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ESTIMATION OF EVAPOTRANSPIRATION LOSSES FROM AGRICULTURAL LANDS - CLIMATOLOGICAL APPROACHES

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PREFACE

Accurate and consistent estimates of daily evapotranspiration are important in irrigation planning and scheduling and in detailed water resources and hydrologic studies. The processes which affect evapotranspiration broadly can be classified in three categories, which are climate, crop characteristics and local conditions and agricultural practices. Evapotranspiration can be determined from direct measurements, empirical climatic formulae, or by using evaporation measurements as indices.

In this technical note it has been envisaged to review all available methods for estimating evapotranspiration from agricultural lands and present status of these methods, limitations, adaptability and usefulness in terms of data availability including recommendations for further research under Indian conditions.

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ABSTRACT

Evapotranspiration from agricultural lands forms an important part in the root zone water balance study. For last few years due to continued occurrence of drought conditions, it has become important to conserve soil moisture from rainfed crops. Knowledge of water requirements (or ET) of crops has values in several areas of agronomy, including irrigation, evaluation of drought severity and in hydrological studies. Evapotranspiration can be determined from direct measurements, empirical climatic formulae, or by using evapotration measurements as indices. Direct measurements are performed by many techniques including tanks and lysimeters, soil water depletion, field plots, energy balance and water balance methods etc. In this report it has been envisaged to review all available methods for estimating evapotranspiration from agricultural lands and present status of these methods, limitations, adaptability and usefulness in terms of data availability including recommendations for further research under Indian conditions.

1.0 INTRODUCTION

The increase in world population and demands for greater food production have placed a heavy burden on many countries where food production is limited because of climatic, environmental and technological factors. Management practices for conservation of water have been increasingly emphasised because of sparse natural precipitation, high evapotranspiration and excessive depletion of limited ground water resources. On the other hand, water is a very important natural resource with multiple uses and limited availability. On an average about 60% of the total precipitation in India (116 cm) goes to evapotranspiration and the need for its measurement is very important. This information is needed for judicious and scientific planning, development, and management of water resources and irrigation scheduling. ET is that part of the hydrologic cycle which deals with the return of water back into the atmosphere through the direct transpiration by plants from soil surface etc. Knowledge of water requirements (or ET) of crops has value in several areas of agronomy, including irrigation, evaluation of drought severity and in hydrological studies.

Evapotranspiration can be determined from direct measurements, empirical climatic formulae, or by using evaporation measurements as indices. Direct measurements are performed by many techniques including tanks and lysimeters, soil water depletion, field plots, energy balance, water balance etc.

2.0 REVIEW OF LITERATURE

2.1 General

The continuous increase in the population of India and demand for greater food production have placed a heavy burden on our country where food production is highly dependent on rainfed agriculture, and also highly affected because of uncertainty of monsoon behaviour.

Management practices for conservation of water have been increasingly emphasised because of sparse natural precipitation, high ET; and excessive depletion of limited groundwater resources.

2.2 Scope of Study

Knowledge of water requirements (or evapotranspiration) of crops has value in several areas of agronomy, including irrigation, evaluation of drought severity and in hydrological studies. In arid and semi arid regions, values of ET are needed for studying the economics of dry land farming, as well as in irrigation. ET values are needed for planning irrigation projects, farm irrigation systems layout and improving irrigation practices. The increasing demand for food and the limited supplies of water for irrigation makes it important to use the available water in the most economic way. It is clear that a knowledge of minimum water needs of crops, such that yields are not affected during the different stages of plant growth under arid and semi-arid conditions would be very useful.

The problems associated with limited production in such conditions can be minimized through proper application of such information.

2.3 Evapotranspiration or Consumptive Use

Evapotranspiration (ET) or consumptive use, is the evaporation from all water, soil, snow, ice, vegetative and other surfaces plus transpiration. Consumptive use or ET is an important element of estimating irrigation water requirement and in water resources management. The term consumptive use is used to designate the losses due to evapotranspiration and the water that is used by the plant for its metabolic activities since the water used in the actual metabolic processes is insignificant (less than 1% of ET) the term consumptive use is generally taken equivalent to ET.

2.4 Mechanism of ET

The mechanism of ET is the combination of the mechanism of two processes i.e. evaporation and transpiration. By evaporation the water which is present in lakes, reservoirs, saturated soils and on the surface of leaves of plants as interception, in liquid state is changed to vapour state. The mechanism of transpiration is essentially the same as evaporation except that the surface from which water molecule escape is not a free water surface but the numerous pores of stomata in the leaves.

2.5 Factors Affecting ET

ET from agricultural lands is affected by several processes like radiation exchange, vapour transport and biological growth operating within a system involving the climate, crop and soil. Several workers have provided good descriptions of these primary variables which determine ET (Tanner, 1957, Penman et.al. 1967; Campbell, 1977). The processes which affect ET broadly can be classified in three categories, which are climate, crop characteristics and local conditions and agricultural practices. While estimating ET, one has to take into account the above mentioned factors.

2.6 Concept of Potential Evapotranspiration & Reference Crop Evapotranspiration

On the basis of experimental evidence available, it was for many years believed that the type and form of vegetation cover on the earth's surface had little effect on the rate of natural evaporation, providing this was limited by the heat supplied to the surface and not by the availability of surface water. Knowing this fact, a term called potential evapotranspiration was conceived, which might be conservative at a particular location and determined mainly by meteorological conditions.

Thornthwaite (1948) suggested that soil moisture may have considerable effect on evapotranspiration and suggested that potential evapotranspiration was the ET that would occur when there was an adequate supply of soil moisture at all the times. Penman (1956) defined potential ET as "the amount of water transpired in unit time by a short green crop, completely shading the ground, of uniform height and never short of water". Van Badvel (1966) defined Potential Evapotranspiration as the Evapotranspiration (ET) that occurs when the vapour pressure at the evaporating surface is at the saturation point. Gangopadhyaya et al. (1966) defined Potential ET as the maximum quantity of water capable of being lost, as water vapour, in a given climate, by a continuous, extensive stretch of vegetation covering the whole ground when the soil is kept saturated. Jensen (1983) defined Potential ET as the rate of 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. All the concepts given by various researchers regarding potential evapotranspiration includes both evaporation from the soil and from the vegetation for a specified region over a given time interval. These researchers initially thought that the phenomenon of ET depends less on type of vegetation cover when water is potentially available and potential ET represents a maximum rate, which implies that energy advection is a scarce and transient phenomenon. These conclusions might be connected to the fact that many of the original studies took place over short crops. With such crops the control exerted by the atmosphere itself is maximised, since it dictates not only the driving potential in the diffusion process, but also generates the dominant resistance to vapour pressure.

It has been found that ET 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 potential 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. Doorenbos and Pruitt (1977) stated that the climate was the most important factor to take into account and the effect of which on crop water requirements was given by the reference crop evapotranspiration (ET) which is defined as "the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water".

There is considerable overlap between the concept of potential ET and Reference ET, particularly in regard to the empirical formula used to estimate them. The better definition of Reference Crop ET avoids the problems of vegetation control and advection, and therefore increases the probable universality of locally derived empirical equations.

2.7 Measurement of Potential Evapotranspiration

There are so many ways defined and discussed by various research workers for the measurement of potential ET. Following three main approaches to the measurement of potential ET have been evolved:

i) The transformation of measurements made from non-vegetated surfaces

ii) the direct measurement of water losses from moist vegetative surfaces, and

iii) more or less empirical formulae

2.7.1 In first approach use of evaporimeters and evaporation pans is suggested. There are so many evaporimeters designed by different research workers. Evaporimeters provide a measure of the drying power of the air. The consistency and accuracy of these evaporimeters are always doubtful as they are not able to provide a value which closely approximates potential water loss.

There are a variety of pans of different shapes and forms with latest designs concentrating on small diameter, heavily insulated fibre-grass pans in which a reasonably close control of heat budget of the pan is possible. As far as popularity and use is concerned, the two main types of pans in use are the U.S. Weather Bureau class A pan and the British Meteorological office sunken pan. Various authors have studied this aspect and published papers. Some of the important ones are by Stanhill (1961, 1962), Fuchs and Stanhill (1963), Pruitt & Jensen (1965), Pruitt (1960), Jensen, et.al. (1961). Although, one would not expect a water surface to behave like a normal vegetated one, it is of interest to note that under normal climatological conditions in the Netherlands, maximum evapotranspiration from a grass cover of 10-15 cm height closely approximates the evaporation rate from sunken pans.Rijtema (1965) found a close agreement between measured evaporation loss from sunken pans and the Eo values calculated with the Penman equation using Dutch data. Chang (1965) concluded after reviewing evaporation pan and other measured data and concluded that "the evaporation pan is as accurate as any formula or field instrument for estimating potential evapotranspiration in a humid climate and when properly exposed, the potential maximum evapotranspiration in an arid climate". Doorenbos & Pruitt (1977) have described evaporation pan method to estimate reference crop ET as follows:

$$ET_o = K_p E_{pan}$$

where ET_o = reference from ET (mm/day)

K_p = pan coefficient

E_{pan} = pan evaporation (mm/day)

Values of pan coefficient depend upon ground cover around the pan, mean relative humnidity, wind velocity and type of pans.

2.7.2 The direct measurement of evapotranspiration losses from moist vegetated surfaces involves the use of irrigated evapotranspirometers in which soil moisture content is maintained at a level which permits water losses to occur at the potential rate and for which, therefore, a simple balancing of precipitation and irrigation inputs against drainage output suffices to permit the calculation of potential ET. The theory of operating irrigated evapotranspirometers have previously been quite fully discussed by Green (1959) and Ward (1963 b). The only point which needs re-emphasis at this stage is that provided the correct operating conditions are adequately maintained evaporimeters should provide an accurate measure of potential water loss. The use of irrigated evapotranspirometers is certainly preferable to an evaporation pan.

2.7.3 So many empirical relations have been developed so far by various researchers. Out of these, the formulae developed by Penman and Thornthwaite have emerged as the most generally applicable. As both the procedures were largely empirical, particularly as originally stated, and that this has resulted in many attempts to refine and improve them both by the authors themselves and by subsequent workers.

One of the measure improvement in the potential ET measurement technique by Penman method is insertion of measured radiation values in place of the original radiation terms. Hershfield (1957) pointed out that this will result in an improved estimate of potential ET only if the network of radiation instruments is sufficiently dense to enable a representative sampling of vegetation type having different albedo, and surface temperatures. A more practical approach to solve this problem is to measure the global radiation and then to use the proper albedo of the different vegetation covers, using an empirical relation, such as the one proposed by Penman, to calculate the net long wave radiation. The main advantage of the procedure is that the measured global radiation data holds good for large areas.

Chang (1959), Pelton (1960) and Ward (1967) discussed Thornthwaite's temperature based formula for potential ET in those conditions in which air temperature and net radiation availability are closely related, the formula works quite effectively; in other conditions it is more or less unsatisfactory but continues to be widely used because of its minimal input data requirements.

2.8 Measurement of Actual Evapotranspiration

For estimating evapotranspiration from naturally wet or irrigated fields one has to consider actual evapotranspiration and also the great difficulties of measuring this phenomenon. After removing the constriction of adequate water supply imposed by the concept of potential ET, it is necessary to consider all the factors relating to the soil and plant cover. As the conditions inside the soil changes everyday, no formulae or equation which relics on meteorological or climatological observations can be expected even to approximate the rate of evapotranspiration. Keeping in view the above mentioned facts Penman (1949) suggested that one could obtain reasonable results by simply calculating potential ET from one or more reliable formulae and then reducing the values obtained in proportion to the degree of soil moisture depletion. This approach was also adopted by the U.K. meteorological office in their mapping of soil moisture deficit and actual ET (Grindlay, 1970).

To estimate actual ET for long periods of time, e.g. one year, it has been found that formulae such as those of Turc (1954) and Budyko (1958) give comparatively satisfactory results.

The situation in case of short term estimates of actual ET is far more complex. Three main approaches to estimate actual ET are:

i) Theoretical modelling of entire ET process from soil to atmosphere using combination of energy balance and mass transfer formulae and taking into account surface and other resistances of the evaporating vegetation surface. This approach has been successfully developed by a number of workers including Monteith (1965), Riztema (1965), Sceicz et.al. (1969).

ii) The estimation of actual ET can be made through physical modelling of the ET system in the sense of water balance calculations. These water balance calculations are done for known areas or volumes of vegetations or vegetation covered ground surface in which evaporative loss is derived as the residual item, in the water balance equation:

Inflow = Outflow + Storage

iii The correct estimates of actual ET can be made through the measurement of the flux of moisture above the evaporating vegetation surface. This water loss in the form of actual ET passes into the overlying air layers where it is reflected in humidity and temperature gradient.

The above mentioned approaches are discussed briefly in the forthcoming sections:

2.8.1 Combination of Energy Balance & Mass Transfer Formulae

After suitable modifications and improvements in Penman formulae it become a successful means of estimating not only potential ET but also actual ET if appropriate crop and soil factors are incorporated. Initially the combination formulae were based on the assumption of a wet vegetation surface but in case if the vegetation is not wet, it will reduce the rate of evaporation because of the diffusion resistances imposed by the soil pores and stomata. Penman & Schofield (1951) and subsequently Monteith and Sceiez (1962) modified the combination formulae taking into account the stomatas and other surface resistances. Monteith and Sceicz (1962) showed that the effective surface resistance of field crops could be estimated from their radiative temperature. Monteith (1963) suggested that the effective surface resistance could also be calculated from temperature, vapour pressure and wind profiles over the vegetation surface. Sceicz et al (1969) and Sceicz and Long (1969) showed that the mean aerodynamic resistance can be calculated from windspeed and surface roughness by reference to crop height. Rijtema (1965), 1968a, 1968b) showed that by taking into account soil physical properties as soil moisture suction and capillary conductivity and vegetational properties such as rooting characteristics, internal resistance to liquid tissue in relation to stomata reaction, ground coverage and vegetation height in addition to meteorological conditions,actual ET for weekly periods could be calculated using a combined aerodynamic and energy balance approach. Rijtema (1968a) compared fortnightly data of calculated and measured ET from both irrigated and non-irrigated summer wheat which showed acceptable agreement.

2.8.2 Water balance approach

This approach of estimating ET is based on the concept of balancing the continuity equation consisting measurable quantities i.e. inflow, outflow and storage by the amount of water which represent evapotranspiration. This concept has been used for the estimation of ET at different scales including lysimeters, water table fluctuations, river basins and small experimental watersheds, and moisture fluctuation within the profile.

i) A number of lysimeter studies have been reported in the literature. Lysimeter studies involve the growing of crops in large containers (lysimeters) and measuring their water loss and gains. There are so many difficulties associated with the reproduction of soil profile accurately. In most of the cases, the shallow depth of these instruments prevents both deep percolation and the capillary rise of moisture from some depth within the soil profile, unless a water table is maintained artificially, in which case the lysimeter may be representative only of rather special shallow water table conditions.In lysimeters developed by Feddes (1968) water table depth is controlled by the surrounding field water table level so that water management within the lysimeter closely approximates that in the area represented by it. Finally the main problem which can not be solved is of limitation of the space provided for soil inside the lysimeter as the size of the lysimeter is determined by the cost of installation. The development of neutron probes for measuring lysimeter moisture changes can suitably overcome the restriction of normal size.

ii) The technique of estimating evapotranspiration from water table fluctuations is one of the simplest way of water balance approach discussed and used by White (1932) and recently by Meyboon (1965). However, the components used in this technique e.g. groundwater flow in to and out of the area are difficult to determine thus rendering this method unsuitable for the case in which water table is at a large depth below the ground surface.

iii) By measuring water balance of a river basin long term ET can be estimated assuming one year sub-surface storage changes are negligible. The simplified water balance equation for estimating long term ET will be;

ET = Precipitation - runoff

In case of very small basins, there are difficulties in obtaining reliable values of precipitation from existing gauge networks and also storage lag problems at each year end when late precipitation may not appear as runoff until the early months of the following year.

2.8.3 Estimation of actual ET through moisture flux measurement

Different theories and experimental methods depending upon different situations have been investigated by a number of research works for determination of actual ET from measurement of flux of moisture above the evaporating surface.

Thornthwaite and Holzman (1939), Pasquill (1949, 1950) and Rider (1954, 1957) developed and modified an approach based upon the fact that evapotranspiration into the lower layers develops a moisture gradient from the evaporating surface into the overlying air. The turbulent motion of air will break the moisture gradient establishing uniform moisture conditions. The contribution of water vapour from evapotranspiration process can be determined by measuring moisture gradient and the turbulent motion of the air. Instrumental limitations and the non generality of the formulae were the main constraints in wider development of this approach.

Direct measurement of flux can also be done by leaf chamber and eddy correlation method. Bierhuizen and Slatyer (1964) and Jarvis and Slatyer (1966) reported that independent, continuous and simultaneous measurements are possible of the water vapour and carbon dioxide exchanges between each surface of a leaf and the surrounding atmosphere under controlled conditions of visible and total radiation, air and leaf temperatures, and carbon dioxide and water vapour concentrations. The plant chambers for field measurements was developed by F.W. Went and described by Ashby (1957) and Stark (1967, 1968). As the leaves do not exist in isolation but in large numbers, moisture movement and moisture stress within the chamber are affected due to the mutual interference in terms of incoming and outgoing radiation, humidity and sensible heat. This affects the accuracy and reliability of leaf and plant chamber approach of estimating actual evapotranspiration.

Swinbank (1951) suggested eddy correlation method to over come the drawbacks of leaf and plant chamber approach. Swinbank determined the moisture fluxes from the correlation of temperature and humidity fluctuations with the vertical component of wind velocity. Later on Evapotron and fluxatron were developed on the basis of the concept of Swinbank. Dye & Mather (1965) and Dye et al. (1967) conducted a number of experiments by these instruments and described their performance very close to the accurate values

Although such instruments are still in the developmental stage, yet these are being used as a standard measuring device. As mentioned earlier it is useful to create standard evaporation rates namely Potential ET and Reference crop ET, which attempt to provide some measure of the atmosphere's ability to support the evaporation process. Some of the estimation techniques attempt to estimate one or more of these conceptual entities rather than actual ET. All these 'Standard' ET rates are meant to be a measure of meteorological control at a particular location with as little dependence on surface effects as possible. The vast range for estimation of ET techniques available makes it difficult to choose or select a batter one. Stewart (1979) has helped to classify a broad group of techniques by making explicit their inter-relationship through the meteorological input they contain. W.J.Shuttleworth (1979) extended the classification of Stewart (1979) in an attempt to show that it is possible to include most of the methods based on individual meteorological parameters. However, direct approach of measuring rate of evaporation through evaporation pans does not depend on meteorological information.

The classification shown in Table 1 (W.J. Shuttleworth, 1979), attempts to tabulate the various evaporation estimation techniques together with their data requirement, the type of evaporation they will provide, e.g. Actual ET, potential ET etc., and the assessment of the level of current usage growing or

TABLE 1

Classification of Various Evaporation Estimation Methods

Model class	Evapaoration estimated	Data Requirement	Current Usage
(a) Simulation i) Numerical (SPAM)	Actual	i) Detailed models of physilogical response	Small
ii) Analytic (Shuttleworth)		ii) Detailed information on canopy exchange processes iii) Detailed information on canopy structure iv) Short term measurements of meteorological data	increasing interest
(b) Single source i) Transpiration (Penman-Monteith)	Actual	i) Submodels of surface resistance ii) Coarse measurement of canopy structure	small increasing usage
ii) Interception (Rutter)		iii) Short term measurements of meteorological data	
(c) Intermediate (Tom-Oliver-Crash)	Potential ET	i) Daily meteorological data ii) Coarse measurements of canopy structure iii) Information on rainfall pattern	minimal increasing interest
(d) Energy Balance (e.g. Penman)	Reference crop ET Potential ET (short crops)	Daily meteorological data (T, RN, U, D)	large, stable
(e) Radiation (e.f. Priestley-Taylor) (Shuttleworth/Calder)	Reference crop ET Potential ET (short crop) Potential ET	Daily meteorological (T,RNO) Daily meteorological data (T,RN,P)	medium scale increasing
(f) Humidity (e.g. Dalton)	Reference crop ET Potential ET (short crop)	Daily meteorological data (T, u, e)	small decreasing
(g) Temperature (e.g. Blaney-Criddle)	Reference crop ET Potential ET (short crop)	Daily meteorological data (T)	medium scale stable
(h) Direct methods i) Evaporation pans ii) Atmometers	Potential Evaporation (estimation measurement usage only)	Daily water loss measurements	large, stable

NOTE : Here
P - Precipitation
T - Temperature
RN - Net Radiation
u - wind velocity
e - vapour pressure
D - vapour pressure deficit measured at screen height.

Source : SHUTTLEWORTH (1979)

declining. Today, the present trend of research is towards the development of techniques capable of estimating actual evapotranspiration directly. For this ,one requires greater data input. The success of a particular method depends in the widespread availability of data required for its use.

3.0 PREDICTION AND ESTIMATION OF EVAPOTRANSPIRATION

In designing the water use by crops evaporation and transpiration are combined into one term evapotranspiration (ET), as it is difficult to separate these two losses in cropped fields. The relative amounts of direct evaporation from land and water surfaces and transpiration depends usually on the amount of ground cover. For most of the crops covering the soil surface only, a very small amount of water is lost from the ground surface. Under field conditions incoming solar radiation supplies the energy for the evapotranspiration process. Wind is important in removing water vapour from the cropped areas and the prevailing temperature and humidity conditions result from the interaction of two processes

There are three ways for determination of ET (or consumptive use) namely : i) Direct measurements; ii) using evaporation measurements as indices; iii) Empirical climatic formulae.

Out of these three ways, direct measurements are performed by following techniques:

i) tanks & lysimeters
ii) field plots
iii) soil moisture depletion
iv) water balance
v) energy balance

As the evaporation pans provide a measurement of the integrated effect of radiation, wind, temperature and humidity on evaporation from a specific open water surface, evapotranspiration can be estimated by applying suitable pan coefficient to pan evaporation values. However, there are a number of factors which may produce significant differences in loss of water from evaporation pans & crops. However, in the absence of direct measurements of ET climatic methods which are empirical in form and depend upon the establishment of known correlations between ET and one or more measured climatic variables such as evaporation, temperature, radiation humidity, windspeed and percent of sunshine, are very useful.

3.1 Direct Measurements

3.1.1 Lysimeter measurements

This method is commonly used to determine evapotranspiration of individual crops and natural vegetation, by growing the plants in tanks, or lysimeters and then measuring the losses of water, necessary to maintain the growth satisfactorily. The tanks used are generally about 2 to 3 ft. in diameter and 6 feet deep, although large sizes upto 10 ft. in diameter and 10 ft. deep have been used. If the overall condition in the tank is maintained almost the same as the field conditions by using a large-size tank and keeping the surface of the soil in the tank at the same level as that in the surrounding field, the results may become relatively satisfactory.

3.1.2 Field plot method

ET can also be estimated from selected test plots under actual field conditions. Water input to the plot is determined from measurements of precipitation and irrigation water, while water losses include surface runoff and deep percolation in addition to consumptive use. Since deep percolation cannot be measured, irrigation must be applied in small quantities to minimise this factor. Furthermore, the water table must be at such a depth that the plants cannot obtain water from the capillary fringe. ET can be computed as the difference between total input and surface run off, adjusted for changes in soil moisture. Systematic measurements of soil moisture must be taken for some distance below the root zone.

This method provides reliable estimates of ET than the lysimeter method because observations are made under the natural conditions. However, the assumption that there is no deep percolation introduces an error which may be considered under some conditions.

3.1.3 Soil moisture depletion method

This method is usually employed to determine the consumptive use of irrigated field crops grown on fairly uniform soils when the depth to the ground water is such that it will not influence the soil moisture fluctuation within the root zone. The cosumptive use is calculated from the change in soil water content in successive samples from the following relationship

$$u = \sum_{i=1}^{n} \frac{M_{1i} - M_{2i}}{100} A_i D_i \qquad \text{.......(1)}$$

where u is the water use from the root zone for successive sampling periods or within one irrigation cycle in mm, n is the number of soil layers sampled in the root zone depth D, M_{1i} and M_{2i} are the moisture percentage at the time of the first second sampling in the i^{th} layer respectively, A_i is the apparent specific gravity of the i^{th} layer of the soil and D_i is the depth of i^{th} layer of soil in mm. The seasonal consumptive use is calculated by summing the consumptive use values of each sampling interval. A correction is made by adding PET value(s) for accelerated water loss for the interval(s) just after irrigation(s) and before soil moisture sampling.

3.1.4 Water table fluctuations

Where vegetation obtains its moisture from the capillary fringe or zone of saturation the height of the water table is influenced by the amount of water absorbed by the plants and its fluctuations can be used as a basis for computing consumptive use. On the basis of studies of the diurnal fluctuations of shallow water tables. White (1932) developed the formula:

$$Uc = \Upsilon_s (24a + b) \qquad \ldots . \quad (2)$$

where Uc is the consumptive use in inches per day, Υ_s is the specific yield of the soil, a, is the rate of rise of the water table in inches per hour from midnight to 4 A.M., and b, is the net change in water table elevation during the day in inches. The method is applicable only in areas where the water table is near the surface .

3.1.5 Energy balance method

The energy budget approach, like the water budget, employs a continuity equation required to maintain a balance. Although the continuity equation in this approach is one of energy. The region over which incoming energy is partitioned extends over a finite height range between the soil surface and the ground level or above the vegetation at which radiation is measured. Within this region temperature changes occur in both the atmosphere and the vegetation, and changes occur in the absolute humidity of the air. Such changes represent a loss or gain in the energy available for partition into latent and sensible heat for any particular period, the magnitude being proportional to the rate of change of temperature and humidity with time. Energy lost or gained in this way is called storage which is assumed to have been used for ET. 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 advecticve energy can be neglected for short durations. This method is generally more accurate when soil moisture is not limiting evapotranspiration. In mathematical models of the vegetation/atmosphere,interaction involving energy partition at several different levels in the canopy, it is necessary to consider energy available at each height. Tanner (1960), Fritschen (1965), Sinclair et al (1971), Shuttleworth (1976) and Goyal & Sikka (1986) have discussed this method. thoroughly with the instrumentation requirements for measurement of various components of energy balance.

3.2 Estimating ET from Pan Evaporation Data

It has been observed that a close relationship exists between evapotranspiration and the rate of evaporation from a properly located evaporation pan. Gangopadhyaya et.al. (1966) list 27 examples and suggest that their tabulation was undoubtedly far from complete. The point of discussion is not the validity of the measurement produced by evaporation pan but it is the diversity of its (evaporation pan) application which (diversity) distracts attention away from the primary issue, whether an evaporation pan does or does not provide a number which is (or can be easily related to) potential evaporation, into the side issue of intercalibration of pan types. It is clear that the energy exchange of all pans will differ from that of a reference crop. This difference first of all lies in the energy storage. The energy stored in the evaporation pans (particularly of deep pans) is greater than that of vegetation so that the surface temperature of the water tends to be lower during the days, when most evaporation occurs, and higher at night. If the tanks on pan is elevated above the surface, additional radiation exchange at the sides , and sensible heat exchange at the sides and surface, can also give rise to differences. A lot of work already has been done to convert the evaporation pan data into actual evapotranspiration through empirical relations and to assess the relative merits of pan types with respect to their energy exchange. The standard US Whether Bureau Class A open pan evaporimeter or the sunken screen open pan evaporimeter (Sharma and Dastane, 1968) have now been selected as a world wide standard for use in all new applications. It is hoped that ultimately, simple, reliable instrumentation, capable of measuring actual evapotranspiration, will be developed, and become cheap enough to remove the need for this usage. Meanwhile, evaporation pans will certainly continue to be used as a low technology replacement for the present alternative of an 'estimation measurement' based on (say) the Penman equation. It is fortunate that there is often a good correlation between the 'standard rates ' of evaporation and measured evaporation from pans, and that a great deal of empirical data are available describing this correlation, at least for the more common types of pan. Doorenbos and Pruitt (1977) described how to estimate actual ET from pan evaporation data of two of the most common types, namely the 'Class A' pan, and the 'Colorado Sunken Pan'. The high level of empiricism implicit in their description should be recognised as a real and permanent influence on the reliability of pan estimation techniques.

3.3 Empirical Climatic Formulae

Owing to the difficulty in obtaining accurate direct measurement of pan evaporation under field conditions, ET is often predicted on the basis of climatological data. The approaches followed are to relate the magnitude and variation of ET to one or more climatic factors (temperature, day, length, humidity, wind, sunshine etc.). The lack of basic data required in the field methods and the difficulties in measurement have accounted for great efforts made to develop ET equation that can relate ET with some readily available climatic data. Often such formulae have to be used under climatic and agronomic conditions different from those for which they were originally developed. It is therefore necessary to test the adaptability of the formulae before using them under a new set of conditions. The most commonly used formulae in estimating ET have been discussed in forthcoming paragraphs

3.3.1 Thornthwaite's method

Thornthwaite carried out many experiments in the USA using lysimeters and extensively studied the correlation between temperature and evapotranspiration. Based on studies, he proposed a method for estimation of potential evapotranspiration from short, close-set vegetation with an adequate water supply.

If t_n = average monthly temperature of the consecutive months of the year in ^{o}C (where n = 1, 2, 3,...........12) and j = monthly heat index; then

$$J = \frac{t_n^{1.514}}{5} \qquad \text{--- (1)}$$

and the yearly 'heat index', J, is given by

$$J = \sum_{1}^{12} j \qquad \text{---(2)}$$

The potential evapotranspiration, PE_x, for any month with average temperature t(^{o}c) is then given by

$$PE_x = 16\left(\frac{10t}{J}\right)^{a} \text{ mm per month} \qquad \text{--- (3)}$$

$$\text{where } a=(675\times10^{-9})J^{3}-(771\times10^{-7})J^{2}+(179\times10^{-4})J+0.492 \qquad \text{...(4)}$$

PE_x is a theoretical standard monthly value based on 30 days and 12 hours of sun shine per day. The actual PE for the particular month with average temperature t (^{o}C) is given by

$$PE = PE_x \frac{DT}{360} \text{ mm} \qquad \text{----(5)}$$

where D is the number of days in the month and T is the average number of hours between sunrise and sunset in the month. The above equation can also be simplified as follows:

$$j = 0.09t_n^{3/2} \qquad \ldots(6)$$

$$a = 0.016J + 0.5 \qquad \ldots(7)$$

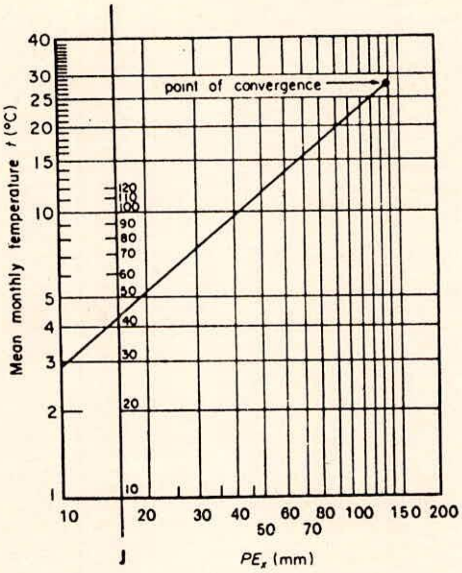
This method of estimating potential evapotranspiration is empirical and complicated and requires the use of a nomogram for its solution. Thornthwaite developed such nomograph and is shown in fig.1. The first step is to obtain the heat index J from Fig 1. Obtain the unadjusted value of potential evapotranspiration by drawing a straight line from the locations J value through the point of convergence at $t = 26.5^{o}$ (If t is greater than 26.5^{o}C,use the table alongside Fig.1. PE_x for the month can then be read off, corresponding to its given mean temperature. Twelve values are obtained for each of the 12 months. These unadjusted values can then be adjusted for day and month length by equation (5) and totaled to give annual potential evapotranspiration.

It has been found that the method gives reasonably good results whatever the vegetation cover, though different types of vegetation will affect a particular locality's true value. The formulae is based on temperature, which does not necessarily correspond to incoming solar radiation immediately, because of 'heat inertia' of land and water. Transpiration, however, responds directly to solar radiation.

3.3.2 Jensen Haise method

Jensen and Haise (1963, 1966) have presented an energy balance approach for estimating evapotranspiration that is simpler in application than Penman's equation. The Jensen-Haise

Evaporation and Transpiration



t (°C)	PE_x
26·5	135·0
27·0	139·5
27·5	143·7
28·0	147·8
28·5	151·7
29·0	155·4
29·5	158·9
30·0	162·1
30·5	165·2
31·0	168·0
31·5	170·7
32·0	173·1
32·5	175·3
33·0	177·2
33·5	179·0
34·0	180·5
34·5	181·8
35·0	182·9
35·5	183·7
36·0	184·3
36·5	184·7
37·0	184·9
37·5	185·0
38·0	185·0

Source : C.W. Thornthwaite (1946)

Fig. 1 : Nomogram and Table for finding Potential Evapotranspiration PE_x

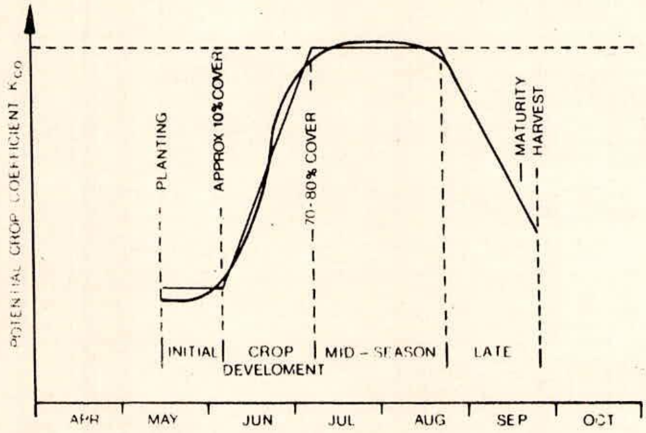


Fig. 2 : Typical variation in Potential Crop Coefficient K_{co}

method for potential ET for well-watered alfalfa (30 to 50 cm height) developed in the western U.S. is

$$ET = C_t\ (t_c - t_x)\ R_x = 0.025\ (t_c + 3) Rs \quad \text{--(8)}$$

in which

ET = Potential evapotranspiration (in mm day)

C_t = Temperature Coefficient

t_c = Mean air temperature ^{o}C.

t_x = Intercept of ET/Rs vs t regression line with the temperature axis

R =Solar radiation as equivalent depth of evaporation in mm/day

The coefficients C_t and t_x can be obtained from accurate ET and climatic data for a local area. Actual ET for a crop is obtained by multiplying the potential ET by a crop coefficient. This coefficient varies with the stage of growth of the plant.

3.3.3 Blaney-Criddle method

Blaney and Criddle (1950) observed that the amount of water consumed by crops (actual ET) during their growing seasons was closely correlated with mean monthly temperatures and daylight hours. The relationship developed by Blaney and Criddle in FPS Units may be stated as follows:

$$U = KF = \sum Kf = \sum u = \sum \frac{K t \cdot p}{100} \quad \text{-----(9)}$$

where U = seasonal consumptive use of water by the crop for a given period, inches

u = Monthly consumptive, inches

k = Empirical seasonal consumptive use coefficient for the growing season

F = Sum of monthly consumptive use factors (f) for the growing season

k = Empirical consumptive use crop coefficient for the month, u/f

f = $(t.p)/100$

t = Mean monthly temperature, ^{o}F

p = Monthly daylight hours expressed as percent of daylight hours of the year.

The Blaney-Criddle formulae has generally given sufficiently accurate estimates of seasonal consumptive use owing to the inclusion of locally developed crop coefficient factor (k). Basically, however it assumes that the consumptive use of water is dependent only on temperature and day length which is not fully true. Crop water requirements have been found to vary widely between climates having similar air temperature but different humidity and wind conditions. The consumptive use crop coefficient K will, therefore, vary not only with crop but also with climatic conditions.

Limitations of Blaney-Criddle Method:

The method has been evaluated by many investigators, and it has been generally found that whereas it is simple to use, and widely applicable, it tends to be less reliable in the following areas:

i) Equatorial regions where temperatures and day lengths fluctuate over a very small range even though over climatological factors may vary.

ii) Small islands where the air temperature is greatly influenced by the sea temperature, as is the humidity.

iii) High altitudes where cold nights bring down the mean temperature and daytime radiation levels are very high.

iv) Climates with a great fluctuation in sunshine hours during spring and autumn, and monsoon seasons.

3.3.4 Penman's Equation:

Penman's equation is based on sound theoretical reasoning and is obtained by a combination of the energy-balance and mass transfer approach. Penman's equation, incorporating some of the modifications suggested by other investigators is

$$PET = \frac{A.H_n + E_a \gamma}{A + \gamma} \qquad \ldots(10)$$

where: PET = Daily potential evapotranspiration in mm/day

A = Slope of the saturation vapour pressure vs temperature curve at the mean air temperature, in mm of mercury per °C.

H_n = Net radiation in mm of evaporable water per day.

E_a = Parameter including wind velocity and saturation deficit

γ = Psychrometric constant = 0.49 mm of mercury / °C.

H_n = Net radiation and is calculated by the following equation

$$= H_a (1 - \alpha) \left(a + b\frac{n}{N}\right) - \sigma T_a^4 \left(0.56 - 0.092\sqrt{e_a}\right) . \left(0.10 + 0.90\frac{n}{N}\right) \qquad \text{-----(11)}$$

H_a = incident solar radiation outside the atmosphere on a horizontal surface expressed in mm of evaporable water per day (it is a function of the latitude and period of the year)

α = reflection coefficient (albedo). The value of α for close ground crops is generally varies from 0.15-0.25.

a = a constant depending upon the latitude ϕ and is given by $a = 0.29 \cos\phi$

b = a constant with an average value of 0.52

n = actual duration of bright sunshine, hrs.

N = maximum possible hours of bright sunshine

σ = Stefan-Boltzman constant = 2.01×10^{-9} mm/day

T_a = mean air temperature in ^{o}K

e_a = actual mean vapour pressure in the air in mm of mercury.

The parameter E_a is estimated as

$$E_a = 0.35 \left(1 + \frac{u_2}{160}\right) (e_w - e_a) \qquad \text{...(12)}$$

in which

u_2 = mean wind speed at 2m above the ground in km/day

e_w = saturation vapour pressured at mean air temperature in mm of mercury.

e_a = actual vapour pressure

For the computation of PET data on n, e_a, u_2 mean air temperature and nature of surface (value of α) are needed. These can be obtained from actual observations or through available meteorological data of the region.

3.3.5 Turc method

The method developed by Turc in 1960 is also based primarily upon radiation and temperature and has the following formula:

$$PET^* = 0.40\,(59\,R_s + 50)\,\frac{t}{t+15}\cdot C \qquad \ldots(13)$$

where

PET^* = Unadjusted potential evapotranspiration, mm/month

R_s = Mean daily solar radiation reaching the ground in the month under consideration, mm/day

t = Mean monthly temperature, °C.

C = Correction factor depending upon average relative humidity RH. For RH less than 50%

$$= 1 + \frac{50-RH}{70}$$

For RH equal or greater than 50%; C=1

The following relationship is used to calculate PET (adjusted):

$$PET(Adjusted) = PET^*\,\frac{n}{12}\cdot\frac{1}{DM} \qquad \ldots(14)$$

where

N = average daylight hours in the month, and

DM = number of days in the month. To obtain the actual radiation reaching surface R_s, Truc proposed the following formula:

$$R_s = R_a \left(0.29 \text{ Cos latitude} + 0.54 \frac{n}{N}\right) \quad \ldots(15)$$

where

R_a = the extraterrestrial radiation, n = the average daily actual sunshine hours, and

N = the meanmaximum number of daylight hours in the period.

3.3.6 Lowry-Johnson method:

Lowry-Johnson (1942) developed a procedure for estimating water requirement for irrigation projects which has been used by the United States Bureau of Reclamation. This method applies to a valley not to an individual farm, and has been widely used with good results by the Bureau in the arid western portions of the USA.

A linear relationship is assumed between 'effective heat' and consumptive use. Effective heat is defined as the accumulation, in day-degrees, of maximum daily growing season temperatures above 32 °F.

The approximate relationship

$$CU = 0.8 + 0.156\ I_f \quad \ldots\ldots. (16)$$

is used in estimating the valley consumptive use by the lowry-

Johnson method, where CU = consumptive use in acre-feet per acre, and I_f effective heat in thousands of days-degrees.

4.0 DETERMINATION OF 'ACTUAL FROM POTENTIAL EVAPOTRANSPIRATION

Actual evapotranspiration is required for most of the practical applications. Keeping in view the limitations of the methods & techniques discussed in section 2.8 for determination of actual ET one can determine actual ET from standard evaporation rates (Potential or Reference crop evapotranspiration) by multiplying an additional factor, Kc (crop coefficient). The values of Kc relates to evapotranspiration of a disease free crop grown in large fields under optimum soil water & fertility conditions and achieving full production potential under the given growing environment (Doorenbos and Pruitt, 1977). Crop coefficients are empirical ratios of crop actual ET to some standard (or reference) ET and are generally derived from experimental data.

$$ET_{crop} = K_c . ET_o \qquad ...(17)$$

where, ET_{crop} = Actual evapotranspiration

ET_o = Potential or reference evapotranspiration

Procedures for selection of appropriate Kc values are given, which take into account the crop characteristics, time of planting or sowing, and stages of crop development and general climatic conditions.

Factors affecting the value of the crop coefficient (Kc) are mainly the crop characteristics, crop planting or sowing data, rate of crop development length of growing season and climatic conditions. Particularly following sowing and during the early growth stage, the frequency of rain or irrigation is important. Approximate ranges of seasonal ET crop for different crops are given in table - 2 (Doorenbos and Pruitt, 1977). The

Table 2 - Approximate Range of Seasonal Crop Evapotranspiration

S.No.	Crop	Seasonal ET_{crop} (mm)
1.	Alfalfa	600-1500
2.	Avocado	650-1000
3.	Bananas	700-1700
4.	Beans	250-500
5.	Cocoa	800-1200
6.	Coffee	800-1200
7.	Cotton	550-950
8.	Dates	900-1300
9.	Deciduous trees	700-1050
10.	Flax	450-900
11.	Grains (small)	300-450
12.	Grape fruit	650-1000
13.	Maize	400-750
14.	Oil seeds	300-600
15.	Onions	350-600
16.	Orange	600-950
17.	Potatoes	350-625
18.	Rice	500-950
19.	Sisal	550-800
20.	Sorghum	300-650
21.	Soybeans	450-825
22.	Sugarbeets	450-850
23.	Sugarcane	1000-1500
24.	Sweet potatoes	400-675
25.	Tobacco	300-500
26.	Tomatoes	300-600
27.	Vegetables	250-500
28.	Vineyards	450-900
29.	Walnuts	700-1000

[Source: Doorenbos and Pruitt (1977)]

determination of a reference evapotranspiration or ET for a single reference crop, like alfalfa, and the use of empirical crop coefficients provides a conservative means of estimating ET or other crops at progressive stages of growth. The distribution of the crop coefficients for a particular crop as a function of time constitutes a crop curve.

The crop coefficient (Kc), from the study of equation (17), can be seen to be a measure of the term

$$K = \frac{\Delta + \gamma}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \qquad ---(18)$$

where r_a and r_s are the 'effective' aerodynamic resistance and surface resistance of the crop. The term K, will have its dependence on meteorological parameters (as temperature in Δ, windspeed in r_a and rainfall in r_s), vegetation structure through r_a and its stomatal behaviour through r_s. The stomatal control itself might also be related to current or past meteorological parameters. The use of crop coefficient (Kc) for determination of actual ET should be made with proper realization of the risks involved. Although the basis and definition of the crop coefficient is essentially scientific, its complexity is such that its application is an art. In practice a great many applications are concerned with the implementation of irrigation for agricultural crops. The objective is usually to supply water which is adequate (neither less to limit growth nor excessive) so that the soil surface is not wet. Such conditions are essentially those used to specify potential evapotranspiration. In this case an entity which can be called 'potential crop coefficient', 'Kco' might be relevant. It is observed that Kco is less variable than Kc in moving from one location to the next, since r_s is likely to be a purer measure of stomatal resistance, which in turn is probably less variable since the soil moisture deficit remains small. So many research workers, have measured the potential crop coefficient, Kco, as a function of time for different crops. The seasonal variation in the value of Kco for agricultural crops is illustrated schematically in fig.2. Crop coefficients (Kc) for given stages of crop development and different climatic conditions one presented in table - 3. The values of Kc for Alfalfa, Clover, Grass-Legumes, Pasture, Bananas, Citrus, Deciduous fruit and Nut trees, Grapes, Rice, Sugarcane and Aquatic weeds are shown in tables 4 to 11. (Doorenbos & Pruitt, 1977). From tables 3 to 11 the values of Kc for different types of crops may be used to provide estimates of ET crop, using equation (17), for different stages in the development of a great many irrigated annual crops (Doorenbos & Pruitt, 1977). The variation in Kco is not prominent is case of irrigated perennial and fruit crops. In case of non-irrigated crops the water status of the soil can became important through surface resistance & Kc becomes the relevant crop coefficient in such situations. In areas where rainfall occurs fairly frequently throughout most of the year, resulting in moist climate, an average time dependent empirical description of Kc is probably the best that can be attempted. In this situation Kc remains close to unity for most of the short crops but tall crops (forests) remain the primary exceptions in such climates because of the real possibility of significant advective enhancement in the evaporation rate (Shutteworth and Calder, 1979). In climates with large seasonal variations in rainfall, evaporation rates in the rainy season will again

Table 3 : Crop Coefficient of Various Crops at Different Growth Stages

CROP	Crop Development Stages					Total growing period
	Initial	Crop Development.	Mid Season	Late Season	At harvest	
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
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

Table 4 - K_c Values for Alfalfa, Clover, Grass-legumes and Pasture

		Alfalfa	Grass for hay	Clover, Grass-legumes	Pasture
Humid	K_c mean	0.85	0.8	1.0	0.95
Light to moderate wind	K_c peak	1.05	1.05	1.05	1.05
	K_c low 1/	0.5	0.6	0.55	0.55
Dry	K_c mean	0.95	0.9	1.05	1.0
Light to moderate wind	K_c peak	1.15	1.1	1.15	1.1
	K_c low 1/	0.4	0.55	0.55	0.5
Strong wind	K_c mean	1.05	1.0	1.1	1.05
	K_c peak	1.25	1.15	1.2	1.15
	K_c low 1/	0.3	0.5	0.55	0.5

K_c(mean) represents mean value between cutting, K_c(low) just after cutting, K_c(peak) just before harvesting.

1/ Under dry soil conditions; under wet conditions increase values by 30%.

Table 5 - K_c Values for Bananas

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Mediterranean climate												
First-year crop, based on March planting with crop height 3.5m by August:												
Humid, light to mod. wind	-	-	.65	.6	.55	.6	.7	.85	.95	1.0	1.0	1.0
Humid, strong wind	-	-	.65	.6	.55	.6	.75	.9	1.0	1.05	1.05	1.05
Dry, light to mod. wind	-	-	.5	.45	.5	.6	.75	.95	1.1	1.15	1.1	1.1
Dry, strong wind	-	-	.5	.45	.5	.65	.8	1.0	1.15	1.2	1.15	1.15
Second season with removal of original plants in Feb. and 80% ground cover by August:												
Humid, light to mod. wind	1.0	.8	.75	.7	.7	.75	.9	1.05	1.05	1.05	1.0	1.0
Humid, strong wind	1.05	.8	.75	.7	.7	.8	.95	1.1	1.1	1.1	1.05	1.05
Dry, light to mod. wind	1.1	.7	.75	.7	.75	.85	1.05	1.2	1.2	1.2	1.15	1.15
Dry, strong wind	1.15	.7	.75	.7	.75	.9	1.1	1.25	1.25	1.25	1.2	1.2

Tropical climates

months following planting:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	.4	.4	.45	.5	.6	.7	.85	1.0	1.1	1.1	.9	.8	.8	.95	1.05
	suckering						shooting			harvesting					

Table 6 - K_c Values for Citrus (Grown in Predominantly Dry Areas with Light to Moderate Wind)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Large mature trees providing ≃ 70% tree ground cover-Clean cultivated	.75	.75	.7	.7	.7	.65	.65	.65	.65	.7	.7	.7
No weed control	.9	.9	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85
Trees providing ≃ 50% tree ground cover-Clean cultivated	.65	.65	.6	.6	.6	.55	.55	.55	.55	.55	.6	.6
No weed control	.9	.9	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85
Trees providing ≃ 20% tree ground cover-Clean cultivated	.55	.55	.5	.5	.5	.45	.45	.45	.45	.45	.5	.5
No weed control	1.0	1.0	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95

Table 7 - K_c Values for Full Grown Deciduous Fruit and Nut Trees

	With ground-cover crop 1/									Without ground cover crop 2/ (clean cultivated, weed free)								
	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov
COLD WINTER WITH KILLING FROST : GROUND COVER STARTING IN APRIL																		
Apples, cherries																		
humid, light to mod. wind	-	.5	.75	1.0	1.1	1.1	1.1	.85	-	-	.45	.55	.75	.85	.85	.8	.6	-
humid, strong wind	-	.5	.75	1.1	1.2	1.2	1.15	.9	-	-	.45	.55	.8	.9	.9	.85	.65	-
dry, light to mod. wind	-	.45	.85	1.15	1.25	1.25	1.2	.95	-	-	.4	.6	.85	1.0	1.0	.95	.7	-
dry, strong wind	-	.45	.85	1.2	1.35	1.35	1.25	1.0	-	-	.4	.65	.9	1.05	1.05	1.0	.75	-
Peaches, apricots, pears, plums																		
humid, light to mod. wind	-	.5	.7	.9	1.0	1.0	.95	.75	-	-	.45	.5	.65	.75	.75	.7	.55	-
humid, strong wind	-	.5	.7	1.0	1.05	1.1	1.0	.8	-	-	.45	.55	.7	.8	.8	.75	.6	-
dry, light to mod. wind	-	.45	.8	1.05	1.15	1.15	1.1	.85	-	-	.4	.55	.75	.9	.9	.7	.65	-
dry, strong wind	-	.45	.8	1.1	1.2	1.2	1.15	.9	-	-	.4	.6	.8	.95	.95	.9	.65	-
COLD WINTER WITH LIGHT FROST : NO DORMANCY IN GRASS COVER CROPS																		
Apples, cherries, walnuts 3/																		
humid, light to mod. wind	.8	.9	1.0	1.1	1.1	1.1	1.05	.85	.8	.6	.7	.8	.85	.85	.8	.8	.75	.65
humid, strong wind	.8	.95	1.1	1.15	1.2	1.2	1.15	.9	.8	.6	.75	.85	.9	.9	.85	.8	.8	.7
dry, light to mod. wind	.85	1.0	1.15	1.25	1.25	1.25	1.2	.95	.85	.5	.75	.95	1.0	1.0	.95	.9	.85	.7
dry, strong wind	.85	1.05	1.2	1.35	1.35	1.35	1.25	1.0	.85	.5	.8	1.0	1.05	1.05	1.0	.95	.9	.75
Peaches, apricots, pears, plums, almonds, pecans																		
humid, light to mod. wind	.8	.85	.9	1.0	1.0	1.0	.95	.8	.8	.55	7	.75	.8	.8	.7	.7	.65	.55
humid, strong wind	.8	.9	.95	1.0	1.1	1.1	1.0	.85	.8	.55	.7	.75	.8	.8	.8	.75	.7	.6
dry, light to mod. wind	.85	.95	1.05	1.15	1.15	1.15	1.1	.9	.85	.5	.7	.85	.9	.9	.9	.8	.75	.65
dry, strong wind	.85	1.0	1.1	1.2	1.2	1.2	1.15	.95	.85	.5	.75	.9	.95	.95	.95	.85	.8	.7

1/ K_c values need to be increased if frequent rain occurs. For young orchards with tree ground cover of 20 and 50%, reduce mid-season K_c values by 10 to 15% and 5 to 10% respectively.

2/ K_c values assume infrequent wetting by irrigation or rain (every 2 to 4 weeks). In the case of frequent irrigation for May to October use K_c values of table "with ground cover crop". For young orchards with tree ground cover of 20 and 50% reduce mid-season K_c values by 10 to 15%.

3/ For walnuts March-May possibly 10 to 20% lower values due to slower leaf growth.

Table 8 - K_c Values for Grapes (Clean Cultivated, Infrequent Irrigation, Soil Surface Dry Most of the Time)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Mature grapes grown in areas with killing frost; initial leaves early May, harvest mid-September; ground cover 40-50% at mid-season												
humid, light to mod. wind	-	-	-	-	.5	.65	.75	.8	.75	.65	-	-
humid, strong wind	-	-	-	-	.5	.7	.8	.85	.8	.7	-	-
dry, light to mod. wind	-	-	-	-	.45	.7	.85	.9	.85	.7	-	-
dry, strong wind	-	-	-	-	.5	.75	.9	.95	.9	.75	-	-
Mature grapes in areas of only light frosts; initial leaves early April, harvest late August to early September; ground cover 30-35% at mid-season												
humid, light to mod. wind	-	-	-	.5	.55	.6	.6	.6	.6	.5	.4	-
humid, strong wind	-	-	-	.5	.55	.65	.65	.65	.65	.55	.4	-
dry, light to mod. wind	-	-	-	.45	.6	.7	.7	.7	.7	.6	.35	-
dry, strong wind	-	-	-	.45	.65	.75	.75	.75	.75	.65	.35	-
Mature grapes grown in hot dry areas; initial leaves late February-early March, harvest late half of July; ground cover 30-35% at mid-season												
dry, light to mod. wind	-	-	.25	.45	.6	.7	.7	.65	.55	.45	.35	-
dry, strong wind	-	-	.25	.45	.65	.75	.75	.7	.55	.45	.35	-

Table 7 - K_c Values for Rice

	Planting	Harvest	First & Second month	Mid-season	Last 4 weeks
Humid Asia					
wet season (monsoon)	June-July	Nov-Dec			
light to mod. wind			1.1	1.05	.95
strong wind			1.15	1.1	1.0
dry season 1/	Dec-Jan	mid-May			
light to mod. wind			1.1	1.25	1.0
strong wind			1.15	1.35	1.05
North Australia					
wet season	Dec-Jan	Apr-May			
light to mod. wind			1.1	1.05	.95
strong wind			1.15	1.1	1.0
South Australia					
dry summer	Oct	March			
light to mod. wind			1.1	1.25	1.0
strong wind			1.15	1.35	1.05
Humid S.America					
wet season	Nov-Dec	Apr-May			
light to mod. wind			1.1	1.05	.95
strong wind			1.15	1.1	1.0
Europe (Spain, S. France and Italy)					
dry season	May-June	Sept-Oct			
light to mod. wind			1.1	1.2	.95
strong wind			1.15	1.3	1.0
U.S.A.					
wet summer (South)	May	Sept-Oct			
light to mod. wind			1.1	1.1	.95
strong wind			1.15	1.15	1.0
dry summer (Calif.)	early May	early Oct			
light to mod. wind			1.1	1.25	1.0
strong wind			1.15	1.35	1.05

1/ Only when RHmin > 70%, K_c values for wet season are to be used.

Table 10 - K_c Values for Sugarcane

Crop age		Growth stages	RHmin > 70%		RHmin < 20%	
12 month	24 month		light to mod.wind	strong wind	light to mod.wind	strong wind
0-1	0-2.5	planting to 0.25 full canopy	.55	.6	.4	.45
1-2	2.5-3.5	0.25-0.5 full canopy	.8	.85	.75	.8
2-2.5	3.5-4.5	0.5-0.75 full canopy	.9	.95	.95	1.0
2.5-4	4.5-6	0.75 to full canopy	1.0	1.1	1.1	1.2
4-10	6-17	peak use	1.05	1.15	1.25	1.3
10-11	17-22	early senescence	.8	.85	.95	1.05
11-12	22-24	ripening	.6	.65	.7	.75

Table 11 - K_c Values for Aquatic Weeds

Type of vegetation	Humid		Dry	
	light to mod. wind	strong wind	light to mod. wind	strong wind
Submerged (crassipes)	1.1	1.15	1.15	1.2
Floating (duckweed)	1.05	1.05	1.05	1.05
Flat leaf (water lilies)	1.05	1.1	1.05	1.1
Protruding (water hyacinth)	1.1	1.15	1.15	1.2
Reed swamp (papyrus, cattails)				
standing water	.85	.85	.9	.95
moist soil	.65	.65	.75	.8

probably be close to potential or reference crop evapotranspiration (ETo) for short crops, but might exceed ETo for tall crops, depending upon the details of interception phenomena. In the dry season significant fall in Kc will usually be observed as the surface resistance responds to the increasing soil moisture deficit. Studies have been made of the variation in Kc in response to decreasing soil water content. Upto wilting point Kc for the soil (or crop) remains fairly constant (i.e. nearly unity) but begins to decrease in response to decreasing soil water content. In conditions of prolonged drought the crop (if present) begins to die and the evaporation rate is no longer controlled by meteorological conditions, but by soil characteristics, especially hydraulic conductivity.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Knowledge of water requirements (or ET) of crops has great importance in several areas of agronomy, including irrigation and water balance studies. Evapotranspiration can be determined from direct measurements, empirical climatic formulae, or by using evaporation measurements as indices. Direct measurements are performed by many techniques including tanks and lysimeters, soil water depletion, field plots, energy balance, water balance etc. The present study is an attempt towards understanding the estimation of potential evapotranspiration and determination of actual evapotranspiration (i) by direct measurements (ii) by multiplying crop coefficient to potential ET.

In previous chapters review of all available methods have been made for estimating evapotranspiration from agricultural lands and present status of these methods, limitations, adoptability and usefulness in terms of data availability.

Recommendations for further research under Indian conditions are as follows:-

- The adoptability of empirical formulae must be tested before using them under a new set of conditions.
- Efforts should be made for the development of techniques capable of estimating actual evapotranspiration directly.
- Further improvements needed include development of crop growth models to permit partitioning of soil evaporation & plant transpiration and to provide a basis for directly relating the crop coefficient to crop development.
- The actual crop water requirements should be computed from the consumptive use coefficient K for which observed values for different crops are available.

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