CASE STUDY CS-(AR) 180

ESTIMATION OF EVAPORATION FROM FREE WATER SURFACE IN SEMI ARID AREAS

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PREFACE

Evaporation is an important component of hydrological cycle from the time water fall up on the land as precipitation until it reaches or returned to atmosphere. The evaporation includes evaporation from free water surfaces, land surfaces, soils, man made surfaces etc. It has increasingly importance in water resources planning especialy in arid and semi arid areas. Evaporation over a reservoir can be a major water management problem, more so if the reservoir is shallow or is meant for storing water for a specific use over a period of several years. For the efficient management of available water in the reservoirs, reasonably accurate estimates of monthly or weekly evaporation are needed. The estimation of such evaporation requires either detailed instrumentation of the reservoir or an intuitive application of local physical and climatic data. This study deals with the estimation of evaporation losses from free water surface at Bargi reservoir located in Jabalpur district in Madhya Pradesh. It is expected that the methods presented in this report will be use full for field engineers for planing and management of water resources in semi-arid areas.

This study has been carried out by Shri R. P. Pandey, Scientist 'B'. The guidence was provided by Dr. K. S. Ramasastri, Scientist 'F' and Head of Drought Studies Divosion. The assistance was provided by Shri Y.K.Dhama

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ABSTRACT

Actual evaporation losses from natural water surfaces can still not be determined by direct measurements. The relationship between natural evaporation and pan evaporation is a perplexing problem in comperative studies. In literature, the pan to lake coefficients have greater variation with time and space. Also, because of the thermal regimes of pans and lakes are markedly different owning to size, exposent and container effect.

The study aims at assessing the adaptability of different methods and use of pan lake coefficient for estimation of evaporation from free water surface in semi arid areas. Estimates of evaporation obtained through four methods namely Penman, Kohler, Van Bavel and Morton and observed values of US class A Pan have been compared on monthly, seasonal and annual basis. It was seen thatthe estimates of the mean value of evaporation in winter months are lower than those of pan values, where as in monsoon, post monsoon and summer season differences are comparatively less and estimates are closer to pan values. The comparison of pan values with the estimates indicated that the Kohler method provides better estimates of evaporation for all the months. Also, on the basis of comparison of annual values, Kohler and Morton methods were found to provide better estimates as compared to Penman and Van Bavel models.

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1.0 INTRODUCTION

Semi arid areas in India, occupy a large stretch of land from north to south. Evaporation plays an important role in the water regime of water bodies and yield of lakes/reservoir could be seriously affected by the evaporation loss. Semi arid areas of country have highly erratic rainfall, the accurate information on evaporation is important in planning and development of water resources specially in areas where water is to be stored for drought management. A review of various studies on evaporation in India indicated that the annual evaporation losses from reservoirs in arid and semi arid areas vary from 1.5 m to 3.0 m, which represents about 20 to 25% of.their water budget. It has been estimated that the average annual evaporation from lake Mead above Hoover dam is about 6 ft. The National Commission on Agriculture (1976), Water Management Forum (1988) and Central Water Commission (1990) reported that the evaporation losses from surface storages in India are in the order of 50,000 to 60,000 MCm. According to Water Management Forum (WMF), the above losses would be adequate to meet the entire urban and rural water needs of India until 2000 A.D.

Evaporation, which is a complex natural process, is one of the most obscure components of hydrologic cycle to measure accurately. There are two basic reasons for this obscurity. First, no instrumentation exists which can measure actual evaporation from a natural surface. Second, the limitations of indirect methods, which are not able to represent the physical process of evaporation completely through mathematical expression. Estimation of evaporation would require either measurement with approprite instrumentation or a judicious application of climatic and physical data through reliable or acceptable methods..

The pan evaporation does not represent the lake evaporation due to phase difference in the storage of heat due to solar radiation in pans and lakes. The other factor is the difference in way the pans and lakes are affected to advective heat transfer, which is due to their different aerial extent and exposure to wind. Reliable estimates of lake evaporation can, however,be obtained by application of the appropriate pan to lake coefficient. (WMO, Tech. Note 126).

There are more than 112 evaporation pans in India out of which about 80 are located in semi arid areas. The objective of the study is to evaluate pan coefficient which may be useful to get reliable estimates of evaporation from free water surface in a semi arid region.

2.0 FACTORS RESPONSIBLE FOR PHYSICAL PROCESSES OF EVAPORATION

Evaporation is the process by which water is changed from the liquid or solid state into the gaseous state through the transfer of heat. For evaporation to occur continuously, there should be a supply of energy to provide the latent heat of vaporization (600 cal./gm of water) and some mechanism to remove the water vapour.

Clearly, evaporation depends on the supply of heat energy and the vapour pressure gradient, which in turn depends on the meteorological factors such as water and air temperature, wind, atmospheric pressure, solar radiation, quality of water and nature and shape of evaporation surface.

Because evaporation is basically an energy exchange process, solar radiation is the most important factor governing evaporation. It directly affect the temperature of the evaporating surface. As such, the temperature at the water surface is very significant for the estimation of evaporation. There are number of physical processes which transfer heat energy within the water mass. They vary in importance from climate to climate, from lake to lake and from season to season. They determine the vertical and horizontal temperature distributions in the water body and affect essentially its chemical and biological characteristics. Water temperature and vapour pressure are not independent of wind speed. The vapour pressure of a water body increases with temperature. Equal temperatures increases of water surface and overlying layer may not increase rate of evaporation. Depending upon the size of the water body, the water temerature may lag behind air temperature. However, evaporation is not dependent on air temperature alone.

The effect of wind on the evaporation also depends on the size of the water body. Large water bodies may require high velocity and turbulent air movement for maximum evaporation. Winds upto 25 miles/hr may be needed to increase evaporation. in the long run, a 10% change in the wind speed will change the evaporation 1 to 3% only.

A body of water with a flat surface has greater vapour pressure than one with a concave surface but less than one with a convex surface under the same conditions. Melting point of snow and ice ($0^{o}C$) lies within the range of normally experienced range of temperature. So, evaporation can only occur if the dew point is lower than that of the temperature of the snow. Evaporation from snow is less than that from water. With snow at $-1^{o}C$ and due point of $-6.7^{o}C$ the evaporation rate is only one-fifth that from a water surface at $26.6^{o}C$ when the dew point is $24^{o}C$, wi6th the same wind speed assumed in both the cases. Moreover it requires more heat to evaporate snow than water; at the latent heat of sublimation is 677 cal/gm. and the heat of evaporation 597 cal/gm.

The rate of evaporation decreases with increase in specific gravity (Singh, 1989).. Dissolved salts bring down vapour pressure of the solution. The vapour pressure of sea water (35,000 ppm dissolved salts) is about 2% less than of pure water at the same temperature. The reduction in evaporation is less than that indicated by the change in vapour pressure because with reduced evaporatin there is an increase in water temperature which partially offsets the vapour pressure reduction. Even in the case of sea water, the reduction in evaporation is never in excess of a few percent (over an extended period of time), so that salinity effects can be neglected in the estimation of lake evaporation (Varshney, 1974).

Wind stir up the air and remove the lowest moist layers adjacent to the lake water surface and to mix them with upper driven layer. So, wind affects the evaporation from the lake - quantity of availablewater. However, the relationship between wind speed and evaporation holds good only to a certain point, beyond a certain critical value, any further increase in wind speed leads to no further increase in evaporation. Actually, wind does not cause evaporation from the lake, but by "clearing the air" it permits a given rate of evaporation to be maintained. Evaporation of water from lake is greatest in warm, dry conditions because of saturation deficit is large (Ward, 1967).

3.0 REVIEW OF LITERATURE

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 surveys of water body and making it an expensive deal. Several other methods are less accurate but are considered reliable for estimate of evaporation from free water surfaces.

Although the subject of evaporation from a free water surface has been studied for at least two hundred years, the methods of measurement and estimation used are still inadequate.

Three groups of methods exist for the study of evaporation from water surfaces (Winter, 1981)..

1. Balance methods; the application of energy and/or water balance.
2. Comparative methods; the use of evaporation pans .or tanks, followed by the use of pan or tank coefficients.
3. Aerodynamic methods; eddy correlation, mass transfer and gradient methods.

Use of the balance method requires the measurement of all other components of the respective balance equation except the component related to evaporation. In the case of the energy balance equation, this implies the measurement of incoming short, wave and ong wave radiation, air temperature, deq point, wind velocity and surface water temperature. besides these, periodic temperature surveys of the entire water body are needed. It advective energy cannot be neglected, The temperature and amount of the different components of the water balance should also be measured or estimated. Lake Toba is in north Sumatra, Indonesia and is largest fresh water lake in Indonesia. A detailed study (Sene et.al., 1991) has been done on this tropical lake perhaps for the first time to estimate evaporation on the basis of energy budget methods. The investigators have indicated the appllicability of energy budget method with the assumption that the average energy for evaporation is equal to the net radiation. It is estimated that the annual average evaporation from the lake is about 1.5 m. Lake Kinneret (average area = 160 sq. km.) in Israel and in which river Jordan falls is a major contributor to the Israeli water supply scheme. Evaporation from this lake is quite high and has been estimated to be 30% of its water budget (Simon and Mero, 1985).

In comparative methods, the perplexing problem is the relationship between lake evaporation and pan evaporation. The thermal regimes of pans and lakes are usually markedly different. Seasonal changes in sub surface heat storage are not reflected in pan observations. Although floating pans can be used to overcome some difficulties, the ultimate goal has been to find a method that would permit the estimation of lake evaporation from pans installed on the surrounding land. In the studies being done at the Institute of Hydrauulics and Hydrology, Poondi, to find a material for floating evaporimeter whose thermal conductivity is equivalent to that of water (0.556 W/m C) and at the same time non leaky and light in weight, perspex sheet which is akin to glass but at the same time non brittle, non leaky and workable was chosen for the fabrication of floating evaporimeter installed at Poondi reservoir. The unit has the sliding arrangement which follows the water surface and could be fixed at the desired location. A graduated gauge of requisite least count when fixed to the frame work shall enable the observation of water level fluctuations at the site of evaporation through the transparent perspex sheets (Makwana, 1992).

A number of studies comparing techniques of estimating evaporation are found in the literature (Antal et al., 1973; Keijman and Koopmans, 1973; Ficke, 1972; Harbech, 1962; Winter, 1981 etc). WMO (1966) reported many examples of comparative studies of various types of pans and tanks done world over. Antal et al.(1973) compared five evaporation formula to estimate evaporation from lake Balaton in Hungary and found that the monthly evaporation values differed by 10 to 15 percent from the average of all the methods whereas annual values showed a deviation of 5 percent from mean value. Keijman et.al.(1973) compared the energy budget, mass transfer, penman and pan coefficient methods in lake studies conducted at Flevo, the Netherlands, they found that the standard error of all the methods was 6 to 8 percent, except for the pan coefficient which was found to be about 20 percent. Ficke (1972) reported that the energy budget estimates tend to be lower than other methods during spring and autumn low evaporation rate seasons and higher during the summer high evaporation rate season. He stated that the spring time and short term energy budget data are perhaps less reliable as compared to mass transfer data.

Evaporation losses in tropical countries like India are high because of intense solar radiation, grater number of sunshine days, high wind speeds and long rainless periods. Various studies on evaporation in India indicated that the annual evaporation losses from the reservoirs in arid and semi arid areas vary from 1.5 m to 3.0 m. Monthly and annual evaporation charts based on Rowher's empirical formulae are widely used in India for the purpose of estimating evaporation losses from reservoirs. Sarma (1973) conducted a comparative study of observed and estimated values of evaporation in India. He described with an explanation of the anomalies between the observed and empirically estimated Rowher's values. Gangopadhyaya (1970) discussed the importance of global radiation in estimating pan evaporation from meteorological factors and presented computations of monthly values of pan evaporation for 9 stations located in different Agroclimatic Zones of India, to demonstrate the practical applicability of the method suggested. He concluded that the Kohler's formula by and large gave acceptable evaporation estimates.

In an attempt for estimating evaporation losses from large reservoirs in India, Venkataraman & Krishnamurthy (1973) also compared few methods of estimating mean daily shallow lake evaporation. They reported that Penman's classical equation gives rational estimates and Kohler's coaxial graphical technique using climatologically derived estimates of radiation term also seems to be adequate.

4.0 PAN-LAKE EVAPORATION RELATIONSHIP

The rate of evaporation from a pan is greater than that from large water bodies. So a suitable pan coefficient may be used to convert the pan observation to get an estimated value of evaporation for a lake. Kohler (1959) and Andersen et.al (1982) had calculated evaporation from lakes by converting measured evaporation from pans by applying a coefficient. Bleney had studied the effects of high altitude on evaporation from pans and determined suitable coefficients. Studies by Bigelow has shown that the location of pans relative to the water of a reservoir has significant effect on the calculated evaporation. He concluded that evaporation from natural lakes or reservoirs is about five eighth of that measured from an isolated pan placed outside the vapour blanket Further studies by Rohwer, Kohler, Mansfield showed that the evaporation coefficient ranges anywhere between 0.2 to 1.5 and this factor is dependent upon the size, depth and location of pan. With this kind of evaporation measurement, it is essential that the coefficient of evaporation be measured under all different conditions, which is not practically feasible in large water storage systems. The ratios of annual reservoir evapooration to pan evaporation are found to be consistent from year to year and region to region but exhibit considerable variation from month to month. Pan should not be used to estimate evaporatin for shorter time period.

The most commonly used coefficient to estimate annual or seasonal lake evaporation from a Class A pan data is 0.7. It is widely recognized that the coefficient should be lower for lakes in arid regions than for lakes in humid climates. A value of 0.52 was obtained for the Salton Sea, California and 0.81 for Lake Okeechobee, Florida (Hounam,. 1973) vide Kuusisto, 1985). The annual average Class A pan coefficient to be 0.69 for lake Hefner, Oklahoma. This is in fair agreement with the results of other investigations indicating that the evaporation pan method of determining annual lake evaporation may be accurate to within perhaps 10 or 15 percent, provided care is taken in measuring pan evaporation and selecting the coefficient to be used. In cold climates where lakes are ice covered in winter, the Class A pan coefficient for the open water season also tends to be large (Jarvinen, 1978). In addition to the regional variation of pan coefficients, there is a remarkable seasonal variation for many climates. The monthly evaporation pan coefficients vary more widely and with a greater range of probable error than the annual coefficients. The coefficients tend to be smaller than the annual average in the winter and spring and larger in summer because of the lag between lake water temperature and the pan water temeperature. Since the temperature lag is greater for deep lakes, it is expected that the monthly variation in the coefficients is greater for deep lakes for a climate which has large seasonal variations in temperature. Obiviously the use of constant value for each month can lead to serious error.

Also the studies conducted in India indicate that the pan to lake coefficients show considerable variation both in space and time. Ramdas (1957) has described how estimates of natural evaporation may be made from pan evaporation. He reported that pan coefficients may vary somewhat with the season (and even monthly), locality and difference in exposure. He suggested the pan coefficient of the order of 0.87 for wet period (when ground saturated, after rain). once a rainy spell is over, the pan coefficient drops down between 0.87 to 0.60, and for dry weather period it is lower, of the order of 0.60. In order to account for variation of the lake-pan relationship under different climatic regions in India, Bureau of Indian standard (IS:6939-1973) recommended the pan factor (for India) between 1.10 to 0.9 for lake evaporation of the order of 4 to 5 mm/day, between 0.75 to 0.65 for lake evaporation of the order of 10 mm/day and about 0.8 for transition months. Sarma (1973) concluded that for class A Pan, the coefficient range from 0.60 in winter to 0.82 in summer. Ramasastri (1987) recommended pan factor as 0.7 for the conditions when the pan water temperature and air temperature is on the average equal. In warm and arid areas, the pan water temperature is on the average less than the air temperature and, when compared with evaporation from lakes or tanks the coefficient would approach 0.60. In humid areas, the average pan water temperature exceeds air temperature and coefficient would tend to be nearly

0.80 (Ramasastri, 1987). He suggested the following pan-lake coefficients for different seasons in india.

		Coefficient		
		0.6	0.7	0.8
I	North of 22^{O} latitude	Nov-Feb	Mar-Apr Sep-Oct	May-Aug
II	South of 22^{O} latitude	Dec-Jan	Feb-Mar Sep-Nov.	May-Aug

5.0 DESCRIPTION OF THE STUDY AREA

District Jabalpur fall in a semi-arid agro-climatic zone. The Bargi reservoir is constructed across river Narmada located near village Bargi inJabalpur district (between $22^{O}56'30''$ N latitude and $79^{O}55'30''$ E longitude). The reservoir has water spread area of about 27297 ha. at FRL 422.76 m with live storage of 3.18 billion m^3. In this region the maximum and minimum value of humidity and temperature ranges from 95% to 22% and $42^{O}C$ to $7^{O}C$ respectively. This study has been carried out using the meteorological data of a meteorological observatory, located at Adhartal in Jabalpur district in Madhya Predesh.

In this study the meteorological data collected at above observatory has been used for estimation of evaporation. The data include air temperature (maximum & minimum), due point temperature, actual sun shine hours, wind speed, pan evaporation.

6.0 METHODOLOGY

Four well known and widely used methods have been selected for estimation of evaporation from free water surface. These methods are (1) Morton (1979)(2) Penman (1963) (3) Kohler et. al (1954) and(4) Van-Bavel Businger (1966). The measured pan evaporation at the dam site has been utilised to derive Pan-to-lake correction factors for winter (December to February), monsoon (June to September), postmonsoon (October and November) and summer (March to May) seasons. In present study a correction factor of 1.144 for the mesh cover on pan (WMO 1966) has been considered seperatly.

The pan evaporation values and models' evaporation estimates are compared on monthly, seasonal and annual basis. The linear regression analysis were carried out in order to derive relationship between models' estimates and pan values. The models' results are also subjected to statistical analysis to evaluate their adoptability for arriving at acceptable estimates.

6.1 DESCRIPTION OF METHODS USED FOR EVAPORATION ESTIMATION

There are several well recognized methods available for evaporation estimation. These methods include various equations primarily based on solar radiation, humidity, temperature, wind and miscellaneous principles. The selection of method for a particular use may depend on the accuracy of available meteorological data and the general acceptance of previous estimates. In this study the four recommended methods have been selected for estimation and evaluation of evaporation from Bargi reservoir in Jabalpur districti in Madhya Pradesh. These methods are (i) Morton (1979) (ii) Penman (1963), (iii) Kohler et.al.

(1954), and (iv) Van Bavel & Businger (1966,1956). Computer programmes have been developed for all the four methods.

6.1.1 Morton Method

Morton (1979) defined the lake evaporation as evaporation form a water surfaces so large that the effects of the upwind share line transition can be ignored. He used the following equations as the basis for the model that provides monthly estimates of lake evaporation from climatological observations. This model was recommended to estimate evaporation from lakes in anywhere in the world.

$$E_W = \psi \, (R_n + M) \qquad \ldots(1)$$

In which E_W = lake evaporation, R_n is net radiation if the surface were at air temperature, and the energy weighting factor ψ and advection energy M is defined by

$$\psi = 0.26\left[1+\frac{\lambda}{\Delta}\left(\frac{0.5+5r+\lambda/\Delta}{r+\lambda/\Delta}\right)\right]^{-1} \qquad \ldots(2)$$

$$M = 0.66 \, B - 0.44 \, R_n \qquad \ldots\ldots\ldots\ldots(3)$$

$$M \geq 0 \qquad \ldots\ldots\ldots\ldots(4)$$

Where r is relative humidity, equal to V_D/V. V_D and V are saturation vapour pressure at due point and air temperature respectively, B is net long wave radiation loss if the surface were at air temperature, λ is heat transfer coefficient and Δ is rate of change of saturation vapour pressure with respect to air temperature.

The procedure that is used in applying the model is as follows:

(1) For each station the model needs the following

(a) As input data

φ = latitude in degrees (negative in southern hemisphere)

$\bar{P}$ =long -term average annual precipitation ,mm/yr.

P = Average atmospheric pressure , millers.

H = Altitude above sea level, meters.

(b) Computation of the ratio of atmospheric pressure at the lake to that at sea level (p/p_s) . If the observations are available,divide the average by 1013 bar . If not, use the pressure correction equation for the standard pressure.

$$\frac{p}{p_s} = \left(\frac{228 - 0.0065H}{288}\right)^{5.256} \qquad \ldots\ldots\ldots\ldots\ldots (5)$$

(c) Estimate the minimum albedo for the land environment, if the sun were at the zenith a_z:

$$a_z = 0.11 + 0.86 \exp\left(- \frac{\bar{P}}{920(p_s/p - \sin|\varphi|)}\right)^5 \qquad \ldots\ldots\ldots\ldots (6)$$

(d) Estimate the transmittancy of cloud to clear sky global radiation τ_c:

$$\tau_c = 0.28 + 0.10 \exp\left[-\left(\frac{\varphi}{38}\right)^8\right] - 0.04 \exp\left[-\left(\frac{\varphi}{6}\right)^8\right] \ldots. (7)$$

2 . For each time period required input and calculation are

(i) Assemble input.

T = Average of maximum and minimum air temperature, °C;

T_D = Average dew point temperature , °C;

S = Ratio of observed to maximum possible sunshine duration;

i = Month number beginning with 1 in January and ending with 12 in December;

n = number of days in the month.

(ii) Compute the following :

$$v_D = 6.11 \exp\left(\frac{17.27\; T_D}{T_D + 237.3} \right) \qquad \ldots\ldots\ldots(8)$$

$$v = 6.11 \exp\left(\frac{\alpha\; T}{T + B} \right) \qquad \ldots\ldots\ldots(9)$$

$$\Delta = \frac{dv}{dT} = \frac{\alpha\, \beta\, v}{(T + \beta)^2} \qquad \ldots\ldots\ldots\ldots(10)$$

in which α and β are 17.27^{o} and 237.3^{o}, respectively, when $T \geq 0^{o}C$; or 21.88^{o} and $265.5^{o}C$, respectively ,when $T < 0^{o}C$.

(iii) Compute various angles and functions leading up to an estimate of the extra-atmospheric global radiation G_E :

$$\theta = 23.2 \sin (29.5\, i - 94) \qquad \ldots\ldots\ldots\ldots\ (11)$$

$$\theta \geq \varphi - 89.999 \qquad \ldots\ldots\ldots\ldots\ldots(12)$$

$$\theta \leq \varphi + 89.999 \qquad \ldots\ldots\ldots\ldots\ldots(13)$$

$$\cos w = -\tan \varphi \tan \theta \qquad \ldots\ldots\ldots\ldots\ldots(14)$$

$$\cos w \geq -1 \qquad \ldots\ldots\ldots\ldots\ldots(15)$$

$$\cos z = \sin \varphi \sin\theta + \frac{180}{w\,\pi} \cos \varphi \cos \theta \sin w \qquad \ldots\ldots\ldots(16)$$

$$\eta = 1 + \frac{1}{60} \sin (29.5 i - 106) \qquad \ldots\ldots\ldots\ldots(17)$$

$$G_E = (1354/\eta^2)(w/180) \cos z \qquad \ldots\ldots\ldots\ldots(18)$$

in which θ is the declination of the sun , w is the number of degrees the earth rotates between sunrise and noon , z is the average angular zenith distance of the sun , and η is the radius vector of the sun.

(iv) compute the minimum albedo a_L and the maximum albedo a_U :

$$a_L = 0.04[\exp(0.855) - (1.71/\pi)\cos|\varphi-\theta| + \sin|\varphi-\theta|)$$
$$\exp(0.0095)|\varphi-\theta|)]/[1.296(1-\sin|\varphi-\theta|)]^{-1} \qquad \ldots(19)$$

$$a_U = a_L + (a_U - a_L) \qquad \text{...........(20)}$$

in which $(a_U - a_L)$ is 0.00 when $T \geq 0^{\circ}C$, and 0.60 when $T < 0^{\circ}C$.

(v) Compute various functions leading up to an estimate of the incident global radiation G :

$$W = \frac{V_D}{0.49 + T/129} \qquad \text{................. (21)}$$

$$j = [0.47 + \cos^2(\varphi - \theta)] \exp\left[84.2\left(\frac{p}{p_s} - 1\right)(0.17 - a_Z\right] \qquad \text{.......(22)}$$

$$\tau = \exp\left[-0.089\left(\frac{p}{p_s \cos Z}\right)^{0.75} - 0.083\left(\frac{j}{\cos Z}\right)^{0.9} - 0.0288\left(\frac{W}{\cos Z}\right)^{0.6}\right] \qquad \text{..........(23)}$$

$$\tau_a = \exp\left[-0.05 - 0.01\left(\frac{j}{\cos Z}\right)^{1.8} - (0.00288)^{0.5}\left(\frac{W}{\cos Z}\right)^{0.3}\right] \qquad \text{.....(24)}$$

$$\tau_a \geq \exp\left[-0.05 - 0.01\left(\frac{j}{\cos Z}\right)^{1.8} - 0.0288\left(\frac{W}{\cos Z}\right)^{0.6}\right] \qquad \text{...(25)}$$

$$\tau_a \geq \tau \qquad \text{.................(26)}$$

$$G_O = G_{ET}\left[1 + \left(1 - \frac{\tau}{\tau_a}\right)(1 + a_Z a_L \tau/0.04\right] \qquad \text{........(27)}$$

$$G_O = G_{ET}\left[\tau_c(1 - S) + S\right] \qquad \text{........(28)}$$

in which W is the precipitable water vapor , j is the a turbidity coefficient , τ is the transmittancy of clear skies to direct beam solar radiation , τ_a is the part of τ that is the result of absorption , and G_O is the clear sky global radiation .

(vi) Compute various quantities leading up to an estimate of the net longwave radiation loss B :

$$S^{*} = \frac{G/G_{E} - 0.18}{0.55} \tag{29}$$

$$0 \leq S^{*} \leq 1 \tag{30}$$

$$C = (\ 1 - S^{*})^{0.75} \tag{31}$$

$$\rho = 1+[0.25-0.005\ (v-v_{D})]C^{2} \tag{32}$$

$$\rho \geq 1 \tag{33}$$

$$B = \varepsilon\sigma(T+273)^{4}[1-\rho\ (0.707+v_{D}/158)] \tag{34}$$

in which S^{*} and C are the sunshine duration ratio and the cloud cover ratio estimated from global radiation , ρ is the ratio of average to clear sky atmospheric radiation , ε is the emissivity , and σ is the Stefan-Boltzmann constant. With ε assumed to be 0.97, $\varepsilon\sigma$ is $5.50\times10^{-8}\ \mathrm{Wm}^{-2}(^{o}\mathrm{K})^{-4}$.

(vii) Compute the minimum net radiation R_{WL}, the maximum net radiation R_{WU} , the stability factor ζ , the relative humidity r , the vapor transfer coefficient f_{w}, and the heat transfer coefficient λ :

$$R_{WL} =(1 - a_{U})G - B \tag{35}$$

$$R_{WU} =(1 - a_{U})G - B \tag{36}$$

$$\zeta =\left(\frac{|v - v_{D}|}{v_{o}} \right)^{0.12} \tag{37}$$

$$r = v_{D}/v \tag{38}$$

$$f_{w} = (\ \zeta f_{w})/\zeta \tag{39}$$

$$\lambda = (\gamma p_{s})\frac{p}{p_{s}} + \frac{4\ \varepsilon\sigma(T+273)^{3}}{f_{w}} \tag{40}$$

in which v_o is the saturation vapor pressure at 0^oC (6.11 mbar), ζf_w and γp_s are 22.0 W m^{-2} $mbar^{-1}$ and 0.66 mbar $^oC^{-1}$, respectively, when $T \geq 0^oC$, or (22.0 x 1.15)W m^{-2} $mbar^{-1}$ and (0.66/1.15) mbar $^oC^{-1}$, respectively, when $T<0^oC$.

(viii) Compute in the order shown ,

$$D = \left(1+ \frac{\lambda}{\Delta}\right)^{-1} \tag{41}$$

$$\psi = \left[1 + \frac{\lambda}{\Delta}\left(\frac{0.5 + .5r + \lambda /\Delta}{r + \lambda /\Delta}\right)\right]^{-1} +0.26 \tag{42}$$

$$M = 0.66 B - o.44 R_{WU} \tag{43}$$

$$M \geq 0 \tag{44}$$

$$E = f_w(v- v_D) \tag{45}$$

$$E \geq \frac{0.7 \psi}{1 - D} M + \frac{\psi - D}{1 - D} R_{WL} \tag{46}$$

$$M \leq \frac{(1 - D)}{\psi}E + \frac{(\psi - D)}{\psi} R_{WL} \tag{47}$$

$$R_n = R_{WU} \tag{48}$$

$$R_n \leq \frac{1 - D}{\psi - D} E \frac{\psi}{\psi - D} M \tag{49}$$

$$E_P = DR_n+(1-D)E \tag{50}$$

$$E_w = \psi(R_n+M) \tag{51}$$

Where E is defined in (45) and (46) and all other symbols have been defined previously .

(ix) Divide R_n, E_P , and E_W by the latent heat of vaporization (28.5 W-day/Kg^{-1}) when T $\geq$ 0^oC , or by the latent heat of sublimation (28.5 x 1.15 W-day/Kg^{-1}) when T < 0^oC and then multiply the number of days n to change W m^{-2} to Kg m^{-2}. For water, this is equivalent to millimeters of depth .

6.1.2 Penman Method

Penman in (1948) first derived the equation (52) based on latent heat supply of the evaporating surface. This equation was modified considering that water is not limited and vapour Pressure is at the saturation vapour pressure at the surface. In 1963, he suggested equation (53) for estimation of daily potential evaporation, which is the original Penman formula.

$$\lambda E= \frac{\Delta(Rn+G)+\rho Cp(e^o_z - e_z)/ra}{\Delta+\gamma} \quad ... (52)$$

$$Ep=\frac{\Delta}{\Delta+\gamma}(Rn+G)+ \frac{\gamma}{\Delta+\gamma}15.36(1.0-0.0062u_2)(e^o_z - e_z) \quad ... (53)$$

where, Ep = Evaporation from a free water surface,

ra = Diffusion resistance of air layer

Following the evaporation studies at Lake Hefner, Oklahoma, and Penman suggested that the wind term in equation (53) be replaced by (0.5+0.01 u_2) for estimation of evaporation from large water surfaces. Finally the equation (54) is considered with all recommended modification

$$Ep=[\frac{\Delta}{\Delta+\gamma}(Rn+G)+\frac{\gamma}{\Delta+\gamma}15.36(0.5-0.01u_2)(e^o_z - e_z)]/59 \quad ...(54)$$

Where, Ep = Evaporation (mm day^{-1}); Rn = Net radiation (langley day^{-1}); G = soil heat flux(considered as zero for water surface); γ = Psychrometric constant; Δ = slope of saturation vapour pressure - temperature curve (de/dT) (mb C^{-1}); $e_z^o - e_z$ = Vapour pressure deficit (mb.); and u_2= Wind speed (mile day^{-1}).

6.1.3 Kohler Method

Kohler, Nordenson and Fox (1955) adopted the Penman equation to class A Pan evaporation by using γ_p = 0.00157P, mb C^{-1} , and for lake or open water evaporation by multiplying the solution by 0.7 with γ_l = 0.000661P, mb C^{-1} . The Kohler et.al. suggested the following equation for estimation of evaporation losses from lake/reservoir. They recommended this model for evaporation estimation on daily basis.

$$EK = 0.7\left[\frac{Rn\ \Delta}{\Delta+\gamma_l} + \frac{\gamma_l}{\Delta+\gamma_l} Ea\right] \qquad \text{..... (55)}$$

Where,

$$Ea = (e_z^o - e_z)^{0.88}(0.37+0.0041u_2) \qquad \text{...... (56)}$$

EK = Evaporation from lake/reservoir (inches day^{-1}); Rn = Net radiation (equivalent to inches of water); Δ & γ_l = Psychrometric constants (inches of Hg ^{o}F); $e_z^o - e_z$ = Vapour pressure deficit (inches of Hg.); and u_2 = Wind speed (mile day^{-1})

6.1.4 Van Bavel and Businger Method

A modification of the transfer coefficient proposed by Businger (1956) and derived from the Thornthwaite and Haltzman (1939), equation was presented by Van Bavel (1966). It assumes adiabatic conditions and transfer coefficient for heat equals to transfer coefficient for vapour (h_h = h_v). He suggested the following equation for estimation of potential evaporation.

$$Ev=[\frac{\Delta}{\Delta+\gamma}(Rn+G)+\frac{\gamma}{\Delta+\gamma}[\frac{0.622\lambda\rho k^2}{P}\frac{u_z}{[\ln z/z_o]^2}(e^o_z-e_z)]/59 \qquad ...(57)$$

Where, Ev = Evaporation (mm day^{-1}); Rn = Net radiation (langley day^{-1}); G = soil heat flux(considered as zero for water surface); γ = Psychrometric constant; Δ = slope of saturation vapour pressure - temperature curve (de/dT) (mb C^{-1}); $e^o_z - e_z$= Vapour pressure deficit (mb.); and u_z = Wind speed (Km day^{-1}).

since ρ and p decrease with increase in elevation with λ =585 cal g^{-1} and p = 1000 , the factor $0.622\lambda\rho k^2/p$ is considered as constant. Where,λ= latent heat of vaporization(cal gm.$^{-1}$); ρ= air density(gm. cm^{-3}); p = atmospheric pressure (mb); and k = Von Karman's constant.

6.2 ESTIMATION PARAMETERS

This section discusses the controlling characteristics and variables of atmospheric system which governs the physical properties of evaporation process at water-air interface. The Governing parameters of Penman, Kohler and Van Bavel models have been estimated as follows.

6.2.1 Net Radiation (Rn):

Net radiation is the difference between all incoming and outgoing radiations. It can be measured, but such records were not available. It has been calculated from sun shine hours, temperature, and humidity data using following relationships.

$$R_{bo} = \varepsilon'\sigma(T+273)^4 \qquad ..... (58)$$

$$R_{so} = \frac{R_s}{[0.35+0.6(\frac{SSH}{MSH})]} \qquad ..... (59)$$

$$R_b = R_{bo}[\frac{1.2\ R_s}{R_{so}}) -0.2] \qquad \ldots\ldots (60)$$

$$R_s = 59[0.31+0.49(\frac{SSH}{MSH})]R_A \qquad \ldots\ldots (61)$$

$$R_n = (1.0-\alpha)R_s - R_b \qquad \ldots\ldots (62)$$

Where, R_n=Net Radiation (langley day^{-1}); α = Short wave reflectance (α =0.5 for free water surface); SSH=Actual sun shine hours (hours day^{-1}); MSH=Maximum possible sun shine hours based on latitude and the time of the year (hours day^{-1}); ε' = Emissivity constant = $(0.39-0.05\ \sqrt{e_d})$; σ = Stefan-Boltzmann constant = (11.71×10^{-8})cal $cm^{-2}\ {}^{o}k^{-4}\ day^{-1}$; e_d= Saturation vapour pressure at due point temperature (mb); T = Temperature (^{o}k); and R_A= Extraterrestrial solar radiation based on latitude and the time of the year (equivalent to mm day^{-1}).

Values of MSH and R_A have been taken from published tables.

6.2.2 Vapour Pressure Deficit:

The difference between mean saturation water vapour pressure (e_z^o) and mean actual vapour pressure (e_z) is expressed as vapour pressure deficit. Actual air-vapour pressure can either be computed using relative humidity times the saturation vapour pressure at the air temperature or as the saturation vapour pressure at due point temperature. Since the data for due point temperature was not available, therefore the actual vapour pressure has been estimated using relative humidity records. The saturation vapour pressure at a given temperature has been estimated using following relationship.

$$e_z^o = 33.86[0.000738T+0.8072)^8 - 0.000019|1.8T+48|+0.00136] \quad ...(63)$$

$$e_z = e_z^o \times \frac{Rh}{100} \quad ...(64)$$

where, e_z^o = Saturation vapour pressure (mb); e_z = Actual vapour pressure at temperature (mb); Rh = Relative humidity (%); T = Temperature (^{o}C).

6.2.3 Common parameters

a) Psychrometric constant (γ): Psychrometric constant represents a balance between the sensible heat gained from air flowing past a wet bulb temperature and the sensible heat transformed in to latent heat (Brunt, 1952). It is calculated as

$$\gamma = \frac{C_p P}{0.622 \lambda} \quad ...(65)$$

(γ in mb $^oC^{-1}$)

$$\lambda = 595 - 0.51 T \quad ...(66)$$

Where, λ = Latent heat of vaporization (cal g^{-1}); C_p = Specific heat at constant pressure (cal g^{-1} ^{o}C)

b) Slope of saturation vapour pressure curve (Δ): Change in saturation vapour pressure (Δ) with temperature is evaluated using Bosen's formula for saturation vapour pressure.

$$\Delta = \frac{de^o}{dT} = 33.8639[0.05904(0.00738T+0.8072)^7 - 0.0000342] \quad ....(67)$$

(Δ in mb $^oC^{-1}$)

c) Atmospheric pressure (P) and density (ρ): The following linear relationships which are based on NACA (National Advisory Committee for Aeronautics, USA) standard atmosphere, are used to estimate atmospheric pressure and density.

$$P = 1013 - 0.1055EL \qquad \ldots(68)$$

(P in mb)

$$\rho = 0.00123 - 0.000034E/1000 \qquad \ldots(69)$$

(ρ in g cm^{-3})

where, EL = Elevation (m)

7.0 RESULTS AND DISCUSSION

The estimates of evaporation from water surface obtained by Penman, Kohler, Van Bavel and Morton equations and observed pan values have been utilised to derive pan to lake coefficients for four different seasons (Table 1). The seasonal variation of the pan coefficient value, is likely to be pronounced over Jabalpur region because of temperature variation, in different seasons, on account of differential heating of the water in pan and lake and consequent water temperature difference over the two surfaces. A comparison of calculated pan to lake coefficients with that of ISI (1973), Sarma(1973) and Ramasastri (1987) shows that the values derived with Kohler method are in good agreement.

Table: 1. Pan to lake coefficient for different methods

Sl No.	Season	Penmen	Kohler	Van Bavel	Morton
1	Winter	.44	.80	.40	1.10
2	Monsoon	.70	.91	.76	.96
3	Post monsoon	.50	.99	.53	1.15
4	Summer	.50	.76	.53	.70

The estimates obtained by Penman and Van Bavel models appear to be lower. Specially in winter months, these estimates are lower, on average by 100% or more. The estimates based on Kohler and Morton methods are closer to pan values, (on average within ±10% for all the months) and results are comparable. Also on the annual basis, the results of estimates by Kohler and Morton methods are closer to observed pan values. However, Gangopadhaya et.al (1970) found evaporation estimates by Penman's or Kohler's methods to be under estimates in parts of India. A comparison of monthly and annual estimates by the different methods is given in Table 2.

Table: 2. Monthly values of free water surface evaporation averaged over 20 years (1971 to 1990) in mm/month

Month	Pan value	Penman Model	Kohler Model	Van Bavel Model	Morton Model
Jan	82.31	36.21	79.47	32.98	91.35
Feb	104.90	47.63	91.38	46.24	108.45
Mar	188.01	96.10	160.05	95.82	157.65
Apr	287.40	143.25	211.26	151.59	191.30
May	377.27	187.60	251.13	210.65	218.60
June	279.60	147.39	190.27	168.68	178.70
July	129.50	92.09	114.50	99.82	112.75
Aug	102.15	79.48	99.03	83.92	104.90
Sept	115.89	82.38	116.43	84.53	146.35
Oct	119.54	73.33	122.78	70.53	144.15
Nov	98.81	45.60	94.98	40.88	106.10
Dec	76.57	30.94	75.04	26.01	86.05
ANNUAL	1961.95	1062.00	1606.32	1111.65	1646.35

Linear regressions have been developed in order to get one to one relationship among estimates from four methods and with pan values. Results of cross correlation matrix are shown in table 3.

Table:3 Cross Correlation Matrix for monthly values of estimated evaporation and pan evaporation

	Pan	Penman	Kohler	V'Bavel	Morton
Pan	1.000				
Penman	.950	1.000			
Kohler	.972	.965	1.000		
V'Bavel	.944	.996	.948	1.000	
Morton	.904	.911	.958	.886	1.000

General statistics of monthly values presented in table 4, also indicates relatively better performance of Kohler and Morton methods. The statistical parameters such as Variance, and range, are observed to be relatively higher for Van Bavel and Kohler methods. This indicates that the estimated monthly values by Van Bavel method and Kohler method have greater dispersion. The skewness of the data series is different from zero, which indicates that the data/estimates do not follow the normal distribution, but is skewed either positively or negatively.

Based on the above results it may be said that both Kohler and Morton methods may be considered as comparatively useful approach for reliable estimation of evaporation from free water surfaces.

Table:4 Statistical abstract of monthly values of pan and estimated evaporation (1971 to 1990)

Variable:	Pan	Penman	Kohler	Van Bavel	Morton
Sample size	240	240	240	240	240
Mean	163.861	88.707	134.088	92.861	137.402
Geometric mean	140.797	76.452	123.783	76.370	130.646
Variance	9680.55	2303.49	3165.06	3250.72	1892.21
Standard deviation	98.389	47.994	56.258	57.015	43.499
Standard error	6.364	3.104	3.639	3.688	2.813
Minimum	48.67	25.73	62.93	17.67	42
Maximum	465	217.93	288.92	250.17	243
Range	416.33	192.2	225.99	232.5	201
Skewness	1.211	0.788	0.910	0.882	0.440

8.0 CONCLUSIONS:

The comparison of pan valuesand estimated evaporation values indicate that the Penman and Van Bavel model provide under estimates of evaporation from free water surface, where as, the estimates obtained by Kohler model and Morton model have better correlation with observed pan values during all the months. Also, on the basis of comparison of annual values, the results of both Kohler and Morton model are in good agreement and look much more optimistic than that of Penman and Van Bavel models. Thus it is concluded that the Kohler model and Morton Model are acceptable for estimation of evaporation from free water surface.

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