Performance Evaluation of Different Methods for Estimation of Evapotranspiration in Pakistan's Climate

Ghulam Rasul and Arif Mahmood*

Abstract

Pakistan experiences a variety of climates ranging from a small humid patch in the north to extremely arid southern plains. Evapotranspiration is not a directly measurable element among agrometeorological parameters influencing crop growth and development. Many empirical and semi-empirical methods for estimation of crop evapotranspiration exist and are being used by individual scientists and researchers in Pakistan as per their claimed validations in other parts of the world. In this paper a comparison is made in reference with pan evaporation to test the performance of four widely used methods in the world under various climatic conditions of Pakistan. Although lysimeteric data are believed to be the best judge to assess the performance of any method yet the date are not available in continuous series at all location. The second best of choice is made on evaporation well documented in PMD archives from four Regional Agro-Metrological Centers representing four major agro-climatic zones of Pakistan. FAO Penman-Monteith equation worked well in all the major climatic zones of Pakistan and may be adapted to draw closer and more realistic estimates of evapotranspiration for crop water requirements, various operational agricultural practices and water balance studies.

Introduction

Evapotranspiration process is the combination of two separate processes commonly known as Evaporation and Transpiration. In this process water is lost on the one hand from the top soil or water surface by evaporation and on the other hand from the crop plant tissues through transpiration by stomatal dynamics.

Evaporation and transpiration occur simultaneously therefore there is no easy way of distinguishing between the two processes. Instead of water quantity in the topsoil, the evaporation from a cropped soil is mainly determined by the fraction of the solar radiation reaching the soil surface. When the crop is small, water is predominately lost by evaporation from the soil surface, but once the crop is well developed and completely covers the soil, transpiration becomes the main process (Allen et. al., 1996).

Estimates of evapotranspiration provide an outlook of soil water balance in association with the amount of precipitation. Such estimates are of immense importance for calculation of water demand of the field crops and irrigation scheduling (Rasul, 1992). It also determines the nature of agro-climate a region has, agro-climatic potential of that region and suitability of crops or varieties, which can be grown successfully with the best economic returns (Rasul et al., 1993).

Evapotranspiration is not easy to measure. Specific devices and accurate measurements of various physical parameters or the soil water balance in lysimeters are required to determine evapotranspiration. The methods are often expensive, complex, demanding in terms of accuracy of measurement and can only be fully exploited by well-trained research personnel. Many scientists developed mathematical equations to estimate

* Pakistan Meteorological Department

evapotranspiration in different parts of the world but no one can be universally recommended and adopted. Sometimes error upto the unacceptable limits appear when applied in climates different than where they were originally developed.

Pakistan is inherited by a variety of climates ranging from extremely arid to humid having similarities with desert to temperate climates. The local scientists generally apply the well-known methods believed to be giving good results in other parts of the world despite the fact that their accuracy is highly sensitive to climate. An effort has been made in this paper to compare the accuracy of various widely used methods under Pakistan's climatic conditions and to identify the best suited method giving the more accurate approximation of this most important agro-climatic and agro-hydrological parameter.

Materials and Methods

The relationships developed in different parts of the world were often subject to rigorous local calibrations and proved to have limited validity. Testing the accuracy of the methods under a new set of conditions is laborious, time-consuming and costly. It has been stated earlier that Iysimeters data is the reliable tool to test the accuracy of a method but it should cover a period of years to incorporate possible climatic fluctuations on one hand and its installation, maintenance and accuracy of measurements are also another highly demanding aspect. All that was not economically and practically viable. Hence the evaporation from a standard pan (WMO class-A) exposed to the natural environment has been taken as reference to carry out this comparison. These pans are installed in the same enclosure where other meteorological parameters are recorded for estimation of evapotranspiration with the help of methods under comparison.

Data

The data on meteorological parameters like maximum and minimum temperatures (ºC), relative humidity (%), wind speed (m/s) and sunshine duration on daily basis for the period of last seventeen years (1989-2006) were obtained from the records maintained by Meteorological Services of Pakistan. The evapotranspiration was calculated by each method for all the selected stations on daily as well as monthly basis. Evaporation from Class-A pan recorded at all the four stations was also considered for comparison. Evaporation from Class-A was taken as reference because same instrument was used at all the four places and uniform method for measurement was adopted (WMO1983). Evapotranspiration calculated by four methods under review was then compared with daily and monthly class-A pan evaporation values. The normal values based on 30 years average (except Tandojam for which 15 years average is taken) of rainfall (mm), relative humidity (%) as well as maximum and minimum temperatures (ºC) for selected climatic zones are presented in the table. Except Rawalpindi, all the other three locations are deficient of rainfall. On the other hand, the temperatures are extremely high in summer which keeps the water balance mostly in negative.

Selected Climatic Zones

Four major agro-climatic zones having significant contribution to agricultural production and representing large areas with more or less homogeneous characteristics were selected. The climatic features of these agro-climatic zones are briefly stated in the table. The selection criteria of representative stations for major agro-climatic zones are stated as under.

Potohar Plateau of North Punjab

Rawalpindi is selected as the representative station located at the northern edge of the Potohar plateau. It encompasses the vast rainfed plains down to Jhelum, Chakwal and Attock. Wheat, groundnut and fodder are the major cultivars. These plains lie under Sub-Humid agro-climate, which varies from Dry Sub-Humid in the south to Wet Sub-Humid in the north (Chaudhry, et al, 2004). The rainfall pattern is bi-modal and summer rains attain their peak in August while winter rains indicate the maxima during March. Temperatures occasionally drop below freezing in January and stay above 40°c during summer months before the onset of Monsoon during first week of July. Pre-monsoon (April-May) and post-monsoon (October-November) are rainfall deficient periods. Former coincides with extremely dry and hot period when evapotranspiration reaches it maximum.

Irrigated Plains of Punjab

Faisalabad represents irrigated plains of central and southern Punjab. This zone possesses the Dry Semi-Arid agro-climatic characteristics but well managed canal irrigation system has placed it among the highly crop productive zones. Mainly summer monsoon produces rainfall and winter has a little contribution. Cotton, Rice, wheat and sugarcane are the major field crops while mango and citrus are prominent among fruits. The highest day temperatures termed as maximum temperatures range in higher 40s degree Celsius from April to September except some occasional relief from monsoon rains. Extreme heat-wave conditions prevail during April-June when maxima start touching 50°C toward the end of this hot and dry period. Monsoon airmass brings the mercury down to some extent moderating the heat waves condition during July and August and increased atmospheric moisture decreases the evaporative demand of the atmosphere too.

Arid Plains of Balochistan

Arid and high elevation agricultural rainfed plains of Balochistan province are represented by Quetta. These plains do not come under the influence of summer monsoon rains, however, presence of monsoon airmass in other parts of the country increases the water vapours. Hence precipitation is mainly from snowfall/rainfall in winter when temperature generally remains below 0°C. Soil freezing is very frequent up to 7cm depth. Wheat is the major field crop which remains in dormancy for about three months because the ambient temperature falls below the biological zero i.e. 5°C for the wheat crop. Fruits like apple, apricot, pears, plum etc. are grown widely in this zone and they are known for their good quality perhaps due to dry atmosphere. Aridity and uncertainty of rainfall often poses a serious threat towards crop failure. The atmosphere remains very dry from May to Sep except some moisture incursions for the Arabian Sea. Water balance reaches its depletion maximum due to strong surface heating and very dry crop environment. The relative humidity sometimes drops to even 5% during May and June. The loss of moisture through evapotranspiration reaches its maximum during this period whereas it is minimal in peak winter.

Irrigated Plains of Sindh & Balochistan

Tandojam represents the irrigated agro-climates of Sindh and Balochistan (Nasirabad). Being representative of Arid agro-climate, the crops are grown under extensive canal irrigation. Clay content is high which categorized the regional soil as heavy soil. The Regional Agro-Meteorological Center started its operation in 1989 at Agricultural Research Institute, keeping academic liaison with Agriculture University, Tandojam. There was no meteorological observatory at that station, therefore 30 years records were not available. However, 15 years average meteorological data are used for this study for the period 1991-2005. Water table is generally high and become a serious problem in case of pre-monsoon tropical cyclones and during summer monsoon rainy season. Due to poor absorption, water from a single event stays stagnant in the fields for a couple of weeks which hinders the roots respiration in hot water. The winter rainfall amount is insignificant while southwest summer monsoon produces substantial precipitation from July to August. Cotton, wheat, rice and banana are the major field crops grown in this zone along with mango.

Table 1: Normal Climatic Features of representative stations Rawalpindi, Faisalabad, Quetta and Tandojam

Faisalabad					**Quetta**				
Month	Rainfall (mm)	Temperature (°C)		Relative Humidity (%)	Month	Rainfall (mm)	Temperature (°C)		Relative Humidity (%)
		Max	Min				Max	Min	
Jan	11.0	19.4	4.3	67	Jan	64.0	10.8	4.1	65
Feb	19.1	21.8	6.9	62	Feb	49.5	12.8	6.2	63
Mar	22.0	26.5	12.2	57	Mar	61.7	18.1	11.1	58
Apr	21.5	33.7	18.0	45	Apr	22.2	25.3	17.0	47
May	13.8	38.8	23.2	36	May	5.3	30.8	21.6	37
Jun	35.0	40.4	26.5	42	Jun	1.5	35.4	26.1	32
Jul	117.0	37.1	27.0	62	Jul	16.2	36.1	28.0	40
Aug	84.7	36.1	26.5	66	Aug	13.2	35.0	26.6	39
Sep	37.6	35.6	23.8	60	Sep	2.4	31.6	21.6	36
Octr	4.4	32.9	17.0	56	Oct	6.5	25.5	15.1	36
Novr	2.5	27.4	10.3	64	Nov	4.4	19.7	9.9	45
Dec	5.9	21.6	5.4	68	Dec	37.5	14.0	5.9	58

Tandojam					Rawalpindi				
Month	Rainfall (mm)	Temperature(°C)		Relative Humidity (%)	Month	Rainfall (mm)	Temperature (°C)		Relative Humidity (%)
		Max	Min				Max	Min	
Jan	1.8	24.1	9.1	67	Jan	59.2	17.6	3.1	66
Feb	5.8	27.3	11.3	64	Feb	79.7	19.2	5.4	62
Mar	2.2	33.1	16.1	57	Mar	97.1	23.7	10.1	57
Apr	2.4	38.0	21.2	53	Apr	63.1	30.2	15.4	47
May	4.3	40.3	25.0	58	May	34.1	35.6	20.1	36
Jun	1.6	42.2	25.9	65	Jun	70.1	38.4	23.5	39
Jul	55.2	36.2	27.0	72	Jul	305.3	34.8	24.2	65
Aug	31.3	35.3	26.1	73	Aug	348.1	33.4	23.6	72
Sep	8.0	35.3	24.4	71	Sep	113.2	33.5	20.7	64
Octr	7.8	35.1	20.4	66	Octr	29.8	30.9	14.0	59
Novr	2.3	30.8	14.8	62	Novr	15.6	25.9	7.9	62
Dec	0.2	26.0	10.6	68	Dec	31.2	20.0	4.0	68

Being located at around 25°N latitude, the intensity of solar radiation is very strong therefore the crop water requirement is much higher than rest of the agroclimatic zones. The rate of evaporation from soil surface and plant transpiration is high due to intense heating associated with low relative humidity and high windy conditions.

Methods under Comparison

Reference crop evapotranspiration (ETO) is direct measure of evaporative demand of the atmosphere and considered to be the most reliable tool for calculation of crop water requirement (Allen et al 1998). It can not be measured by instruments, however, estimated by various empirical formulae. Most of them make use of weather elements instead of crop or soil characteristics.

Radiation Method

This method is suggested for areas where available climatic data include measured air temperature and sunshine, cloudiness or radiation, but not measured wind and humidity. Knowledge of general levels of humidity and wind is required in qualitative terms. Radiation method as a whole, in equatorial regions, on small islands, or at high altitudes, may be reliable even if measured sunshine or cloudiness data are not available. In this case solar radiation maps prepared for most locations in the world would be used. The mathematical relationship is expressed as under:

$$ETo = c(W.Rs) \text{ mm/day}$$

Where

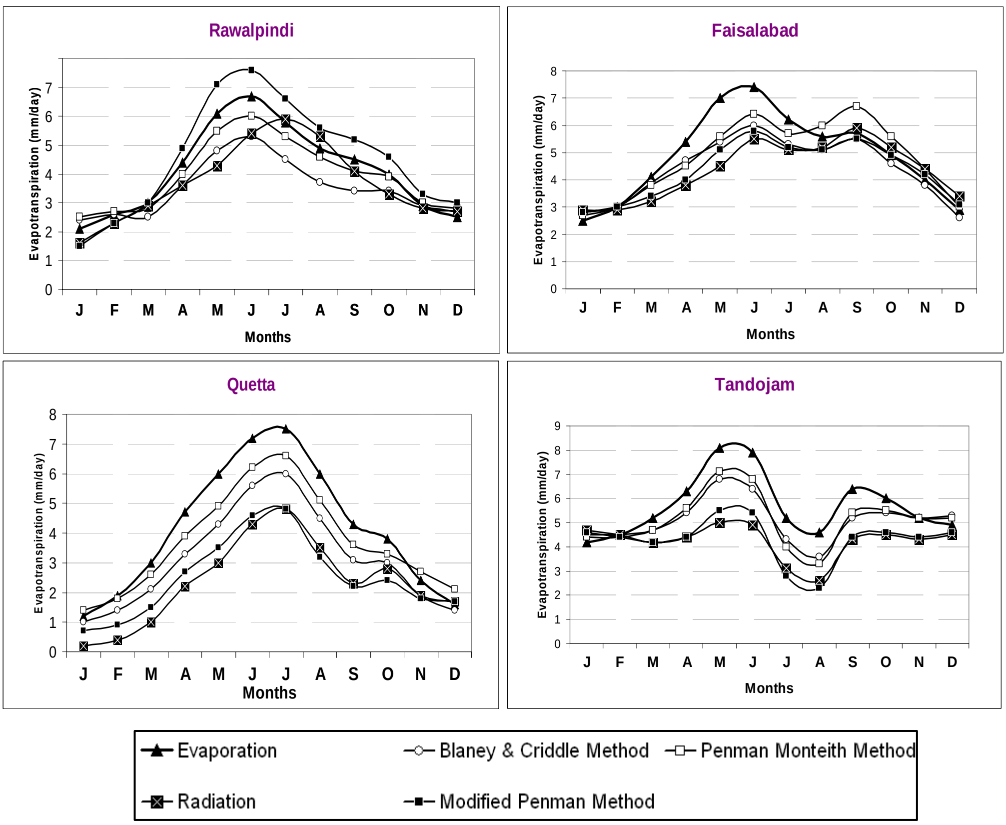
ETo	Reference crop evapotranspiration in mm/day for the periods considered.
Rs	Solar radiation in equivalent evaporation in mm/day.
W	Weighting factor, which depends on temperature and altitude.
c	Adjustment factor which depends on mean humidity and daytime wind.

Rs is further calculated with the help of following relationship:

$$Rs = \left(0.25 + 0.50 \times \frac{n}{N}\right) \times Ra$$

Where

n	Actual measured bright sunshine hours.
N	Maximum possible sunshine hours under clear sky conditions.
Ra	Amount of radiation received at the top of the atmosphere.



Modified Penman Method

The equation formed as a result of combination of radiation term and aerodynamic term which is given as:

$$ETo = c\left(W/Rn + (1-W).f(u).(ea - ed)\right)$$

Where

ETo	Reference crop evapotranspiration in mm/day
W	Temperature related weighing factor.
Rn	Net radiation equivalent evaporation in mm/day.
f(u)	Wind related function
(ea-ed)	Difference between saturated vapor pressure at mean air temperature and the actual vapor pressure of the air, in mille-bar.
c	Adjustment factor to compensate for the effect of day and night

Blaney and Criddle Formula

Blaney-Criddle equation (1950) involves the calculation of the consumptive use factor (f) from mean daily temperature (T) and percentage (P) of total annual daylight hours occurring during the period being considered. The recommended relationship representing mean value over the given month, is expressed as:

$$ETo = c\left[p(0.4T + 8.13)\right]$$

Where

ETo	reference crop evapotranspiration (mm/day) for the month considered.
T	mean daily temperature (°C) over the month considered.
p	mean daily percentage of total annual daytime hours.
c	sunshine hours and daytime wind estimates.

The equation includes n/N ratio, Relative Humidity *(RH)* and windspeed *(U)* in meter/second parameters in addition to the mean daily temperature which are explained below:

n	Actual daily sunshine duration (hours)
N	Maximum possible daily sunshine hours
R.H.	Minimum relative humidity (%) during the day
U	Mean daytime wind-speed (meter per second) at 2 meters height above the ground

Fao Penman-Montheith Equation

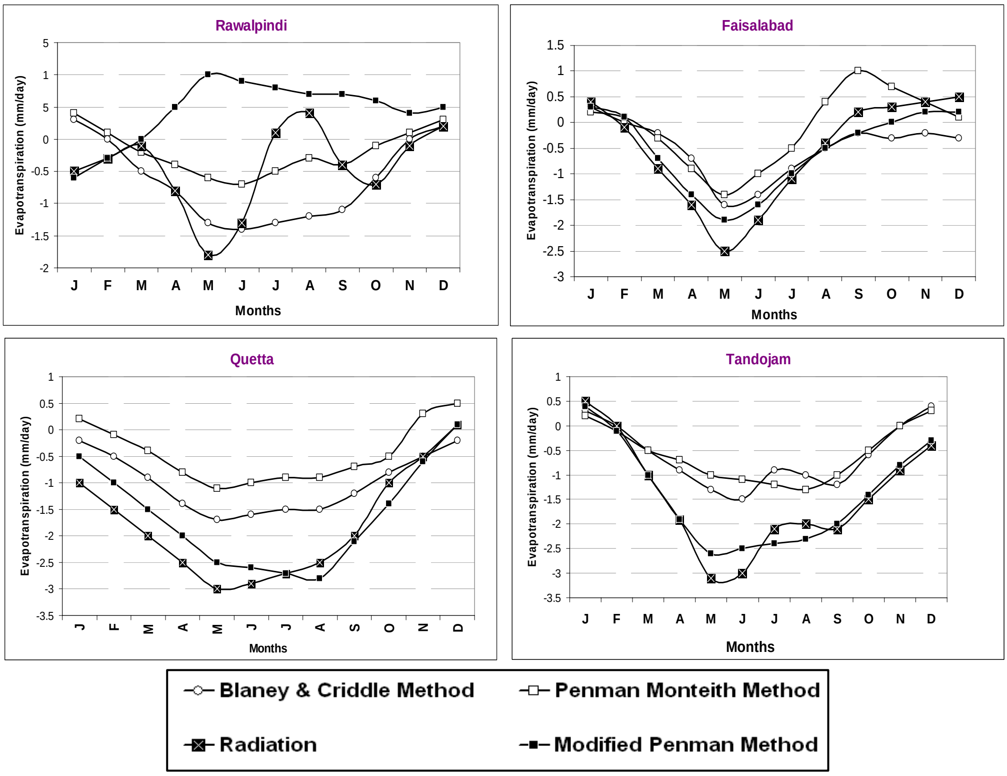
A consultation of experts and researchers was organized by FAO in May 1990, in collaboration with the International Commission for Irrigation and Drainage and with the World Meteorological Organization, to review the FAO methodologies on crop water requirements and to advise on the revision and update of the procedures. The FAO Penman-Monteith equation is a close, simple representation of the physical and physiological factors governing the evapotranspiration process. The mathematical expression for the sake of calculation is simplified as follow:

$$ETo = \frac{0.408\Delta(R_a - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)}$$

Where

ETO	reference evapotranspiration (mm per day),
Ra	net radiation at the crop surface (MJ/m² per day)
G	soil heat flux density (MH/m² per day),
T	mean daily air temperature at 2m height (°c).
U_2	wind speed at 2m height (m/s),
e_s	saturation vapor pressure (kPa),
e_a	Actual vapor pressure (kPa),
$e_s - e_a$	saturation vapor pressure deficit (kPa),
Δ	Slope of vapor pressure curve(kPa per °C),
γ	Psychometric constant (kPa per °C)

The equation uses standard meterological records of solar radiation (sunshine), air temperature, humidity and wind speed. To ensure the integrity of computations, the measurements of weather parameters should be made at 2m (or converted to that height) above an extensive surface of green grass, shading the ground and not short of water. It should be kept in mind that all the parameters are recorded at the same place, standard hours and under the same environment.



Results

Evapotranspiration calculated by four widely used methods in the world by scientists and planners was compared to test the accuracy of results best suited to Pakistan's diverse climate. Four major agricultural production zones under rainfall and irrigated conditions represented by Rawalpindi, Faisalabad. Tandojam and Quetta were considered for this purpose. The results obtained by each individual method in selected four agro climatic zones are discussed as under:

Radiation Method

It gave better performance for Rawalpindi during all the four seasons in conformity of FAO recommendations. It has already been motioned that Rawalpindi lies in sub-humid zone representing vast potohar were mainly cultivation is exercised. The major deviation has been seen in dry summer (pre-monsoon) where it showed little overestimation. In rest of the three climatic zones which vary from Semi-Arid to Arid, the evapotranspiration estimates are highly erratic. During summer underestimation is very high as it reaches 20% to 25% less than pan evaporation, however winter shows comparatively good results.

Modified Penman Method

Penman method was found overestimation evapotranspiration for low evaporative CONDITIONS LIKE RAWALPINDI WHERE SUMMERS ARE MODERATE AND WINTERS ARE relatively cooler. In Semi-Arid and Arid climates, this method practically failed to give representative results, (Hashemi et a11999). It highly underestimates evapotranspiration when compared with pan evaporation in the same climatic condition. The deviation in summer season was as high as 35% whereas during winter it was around 15%. The results from this method may mislead the user under Pakistan's climatic conditions as abut tow-third of Pakistan lies under arid climate.

Blaney-Criddle Method

It shows comparatively closer estimates in variety of climatic conditions of Pakistan. It generally underestimates in summer and overestimate during winter, however the daily average variation ranged between + 1 and – 1mm. The deviations are relatively large in hot and dry summer as compared to winter. The winter estimates of evapotranspiration practically tally with pan evaporation, however it underestimates at the rate of 10% to 15% during summer. The peak deviation of 20% was seen during hot and dry summer whereas it was lowered down to 10% in monsoon season.

Fao Penman-Montith

The results obtained from FAO Penman- =Monteith in this comparative study may be graded as the best as far as diversified climatic conditions of Pakistan are concerned. It gave more or less similar results as from Blaney- Criddle in case o sub-humid region represented by Rawalpindi. The computations in Semi-Arid and Arid climates show a little consistency in results. Arid region represented by Quetta where agricultural practices are carried out under rainfed conditions, indicate about 10% underestimation in summer and 3% overestimation of evapotranspiration in winter. On the other hand similar climatic zone but land irrigated with canal water represented by Tandojam gave altogether different results. In summer, evapotranspiration estimates were 10% to 15% lower and 5% higher than pan evaporation during winter. Faisalabad representing Semi-Arid climate also behaves like Tandojam but amplitude of variations is much less during both the summer and winter seasons.

Discussion

Advances in research and the more accurate assessment of crop water use have revealed weaknesses in the methodologies. Numerous researchers analyzed the performance of various methods for different locations. Although the results of such analyses could have been influenced by site or measurement conditions or by bias in weather data collection, it became evident that the proposed methods do not behave the same way in different locations in diverse climatic regimes. Deviations from computed to observe values were often found to exceed acceptable ranges indicated by FAO. The modified penman was frequently found to overestimate ETo, even upto 2% for low evaporative conditions.

Ready (1993) stated that the suitability of individual methods, for the estimation of evapotranspiration, depends not only upon the accuracy of the estimates but also on the availability of necessary input data, which is very important in developing countries. Availability of input meteorological data is not, however, the problem in case of Pakistan as far as four methods under comparison concerned.

A major comparative study was undertaken under the auspices of the Committee on Irrigation Water Requirements of the American Society of Civil Engineers (ASCE). ASCE study analyzed the performance of 20 different methods, using detailed procedures to assess the validity of the methods compared to a set of carefully screened Iysimeters data from 11 locations with variable climatic condition. The study showed widely varying performance of the methods under different climatic conditions. In a parallel study commissioned by European Community, a consortium of European research institutes evaluated the performance of various evapotranspiration methods using data from different lysimeter studies in Europe.

The studies confirm the overestimation of the Modified Penman introduced in FAO Irrigation and Drainage Paper No. 24, (Doorenbos et al 1975) and available performance of the different methods depending on their adaptation to local conditions. Those comparative studies may be summarized as follow.

- The Penman methods may require local calibration of the wind function to achieve satisfactory results.
- The radiation methods show good results in humid climates where the aerodynamic term is relatively small, but performance in arid conditions is erratic and tends to underestimate evapotranspiration.
- Temperature methods remain empirical and require local calibration to get satisfactory results.
- The relatively accurate and consistent performance of the Penman-Momeith approach in both arid and humid climates has been indicated in the ASCE and European studies.

The most reliable comparison may be carried out with the help of lysimeters ideally installed and operated in the closest vicinity of meteorological observatories (Makink 1957). It must be condacted in variety of climates under the supervision of trained professional. However, it would be very expensive to afford, a special study / project could be launched under the financial assistance of some donor. It is, no doubt, the most important parameter in agro hydrological and agricultural practices for sustainable research and development. For the time being this study proposed the FAO Penman–Monteith as most suitable followed by Blaney-Criddle method under various climatic conditions of Pakistan which produce results in reasonable acceptable limits.

Conclusion

The overall performance of FAO Penman-Monteith under variety of climates of Pakistan may be treated as the best. Showing the minor deviations from actual evapotranspiration data throughout the year. The Blaney- Criddle method is graded as second best option, which also shows the amplitude of deviation within acceptable limits. The modified Penman and Radiation methods cannot be recommended for adaptation under Pakistan's climatic condition due to large seasonal and spatial deviations from observed pan evaporation data.

References

Allen, R.G., Pruitt, W.O., Businger, J.A., Fritchen, L.J., Jensen, M.E., and Quetta, F.H. 1996. Chapter "Evaporation and Transpiration" in a ASCE Handbook of HYDROLOGY. New York, NY=. P. 125-252.

Allan R.G, Pereira, L.S., Raes, D. and Smith, M. 1998-Crop Evapotranspiration. Guidelines for computing Crop Water requirement, Irrigation and Drainage Paper No. 56, Food and Agriculture Organization of the United Nations, Rome, Italy

Blaney, H.F. and Criddle, W.D.1950. Determining water requirements in irrigated areas from climatologically and irrigation data. USDA Soil Conserv. Serv. SCS-TP96.44pp.

Chaudhary, Q.Z. and G. Rasul 2004: Climatic Classification of Pakistan. Science Vision, Vol. 9 No. 1-2 (Jul-Dec, 2003) & No. 3-4 (Jan-Jun, 2004). Pp. 59-66.

Doorenbos, .J. and Pruitt, W.O.1975. Guidelines for predicting crop water Organization, of the United Nations, Rome, Italy.

Hashemi, F. and Habibian, M.T. 1979. Limitation and temperature based methods in estimating crop evapotranspiration in arid-Zone agricultural development project. Agri. Meteorol.20.237-247.

Makkink, G.F.1957. Testing the Penman formula by means of lysimeter. J. inst. Water Engang 11 (3):277-288.

Rasul, G. 1992: Water Requirement of Wheat Crop in Pakistan. J. of Engg. & App. Sci. Vol. 3 No.1. pp. 65-79

Rasul, G. and A. B. Farooqi, 1993: Water Requirement of Cotton Crop in Pakistan. J. of Engg. & App. Sci. Vol. 4 No.2. pp. 154-165.

Reddy, S. J. 1993. Agrometeorological and Agroclimatic Techniques in Semi Arid Tropics. Science Publications, New Delhi-India.