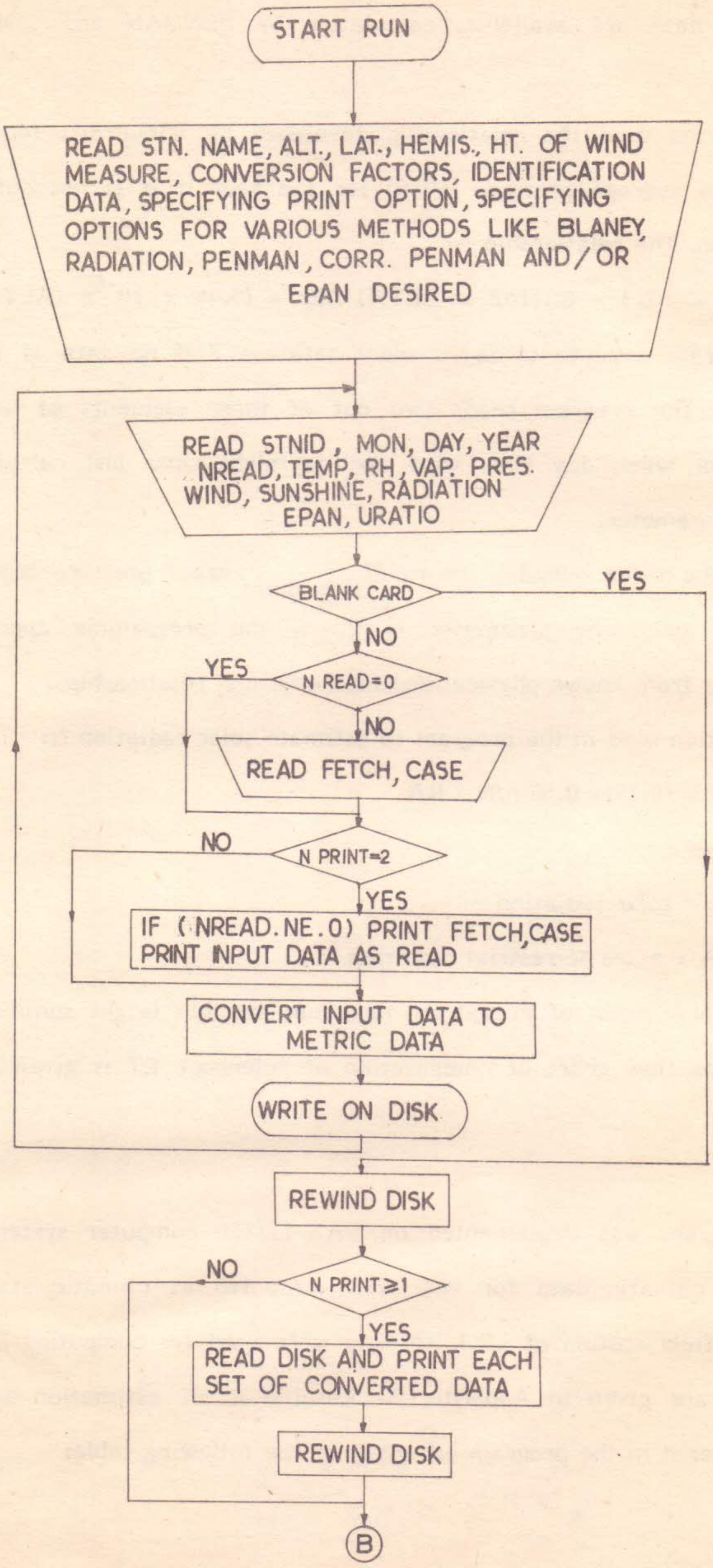

FIGURE 1–COMPUTATION OF REFERENCE ET–MACRO FLOW CHART

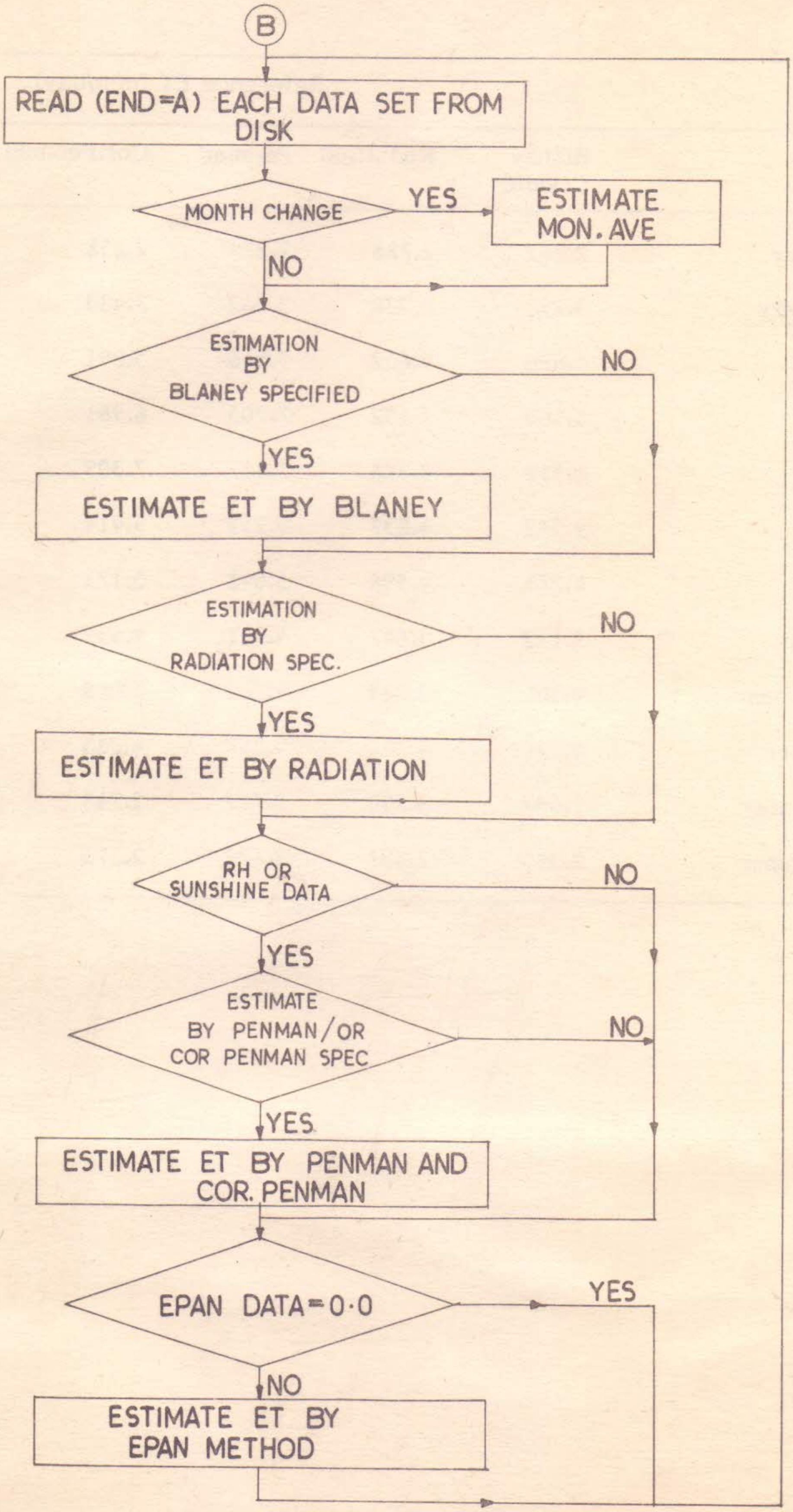
B
READ (END=A) EACH DATA SET FROM DISK
MONTH CHANGE
YES
ESTIMATE MON. AVE
NO
ESTIMATION BY BLANEY SPECIFIED
NO
YES
ESTIMATE ET BY BLANEY
ESTIMATION BY RADIATION SPEC.
NO
YES
ESTIMATE ET BY RADIATION
RH OR SUNSHINE DATA
NO
YES
ESTIMATE BY PENMAN/OR COR PENMAN SPEC
NO
YES
ESTIMATE ET BY PENMAN AND COR. PENMAN
EPAN DATA=0·0
YES
NO
ESTIMATE ET BY EPAN METHOD

FIG 1(contd.)

Month	Reference ET (mm/day)				
	Blaney Criddle	Radiation	Penman	Cor.Penman	Pan.Evap.
January	2.265	2.788	2.274	2.258	1.677
February	3.29	3.938	3.562	3.483	2.717
March	4.696	5.602	5.046	5.091	4.038
April	6.060	7.132	7.205	6.961	4.911
May	6.512	7.386	7.417	7.309	4.883
June	4.542	4.857	5.252	5.414	3.266
July	4.274	4.596	5.048	5.173	2.962
August	3.112	3.647	4.011	4.139	2.259
September	4.500	5.229	4.709	5.048	3.231
October	4.246	4.740	4.247	4.283	2.825
November	2.697	3.290	2.712	2.743	1.700
December	2.340	2.897	2.172	2.175	1.362

6.0 CONCLUSION

The various experimental methods and empirical relations have been discussed with suitability of their application. The computation of ET by various methods varies in degree of accuracy and very much depends on the data availability and quality of data. In order to apply a particular empirical equation for computing ET, it is necessary to know the conditions under which the equation was developed. Most of the empirical equations described were developed by researchers in the USA and European countries hence to apply the equations as they are to Indian situations may not yield good results. The applicability of empirical relations should be checked by comparing the results obtained from experimental methods. Development of crop coefficient values is quite an important task which is to be taken up on urgent basis. The method suggested by FAO paper 24 for computing crop coefficient gives very general values of crop coefficient.

Once it is possible to correctly estimate the crop water requirements, the task of scheduling irrigation will become relatively easier. This will ensure proper and judicious application of irrigation water which is basic demand of irrigation water management. The correct and timely application of water will lead to increase in crop yield which is urgently required keeping the fact in view that population is increasing at an alarming rate.

REFERENCES

1. Anonymous(1930),"Consumptive Use of Water in Irrigation",Trans.Am.Soc. Civil Engr.,Prog.Rept.,Duty of Water Committee, Irrig.Div.,24: 1349-1399.

2. Anonymous (1934),"Report of the Committee on Absorption and Transpiration", 1933-34,Trans.Am.Geophys.Union,Part II,pp.295-296.

3. Anonymous (1935),"Letters, Symbols and Glossary for Hydraulics", Manual of Eng.Practice No.11, Am.Soc.of Civil Engrs.

4. Blaney,H.F.,C.A.Taylor and A.A.Young (1930),"Rainfall Penetration and Consumptive Use of Water in Santa Ana Valley and Coastal Plain",Calif.Dept. of Public Works ,Div.of Water Resources, Bull.33,158 pp.

5. Blaney,H.F.,P.E.Ewing, O.W.Israelsen and others(1938),"Regional Planning, Part VI-Upper Rio Grande: Part III, Water Utilization", Nat.Resources Comm., pp.293-428.

6. Blaney,H.F., and W.D.Criddle (1945),"Determining Water Requirements in Irrigated Areas from Climatological Data", (Processed),17 PP.

7. Blaney,H.F. and W.D.Criddle (1950),"Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data", U.S.Dept.Agr.Soil. Conserv.Serv.,SCS-TP 96,(Processed) 44 pp.

8. Blaney, H.F. and W.D.Criddle(1962)."Determining Consumptive Use and Irrigation Water Requiroements,"U.S.Dept.Agr.Tech.Bull.1275,59 pp.

9. Behnke,J.J. and G.B.Maxey (1969),"An Empirical Method for Estimating Monthly Potential Evapotranspiration in Nevada", J.Hydrol.,8:418-430.

10. Blaney,H.F.,and K.V.Morin (1942),"Evaporation and Consumptive Use of Water Empirical Formulas", Am.Geophys.Union Trans.,August, pp.76-83.

11. Bowen,I.S.(1926),"The Ratio of Heat Losses by Conduction and by Evaporation from any water surface", Phys.Rev.,Vol.27,pp.779-787.

12. Chow,V.T.(ed),(1964),"Handbook of Hydrology", McGraw-Hill, New York,

13. Christiansen, J.E.(1968),"Pan Evaporation and Evapotranspiration from Climatic Data," J.Irrig. and Drain.Div.,Am.Soc.Civ.Engrs,94: 243-265.

14. Christiansen,J.E.and G.H.Hargreaves (1969),"Irrigation Requirements from Evaporation", Trans.Intern.Comm.on Irrig. and Drain.,Vol.III,23.569-23.596.

15. Campbell,R.B., J.H.Chang, and D.C.Cox,(1959),"Evapotranspiration of Sugarcane in Hawaii as measured by In-field Lysimeters in Relation to climate", Proc.10th Congr.Intl.Soc.Sugarcane, Techn.,pp.637-645.

16. Chang, J.,R.B.Campbell and F.E.Robinson,(1963),"On the Relationship between Water and Sugarcane Yield in Hawaii",Agron.J.,55:450-453.

17. Dooresbos, J., and W.O.Pruitt,(1977),"Crop Water Requirements", FAO Irrig. and Drainage Paper No.24, Rome.

18. Fuchs, M., and G.Stanhill,(1963),"The Use of Class A Evaporation Pan Data to Estimate the Irrigation Water Requirements of the Cotton Crop", Israel J.Agr.Res.13(2): 63-78.

19. Fritschen,J.J.,(1965),"Accuracy of Evapotranspiration Determinations by the Bown ratio method", Bul.Internl.Assoc.Sci Hydrol.10 ; 38-48.

20. Hamon,W.R.(1961),"Estimating Potential Evapotranspiration", J.Hyd.Div.,Am. Soc.Civ.Engr.,87:107-120.

21. Ivanov, N.N.(1954),"The Determination of Potential Evapotranspiration", Izvest.Vsesoyuznogo.Geograf.Obs.,86:2.

22. Jensen,M.E.(ed.) (1973),"Consumptive Use of Water and Irrigation Water Requirements", A.S.C.E.Publication, New York.

23. Jensen, M .E.(1983),"Design and Operation of Farm Irrigation Systems", ASAE Monograph, No.3, Published by ASAE, St.Joseph, Michigam,USA.

24. Jensen, M.E., and H.R.Haise,(1963),"Estimating Evapotranspiration from Solar Radiation", J.Irrig.& Drain Div.,Am.Soc.Civ.Engr.,89:15-41

25. Jensen, M.E.,J.L.Wright and B.J.Pratt,(1971),"Estimating Soil Moisture Depletion from Climatic, Crop and Soil Data", Trans.Am.Soc.Agr.Engr.,14:954-959.

26. Knox, C.E.,and T.J.Nordenson,"Average Annual Runoff and Precipitation in the New England, New York area", USGS Hydrol.Invest.Atlas HA-7, undated.

27. Linsley (JR.) , R.K., M.A.Kohler and J.L.H.Paulhus,(1975),"Hydrology for Engineers", Mc-Graw Hill International Book Company.

28. Lowry,R.L., and A.F.Johnson,(1942),"Consumptive Use of Water for Agriculture", Am.Soc.Civ.Engr.Trans.,107:1243-1302.

29. Makkink, G.F.,(1957),"Testing the Penman Formula by means of Lysimeters", J.Inst.Water Eng.,11 (3):277-278.

30. Olivier H.,(1961),"Irrigation and Climate", Edward Arnold Ltd.,London, 250 pp.

31. Ostromecki(1965),"Remarks on Methods of Computation of Water Requirements of Fields and Grasslands", Translated from Polish, U.S.Dept.Int.TT. 67-56062,23 pp.

32. Papadakis, J.(1966),"Climates of the World and their Agricultural Potentialities", Buenos Aires, Argentina, 174 pp.

33. Penman, H.L.(1948),"Natural Evaporation from Open Water, Bare Soil and Grass", Proc.Roy.Soc.London,A193:120-146.

34. Penman, H.L.(1956),"Evaporation: An Introductory Survey, Netherlands", J.Agr.Sci.,1:9-29, Discussion:87-97,pp.151-153.

35. Pruitt,W.O.(1969),"Relation of Consumptive Use of Water to Climate", Trans. Am.Soc.Agr.Engr.,3(1):9-13,17. Trans ASAE

36. Pruitt,W.O. and M.E.Jensen (1955),"Determining When to Irrigate", Agr.Engr., 36:389-393.

37. Pruitt,W.O.,(1966),"Empirical Method of Estimating Evapotranspiration Using Primarily Evaporation Pan", Proc.Conf.on Evapotranspiration Am.Soc.Agr.Engr., Chicago,Dec.,pp.57-61.

38. Ramdas, L.A.(1957),"Evaporation and Potential Evapotranspiration Over the Indian Subcontinent", Indian J.Agr.Sci,27(2):137-149.

39. Saksena, R.S.et al.(1984),"A Guide for Estimating Irrigation Water Requirements", Tech.Series No.2, Water Management Div., M.O.I.,Govt. of India, New Delhi, May, 1984.

40. Stanhill, G.(1961),"A Comparison of Methods of Calculating Potential Evapotranspiration from Climatic Data", Israel J.Agr.Res.,11,159-171.

41. Stanhill, G.(1962),"The Control of Field Irrigation Practice from Measurements of Evaporation", Israel, J.Agr.Res.,12:51-62.

42. Stephens, J.C.(1965),"Disc. of Estimating Evaporation from Insolation", J.Hydr.Div.Am.Soc.Civ.Engr.91(HY5): 171-182.

43. Tanner, C.G.(1960),"Energy Balance Approaoch to Evapotranspiration from Crops", Soil Sci.Soc.Am.Proc., 24.1-9.

44. Thornthwaite, C.W.,(1948),"An Approach Toward a Rational Classification of Climate, Geograph", Rev.,38-55.

45. Thompson, G.D.,C.H.O.Pearson and T.G.Clessby,(1963),"The Estimation of the Water Requirements of Sugarcane in Natal, Proc.South African Sugar Technol.Assoc,pp.1-8.

46. Turc, L.(1961),"Evaluation des Besoins en Eau d'Irrigation Evapotranspiration Potentielle, Formule Climatique Simplifice, et Mise a Jour (In Frence)(English title: Estimation of Irrigation Water Requirements, Potential Evapotoranspiration: A Simple Climatic Formula Evolved upto Date)", Ann.Agron.12:13-49.

47. Thorthwaite, C.W.(1944),"Report of the Committee of Transpiration and Evaporation", 1943-44, Trans.Am.Geophy.Union,Vol.25,p.687.

48. Van Bavel , C.H.M.,(1966),"Potential Evaporation. The Combination Concept and Its Experimental Verification", Water Resources Res.,2(3):455-467.

APPENDIX A

Data for Roorkee Station for year 1971

Altitude = 268.0 m

Latitude = 29.9°N

Height of wind measurement = 3.44 m

Mean pressure for the year 986.0 m bar

Month	T_{max} (°c)	T_{min} (°c)	RH_{max} (%)	RH_{min} (%)	U_{day} (km. /hr.)	Epan (mm/day)
January	21.2	4.0	78.0	41.0	2.9	2.05
February	24.1	6.9	70.0	35.0	5.0	3.43
March	30.7	11.4	66.0	33.0	5.0	5.17
April	35.2	18.8	53.0	39.0	7.5	6..53
May	35.4	20.9	56.0	38.0	6.7	6.42
June	33.4	23.2	79.0	65.0	5.5	3.96
July	33.1	24.2	84.0	69.0	4.9	3.55
August	30.6	23.8	87.0	80.0	3.0	2.66
September	32.8	21.7	81.0	57.0	1.0	3.89
October	31.9	17.4	70.0	46.0	3.0	3.46
November	25.4	10.8	81.0	55.0	2.8	2.05
December	24.1	6.6	79.0	51.0	2.4	1.65

Note: Sunshine data are not listed above.

18
17
35

36
12
48

APPENDIX B

Crop Coefficient of Various Crops at Different Growth Stages

CROP	Crop Development Stages					Total
	Initial	Crop Develop-ment.	Mid Season	Late Season	At harvest	growing period
1	2	3	4	5	6	7
Banana						
tropical	0.4-0.5	0.7-0.85	1.0-1.1	0.9-1.0	0.75-0.85	0.7-0.8
Subtropical	0.5-0.65	0.8-0.9	1.0-1.2	1.0-1.15	1.0-1.15	0.85-0.95
Bean						
green	0.3-0.4	0.65-0.75	0.95-1.05	0.9-0.95	0.85-0.95	0.85-0.9
dry	0.3-0.4	0.7-0.8	1.05-1.2	0.65-0.75	0.25-0.3	0.7-0.8
Cabbage	0.4-0.5	0.7-0.8	0.95-1.1	0.9-1.0	0.8-0.95	0.7-0.8
Cotton	0.4-0.5	0.7-0.8	1.05-1.25	0.8-0.9	0.65-0.7	0.8-0.9
Grape	0.35-0.55	0.6-0.8	0.7-0.9	0.6-0.8	0.55-0.7	0.55-0.75
Groundnut	0.4-0.5	0.7-0.8	0.95-1.1	0.75-0.85	0.55-0.6	0.75-0.8
Maize						
Sweet	0.3-0.5	0.7-0.9	1.05-1.2	1.0-1.15	0.95-1.1	0.8-0.95
grain	0.3-0.5*	0.7-0.85*	1.05-1.2*	0.8-0.95	0.55-0.6*	0.75-0.9
Onion						
dry	0.4-0.6	0.7-0.8	0.95-1.1	0.85-0.9	0.75-0.85	0.8-0.9
green	0.4-0.6	0.6-0.75	0.95-1.05	0.95-1.05	0.95-1.05	0.65-0.8
Pea,fresh	0.4-0.5	0.7-0.85	1.05-1.2	1.0-1.15	0.95-1.1	0.8-0.95
Pepper,fresh	0.3-0.4	0.6-0.75	0.95-1.1	0.85-1.0	0.8-0.9	0.7-0.8
Potato	0.4-0.5	0.7-0.8	1.05-1.2	0.85-0.95	0.7-0.75	0.75-0.9
Rice	1.1-1.15	1.1-1.5	1.1-1.3	0.95-1.05	0.95-1.05	1.05-1.2
Safflower	0.3-0.4	0.7-0.8	1.05-1.2	0.65-0.7	0.2-0.25	0.65-0.7
Sorghum	0.3-0.4	0.7-0.75	1.0-1.15	0.75-0.8	0.5-0.55	0.75-0.85
Soyabeen	0.3-0.4	0.7-0.8	1.0-1.15	0.7-0.8	0.4-0.5	0.75-0.9
Sugarbeet	0.4-0.5	0.75-0.85	1.05-1.2	0.9-1.0	0.6-1.7	0.8-0.9
Sugarcane	0.4-0.5	0.7-1.0	1.0-1.3	0.75-0.8	0.5-0.6	0.85-1.05
Sunflower	0.3-0.4	0.7-0.8	1.05-1.2	0.7-0.8	0.35-0.45	0.75-0.85
Tobacco	0.3-0.4	0.7-0.8	1.0-0.8	1.0-1.2	0.9-1.0	0.75-0.85

1	2	3	4	5	6	7
Tomato	0.4-0.5	0.7-0.8	1.05-1.25	0.8-0.95	0.6-0.65	0.75-0.9
Watermelon	0.4-0.5	0.7-0.8	0.95-1.05	0.8-0.9	0.65-0.75	0.75-0.85
Wheat	0.3-0.4	0.7-0.8	1.05-1.2	0.85-0.75	0.2-0.25	0.8-0.9
Alfalfa	0.3-0.4				1.05-1.2	0.85-1.05
Citrus						
clean weeding						0.65-0.75
no weed control						0.85-0.9
Olive						0.4-0.6

First figure: Under high humidity (RHmin > 70%) and low wind (U< 5m/sec).
Second figure : Under low humidity (RHmin < 20%) and strong wind (> 5m/sec).
Source: FAO Irrigation and Drainage Paper No.33

APPENDIX C

Water requirement of rice in different parts of the country as measured near the field head

State/Place	Season	Water requirement (mm)	Irrigation requirement (mm)	Reference
West Bengal:				
Kharagpur	Aus(Mar./April-June/July)	1850	N.A.	Pande & Mitra (1972)
	Aman(July/Aug.-Nov.Dec.)	1890	N.A.	
	Boro(Dec./Jan.-Mar./April)	2150	N.A.	
Orissa:				
Cuttack	Kharif(June-Sept)	1300	790	Chaudhry and
	Boro(Jan.-April)	1190	980	Pandey(1968)
Bhubaneswar	Kharif(June-Sept.)	1440	780	Sahu(1967)
	Rabi(Sept.-Dec.)	1650	1630	-do-
Uttar Pradesh:				
Roorkee	Kharif(June-Oct.)	1620	750	Gupta and Bhattacharya (1963)
Dhanauri	Kharif(June-Oct.)	1630	910	Bhattacharya (1972)
Karnataka:				
Sirguppa	Kharif(June-Oct.)	N.A.	1344	Yadav(1972)
	Kharif(June-Oct.)	1520	1170	Patil(1963)
Tamil Nadu:				
Coimbatore	Samba(July/Aug-Dec/Jan.)	1680	N.A.	Chandramohan (1965,1967)
Puttukottai	Samba(July/Aug.-Dec./Jan.)	2650	N.A.	-do-
	Kuruvai (June-Sept.)	2000	N.A.	-do-
Delhi:	Kharif(June-Oct.)	2400	1640	Hukkeri and Sharma(1974)

N.A.= data not available

Scheduling of different Irrigation to wheat at selected locations

(I.C.A.R. ,1972)

S.No.	Centre	Soil type	Date of sowing	First irrigation		Other Irrigations								Depth of each irrigation from 2nd onwards	Total depth of irrigation water (cm)	Yield (q./ha)
				Days after sowing	Depth (cm)	2nd	3rd	4th	5th	6th	7th	8th	9th			
						(* Days after showing)										
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1.	Jobner (Rajasthan)	Loamy	Nov.Ist.half	20	4.5	40	60	80	98	112	124	134	142	4.5	40.5	28.0
		Sand to Sandy loam	Nov.2nd.half	20	4.5	40	58	75	89	102	114	124	132	4.5	40.5	30.0
2	Hissar (Haryana)	Sandy loam	Nov.1st week	26	6.0	42	67	94	111	125	133	-	-	6.0	42.0	38.6
3	Ludhiana (Punjab)	Sandy loam	Nov.1st week	25	6	57	95	118	140	-	-	-	-	7.5	36	41.7
			" 2nd "	25	6	61	95	119	136	-	-	-	-	7.5	36	
			" 3rd "	25	6	61	94	116	131	-	-	-	-	7.5	36	
			" 4th "	25	6	64	91	113	128	-	-	-	-	7.5	36	
			Dec.1st "	25	6	64	88	101	115	-	-	-	-	7.5	36	
4	Roorkee (Uttar (Pradesh)	Sandy loam	Mid.Nov.	25	6	65	100	-	-	-	-	-	-	8	22	40.0
5	Siruguppa (Karnataka)	Heavy black clay	Nov.1st week	0	5	4	23	42	63	83	100				37.5	35.0
						(2.5)	(6.0)	(8.0)	(8.0)	(8.0)	(8.0)					
6	Navasari (Gujarat)	Black clay	Nov.2nd half	1	7.5	7	18	35	55	75	90				60	29.0
						(7.5)	(7.5)	(7.5)	(10.0)	(10.0)	(10.0)					

* For each cm of rain,increase the number of days by 5 upto the end of January and 3 thereafter(Figures in brackets indicate the depth of water used at each irrigation).

Irrigation requirements of maize in different parts of India

Station	Soil type	Season	Irrigation requirement		Reference
			No.	Amount (mm)	
Delhi	Sandy loam	Kharif	2.3	100-150	Badhe(1968)
Hissar (Haryana)	Sandy loam	Kharif	5-6	300-360	Malik (1973) Sharma et.al (1974)
Pantnagar (Uttar Pradesh)	Sandy loam	Kharif	4	225-275	Sharma and Upadhyay(1973)
Udaipur (Rajasthan)	Sandy loam	Kharif	4	300	Singh and Sharma(1968)
Arbhavi (Karnataka)	Sandy loam	Kharif	3	150	Anonymous(1956)
		Rabi	5	330	Anonymous(1956)
Siruguppa (Karnataka)	Clay loam	Summer	10	510	Patil et.al(1969)
Bhubaneshwar (Orissa)	Loam	Kharif	2	100-150	Sahu(1967)
		Rabi	11	500-600	Sahu(1967)
		Summer	18	900	Sahu(1967)
Bhavanisagar (Tamil Nadu)	Loamy sand	Summer	25	1250	Ali et.al(1970)

Irrigation requirement of bajra in different parts of India

Place	Soil Type	Season	Irrigation requirement		Reference
			No.	Amount(mm)	
Siruguppa (Karnataka)	Clay	Kharif	2	150	Patil et al(1969)
Hissar (Haryana)	Sandy loam	Kharif	3	200	D.A.R.E.(1975)
Delhi	"	Kharif	3	150	Pal (1975)
Anand (Gujarat)	"	Summer	10	600	Joshi(1969)

Irrigation requirement of barley in different parts of India

Place	Soil type	Season	Irrigation requirement		Reference
			No.	Amount (mm)	
Bikramganj (Bihar)	Sandy loam	Rabi	2	180	Pandey and Mukherji(1966)
Kanpur (Uttar Pradesh)	"	Rabi	2-3	150 180	Bhan(1975) Warsi (1973)
Ludhiana (Punjab)	"	Rabi	1	75	Singh(1975)
Hissar (Haryana)	"	Rabi	4	250	Malik(1971)
Jobner (Rajasthan)	"	Rabi	5-6	300 360	Bajpai and Singh(1972) Yadav(1972)
Bhind (Madhya Pradesh)	"	Rabi	3	200	Garg and Saraswati(1975)
Delhi	"	Rabi	2	150	Singh (1975)

Irrigation requirement of groundnut in different parts of India

Place	Soil type	Season	Irrigation requirement		Reference
			No.	Amount(mm)	
Bhavanisagar (Tamil Nadu)	Red sandy loam	Rabi	9-13	500-700	Ali et al.(1974)
Hyderabad (Andhra Pradesh)	-do-	Rabi	8	655	Yadav(1972)
Yemmiganur (Karnataka)	-do-	Spring	6-7	300-350	Rao(1966)
Parbhani (Maharashtra)	Clay loam	Summer	8	550	Khuspe(1975)
Kanpur (Uttar Pradesh)	Sandy loam	Kharif	2	150	Bhan(1975)
Hissar (Haryana)	Fine Sandy loam	Kharif	5	350	Singh et al. (1968)
Ludhiana (Punjab)	Sandy loam	Kharif	2	140	Singh and Sandhu(1968a)
"	Loamy sand	Kharif	6	300	Saini et al. (1973)
Chakuli (Orissa)	Loamy sand	Rabi	10	690	Lenka and Misra (1973)

Irrigation requirement of mustard at different places in the country

Location	Soil Type	Irrigation requirement		Reference
		No.	Amount(mm)	
Roorkee (Uttar Pradesh)	Sandy loam	1	60	Yadav(1972)
Kanpur (Uttar Pradesh)	Sandy loam	2	140	Bhan(1975)
Karnal (Haryana)	Sandy loam	1	120	Yadav (1972)
Hissar (Haryana)	Sandy loam	1	70	Singh and Moolani(1972)
Ludhiana (Punjab)	Sandy loam	1	75	Yadav(1975)
Kota (Rajasthan)	Clay loam	2	150	Singh et al.(1974)
Delhi	Sandy loam	3	180	Yusuf(1973)

Irrigation requirement of linseed in different parts of India

Location	Soil type	Irrigation requirement No.	 Amount(mm)	Reference
Kanpur (Uttar Pradesh)	Sandy loam	2	140	Bhan(1975)
Pantnagar (Uttar Pradesh)	Loam	2	150	I.C.A.R.(1973)
Hissar (Haryana)	Sandy loam	1	75	Prashar and Sachan (1967)
Delhi	Sandy loam	3-4	150-200	Yusuf(1973)
Jabalpur (Madhya Pradesh)	Clay loam	1	75	I.C.A.R.(1973)
Kota (Rajasthan)	Clay loam	2	150	Singh et al.(1974)

Irrigation requirements of cotton in different parts of India

Place	Soil type	Season	Irrigation requirement		Reference
			No.	Amount (mm)	
Delhi	Sandy loam	Kharif	2	140	Rajput (1965)
Ludhiana (Punjab)	Sandy loam	Kharif	5	300	Singh and Sandhu(1968 b)
Hissar (Haryana)	Sandy loam	Kharif	4	240	Yadav(1972)
Bhavanisagar (Tamil Nadu)	Red sandy loam	Rabi	9-13	675-770	Ali et al.(1974)
Coimbatore (Tamil Nadu)	Clay loam	Rabi	6	837	Yadav(1972)
Siruguppa (Karnataka)	Clay	Rabi	8	730	Yadav(1972)
Akola (Maharashtra)	Clay	Kharif	2	200	Bathkal et al.(1975)

Irrigation requirement of sugarcane in different parts of India

Location	Soil type	Irrigation requiremenmt	
		No.	Amount (mm)
Delhi	Sandy loam	8	500
Ludhiana (Punjab)	Sandy loam	8	620
Roorkee (Uttar Pradesh)	Sandy loam	11	660
Bikramganj (Bihar)	Loam	7	450
Padegaon (Maharashtra)	Clay loam	25	*1960
Anakapalle (Andhra Pradesh)	Clay loam	20	680

* Irrigation requirement per annum and the requirement for a adsali(18 months) crop will be more. The crop duration in other places is 10-12 months only.

Source: A Guide for Estimating Irrigation Water Requirements, Tech.Series No.2, Water Management Div.,M.O.I.,Govt. of India, May,84.