EVALUATING METHODS FOR ESTIMATING EVAPORATION IN MAJOR RESERVOIRS - SRISAILAM PROJECT

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ABSTRACT

Major reservoirs play a key role in making irrigation feasible and contributing to the economic development and social well-being of people at large. The data and methodology for estimation of evaporation has an impact on the management of the reservoirs towards water security. Acquiring this information is crucial for hydrologists to develop more effective water resource management strategies and policies. The pan coefficients generally used are tentative. In Major reservoirs, the water spread area is enormous and there is also spatial variation which cannot be represented by an open pan. Hence there is a need to develop correlation between climatic variables and evaporation rate. The FAO suggested Penman-Montieth is the best method for estimation of reference evapotranspiration for semi-arid and arid regions. This study assesses the performance of a diverse number of methods namely Penman, Kohler, Van Bavel and Penman-Montieth to estimate evaporation and provides evaporation coefficients on a monthly basis for Srisailam reservoir, a major reservoir in the Krishna Basin. Climatic data of Kurnool Meteorological station which is in vicinity of the reservoir is used to compute evaporation using the above methods on monthly, seasonal and annual basis. The evaporation coefficients developed are an important tool for improving water resource accounting and efficient operation of reservoir. The annual pan coefficient estimated by Kohler's method is 0.68 which has the best regression of 0.94 and also has lesser variation in monthly pan coefficients. The savings accrued in the allocation made for evaporation by the Tribunal will be further, helpful in providing extensive irrigation in water scarce areas of Krishna basin.

1. INTRODUCTION

Water is one of nature's precious gifts, which sustains life on earth. Civilizations over the world have prospered or perished depending upon the availability of this vital resource. Water has been worshipped for life nourishing properties in all the scriptures. Vedas have unequivocally eulogized water in all its virtuous properties. India possesses only 4% of total average runoff of the rivers of the world although it sustains 16% of the world's population. The per capita availability of water in the country is only 1820 m3/year. The total water resources of India are estimated to be around 1,869 Billion cubic meters (BCM). Due to topographic, hydrological and other constraints, only about 690 BCM of total surface water is considered as utilizable as on 2006. It has been assessed that against the utilizable water resources of the order of 1123 BCM, the requirement by 2025 AD to be met from surface water resources will be around 1093 BCM, thereby reducing the surplus to just 30 BCM.

Water evaporation is one of the obscure components of hydrologic cycle. There are two basic reasons for this obscurity. First, no instrumentation exists which can truly measure evaporation from a natural surface. Second, none of the indirect methods used for estimation of evaporation are universally accepted. Estimation of reliable or acceptable value of evaporation requires either a detailed instrumentation or a judicious application of climatic and physical data. The data obtained from pan evaporimeters are at present used in the following ways:

1. To derive empirical relationship for determination of evaporation from reservoirs or to complete missing evaporometric records.
2. To determine pan coefficients as ratio of reservoir to pan evaporation.

2. EVAPORATION

Evaporation occurs when liquid water is converted into water vapour. Factors affecting the rate of evaporation from open surface can be broadly divided into two groups, meteorological factors and surface factors, either of which may be rate-limiting. The meteorological factors may, in turn, be subdivided into energy and aerodynamic variables. Energy is needed to change water from the liquid to the vapour phase; in nature, this is largely supplied by solar and terrestrial radiation. Aerodynamic variables, such as wind speed at the surface and vapour pressure difference between the surface and the lower atmosphere, control the rate of transfer of the evaporated water vapour. The size and shape of the evaporating surface is also an extremely important factor specifically in arid and semi-arid areas.

3. MATERIALS AND METHODS

The methods in use to determine the rate of evaporation from open water surfaces are Water budget or storage equation method, Mass (vapour) transfer method, Energy budget or insolation method, Measurement in an auxiliary pan (or tank) and correlate pan evaporation to natural water surface evaporation, Empirical formulae and graphical methods. The literature suggests that energy budget method may provide better estimates of evaporation as compared to other methods. But it requires extensive instrumentation and frequent surveying of water body, making it an expensive deal. Several other methods are less accurate but reliable to estimate evaporation from water surface. Though measurement of evaporation from pan is the easiest, it is to be noted that the pan is generally kept at the dam site. Since the water spread area of a reservoir is very large and has high degree of spatial variation, the pan data would not be correct representation of the evaporation in reservoirs.

There is a marked difference in vapor pressure over a pan containing water to that of a reservoir. The evaporation of water in a pan is a function of not only the vapour pressure but also the heat absorbed by the water in the pan. In ideal conditions, this heat is due to the incoming solar radiation only. However, the pan also absorbs heat through radiation as the water depth is shallow and the rays penetrate through water and hits the pan enabling it to transfer the heat to the water through convection. When an air mass passes through the pan, it absorbs the moisture and travels, as the amount of water is less, more amount of water is lost as wind waves periodically remove water from pan and travel. As such the pan evaporation does not represent the Reservoir evaporation due to phase difference in the storage of heat due to solar radiation in pans and Reservoirs. The other factor is the difference in way the pan and lake are affected to advective heat transfer, which is due to their different areal extent and exposure to wind. Reliable and reasonable estimates of lake evaporation can, however be obtained by application of the appropriate pan to Lake Coefficient (WMO, 1973).

For the present study, the Energy budget methods namely Penman, Kohler, Van Bavel and Penman-Montieth are used to estimate evaporation on a monthly basis for Srisailam reservoir. The National Institute of Hydrology (NIH), Roorkee suggested that the above methods are suitable for Indian conditions. The FAO - Penman - Montieth model (FAO-PM) is considered since it is standard and globally acceptable approach and provides the precise and acceptable 'PET' estimates in a variety of climates (Adeboye et al., 2009; Garcia et al., 2004; Popova et al., 2006). For the application of this combination model, the requisite meteorological data was collected from Indian Meteorological Department (IMD), Pune for Kurnool station which is in the vicinity of Srisailam reservoir.

4. STUDY AREA

The Srisailam Dam is constructed across the Krishna River in Kurnool district, Andhra Pradesh. The dam was constructed in a deep gorge in the Nallamala Hills. The project is located at the border between Kurnool and Mahabubnagar districts and the dam site is located at latitude of 16o 5' N and 78o 54' E. The Srisailam Project was initially contemplated as Hydro Electric Scheme with FRL of 885' and MDDL of 854'.In the project report approved by the Planning Commission, the depth of evaporation was 72.4'' and the working table was prepared for reservoir operation between 854' to 885'.The evaporation loss of 33 TMC was calculated based on the assumption that at the end of each water year MDDL of 854' will be maintained and the reservoir will maintain carryover storage in good years. The KWDT-I allotted 33 TMC as the evaporation loss in Srisailam reservoir to the State of Andhra Pradesh. The reservoir was fully operated from 1984 onwards. However, due to emerging regional aspirations projects such as Telugu Ganga, Handri Niva Sujala Sravanthi, Galeru Nagari Sujala Sravanthi, Veligonda, Palamuru Rangareddy LIS, Dindi LIS, Mahatma Gandhi Kalwakurthy LIS and AMRP-Srisailam Left Bank Canal have emerged with proposed utilization of 350 TMC from Srisailam reservoir.

Evaporation losses computed for a reservoir at a particular level is a function of the evaporation observed and the water spread area. Area Capacity tables provide the water spread area and the corresponding capacity at a particular level. The reservoir was planned at FRL of 885' with water spread area of 6622 M.sqft or 615.18 sq.km and capacity of 308 TMC. During the period from 1984-85 to 2007-08, withdrawals were being made even at a level of 709.9' or at 216.38 m and upto FRL at 269.9 m. As per the latest sedimentation studies carried out in 2011, the water spread area at FRL was reduced to 5886 M.sqft and the capacity to 215 TMC. The loss of storage worked out to 30.2% and the decrease in water spread area was 27% at water level of 834'.

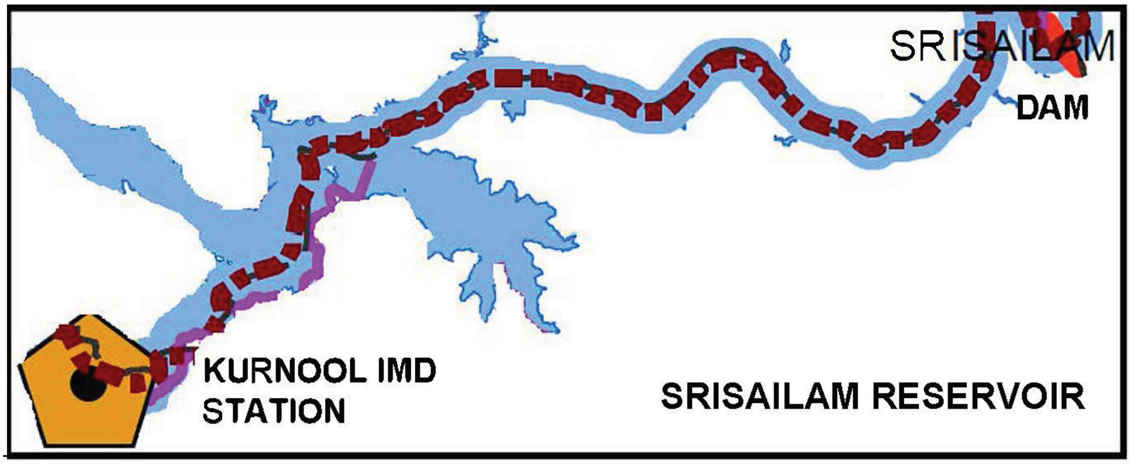

Figure 1 : Location of Srisailam reservoir

5. METHODOLOGY

Srisailam reservoir can be classified as deep water body. The solar radiation does not penetrate fully to the bottom of the dam, the penetration of the radiation is limited to only few meters below the water surface (5m).As a result, due to thermal stratification, the evaporation over such water body will be very less when compared to that of pan and thus has to be calculated using Mass Budget and Energy Budget equations. National Institute of Hydrology estimated the evaporation losses of Tawa reservoir in Madhya Pradesh using energy budget methods based on the data available with the nearest IMD station and concluded that Kohler and Morton methods may provide better estimates of evaporation.

The nearest meteorological station to Srisailam is Kurnool IMD Observatory which is located in the upstream of the reservoir at 15° 50' N and 78° 04' E with an elevation of 281 m .The daily data series of minimum temperature, maximum temperature, dry bulb temperature, wet bulb temperature, station pressure and wind speed are available for the period from 1984-1999 for which fortnightly water levels of the reservoir were measured. The daily data series is transformed to fortnightly basis for analysis. Apart from minimum and maximum temperature, the average readings of all other parameters taken both at morning and in the evening are utilized. The latitude of 16° 5' N of the dam site is used as the input data for calculating radiation.

The data observed at Kurnool Station is transformed so as to represent the conditions at reservoir. The temperatures are adjusted based on the elevation difference between the Kurnool Station and the water level at the reservoir by making use of the standard temperature lapse rate. Based on the adjusted temperature and the water level, the pressure is calculated. The wind speed observed at the station is shifted to the reservoir using logarithmic law and the wind speed at heights of 2m and 10m above the reservoir are calculated. The constants such as specific heat, latent heat of vaporization and density are estimated based on the temperature and elevation. The specific heat of air is found out using gas tables. These adjustments are made and the density of the air mass, specific heat and latent heat of vaporization of water are adjusted based on the mean temperature of the air mass and the level of water in the reservoir.

Based on the above set of data the evaporation rate is estimated by four different methods namely Penman, Van Bavel, Kohler and Penman-Montieth method. The input units of the parameters of all methods except Penman-Montieth method are in non-SI units and as such conversions are to be carried out. Penman-Montieth method is the only method which takes account of the change in heat storage of the water body and the effect of wind current over the water spread area.

The measured pan evaporation at the IMD observatory Kurnool station has been utilized to derive pan to reservoir coefficients for monsoon (June-September), post monsoon (October and November), winter (December-February) and summer (March-May) seasons. In present study a correction factor of 1.144 for the mesh cover on pan has been considered separately.

6. EMPIRICAL METHODS

1. Penman Method

The most widely used formula to estimate evaporation from open water has been the penman equation (Penman, 1948). Its success when applied in many different locations is attributable to its physical basis. Penman combined the mass transfer and energy budget approaches and eliminated the requirement for surface temperature to obtain his expression for the evaporation in mm perday from open water.

$$\mathrm{Eto(mm/day)} = \left(\frac{\Delta(23.901 R_n)}{59(\Delta + \gamma)} + \frac{\gamma(76.8 - 22.9062\, u_2)(e_s - e_a)}{59(\Delta + \gamma)} \right)$$

Equations 1 to 19 in Table 1 describe the formulae to be applied in sequential order to arrive at evaporation rate for this method. This method does not allow for heat storage and was not intended for use in estimating evaporation from deep water bodies with or without components of advected energy. When air travels a long distance over a wet surface it will tend to saturate so that the second term in the above equation tends to become zero. The first term represents the lower limit of evaporation and is referred to as the equilibrium rate. Hargreaves formula is used for estimating solar radiation.

2. Van Bavel Method

Van Bavel modified the Penman equation and assumed the adiabatic condition i.e. transfer coefficient for heat equals to transfer coefficient for vapour and suggested the following equation for estimation of evaporation from free water surfaces.

$$\mathrm{Eto(mm/day)} = \frac{\Delta(23.901\mathrm{R_n})}{59(\Delta+\gamma)} + \frac{\gamma\left(0.622 * \lambda * .023885\rho * \frac{\mathrm{k}^2}{\mathrm{P}}\right)\left(\frac{240\mathrm{u}_2}{\ln\left(\frac{2}{\mathrm{z_o}}\right)^2}\right)(\mathrm{e_s}-\mathrm{e_a})}{59(\Delta+\gamma)}$$

where z_0 is roughness length (m),for water surface z_0 = 0.0002 m.

Equations 1 to 19 in Table 1 describe the formulae to be applied in sequential order to arrive at evaporation rate for this method

3. Kohler Method

Kohler used the results of the detailed U.S. Geologic Survey (USGS) Lake Hefner evaporation study combined with pan evaporation for estimating lake evaporation. One of his objectives was to derive a more reliable procedure for estimating lake evaporation from pan evaporation and related meteorological data normally collected by the Weather Bureau. Kohler, Nordenson and Fox adopted the Penman equation to Class A pan evaporation by using Cp= 0.00157P and for lakes or open water evaporation by multiplying solution by 0.7 with Ci=0.000661P mb/c. The following equation was suggested for estimation of evaporation losses from reservoir for daily basis.

$$\mathrm{Eto(mm/day)} = 0.7\left(\frac{\Delta(0.016R_n)}{\Delta+\gamma_i} + \frac{\gamma_i(0.37+0.06114\mathrm{u}_2)(0.3(e_s-e_a))^{0.88}}{\Delta+\gamma_i}\right)$$

The annual Class A pan coefficient derived for Lake Hefner was 0.69. Monthly coefficients varied because of the temperature lag in the lake due to differences in energy storage capacities of the two water bodies. Pan coefficients tended to be lower in spring months. Kohler concluded that annual lake evaporation could be estimated within 10-15% by applying the annual coefficient 0.70 to Class A pan evaporation. Equations 1 to 19 in Table 1 describe the formulae to be applied in sequential order to arrive at evaporation rate for this method.

4. Penman-Montieth Method

Penman-Montieth Method is a combination method which allows adjustment to the amount of energy available for evaporation based on changes in heat storage within the water body. Such an adjustment can be obtained if the temperature of the water body is known or can be estimated. The model for estimation of water temperature developed based on the concept of an equilibrium temperature (e.g. de Bruin, 1982; Edinger et al., 1968; Keijman and Koopmans, 1973) is applied to Penman-Montieth Method. The equilibrium temperature is defined as the surface temperature at which the net rate of heat exchange would be zero. The change in heat storage of the water body, is central to the open water evaporation model as it affects water surface temperatures and thereby the rate of evaporation. The depth of a water body affects its potential to store energy and there are changes in this heat storage over time.

The wind function, *f(u)*, is used to define the evaporation rate from which latent heat loss is calculated. Studies from a number of different sized water bodies suggest that the evaporation coefficient should be not only a function of wind speed, but also of water body size as the water body size affects the aerodynamic resistance to evaporative mass transfer. As air flows from the land to over the water, the surface roughness reduces abruptly. The turbulence in the air flow gradually adjusts itself to this change at increasing distances from the shore. Further, as water is being gradually evaporated into the air flow, the humidity of the air increases downwind from the shore. Both of these effects, which mostly act in opposite directions to one another, tend to cause variation in evaporation rate over the water surface and so with water body size (area).

The wind function of Sweers (1976) (Equation 20 in Table 1) is a further development of the work of McMillan (1971) at a 5 km2 lake in Wales which has been modified to include effects of water body area based on the methods developed by Harbeck et al. (1962). The following formula is suggested for computing the evaporation.

$$\mathrm{Eto(mm/day)} = \frac{\Delta_\mathrm{w}(\mathrm{R_n^*}-\mathrm{N}) + 86400\rho_\mathrm{a}\mathrm{C_a}(e_s^*-e_a)/r_a}{\lambda(\Delta_\mathrm{w}+\gamma)}$$

Equation 1 to 7, 10 to 17 and 22 to 36 in Table 1 describe the formulae to be applied in sequential order to arrive at evaporation rate for this method.

7. RESULTS AND CONCLUSIONS

The fortnightly evaporation is computed by the above methods and the results obtained in comparison with the evaporation at Kurnool station are in Table-2. The Central Water Commission (CWC) suggested an annual pan coefficient of 0.7. However, a true picture would be known only when monthly coefficients are arrived at. The monthly evaporation and corresponding pan coefficients computed by all methods are in Table-3. The seasonal evaporation (monsoon, post monsoon, winter and summer) and corresponding pan coefficients computed by all methods are in Table-4.

The results indicate variation in the monthly pan coefficients in all the methods and this variation is more pronounced when coefficients are derived season wise. In the present study, the least annual coefficient is given by both Penman and Van Bavel methods and the highest by Penman-Montieth method. Regression analysis of the evaporation estimated by different methods with reference to the observed values is carried out to find the most suitable method. Kohler's method with an annual pan coefficient of 0.68 has the highest regression value of 0.94 which conform to the recommendations made by NIH, for evaporation under semi arid conditions in Tawa Reservoir.

FAO suggested that Penman-Montieth is the best method for estimation of reference evapotranspiration for semi-arid and arid regions. Penman-Montieth method has the adjusted regression value of 0.66 which is less when compared to other methods, due to significant variations in the monthly evaporation values. It has the highest annual pan coefficient of 0.74. This spatial variation is due to high temperature and large diurnal variation on account of differential heating of water in reservoir and pan and consequent difference of water temperature in both surfaces. The lack of correlation is mainly due to evaporation occurring in lag period due to storage heat component advected in to the water body. This can be clearly observed as the pan coefficient values of both Kohler and Penman-Montieth method are similar in both summer and winter. The pan coefficient in both monsoon and post- monsoon in Penman-Montieth is higher than that of Kohler method. It is due to change in heat storage of water body which is a function of reservoir elevation and change in water temperature Outgoing long wave radiation is computed using water temperature, hence physical measurement of water temperature is necessary .

The albedo is potentially time variant and generally varies from 0.06 to 0.20 but in this estimate it is considered as constant 0.08. It is suggested to install pyranometer, anemometer, albedometer and water temperature meter in major reservoirs for accurate estimation of evaporation by energy methods. After obtaining measured data, an accurate pan coefficient can be established, which will be useful in assessment of evaporation of other major, medium, minor reservoirs and tanks which are located in similar climatic conditions.

An annual evaporation of 1839 mm or 72.4" was considered in the project report of Srisailam. The estimated evaporation by Kohler method is 1655 mm which results in saving of 10%. Further, the loss in storage, reduction in water spread area due to sedimentation and increased water demands will lead to considerable reduction in the evaporation loss, whose quantum would be definitely less than 33 TMC. The savings thus accrued in the evaporation losses could be allocated for irrigation purposes out of proposed demand of around 350 TMC with priority to in basin needs of Krishna basin.

Table 1 : List of formulae used in computation of evaporation in all methods

Parameter	**Formula**	**Unit**	**Equation No.**
Mean Temperature (T)	$T = \frac{T_{max} + T_{min}}{2}$ where T_{max} and T_{min} are the maximum and minimum temperatures respectively.	$°C$	1
Pressure (P)	$P = 101.325\left(1 - \frac{0.0065z}{273+T}\right)^{5.256}$ where z is elevation in m	kPa	2
Wind speed at 10 m (u_{10})	$u_{10} = u_k \ln(z+10)/\ln(z_k)$ where z_k is the elevation where the wind speed u_k is known	$kmph$	3
Wind speed at 2 m (u_2)	$u_2 = 0.748u_{10}$	$kmph$	4
Air Density (ρ_a)	$\rho_a = \frac{P}{0.287 * 1.01(T+273)}$	kg/m^3	5
Latent heat of vaporization (λ)	$\lambda = 2.501 - (2.361T * 10^{-3})$	MJ/kg	6
Psychometric constant (γ)	$\gamma = P * \frac{C_a}{0.622\lambda}$ where C_a is specific heat of air in MJ/kg/K	$kPa/°C$	7
Slope of saturated vapour pressure (Δ)	$\Delta = \frac{4098 * 0.6108e^{\left(\frac{17.27T}{T+237.3}\right)}}{(T+237.3)^2}$	$kPa/°C$	8

Saturated air vapour pressure (e_s)	$e_s = \frac{0.6108e^{\left(\frac{17.27T_{max}}{T_{max}+237.3}\right)} + 0.6108e^{\left(\frac{17.27T_{min}}{T_{min}+237.3}\right)}}{2}$	kPa	9
Actual vapour pressure (e_a)	$e_a = 0.6108e^{\left(\frac{17.27T_{wet}}{T_{wet}+237.3}\right)} - 0.008P(T_{dry} - T_{wet})$ where T_{wet} and T_{dry} are wet bulb and dry bulb temperatures respectively	kPa	10
Inverse solar distance (d_r)	$d_r = 1 + 0.033\cos\left(\frac{2\pi J}{365}\right)$ where J is the number of the	$radians$	11
	day in year available in Annex. 2 (Table 2.5) of FAO56		
Solar declination (δ)	$\delta = 0.409\sin\left(\frac{2\pi J}{365} - 1.39\right)$	$radians$	12
Sunset hour angle (ω_s)	$\omega_s = \tan(\delta) * \mathrm{acos}\left(-\tan\left(\frac{\pi\psi}{180}\right)\right)$ where ψ is latitude in degrees	$radians$	13
Extraterrestrial Radiation (R_a)	$R_a = \left(24 * 60 * \frac{0.082\ d_r}{\pi}\right) * (\omega_s \sin\psi \sin\delta + \cos\psi\cos\delta\sin\omega_s)$ where ψ is latitude in radians	$\frac{MJ}{m^2 day}$	14
Incoming Solar radiation (R_s)	$R_s = 0.16R_a\sqrt{T_{max} - T_{min}}$	$\frac{MJ}{m^2 day}$	15
Net Solar Radiation(R_{ns})	$R_{ns} = (1-\alpha)R_s$ where α is albedo, the value being 0.08 for clear water	$\frac{MJ}{m^2 day}$	16
Clear sky solar radiation (R_{so})	$R_{so} = 0.75 + (2 * 10^{-5} z)R_a$ where z is elevation in m	$\frac{MJ}{m^2 day}$	17
Net Long wave Radiation (R_{nl})	$R_{nl} = \sigma(T + 273.15)^4(0.34 - 0.14\sqrt{e_a})\left(\frac{1.35R_s}{R_{so}} - 0.35\right)$ where σ is Stefan Boltzmann Constant $= 4.903*10^{-9}$ MJ/$K^4 m^2$day	$\frac{MJ}{m^2 day}$	18
Net Radiation (R_n)	$R_n = R_{ns} - R_{nl}$	$\frac{MJ}{m^2 day}$	19
Wind function f(u)	$f(u) = \left(\frac{5}{A}\right)^{0.05}(3.8 + 1.57u_{10})$ where A is the water spread area in km^2	$\frac{MJ}{m^2 kPa\ day}$	20
Aerodynamic resistance (r_a)	$r_a = \frac{\rho_a C_a}{\gamma \frac{f(u)}{86400}}$	s/m	21
Incoming Longwave Radiation(L↓)	$L\downarrow = \left(C_f + (1 - C_f)(1 - 0.261e^{-7.77T^2*10^{-4}})\right)\sigma(T + 273.15)^4$ $C_f = 1.1 - \left(\frac{R_s}{R_{so}}\right)$ when $\frac{R_s}{R_{so}} \leq 0.9$ else $C_f = 2\left(1 - \left(\frac{R_s}{R_{so}}\right)\right)$	$\frac{MJ}{m^2 day}$	22
Dew Point Temperature (T_d)	$T_d = \frac{116.9 + 237.3\ln(e_a)}{16.78 - \ln(e_a)}$	℃	23
Neutral Temperature (T_n)	$T_n = \frac{0.00066 * 100T + T_d\left(\frac{4098e_a}{(T_d + 237.3)^2}\right)}{0.00066 * 100 + \left(\frac{4098e_a}{(T_d + 237.3)^2}\right)}$	℃	24
Slope of saturated vapour pressure at wet bulb (Δ_n)	$\Delta_n = \frac{4098 * 0.6108e^{\left(\frac{17.27T_n}{T_n+237.3}\right)}}{(T_n + 237.3)^2}$	$kPa/℃$	25
Outgoing Longwave Radiation at wet bulb (L_n↑)	$L_n\uparrow = \sigma(T + 273.15)^4 + 4\sigma(T + 273.15)^3(T_n - T)$	$\frac{MJ}{m^2 day}$	26
Net Radiation at wet bulb (R_{nw})	$R_{nw} = R_{ns} + L\downarrow - L_n\uparrow$	$\frac{MJ}{m^2 day}$	27
Equilibrium Temperature (T_e)	$T_e = T_n + \frac{R_{nw}}{4\sigma(T + 273.15)^3 + f(u)(\Delta_n + \gamma)}$	℃	28

Water Density (ρ_w)	$\rho_w = \frac{1000}{1+(0.0002(T-4))}$	kg/m^3	29
Time Constant (τ)	$\tau = \frac{\rho_w C_w Z}{4\sigma(T_n + 273.15)^3 + f(u)(\Delta_n + \gamma)}$ C_w is specific heat of water is 4.182*10^{-3} MJ/kgK and Z is the depth of water . In this study it is assumed to be (Level of water at fortnight - 213.36) m	$days$	30
Water Temperature (T_w)	$T_w = T_e + (T_{w0} - T_e)e^{-1/\tau}$ where T_{wo} is the water temperature at the previous time step	$°C$	31
Outgoing Longwave Radiation at water temperature (L↑)	$L\uparrow = 0.97\sigma(T_w + 273.15)^4$	$\frac{MJ}{m^2 \, day}$	32
Change in Heat Storage (N)	$N = \rho_w C_w Z(T_w - T_{w0})$	$\frac{MJ}{m^2 \, day}$	33
Saturated vapour pressure at water temperature (e_s^*)	$e_s^* = 0.6108e^{\left(\frac{17.27T_w}{T_w+237.3}\right)}$	kPa	34
Slope of saturated vapour pressure at water temperature (Δ_w)	$\Delta_w = \frac{4098 * 0.6108e^{\left(\frac{17.27T_w}{T_w+237.3}\right)}}{(T_w + 237.3)^2}$	$kPa/°C$	35
Net Radiation (R_n^*)	$R_n^* = R_{ns} + L\downarrow - L\uparrow$	$\frac{MJ}{m^2 \, day}$	36

Table 2 : Evaporation (mm) calculated by different methods

Year	**Month**	**Observed (Kurnool Station)**	**Penman Method**	**Van Bavel Method**	**Kohler Method**	**Penman-Montieth Method**
1984	January	156.5	113.5	103	106.4	72.5
	February	177.3	118.4	113	119.3	67.3
	March	243.5	163.6	145.5	149.5	67.6
	April	273.3	162.6	158.8	167.9	70
	May	334.4	160.9	171.2	194.1	96.1
	June	239.8	108.3	148.6	184	187.5
	July	207.9	118.8	138.4	148.4	175.5
	August	187.8	118.1	138.3	154.2	178.2
	September	170.4	126.5	129.5	131.5	160.2
	October	132.2	133.2	121	111.3	140.8
	November	146.1	112.4	100.3	100.1	116
	December	132.8	111	100.6	104.6	119.7
1985	January	152	107.4	103.4	113.6	129.8
	February	192.6	121	113.7	125.8	158.6
	March	262.3	159	153.6	166.5	122.1
	April	289.5	146.9	159.4	183.8	72.6
	May	316.9	145.8	169.6	199.4	103.9
	June	214.1	125.7	148.3	165.9	198.3
	July	155.7	126.8	142.3	150.8	180.5
	August	165.6	126.6	137.2	141.3	167.8
	September	157	122.3	129	134.7	161.3
	October	134.2	125.1	118.7	114.4	138

	November	127.2	112.4	102.8	107	122.7
	December	129.2	104.1	97.9	106	117.8
1986	January	124	105.4	99.8	104.8	113.1
	February	163.2	111.8	114	123.8	146.3
	March	247.1	150.9	151.1	165.6	104.8
	April	268.9	158.5	163.4	177.2	47.5
	May	337.9	138.4	171.4	208.2	89.1
	June	228.9	131.9	151.9	165.6	126.1
	July	222.8	124	146.7	163.5	192.4
	August	161.9	119	135.4	146.4	170.4
	September	173.5	130.5	134.8	137.6	167
	October	150	135.6	126.1	121.7	151.4
	November	111.2	109.8	101	95.9	111.6
	December	119.1	104.1	98.8	106.7	118.2
1987	January	135.8	111	104.3	110.2	123.7
	February	177.8	119.7	110.7	122	148.7
	March	243.8	146.3	147.3	164.4	210.6
	April	289.6	149.6	159.9	185.3	108.1
	May	276.5	166.7	172.1	184	108.4
	June	235.9	136.8	158.2	175	164.3
	July	215.1	129.2	148.2	163.9	196.7
	August	161.9	128.8	139.2	140.7	167.7
	September	165.5	133.7	135.4	134	164.4
	October	116.7	127	120.1	108.1	131.4
	November	92.3	100.4	94.4	86.9	95.5
	December	97.6	103.3	93.7	90.6	95.8
1988	January	128.8	118.5	105.1	105.1	116.2
	February	164.6	128.2	121.2	128.7	158.7
	March	236	157.7	151.6	161.1	127.3
	April	247.4	161.6	159.7	165.5	82.7
	May	281.6	154.1	171.7	196.1	116.3
	June	249.3	133.1	154	173.1	211
	July	137.1	130.9	135.6	130.5	160.1
	August	113.9	123.7	128.8	121.9	144.4
	September	102.3	118.7	120.2	111	131.6
	October	146.1	131.1	124.5	125.9	150
	November	144.6	115.2	105.2	109.7	122.6
	December	121.9	105	98.1	103.8	108.7
1989	January	137.1	116.9	105.9	113.1	125.3
	February	167.7	130.4	119.6	128.9	159.5
	March	200.3	148.3	146.9	157.2	196.8
	April	242.5	161.9	163.1	173.7	82.3
	May	317.6	153.3	174.2	199.3	190
	June	213.1	132.3	150.8	162.4	195.4
	July	134	125.4	136.8	137.6	164.7
	August	159.1	124.5	139.7	146.2	169.4
	September	125.8	124.1	127.6	123.3	145
	October	136.3	135.7	128.4	123.9	148.6
	November	119.6	109.5	104.6	106.2	116.1
	December	117.9	101.6	96	101	104.4
1990	January	138.2	118.9	107.8	120.6	135.3
	February	171.2	115.1	113.4	133.4	161.3

	March	249.4	141.2	146.6	166.7	210.4
	April	280.5	156.2	160	177.7	100.9
	May	205.8	147.1	157.6	165.4	204.7
	June	171.3	123.9	140.6	151	179.1
	July	166.7	125	140.9	148.7	174.3
	August	145	120.9	131.6	134.2	154.5
	September	142.5	125.1	129.5	130.3	152.9
	October	117.6	115.4	112.9	106.6	121.2
	November	111.4	106	99.5	97.1	106
	December	108.9	105.2	96.6	97	99.4
1991	January	133.4	115.7	106.5	109.7	120.7
	February	176.1	122.9	115.4	127.6	154.6
	March	254	157.3	149.2	160.3	212.8
	April	256.8	157.3	159.7	169.9	156.2
	May	297.1	165	171	187.3	115.3
	June	162.1	133.1	143.6	147	177.1
	July	135.1	123.6	133.6	132.2	153.5
	August	141.5	120.1	134.1	140.7	160.8
	September	144.9	124.2	130.5	133.3	156.2
	October	139.1	125	123.2	123.7	144
	November	95.7	100.8	96.8	93.8	97.4
	December	109.8	106.3	97.1	100.2	100.7
1992	January	134.3	115.9	105.7	115.8	121.4
	February	168.3	126.6	117.2	128.5	154.8
	March	251.3	164.3	151.5	167.4	227.6
	April	274.9	159.1	159.4	177.8	171.6
	May	286.4	158.2	172.3	192.4	182.6
	June	211.7	142.7	157.2	170.1	211.3
	July	157.2	136.1	147.2	152.3	183.5
	August	132.1	131.9	137.9	133.8	157.6
	September	146.1	128.8	132.2	133.4	156.5
	October	134	128	122.4	119.9	140.4
	November	116.9	104.3	100.5	102.2	111
	December	115.3	109.5	98.5	100.6	100.5
1993	January	142.7	122.5	108.6	118.1	130.1
	February	167.9	115.6	110.6	129	151
	March	234.6	152.4	146.7	161.1	207.4
	April	280.7	155.1	155.4	174.6	234.4
	May	301.5	160.3	172.5	196.5	192.1
	June	265.8	132.4	155	178.8	218.6
	July	191.2	130.7	147.9	161.4	192.3
	August	157.3	133.2	140.7	140.9	164.9
	September	141.6	123.8	127.9	126	146
	October	113.9	124.5	120.7	110.9	128.5
	November	119.8	106.4	100.1	99.8	106.7
	December	93.5	102.2	94.3	93.6	90.5
1994	January	137.6	112.1	105	110.6	116.6
	February	155.7	117.6	112.2	119.6	140.8
	March	215.7	163.2	150.8	160.5	139.2
	April	254.6	150.1	155.6	174.8	183.2
	May	295.6	156.1	169.5	193.4	190.6
	June	236.6	120.6	150.5	178.5	247.8

	July	169.9	120	142.6	156.8	180.6
	August	161.1	125.3	136.2	140.9	161.8
	September	184.2	124.7	133.7	146.2	169.6
	October	116.4	122.4	117.9	108	123.3
	November	99.8	100.4	95.2	92.4	93.4
	December	114.1	110.5	97	97.2	93.9
1995	January	121.5	108.7	101.1	104.6	105.8
	February	157	123.1	114.7	122.4	146.3
	March	237.7	153.8	146.2	158.6	206.4
	April	286.7	159.4	158.3	174.1	212.3
	May	259.7	159	168.7	182.8	188.2
	June	258.8	144.9	160.4	176.3	196.2
	July	164.2	127.8	142.8	150.5	234.1
	August	131.6	135.8	140.1	133.7	159.3
	September	121.8	126.2	128.7	121.7	142.7
	October	106.3	120	116.9	108.8	123.9
	November	122.9	114.1	105.4	106.6	116.2
	December	119.9	111.6	100.6	103.8	105.6
1996	January	143	116.6	107.9	115.9	124.6
	February	169.7	121.9	113.7	123.7	146.2
	March	238.3	163.1	153.8	166.1	219.6
	April	239.1	160.4	158.9	167.1	220
	May	324.6	159.2	173.2	202.4	200.2
	June	192.1	138.8	152	161.3	246.7
	July	169.9	130.7	147.3	156.6	185.7
	August	106.2	124.1	131.5	130.1	149.6
	September	102.4	123.9	123.8	112.8	131.1
	October	100.2	112.9	110.8	102.8	113.1
	November	110	113.3	104.8	100.4	107
	December	94.6	105.5	97	96.9	94.3
1997	January	112.9	110	102.5	105.3	106
	February	150.1	126.2	117.3	128.8	151.6
	March	217.4	165.1	153.2	161.3	209.2
	April	232.1	162.2	155.9	163.2	213.7
	May	276	167.7	169.5	181.7	241.2
	June	254.9	146	159.1	173	215.2
	July	186.1	147.3	153	154	187.8
	August	168.5	138.1	145.8	147	172.6
	September	118.2	135.1	131	119.6	141.8
	October	135.1	133.8	124.9	116.2	135.7
	November	90.5	106.6	99.8	91.4	99.1
	December	90.1	105.6	97.6	91.2	94.1
1998	January	127.1	120	109	111.5	121.9
	February	162.8	129.9	117.9	123.8	149.1
	March	245	160.2	150.4	159.1	207.8
	April	270.2	173.2	163.4	167	144.6
	May	275.2	169.5	171.7	182.6	163.1
	June	242.1	146.7	157.8	169.7	212.6
	July	145.1	147.7	148.4	140	170.8
	August	120.2	142.6	141.3	128.3	153.6
	September	95.5	128.3	125.5	109.6	127.9
	October	88.2	121.6	116.1	102.4	114.6

	November	97.9	112.5	103.3	98.4	104.6
	December	98	113.9	99.3	98.7	95.4
1999	January	113.4	123.4	108	109.2	111.4
	February	159.3	131	117.5	122.1	144.1
	March	207.6	172.9	155.2	157.2	208
	April	258.5	173.7	166.5	173	233.5
	May	228.5	166.9	166.7	166.4	211.1
	June	185	143.8	151.6	150.5	181.2
	July	184.5	140.6	148.1	149.4	179
	August	144.3	134.7	138.6	134.5	156
	September	131.5	127.6	126.2	119.1	138.2
	October	129.8	129.5	121.6	114.9	133.2
	November	129.3	116.6	105	105.5	115
	December	118.7	114.7	100.6	102.4	102.7

Table 3 : Average Monthly Evaporation (mm) for the period 1984-1999 calculated by different methods

Month	**Observed (Kurnool Station)**	**Penman Method**		**Van Bavel Method**		**Kohler Method**		**Penman-Montieth Method**	
		Evaporation	Pan Coeff.	Evaporation	Pan Coeff.	Evaporation	Pan Coeff.	Evaporation	Pan Coeff.
January	133.6	114.8	0.75	105.2	0.69	110.9	0.73	117.2	0.77
February	167.6	122.5	0.64	115.1	0.60	125.5	0.65	146.2	0.76
March	236.5	157.5	0.58	150	0.55	161.4	0.60	179.9	0.66
April	265.3	159.2	0.52	159.8	0.53	173.3	0.57	145.9	0.48
May	288.5	158	0.48	170.2	0.52	189.5	0.57	162.1	0.49
June	222.6	133.8	0.53	152.5	0.60	167.6	0.66	198	0.78
July	171.4	130.3	0.66	143.7	0.73	149.8	0.76	182	0.93
August	147.4	128	0.76	137.3	0.81	138.4	0.82	161.8	0.96
September	139	126.5	0.80	129.1	0.81	126.5	0.80	149.5	0.94
October	124.8	126.3	0.88	120.4	0.84	113.7	0.80	133.6	0.94
November	114.7	108.8	0.83	101.2	0.77	99.6	0.76	108.8	0.83
December	111.3	107.1	0.84	97.7	0.77	99.6	0.78	102.6	0.81
Total	2122.7	1572.8	0.65	1582.2	0.65	1655.8	0.68	1787.6	0.74

Table 4 : Average Seasonal Evaporation (mm) for the period 1984-1999 calculated by different methods

Season	**Observed (Kurnool Station)**	**Penman Method**		**Van Bavel Method**		**Kohler Method**		**Penman-Montieth Method**	
		Evaporation	Pan Coeff.	Evaporation	Pan Coeff.	Evaporation	Pan Coeff.	Evaporation	Pan Coeff.
Monsoon (June - September)	680.4	518.6	0.67	562.6	0.72	582.3	0.75	691.3	0.89
Post-Monsoon (October - November)	239.5	235.1	0.86	221.6	0.81	213.3	0.78	242.4	0.88
Winter (December - February)	412.5	344.4	0.73	318.0	0.67	336.0	0.71	366.0	0.78
Summer (March - May)	790.3	474.7	0.53	480	0.53	524.2	0.58	487.9	0.54

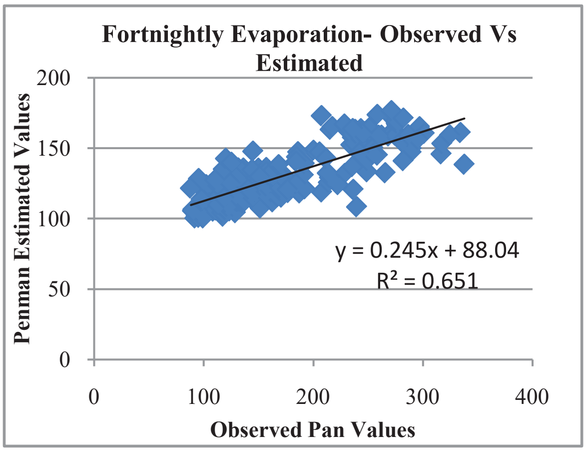

Figure 2 : Regression - Penman Vs Observed Values

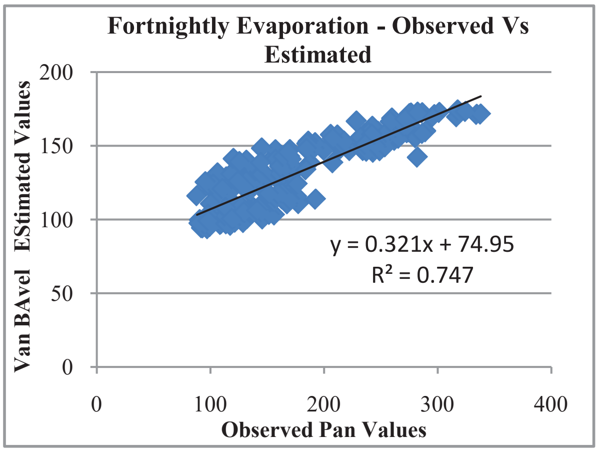

Figure 3 : Regression - Van Bavel Vs Observed Values

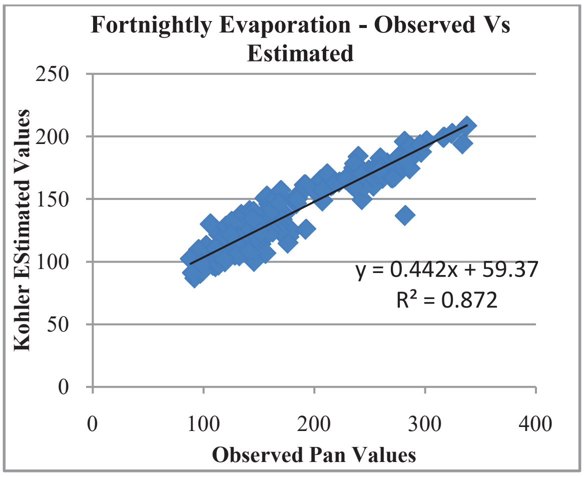

Figure 4 : Regression - Kohler Vs Observed Values

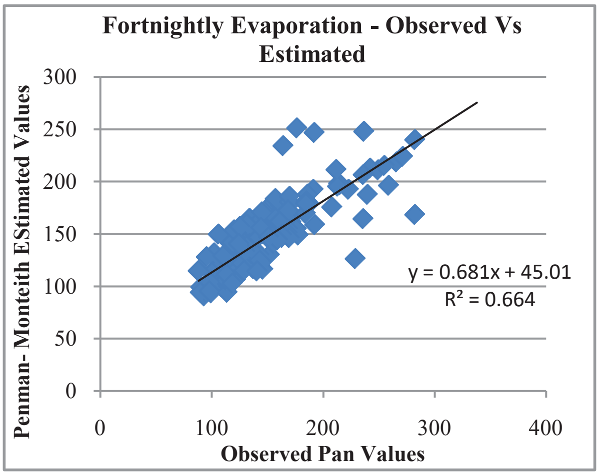

Figure 5 : Regression - Penman-Montieth Vs

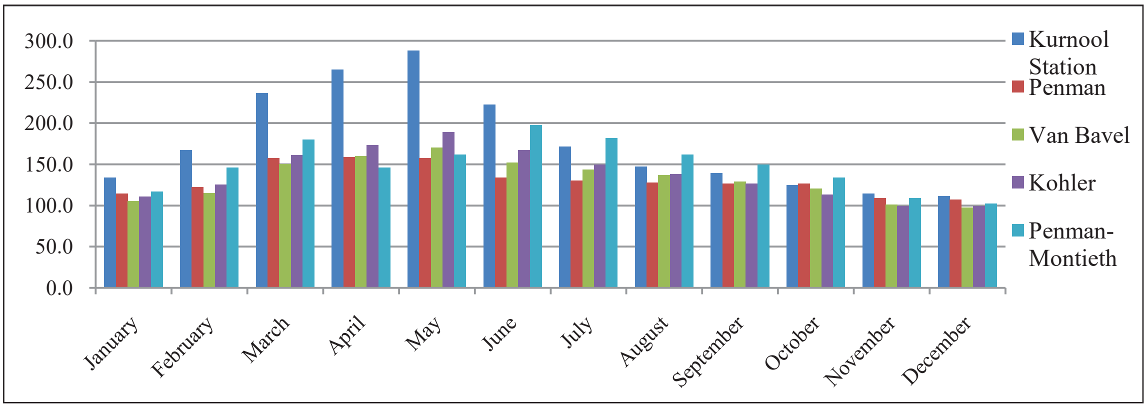

Figure 6 : Average Evaporation (mm) values computed by different methods

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