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ESTIMATING EVAPORATION LOSSES FROM LAKES AND RESERVOIRS

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ABSTRACT

Engineers, planners and all concerned with water resources require an estimate of evaporation losses from lakes and reservoirs for the efficient reservoir operation and the water balance studies, specially in arid and semi arid regions and in drought affected areas while designing drought alleviation schemes. The exhaustive and detailed review of literature indicates that the methods of mass transfer and Penman equation can be considered as good alternative to provide relatively better estimates of evaporation losses from lakes and reservoirs in the absence of large amount of data required for the energy budget method. The evaporation losses obtained for Bhadra Reservoir Project by using mass transfer method generally points towards a lower value. Estimates obtained by Penman method appear to be relatively more reliable and in this method pan coefficient is also relatively more in winter period (i.e.0.99) as compared to that of summer period (i.e.0.88) which is same as the normally accepted trend.

1.0 INTRODUCTION

Evaporation from the water surface is an important and growing loss from the water budget, especially in the arid and semi-arid regions. The loss of stored water by evaporation from lakes, reservoirs and tanks is an important consideration in the planning and design of reservoirs and tanks or any water impounding structure and especially in designing of drought alleviation projects. Annual evaporation from a water surface in the semi-arid tropics may be as high as 2000 mm. In such areas there will be a large net loss of water at the reservoir site, if the annual rainfall of such region is 400 mm or so. It has been estimated that about 62,000 cubic kilometers of water is evaporated annually from the lakes and land surfaces of the earth. In India due to scanty and uncertain rainfall and high prevailing temperatures, huge amount of water is evaporated from large tracts. The estimate made elsewhere indicate that the water loss due to evaporation amounts to about 5 million ha.m from the total storages of 15 million ha.m in the reservoirs, tanks and lakes spread all over the country.

The rate at which water is lost from the lakes and reservoirs by virtue of evaporation is of considerable importance in water resources planning and management. It is an essential component of hydrologic cycle which plays a major role in water balance studies and assessment of water availability from lakes, reservoirs and tanks. Anticipated evaporation is a decisive element in the design of water impounding structures. Engineers, Planners and all concerned with water resources require an estimate of the net loss of water that will result from a new reservoir when it is impounded. The estimates of evaporation are required for the existing reservoirs also for the efficient reservoir operation and the water balance studies. For augmenting water storage and ensuring efficient management of reservoir waters, the exercise of estimating evaporation losses is a must. In drought affected areas, a knowledge of evaporation losses from lakes and reservoirs is required to design drought alleviation schemes. On a smaller scale, the design of a farm pond or an urban lake require a quantitative appreciation of evaporation.

Evaporation from a water body is essentially determined by environmental conditions and is amenable to a physical treatment based on the knowledge of factors governing it. The process of evaporation is sustained as long as there is a supply of energy, supply of moisture, a vapour pressure gradient between the water surface and the atmosphere, and the speed of wind at or near the water surface. Depending on the disciplinary perspectives and data availability the investigators have a wide variety of choice of the methods for either measuring or estimating the evaporation rates. All these techniques require measurement at reservoir sites involving additional difficulties of operation and maintenance of sensitive instruments. The concerned water resources engineer is interested in getting a quick estimates of evaporation with easily available data of routine measurements by employing a relatively less complex method of estimating evaporation which is otherwise a difficult estimate to be made accurately.

The various methods of estimating evaporation from water bodies like lakes and reservoirs have been reviewed and discussed in the report and their intercomparison has also been attempted so as to indicate the choice of methods under different situations. Evaporation from typical reservoirs of Karnataka in the semi-arid region of the country has been estimated by mass transfer and Penman method using the available climatological and reservoir water level fluctuation data.

2.0 REVIEW OF LITERATURE

The Engineer involved in the design, planning and operation of the reservoir is interested in getting a quick estimate of the probable rates of evaporation hence adopts the means of measuring corresponding water loss with the aid of devices, viz. pans, atmometers. The observed value is then extrapolated taking into account the physical characteristics of water body. The scientists and research workers have a different approach towards the subject as their main objective is micrometeorological research. Accordingly, there are the methods of mass diffusion and turbulent diffusion techniques of estimation of evaporation. Some of the theoretical approaches used practically with the incorporation of a few approximations are the Mass and Energy budget methods and the empirical formulae based on climatological data. Before an attempt is made to review the various approaches towards estimating the evaporation rate from a water body, it is essential to understand the mechanism of the phenomenon.

2.1 Mechanism of evaporation

Evaporation is the process by which water is transformed into water vapour. To the hydrologist, evaporation refers to the net rate at which liquid water is transferred into the atmosphere (Linsley et.al 1975).

The state of mass of a substance can be converted from solid to liquid and liquid to gas by increasing the spacings between the corresponding molecules of the substance. This is done by supplying energy to the molecules of the substance by virtue of which work is done against the intermolecular forces binding the molecules together. Vapourisation of liquid water occurs when the energy supplied to the molecules increases the Kinetic energy associated with the molecules. This leads to the separation of molecular spacing farther whereby some of the water molecules escape through water surface into the atmosphere as water vapour. The amount of energy required is directly related to the number of molecules which in turn is directly proportional to the mass of the water involved. The amount of energy per unit mass of liquid water is called the latent heat of vapourisation of water, λ , and is equal to 2.47×10^6 J kg at 10°C. It changes slightly with temperature, by about 0.1% per °C. The main source of energy is the Sun (incident or reflected on to the water body) and the evaporation process is controlled by the rate at which this energy diffuses away from the water surface.

In a mixture of gases, viz.air, each gas exerts a partial vapour pressure independent of other gases. Thus the total pressure subjected by air is equal to the sum of all the partial pressures corresponding to various constituent gases. If the total pressure of humid air were p and the water vapour were removed, the final pressure p' due to dry air alone would be less than p. The difference p-p' resulting from the removal of the water vapour is the vapour pressure e.

The exchange of molecules from water to the atmosphere depends mainly on the temperature of the water at the surface and the vapour pressure of the water vapour above the surface. If molecules are able to diffuse freely away from the surface then vapour pressure 'e' adjacent to the surface remains low. If on the other hand, the volume of air above the liquid is sealed then it is no longer possible for the water molecules to diffuse freely away from the surface.

As more molecules leave the surface the concentration of the water vapour, and its equivalent vapour pressure, increases until there is no longer any evaporation possible. The sealed volume of air is now said to be 'saturated' and can not absorb any more water molecules. At a given temperature this situation occurs at a particular vapour pressure, which is called 'saturated vapour pressure e_s. Fig.1(a) shows the variation of saturated vapour pressure e_s as a function of temperature and it forms an important aspect in building physical models of evaporation.

As explained above, the rate at which molecules leave the water depends on the vapour pressure of the liquid. Similarly, the rate at which molecules enter the water depends on the vapour pressure of the air. The rate of evaporation, therefore, depends on the difference between the vapour pressure of the water e_w and the vapour pressure in the air e_a, i.e.(e_w-e_a), above the water surface. This process continues until e_a becomes equal to e_w. There are various factors influencing this vapour pressure gradient so essential evaporation to take place. Although knowledge of factors influencing evaporation is at hand, an accurate quantitative analysis of the relative effectiveness of each is difficult because of the inter-relationships.

2.2 Factors Affecting Evaporation

2.2.1 Meteorological factors

By far, solar radiation is the most important single factor influencing the evaporation process. As the amount of solar radiation incident at a place is determined by the latitude of the place, season, degree of cloudiness and the number of daylight hours, these factors

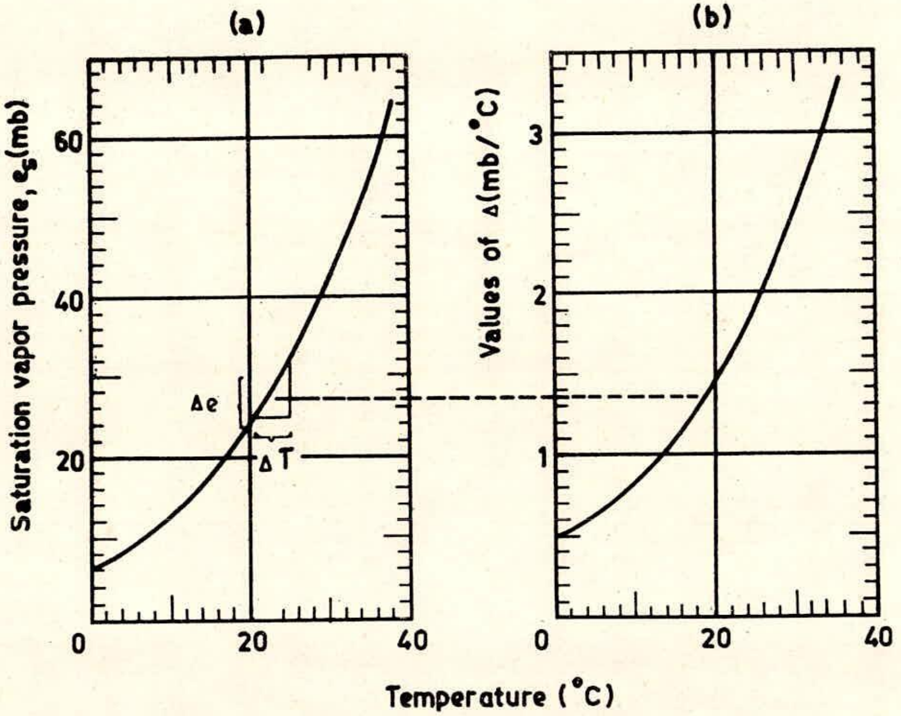


FIG. 1(a) RELATION OF SATURATION VAPOR PRESSURE TO TEMPERATURE
1(b) VARIATION OF Δ (THE SLOPE OF THE CURVE IN FIG. 1(a)) WITH TEMPERATURE

influence the rate of evaporation accordingly. Again the evaporation process is not only influenced by the direct incident solar radiation but also by the energy withdrawn from other convenient sources the overlying air, the ground and/or the water itself. The rate of evaporation from water of specified temperature is proportional to wind speed. This parameter plays a significant role in deciding the vapour pressure of the air over the water surface. If radiation exchange and all other meteorological elements were to remain constant over a shallow lake for an appreciable time, the water temperature and the evaporation rate would become constant. If the wind speed were then suddenly doubled, the evaporation rate would momentarily be doubled. This increased rate of evaporation would immediately begin to extract heat from the water at a more rapid rate than it could be replaced by radiation and conduction. The water temperature would approach a new, lower equilibrium value, and evaporation would diminish accordingly. On a long-term basis, a change of 10 percent in wind speed will change evaporation only about 1 to 3 percent, depending on other meteorological factors (Linsley et.al 1975). In deep lakes which have capacity for considerable heat storage, sudden changes in wind and humidity have longer-lasting effects; heat into or from storage assists in balancing the energy demands. On the whole, evaluation of the relative importance of meteorological factors without an understanding of the mass and energy budgets is difficult and any conclusions drawn must be qualified in terms of the time period considered.

2.2.2 Size of water body

In small lakes, the area of the water body can also affect evaporation rates, particularly in arid and semi arid regions. Hot, dry air moving from a land surface over a lake will supply sensible heat to the water and create a large vapour pressure deficit and high evaporation. If the lake is large, the vapour pressure deficit will decrease as moisture moves into the atmosphere. Therefore, there should be an inverse relationship between the evaporation rate and the size of the lake, at least upto some critical size at which equilibrium conditions are established.

2.2.3 Effects of water quality

The effect of salinity is appreciable only in very saline lake waters. Salinity reduces vapour pressure of the water body. Turk (1970) has published the results of field observations on the depression of evaporation rate as salinity increases. Such considerations are important in studies of the hydrologic regime of closed-basin lakes (Phillips and Van Den burgh 1971).

2.2.4 Effect of floating aquatic plants

Floating aquatic plants effects the lake evaporation. Benton, et al.(1978), indicate that water hyacinth, a floating aquatic plant, can transpire more than three times the amount of water than is lost by open water evaporation. Aquatic plants of all types, if they cover a significant portion of a lake, add complications to estimates of evaporation.

2.2.5 Effect of depth of water body

Rate of evaporation from a reservoir is modified by the heat storage characteristic of the reservoir or lake. In deep lakes, there is greater heat storage during the summer months and consequently lesser evaporation loss during the summer and greater during winter than from shallow lakes.

2.3 Measurement of Evaporation

Evaporation has been measured by using various types of pans and atmometers. All these instruments measure evaporation from very small amounts of water, micro-scopic when compared to volumes considered in engineering hydrology.

2.3.1 Measurement of evaporation by pan

In view of the difficulty of measuring exact quantum of evaporation taking place in the reservoir, most direct measurement, have been made by use of small pans. There is criticism of pan approach justified on theoretical grounds.

There are three types of exposures employed for pan installation:

i) Sunken pan ii) Flooting pan iii) Surface pan.

Different views are held regarding the use of different pans (Mehndiratta 1973). The sunken pan tends to eliminate objectional boundary effects. Such as radiation on the side walls and heat exchange between the air and the pan itself, but creates problem of observation. This type of pan collects more trash and is difficult to install. clean and repair. Leaks occuring in these pans are not easy to detect and the height of the ground vegetation surrounding the pan affects the evaporation from the pan. Moreover, appreciable heat exchange does take place between the pan and the soil, depending on such factors as type of soil, moisture content and vegetative cover.

The floating pan gives conditions more nearly approximate to the conditions pertaining in the lake. However observational difficulties are prevalent with floating pans. Splash frequently occurs due to wave action and renders the data unreliable. The installation and observational expenses of the floating pan are also excessive.

Pans exposed above ground experience greater evaporation than sunken pans primarily because of the radiation energy intercepted by the side walls. Moreover, sensible heat transfer through walls results in geographical variations in lake to pan ratio. Although these deficiencies can be overcome by installing the pan, the method is rather expensive.

Keeping in view the advantages and disadvantages of various types of pans the U.S.Weather Bureau class A surface pan is used most widely in many countries. Class A pan is of unpainted galvanised iron and is 1.22 metre in dia 255 mm deep and is set on a 150 mm high wooden grillage so as to raise the water surface little more than 300 mm above the ground level. The water kept between 50-75 mm below the rim of the pan. It is thus exposed to air on all sides. Evaporation is measured by means of a pointer gauge located in a stilling well.

The evaporation from these pans however remains higher than from reservoir under similar climatic conditions and the values of evaporation as measured with a class A pan have to be multiplied by a coefficient for obtaining probable values of evaporation from reservoirs. The value of this coefficient has been found to range from 0.60 in summer to 0.82 in winter, but for calculation of the annual evaporation loss, an average coefficient 0.70 has been accepted and is found to give reasonably accurate figures of evaporation.

2.3.2 Measurement of evaporation by atmometers

There are two types of atmometers used for measuring evaporation.

(i) Livingstone atmometer

ii) Piche atmometer

i) Living stone atmometer

It is about 5 cm in diameter and about 2.5mm in thickness. It is filled with distilled water and connected to a supply reservoir so that atmospheric pressure on the water surface in the container acts to keep the sphere full. For field use a value must be provided to prevent intake of rainwater.

ii) Piche atmometer

Wet Paper Surfaces consists of a graduated glass tube about 22.5 mm in length and 1 cm internal diameters with one end closed and with a disc of filter paper held against the open end by a spring and metal disk. The tube is filled with distilled water. After the filter and disc are in place, it is inverted.

2.4 Methods of Estimation of Evaporation

The estimation of evaporation from open bodies of water is an inherently a difficult process. Water loss rates are small and vertical transport is accomplished by incompletely understood turbulent processes in the atmosphere. In addition, evaporative rates are dependent on surrounding terrain and the shape of the body of water and vary with unsteady atmospheric condition.

All the above effects, to a greater or less degree, combine to make the insitu measurement of evaporation from an open body of water both difficult and tedious. Various available methods of estimating evaporation have been reviewed and discussed in this section.

2.4.1 Water-budget method

The most direct approach to determine the evaporation from Lakes and Reservoirs would be the direct computation from the observed values of inflow, outflow, precipitation and seepage involved in the maintenance of the water budget. Assuming that storages S, surface inflow I, surface outflow 0, subsurface seepage 0_g and precipitation P can be measured, evaporation E can be computed from the following equation:

$$E = (S_1 - S_2) + I + P - 0 - 0_g \qquad \ldots(1)$$

The approach is simple in theory but application rarely produces reliable results since all errors in measuring outflow, inflow and change in storage are reflected directly in the computed evaporation. Of the parameters mentioned above, seepage is usually the most difficult to evaluate since it must be estimated indirectly from the measurements of ground water levels, permeability etc. If seepage approaches or exceeds evaporation, reliable evaporation determinations by this method are not satisfactory. However, geological and other considerations may indicate that the seepage term, 0_g, is negligible when compared with the other components of the water balance and it is then omitted. Over a sufficiently long period, the change in water storage also becomes negligible compared with the other components and the equation for the total evaporation becomes

$$E = I + P - 0 \qquad \ldots(2)$$

The above value can be divided by the number of years of record to obtain the mean annual evaporation.

The determination of rainfall does not represent a major obstacle provided the average of on-shore measurements is representative of the reservoir. Difficulties in this respect may be expected when the surrounding topography is of high relief and for very large lakes which modify local weather. Again, water-stage recorders are sufficiently precise for determining the storage changes provided that the stage-area relationships are accurate. Variations in bank storages, expansion or contraction of storage water with large temperature changes introduce appreciable errors. However, these errors in the surface inflow and outflow terms vary considerably from lake to lake depending on the extent of ungauged areas,a the reliability of rating curves and the relative magnitude of flows with respect to evaporation. Determinations of streamflow to within 5 percent are normally considered excellent and corresponding evaporation errors may be expected in off-channel reservoir without appreciable outflow.

The water budget method is not feasible for routine measurements of evaporation, but has been used under favourable conditions as a control, against which methods of calculating evaporation can be checked. If a lake presents optimum conditions, errors in estimating monthly evaporation can be kept to ± 10 percent. Successful application of the technique to small lakes can be cheaper if geological and hydrological conditions are favourable (Mckay and Stichling 1961). Ideal conditions occur where subsurface flows are essentially zero and surface outflow is small relative to evaporation. Jukka (1978) applied Water Budget Method to lakes Pyhajarvi and Paajavvi of Finland for determination of evaporation losses during 1971-74. The monthly evaporation values from the water budget method were correlated with those obtained with the bulk aerodynamical method with a coefficient of 0.86 with those measured with GGI-3000 pans with a coefficient of 0.75.

2.4.2 Energy budget method

The energy input to the reservoir and energy output from the reservoir are accounted in the energy budget(heat budget) method in which residual energy is assumed to have been used for evaporation. The energy budget approach, like the water budget, employs a continuity equation required to maintain a balance. Although the continuity equation in this approach is one of energy, an approximate water budget is required since inflow, outflow and storage of water are represneted in terms of energy values in conjunction with their respective temperatures.

The transformation of one gram of water into vapour at normal lake temperatures requires approximately 590 calories of heat energy. The energy budget of a water body for some interval of time is expressed in the following equation:

$$Q_s - Q_{rs} - Q_{lw} - Q_h - Q_e + Q_v - Q_{ve} = Q_\theta \qquad \ldots(3)$$

where

Q_s=incoming solar radiation

Q_{rs}= reflected solar radiation

Q_{lw} = net long wave radiation from the water body into the atmosphere.

Q_h= sensible heat transfered by turbulent exchange from the water body to the atmosphere.

Q_e = energy utilized for evaporation

Q_v= net energy advected into the lake by flows of water.

Q_{ve} = energy advected out of the water body by the evaporated water.

Q_θ = change of energy stored in the lake

All units of equation (3) are in calories per square centimeter of lake surface.

The sensible heat transfer term, Q_h is not measured directly but is incorporated into dimensionless Bowen's Ratio(R) defined as,

$$R = \frac{Q_h}{Q_e} = (\gamma/1000)p\ \frac{(Ts-Ta)}{(es-ea)} \qquad ...(4)$$

where p is the atmospheric pressure (mb), T_s and T_a are the temperature of the water surface and the atmosphere(0_c), while e_s and e_a are the vapour pressure of the water surface and the atmosphere (mb). γ =a constt ranging between 0.58 and 0.66 (Harbeck & Meyers 1970), but having a most probable value of 0.61 according to Bowen. Bowen (1926) perforce assumed that the diffusivities, or eddy- transfer coefficients, of heat and water vapour are equal. There seems to be little argument that the assumption is reasonable when the lapse rate is adiabatic, but uncertainties exist when the lapse rate is strongly stable or unstable. On the average, however, water surface temperature of most reservoirs is usually within a degree or two of air temperature, and the Bowen Ratio procedure is questionable only when large air-water temperature difference exist. The vapour pressure of the water surface depends upon the temperature of the water. The atmospheric vapour pressure can be measured directly with a sling psychrometer or a hygrothermograph.

The energy transfered from the water by the evaporating water can be calculated from

$$Q_{ve} = Q_e\ c(T_s-T_b)/L \qquad ...(5)$$

where

c = specific heat of water (cal/gm/°C)

T_b = an arbitrarily choosen base temperature(usually taken 0^oC)

L = latent heat of vapourisation (590 cal/gm).

According to Harbeck & Meyers (1970) this amount of energy (Q_{ve}) is small and often disregarded item. Basically the theory is that when warm water is evaporated more energy leaves the water than when cold water is evaporated.

Using equations(4) and (5), the equation (3) can be rewritten as

$$Q_e = \frac{Q_s - Q_{rs} - Q_{lw} + Q_v - Q_\theta}{1+R+C(T_s - T_b)/L)} \qquad \ldots(6)$$

The amount of energy utilized for evaporation (Q_e) is related to the depth of evaporation (E_o) by the relationship

$$E_o = Q_e/L\rho$$

where E_o is in cm, and ρ is the density of water (gm/cm^3), combining equations (6) and (7) yields to

$$E_o = \frac{Q_s - Q_{rs} - Q_{lw} + Q_v - Q_\theta}{\rho[L(1+R)+C(T_s - T_b)]} \qquad \ldots(8)$$

After evaluation of each term on the R.H.S. of the equation (8) E_o can be computed.

The advection (Q_v) and storage (Q_θ) terms are evaluated by repeated measurements of the temperature and volume of inflows and outflows and of the water stored in the lake. The surface water temperature ,(T_s) is required for Equations(8) and (4), where it is also used to obtain e_s, which is a function of water temperature as shown in fig(1a). Air temperature (T_a), atmospheric pressure(p), and vapour pressure (e_a) in equation (4) are obtained from direct measurements at the site or from published meteorological records for nearby stations.

Incoming solar radiation(Q_s) can be measured directly by means of a pyrheliometer. There are, however, relatively few stations throughout the world at which instrumented observations of solar radiation are made. In many regions where the water balance of natural and artificial lakes is becoming important in water-resource management, it is necessary to estimate solar radiation from latitude, date, cloud cover, or the duration of bright sunshine. Using records at 150 stations throughout the world, Black (quoted in change 1968) developed a relationship for predicting mean monthly solar radiation:

$$Q_s = I_o(0.803-0.340C-0.458C^2) \qquad \ldots(9)$$

where

Q_s = mean daily solar radiation for the month(cal/cm^2/day)

I_o = solar radiation per day received on a horizontal surface at the exterior of the atmosphere (see table 1).

C = mean monthly clodiness (decimal fraction),

Another method of estimating Q_s is by means of the equation

$$Q_s = I_o(a+b\frac{n}{N}] \qquad \ldots(10)$$

where, a,b = emperical constants(see table 2)

n = observed duration of sunshine (hours)

N = maximum possible duration of sunshine(hours) given in standard meteorological tables (see table 3).

The reflectivity of a surface, henceforth called the albedo, can be measured in the field with an inverted pyrheliometer. Albedo varies as a power function of sun altitutde, with the coefficient and exponent of the power equation depending on cloud type and the extent of cloud cover(Anderson 1954). In most studies, however, the albedo of water is usually assumed to be constant. Thus

$$Q_{rs} = \alpha Q_s \qquad \ldots(11)$$

TABLE - 1 Extra-terrestrial radiation I_o expressed in equivalent evaporation in mm/day.

Northern hemisphere													Southern hemisphere											
Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Lat.	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
3.8	6.1	9.1	12.7	15.8	17.1	16.4	14.1	10.9	7.4	4.5	3.2	50°	17.5	14.7	10.9	7.0	4.2	3.1	3.5	5.5	8.9	12.9	16.5	18.2
4.3	6.6	9.1	13.0	15.9	17.2	16.5	14.3	11.2	7.8	5.0	3.7	48	17.6	14.9	11.2	7.5	4.7	3.5	4.0	6.0	9.3	13.2	16.6	18.2
4.9	7.1	10.1	13.3	16.0	17.2	16.6	14.5	11.5	8.3	5.5	4.3	46	17.7	15.1	11.5	7.9	5.2	4.0	4.4	6.5	9.7	13.4	16.7	18.3
5.3	7.6	10.1	13.7	16.1	17.2	16.6	14.7	11.9	8.7	6.0	4.7	44	17.8	15.3	11.9	8.4	5.7	4.4	4.9	6.9	10.2	13.7	16.7	18.3
5.9	8.1	11.0	14.0	16.2	17.3	16.7	15.0	12.2	9.1	6.5	5.2	42	17.8	15.5	12.2	8.8	6.1	4.9	5.4	7.4	10.6	14.0	16.8	18.3
6.4	8.6	11.4	14.3	16.4	17.3	16.7	15.2	12.5	9.6	7.0	5.7	40	17.9	15.7	12.5	9.2	6.6	5.3	5.9	7.9	11.0	14.2	[illegible]	18.3
6.9	9.0	11.8	14.5	16.4	17.2	16.7	15.3	12.8	10.0	7.5	6.1	38	17.9	15.8	12.8	9.6	7.1	5.8	6.3	8.3	11.4	14.4	17.0	18.3
7.4	9.4	12.1	14.7	16.4	17.2	16.7	15.4	13.1	10.6	8.0	6.6	36	17.9	16.0	13.2	10.1	7.5	6.3	6.8	8.8	11.7	14.6	17.0	18.2
7.9	9.8	12.4	14.8	16.5	17.1	16.8	15.5	13.4	10.8	8.5	7.2	34	17.8	16.1	13.5	10.5	8.0	6.8	7.2	9.2	12.0	14.9	17.1	18.2
8.3	10.2	12.8	15.0	16.5	17.0	16.8	15.6	13.6	11.2	9.0	7.8	32	17.8	16.2	13.8	10.9	8.5	7.3	7.7	9.6	12.4	15.1	17.2	18.1
8.8	10.7	13.1	15.2	16.5	17.0	16.8	15.7	13.9	11.6	9.5	8.3	30	17.8	16.4	14.0	11.3	8.9	7.8	8.1	10.1	12.7	15.3	17.3	18.1
9.3	11.1	13.4	15.3	16.5	16.8	16.7	15.7	14.1	12.0	9.9	8.8	28	17.7	16.4	14.3	11.6	9.3	8.2	8.6	10.4	13.0	15.4	17.2	17.9
9.8	11.5	13.7	15.3	16.4	16.7	16.6	15.7	14.3	12.3	10.3	9.3	26	17.6	16.4	14.4	12.0	9.7	8.7	9.1	10.9	13.2	15.5	17.2	17.8
10.2	11.9	13.9	15.4	16.4	16.6	16.5	15.8	14.5	12.6	10.7	9.7	24	17.5	16.5	14.6	12.3	10.2	9.1	9.5	11.2	13.4	15.6	17.1	17.7
10.7	12.3	14.2	15.5	16.3	16.4	16.4	15.8	14.6	13.0	11.1	10.2	22	17.4	16.5	14.8	12.6	10.6	9.6	10.0	11.6	13.7	15.7	17.0	17.5
11.2	12.7	14.4	15.6	16.3	16.4	16.3	15.9	14.8	13.3	11.6	10.7	20	17.3	16.5	15.0	13.0	11.0	10.0	10.4	12.0	13.9	15.8	17.0	17.4
11.6	13.0	14.1	16.6	16.1	16.1	16.1	15.8	14.9	13.6	12.0	11.1	18	17.1	16.5	15.1	13.2	11.4	10.4	10.8	12.3	14.1	15.8	16.8	17.1
12.0	13.3	14.7	15.6	16.0	15.9	15.9	15.7	15.0	13.9	12.4	11.6	16	16.9	16.4	15.2	13.5	11.7	10.8	11.2	12.6	14.3	15.8	16.7	16.8
12.4	13.6	14.9	15.7	15.8	15.7	15.7	15.7	15.1	14.1	12.8	12.0	14	16.7	16.4	15.3	13.7	12.1	11.2	11.6	12.9	14.5	15.8	16.5	16.6
12.8	13.9	15.1	15.7	15.7	15.5	15.5	15.6	15.2	14.4	13.3	12.5	12	16.6	16.3	15.4	14.0	12.5	11.6	12.0	13.2	14.7	15.8	16.4	16.5
13.2	14.2	15.3	15.7	15.5	15.3	15.3	15.5	15.3	14.7	13.6	12.9	10	16.4	16.3	15.5	14.2	12.8	12.0	12.4	13.5	14.8	15.9	16.2	16.2
13.6	14.5	15.3	15.6	15.3	15.0	15.1	15.4	15.3	14.8	13.9	13.3	8	16.1	16.1	15.5	14.4	13.1	12.4	12.7	13.7	14.9	15.8	16.0	16.0
13.9	14.8	15.4	15.4	15.1	14.7	14.9	15.2	15.3	15.0	14.2	13.7	6	15.8	16.0	15.6	14.7	13.4	12.8	13.1	14.0	15.0	15.7	15.8	15.7
14.3	15.0	15.5	15.5	14.9	14.4	14.6	15.1	15.3	15.1	14.5	14.1	4	15.5	15.8	15.6	14.9	13.8	13.2	13.4	14.3	15.1	15.6	15.5	15.4
14.7	15.3	15.6	15.3	14.6	14.2	14.3	14.9	15.3	15.3	14.8	14.4	2	15.3	15.7	15.7	15.1	14.1	13.5	13.7	14.5	15.2	15.5	15.3	15.1
15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8	0	15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8

TABLE -2 . **Values of constants, 'a' and 'b' in Penman formula**

Place	*Latitude* *°N*	*Value of* *'a'*	*Value of* *'b'*
New Delhi	28.4	0.31	0.46
Jodhpur (Rajasthan)	26.3	0.31	0.49
Ahmedabad (Gujarat)	23.1	0.42	0.30
Nagpur (Maharashtra)	21.1	0.16	0.68
Pune (Maharashtra)	18.5	0.35	0.40
Hyderabad (Andhra Pradesh)	17.4	0.14	0.55
Madras (Tamil Nadu)	13.1	0.30	0.44
Bangalore (Karnataka)	13.0	0.18	0.62
Trivandrum (Kerala)	8.5	0.37	0.38
Shillong (Assam)	24.6	0.18	0.66

(Gangopadhyaya, et. al., 1970)

TABLE - 3 Mean daily maximum duration of bright sunshine hours N for different months and latitudes.

(*Source*: Doorenbos and Pruitt, 1975)

Northern Latitudes	*Jan.*	*Feb.*	*March*	*April*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Southern Latitudes	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*March*	*April*	*May*	*June*
50°	8.5	10.1	11.8	13.8	15.4	16.3	15.9	14.5	12.7	10.8	9.1	8.1
48°	8.8	10.2	11.8	13.6	15.2	16.0	15.6	14.3	12.6	10.9	9.3	8.3
46°	9.1	10.4	11.9	13.5	14.9	15.7	15.4	14.2	12.6	10.9	9.5	8.7
44°	9.3	10.5	11.9	13.4	14.7	15.4	15.2	14.0	12.6	11.0	9.7	8.9
42°	9.4	10.6	11.9	13.4	14.6	15.2	14.9	13.9	12.9	11.1	9.8	9.1
40°	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
35°	10.1	11.0	11.9	13.1	14.0	14.5	14.3*	13.5	12.4	11.3	10.3	9.8
30°	10.4	11.1	12.0	12.9	13.6	14.0	13.9	13.2	12.4	11.5	10.6	10.2
25°	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	11.6	10.9	10.6
20°	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
15°	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	11.8	11.4	11.2
10°	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
5°	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
0°	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1

where α is the albedo, or reflectivity of the water surface. Most studies assume that $\alpha = 0.6$ for water values ranging from 0.05 to 0.10 are commonly used.

Net long wave radiation (Q_{lw}) is more difficult to compute. The earth's surface emits long wave radiation into the atmosphere. The intensity of this terrestrial radiation depends mainly upon the temperature of the surface. Much of the radiation is absorbed by water vapour, clouds, and carbon dioxide in the atmosphere, and a portion is radiated back to the earth as atmospheric radiation. Atmospheric radiation is also generated by solar radiation that is absorbed by water vapour and carbon dioxide and then re-radiated at longer wave-lengths. The intensity of atmospheric radiation depends upon the profile of air temperature, Water vapour content, and cloud cover through out the atmosphere. Because of the difficulty of obtaining measurements of these variables, there have been many attempts to develop relationship between net longwave radiation loss (Q_{lw}) and near surface measurements of its three major controls.

Several emperical equations have been developed for estimating net long wave radiation; the most widely used is the Brunt Equation (Andersen 1954):

$$Q_{lw} = \sigma[\, T_s^4 - (c+d\sqrt{e_2})T_2^4] \; (1-aC) \qquad \ldots(12)$$

where σ = the Stefan-Boltzmann constant

(1.17×10^{-7} cal/cm^2/$^oK^4$/day)

T_s = temperature of the surface (^oK)

T_2 = air temperature at the 2 meter level (^oK)

e_2 = vapour pressure of the air at the 2-meter level (mb)

c,d = emperical coefficients, which can vary geographically(see table 4)

C = cloudiness (decimal fraction of the sky covered)

a = a constant depending upon cloud

Table-4 Empirical values of constants for the Brunt Equation. (Compiled by Anderson 1954.)

PLACE	c	d
Sweden	0.43	0.082
Washington, DC	0.44	0.061
Austria	0.47	0.063
Algeria	0.48	0.058
California	0.50	0.032
England	0.53	0.065
France	0.60	0.042
India	0.62	0.029
Oklahoma	0.68	0.036

type: 0.25, 0.6 and 0.9 for high, medium and low clouds, respectively.

In case data on cloud type are not available (1-aC) may be replaced by (0.10 +0.9C) or by (0.10+0.90n/N), where n/N is defined in equn.(10).

Estimates of net long wave radiation loss can also be made without using the surface temperature. The most common of the emperical equations for doing this is given by Chang (1968) as

$$Q_{lw} = \sigma T_2^4 (0.56 - 0.08\sqrt{e_2})\ (1-aC) \qquad \ldots(13)$$

where T_2 is in ^{o}K and e_2 is in mb.

The estimates obtained by these emperical equations are not very precise, and errors often exceed ± 25 percent, even when measurements are averaged over a day. Under uniform cloud conditions, the errors may be reduced to ± 15 to 20 percent for monthly values.

Net all wave radiation is that portion of incoming radiation that is not reflected or radiated back to the atmosphere; that is.

$$Q_n = Q_s\ (1-\alpha) - Q_{lw} \qquad \ldots(14)$$

This quantity (Q_n) can be measured directly with a total hemispherical radiometer. It can also be calculated as the difference between net short wave radiation and net long wave radiation evaluated by the procedure outlined above. Harbeck, et al (1958), stated that if the indicated errors are combined by adding individual statistical variances, the estimated maximum error of computed monthly evaporation is about 10 percent in summer and 13 percent in winter. They stated further that, on an annual basis, the error should be considerably less than 10 percent, because the percentage of error in evaluating change in energy in the reservoir decreases markedly as the length of period increases. Gunaji (1968) estimated the error in computed evaporation for each of 28 energy budget periods, which averaged

14 days in length and were initiated in 1963. For individual energy budget periods, minimum probable estimates of error was 4.4% and maximum was 27.8 percent. The mean error for the entire period of study was 10.5 percent.

Winter (1981) stated that evaporation calculated by the energy budget method is generally considered to be accurate; with proper care, the error in annual estimates can be 10 percent or less, and seasonal estimates are considered to be with in about 13 percent. When the energy budget is applied for periods of one month with intensive direct measurements of all the terms, evaporation can be determined to an accuracy of 5 to 10 percent. This is expensive, however, and is only used as a means of calibrating less expensive methods. Under less ideal conditions when the energy terms are evaluated by emperical relationships or from observations at standard weather stations, the errors will range from 10 to 20 percent for monthly averages. Hoy and Stephens (1977) and many others recommended the method as the most reliable one for estimating lake evaporation. A comparison between pan estimates and energy balance estimates is shown as an example in Fig.(2) for Perch lake, Canada (Ferguson & den Hartog, 1975). The application of this method is limited due to the large and not routinely measured data, needed for computing heat balance.

2.4.3 Mass Transfer method

The mass transfer or bulk aerodynamic method of estimating evaporation is based on the work of Dalton (1802), who suggested that evaporation rate is proportional to vapour pressure gradient between the evaporating surface and air above the surface, and that

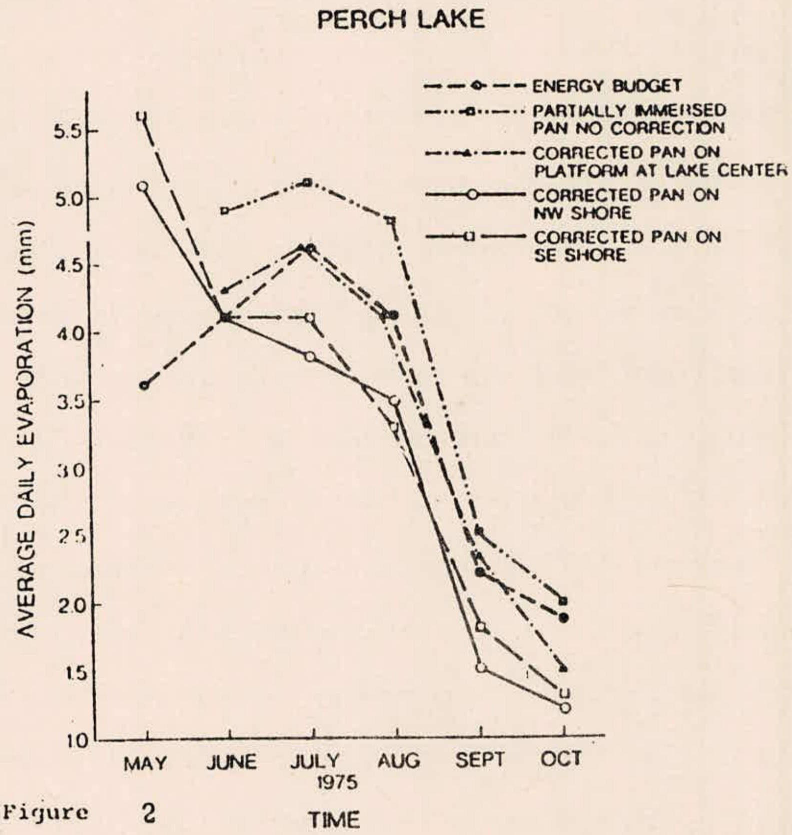


Figure 2

Monthly values of lake evaporation obtained from various Class A pans and from the energy balance at Perch Lake (near Chalk River) Canada (Ferguson and den Hartog, 1975).

the coefficient of proportionality is strongly dependent on wind speed. Prandtl's (1905) description of the boundary layer laid the foundation for treating evaporation as a mass transfer problem. Because evaporation is controlled to a large degree by wind and vapour pressure gradients above the evaporating body, velocity distribution within a boundary layer is a critical factor. The similarity of momentum and vapour transfer was shown by Albertson (1948), whose work confirmed that evaporation is a boundary layer phenomenon.

According to Marciano and Harbeck (1954), turbulent transport of momentum and water vapour are essentially the same. According to them considerable evidence exists that, for turbulent flow without density gradients, velocity in a fully established boundary layer over a plane surface varies with the logarithm of height.

Anderson, et al.(1950), subsequently made refinement of Dalton's Law. This method, also called the bulk aerodynamic method, is based on the equation of following type:

$$E = f(u)\ (e_S - e_a) \qquad \ldots(15)$$

where

$f(u)$ = coefficient of proportionality, often called the wind function;

e_s = vapour pressure of water surface,

e_a = vapour pressure of the air at height, a, above the water surface.

The wind function, $f(u)$, proposed by researchers has the form

$$f(u) = a + Nu^n \qquad \ldots(16)$$

where

a and n = constants for a given water body,

N = mass transfer coefficient, and

u= wind speed representative of conditions over the water body.

Generally, n is assumed to be unity when computing evaporation from lakes, and a is often assumed to be zero, if wind speed is measured over the open water near the centre of the water body. The mass transfer coefficient, N is a constant for a specific lake it accounts for many variables, such as wind profile, size of the lake roughness of the water surface, atmospheric stability, barometric pressure, and density and viscosity of the air(Winter 1981). Harback, et al.(1958), determined that, for many lakes, optimum placement of a single anemometer to obtain data for the mass transfer method is at two meters above the water surface. In addition to the anemometer, the only other instrumentation needed are air and water surface temperatures, and a device to determine humidity(for example, a hygrothermograph or psychrometer).

The key to successfully estimating evaporation by the mass transfer method is determination of the emperical coefficient for a given lake. The mass transfer coefficient, N is commonly determined as the slope of the line relating the mass transfer product, $u(e_s-e_a)$, where a (in equation 16) is assumed zero, to an independent measurement of evaporation. It can also be determined by relating the mass transfer product to change in lake stage, and also by using a functional relationship proposed by Harbeck (1962), which is related to surface area of the water body as discussed below.

a) Evaporation determined by the energy budget is generally considered the best independent estimation of evaporation against which to determine N. The measured rate of evaporation by energy budget is plotted against the product $u_2(e_s-e_2)$, windspeed u time vapour pressure deficit, where the subscript refers to a 2-meter observation height (see fig.3). The slope of the resulting line is the value of N, the mass transfer coefficient in equation (16).

Ficke (1972) provides a thorough discussion of errors in estimating N by calibration against energy budget evaporation. He used several statistical techniques, standard least squares, double weighted regression, and weighting factors proportional to the period lengths for each energy budger period, to determine best fit of the line relating energy budget evaporation to $u(e_s-e_a)$. Relative standard error of the slope of the regression line (N) through the origin was about 6 to 7 percent for the various methods.

At Falcon Reservoir, Texas, Harbeck and Meyers(1970) related energy budget evaporation to $u(e_s-e_a)$ and determined the standard error of estimate of N to be 19 percent of the mean. In a study of the Salten Sea, California, Sturrock (1978) estimated the standard error of N, in percent of energy budget evaporation, to be about 15 percent. In another study of the Salten Sea, Hughes (1967) cautioned on the application of N coefficient to periods other than the calibration period. He states that because N was determined over a two-year period at this site, it should have application to any year long period. For periods shorter than a year, however, its use would produce consistent results only if the measured parameters would represent conditions for Salton Sea with equal faithfulness during all periods of the year.

b) The second common method determining N is by a water Budget method. Net inflow of surface and subsurface flow will cause fluctuations of the lake surface in addition to those due to evaporation. Under these circumstances, surface inflow and outflow and precipitation can be measured directly and used to correct the change of water level in the lake. The net subsurface seepage which is still unknown but can be evaluated from following equation and figure(4).

$$\Delta h = E + S \qquad ...(17)$$

where Δh= net change of water surface elevation adjusted for surface inflow and outflow and for precipitation onto the lake surface. An elevation-volume curve for the lake is needed for the adjustment. During the period of no surface inflow or outflow, this is simply the fall of the water surface, which can be evaluated through repeated observations of water level on a graduated staff set in the reservoir.

E = evaporation (cm/day or mm/day)

S = net groundwater seepage (cm/day or mm/day)

If Δh is plotted against $u(e_s-e_a)$ as shown in Fig.(4) the slope of the regression line is the value of N in Equation (16), in this case 0.000139. The water level recession rate at the zero value of $u_2(e_s-e_a)$ is the seepage rate(S=0.5 cm/day) as read from fig.(4).

This method of estimating both the mass-transfer coefficient and the net seepage rate was first applied by Langbein et al.(1951) to small stock watering reservoirs, and is more reliable under conditions of zero surface flow and zero precipitation. They proposed that seepage could be estimated as a by product of this technique of determining N. During periods when changes in lake stage are not caused by precipitation of surface water inflow and outflow, seepage can be estimated from the graph relating the mass transfer product to change in lake stage, as shown in fig.(4). Turner (1966) found the method useful even for a large reservoir with appreciable surface flow in a humid region. He was also able to relate the net seepage derived in this way to the discharge of a gauged inflow stream. Mayboom (1967) applied the technique successfully to small lake maintained by groundwater seepage in Western Canada, though he found that for

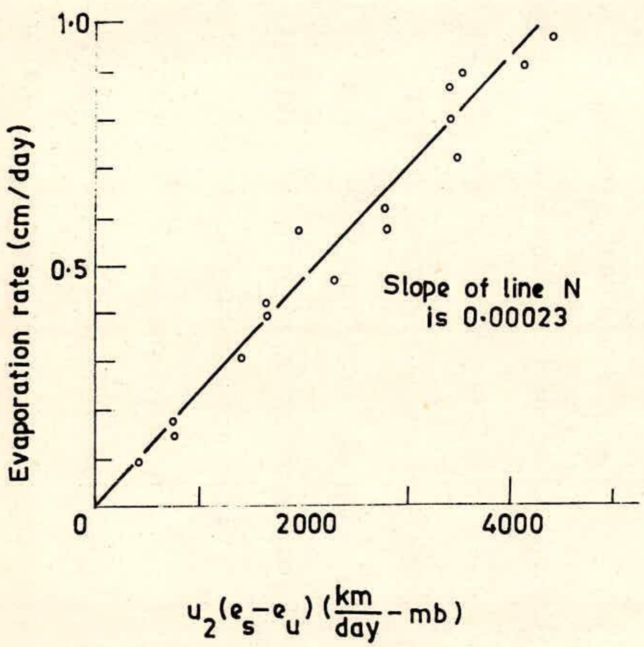


Fig.3 -PLOT OF MEASURED OR CALCULATED EVAPORATION RATE AGAINST $u_2(e_s - e_a)$

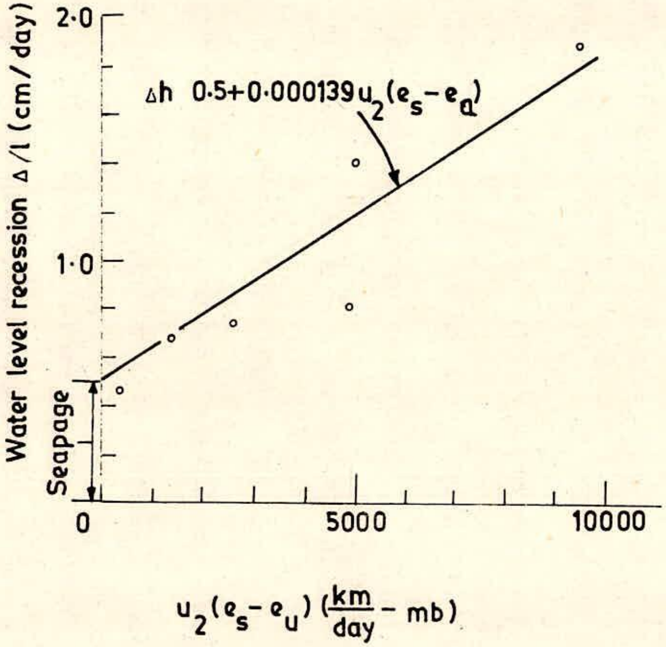


FIG.4 PLOT OF MEASURED CHANGE OF WATER LEVEL AGAINST $u_2(e_s - e_a)$ FOR A STOCK POND WITH SEEPAGE LOSSES (LANGBEIN ET AL 1951)

ponds less than about one hectare, the value of N varied throughout the year.

Concerning the other terms of equation(15), Turner (1966) and Yonts, et al(1973), point out that errors of as much as 25 percent could be introduced in calculating $u(e_s-e_a)$, if the corresponding average daily air and water temperatures T_a and T_s are in error by $1^oC(2^oF)$. Similarly, Ficke (1972) indicates that a $2^oC(4^oF)$ error in surface water temperature during May, for example, could give an error in computed evaporation of more than 40 percent for Pretty Lake, Indiana. Jobson(1972) showed that the time over which meteorological data are averaged should be a day or less when computing evaporation by the mass transfer method.

c) The third method of estimating N makes use of a functional relationship suggested by Harbeck (1962). One merely has to know the surface area of a water body in order to compute N by this method. Harbeck (1962) states the method should be used only to prevent gross errors in estimating evaporation. At Pretty Lake, Indiana, Ficke (1972) found that evaporation determined by the mass transfer method (using the energy budget to calibrate N) differed by 15 percent from that predicted by using this functional relationship. Gangopadhyaya et al (1966), stated that independent estimates of evaporation may differ from that determined by this method by as much as 25 percent or more for individual reservoirs.

Values of N for reservoirs in the arid Southwestern United States may vary with the lake area (A) according to the relation.

$$N = 0.000169\ A^{-0.5} \qquad \ldots (18)$$

where the mass transfer coefficient is calculated for evaporation rates in cm/day, windspeeds in km/day, vapour pressure in mb, and lake area in sq.km. Because of the vibration in units in the literature, care should be taken when comparing the mass transfer coefficients obtained by different authors. Fig.(5) presents the relationship of N as a function of lake area. There is considerable scatter about the relationship described in equation(18) errors of upto 25 percent are possible if N is estimated from this curve, even in the area for which it was developed. Therefore, a field study is necessary for fairly precise estimates of evaporation. Moreover it needs water surface temperature data supposed to have been measured at the centre of the lake and which is generally not available.

For small reservoirs, stock ponds, and urban lakes, rapid and cheap determinations of the mass-transfer coefficient and seepage can be made using the technique illustrated in fig.(4). A graduated staff is placed in the lake to obtain $\triangle h$, and daily observations of the water level are made during periods of no surface inflow or outflow (or the water level change must be corrected for these). Because the rate of seepage varies with the amount and temperature of the water in storage, it may be necessary to repeat the measurements a few times throughout the year and to sketch an approximate annual curve of seepage. If estimates of seepage from one lake are to be transfered to others in the same region, the underlying geologic material should be checked at each site before extrapolating the results.

The water surface temperature is required to derive e_s. If plans for a reservoir are being considered, it will not be possible to measure the water temperature because the lake does not yet exist. In such cases air temperature is often used as a surrogate for the water surface temperature, or pan evaporation data may be used.

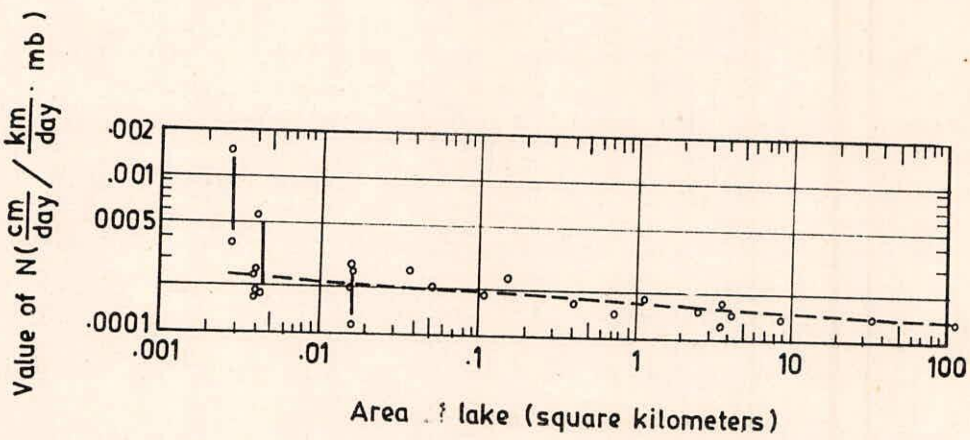


FIG. 5 MASS TRANSFER COEFFICIENT N, AS A FUNCTION OF LAKE AREA

2.2.4 Combination of energy budget and bulk aerodynamic methods

The energy budget and bulk aerodynamic methods can be combined to compute evaporation from small pans and shallow lakes, where energy-storage change can be ignored. Such an analysis is useful for calculating lake evaporation. This approach was first employed by Penman (1948). He studied the evaporation from a small sunken pan of water , ignoring heat-storage changes and the conduction of heat through the walls of the pan. The approximation allows the energy budget in equation (3) to be written in the following simplified form:

$$Q_n = Q_h + Q_e \qquad \text{...(19)}$$

By dividing (ρ L), these energy components can be expressed in terms of equivalent depths (cm) of evaporation as:

$$H = K + E_o \qquad \text{...(20)}$$

The equation states the obvious fact that in the absence of energy storage changes or conduction through the walls of the pan, energy received from net radiation is divided between that used for evaporation and that transfered to the atmosphere as sensible heat. Penman then derived the following expression for evaporation from small sunken pan:

$$E_o = \frac{H\Delta + \gamma E_a}{\Delta + \gamma} \qquad \text{...(21)}$$

where E_o is the evaporation rate in cm/day, H is net radiation cm/day of evaporation.

Δ (mb/°c) is the slope of the curve relating saturation vapour pressure to temperature as shown in fig.(1b), γ is known as the psychometric constant (0.66 mb/°c), and Ea is a term describing the contribution of mass-transfer to evaporation. The last term was determined emperically to be

$$E_a = (0.013 + 0.0001\ u_2)\ (e_{sa} - e_a) \qquad \ldots(22)$$

where E_a is in cm/day, u_2 is the wind speed (km/day) measured at a height of two meters above the ground, e_{sa} (mb) is the saturation vapour pressure of a water surface at the air temperature, and e_a(mb) is the atmospheric vapour pressure. For simplification of calculation, the numerator and denominator of equation (21) can be divided by γ, giving

$$E_o = \frac{H \dfrac{\Delta}{\gamma} + E_a}{\dfrac{\Delta}{\gamma} + 1} \qquad \ldots(23)$$

The term Δ/γ is a function of temperature and is tabulated in Table (5).

Unlike Penman's sunken pan, there is significant transfer of heat by conduction and radiation through the walls and base of a Class A evaporation pan. Kohler et al(1955), however, found that the combination of meteorological variables used by Penman could be related statistically to evaporation from a pan, and then through the use of the pan coefficient, to evaporation from a lake. The graph for computing lake evaporation is shown in Fig.(6). S.Venkataraman and V.Krishnamurthy (1973) computed annual lake evaporation by Kohler's coaxial graphical method for a number of stations spread all over India. They plotted the value of annual evaporation and isolines of evaporation were drawn at interval of 25 cm as shown in Fig.(7). Lamoreux (1962) developed from this graph following expressions that can be used for the rapid processing of meteorological data by computer.

$$\begin{aligned} E_L = [\epsilon^{(T_a'-212)(0.1021-0.01066\ \ln R)} - 0.0001 + 0.0105 \\ (e_s - e_a)^{0.88}(0.37 + 0.0041\ u_p)] \times \\ [0.015 + (T_a + 398.36)^{-2}(6.8554 \times 10^{10})\ \epsilon^{-7482.6/(T_a+398.36)}]^{-1} \end{aligned} \qquad \ldots(24)$$

Vapour pressure deficit $(e_s - e_a)$ can be derived from air and dew point

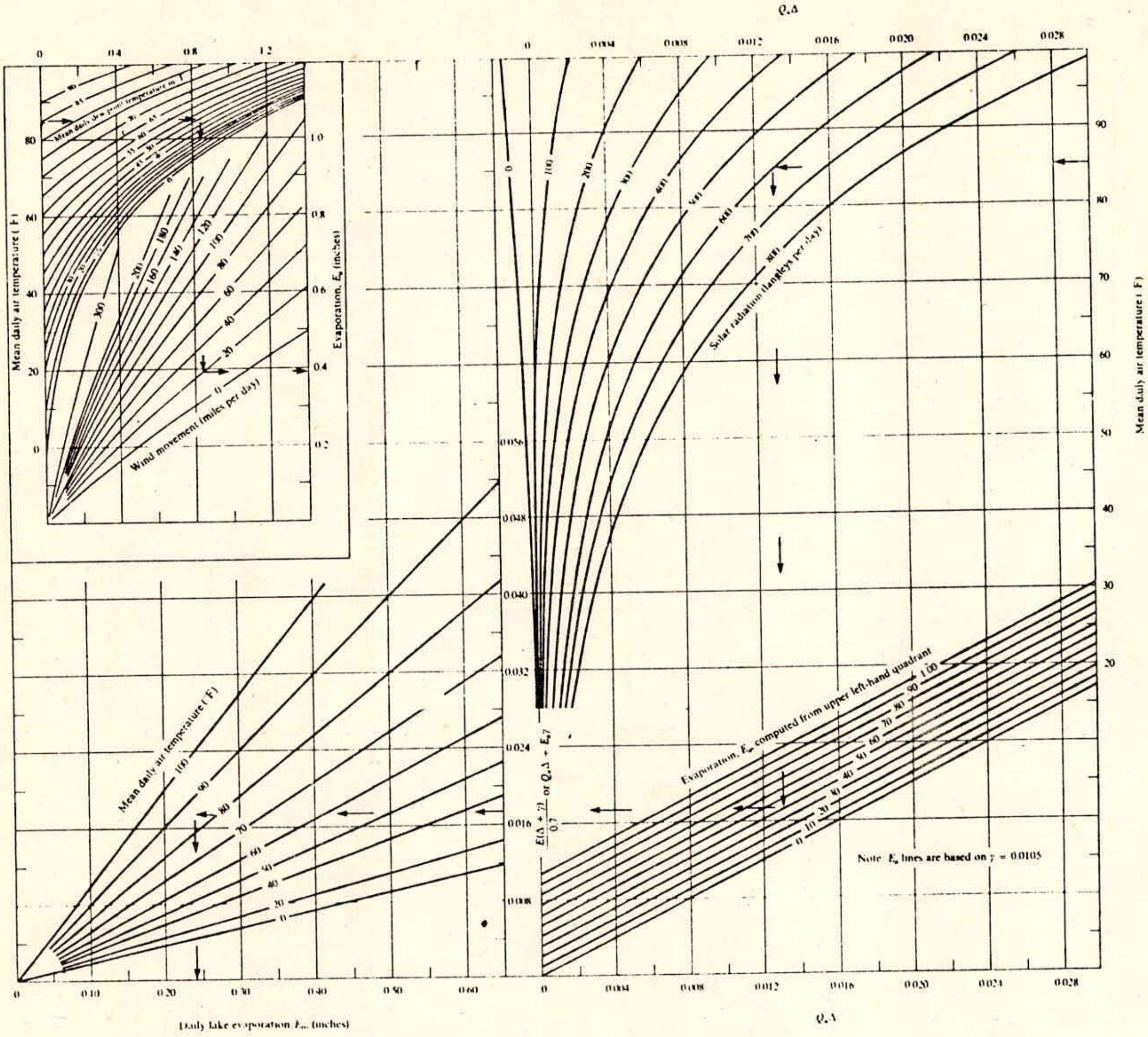
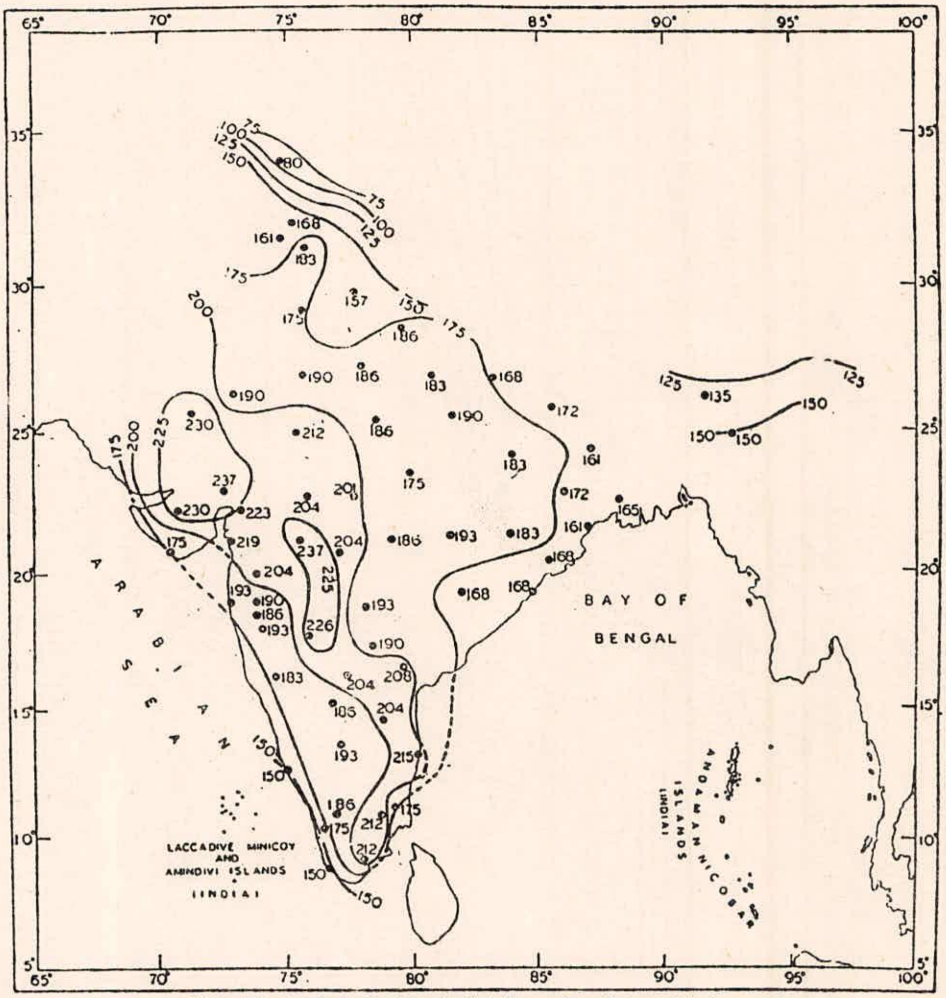


Figure 6 Computation of lake evaporation from meteorological data. To use the diagram: (1) enter upper left diagram with mean daily air temperature; (2) at mean daily dew-point temperature, read down to wind measurement; (3) read horizontally to right scale of E_a; (4) enter upper right diagram with mean daily air temperature, move left to value of solar radiation; (5) move downward to previously computed value of E_a in lower diagram; (6) thence left to lower left diagram to mean daily temperature; (7) thence downward to read answer, daily lake evaporation. The dew-point temperature is the temperature to which the atmosphere must be cooled before its water vapor will condense. It is therefore a measure of the vapor pressure and is routinely published with other weather records. (From Kohler et al. 1955.)



The territorial waters of India extend into the sea to a distance of twelve nautical miles measured from the appropriate base line

FIGURE 7 : Total annual lake evaporation in cm.

Table -5 Values of Penman's dimensionless parameter $\frac{\Delta}{\gamma}$ for various temperatures.

T(°C)	$\frac{\Delta}{\gamma}$	T(°C)	$\frac{\Delta}{\gamma}$
0	0.67	25	2.72
5	0.90	30	3.57
10	1.23	35	4.57
15	1.58	40	5.70
20	2.14		

temperature input;

$$e_s - e_a = 6.4133\times10^{6}[\epsilon^{-7482.6/(T_a+398.36)} - \epsilon^{-7482.6/(T_d+398.36)} \quad \ldots(25)$$

here E_L = Lake Evaporation (inches)

T_a and T_d are air and dew point temperatures (°F)

e_s and e_a are vapour pressure of water surface and atmosphere (inches H_g)

ϵ is the Naperian Base

R is solar Radiation (Langleys/day)

up is wind speed (miles/day)

This technique was used by Roberts and Stall (1966) for mapping lake evaporation throughout Ilinois,USA.

2.4.5 Combination of emperical model of Priestley and Taylor and Penman equation

A number of authors (e.g.,Stewart and Rouse, 1977), discussed the emperical model of Priestley and Taylor (1972) for estimating evaporation from Saturated surfaces. By combining the emperical model of Priestley and Taylor (1972) and the well known Penman equation, a simple expression is obtained for evaporation from a shallow lake.

Under the assumption that the transfer coefficients for moisture and heat are equal, and that the Dalton equation is valid, Penman (1948) showed that the latent heat flux, LE, from a water surface could be written

$$LE = \Delta/_{(\Delta+\gamma)}\,(Q^{*}-G) + \gamma/_{(\Delta+\gamma)}\,f(u)\,(e_s-e) \quad \ldots(26)$$

where

L is the latent heat of vaporisation, E the evaporation, Δ is the slope of saturation vapour pressure temperature curve See fig.(1b), Q^{*} the net radiation, G the surface heat storage, f(u) a function of wind speed u, e_s the saturation vapour pressure at air temperature

T_a, e the vapour pressure and γ the psychrometric constant. The quantities Ta, e and u are determined at 2m. For water bodies Eq.(26) is used only occasionally, because G is difficult to evaluate (Bruin 1978).

Analysing several sets of meteorological data Priestley and Tayler found that the diurnal average of LE is proportional to the first hand term of the equation (26) in the form

$$LE = \alpha_p \Delta/(\Delta+\gamma) \quad (Q^*-G) \qquad \ldots(27)$$

Here α_p is a proportionality constant with a mean value of 1.26. For lakes this value is confirmed by several authors (Ferguson and Den Hartog, 1975 ; Stewart and Rouse , 1976, 1977 ; Davis and Allen, 1973 ; Mukammal and Neumann , 1977). However equation (27), like equation (26) has the practical disadvantage that it still contains G.

This term (Q*-G) can be eliminated by combining Eq.(26) and Eq(27).

This results in

$$LE = \alpha_p/(\alpha_p-1) \quad \gamma/(\Delta+\gamma) \; f(u) \; (e_s-e) \qquad \ldots(28)$$

Evaporation from a water surface can thus be estimated from equation (28), assuming α_p constant at 1.26, if only three parameters are known: air temperature, saturation deficit and wind speed at 2m.

2.4.6 Evaporimeter coefficient method

The emperical evaporimeter coefficients can be used to estimate lake and reservoir evaporation by using pan evaporation data collected near water body using the following emperical relationship

$$E = C_e E_p \qquad \ldots(29)$$

where E = evaporation from lake or reservoir, mm/day or cm/day

E_p = pan evaporation i.e.evaporation from evaporimeter(cm/day)

C_e = emperical evaporimeter coefficient i.e. pan coefficient

The emperical evaporimeter coefficient has a large range of variation due to climatic, geographical, seasonal, instrumental observational and local site factors. The average annual value of C_e for the USSR GGI-3000 evaporimeter is 0.80 and 0.70 for the U.S.Class A pan. Mostly the class A Pan is used for measuring Pan evaporation in the country for which Pan coefficient values have been reviewed. Hounam(1973) presented a list of class A Pan to lake annual coefficients developed for 13 lakes where the values varied from 0.52 for the Salton Sea to 0.86 for lake Eucumbene (Australia). A compilation of data on Pan coefficients from various sources is presented in Table (6). The coefficients shows greatest variation for large, deep lakes in areas with a large annual temperature range. In areas where pan coefficients have not previously derived experimentally, an average annual value of 0.70 to 0.75 is generally assumed, and pan evaporation data are multiplied by this amount in calculating evaporation. If the lake is very small, such as a shallow stock pond, a coefficient of 0.90 or even higher is more appropriate. The value of C_e for floating pan evaporimeter could be considered in the range of 0.70-0.82 and value of 0.80 is normally adopted for computing reservoir evaporation. Kohler et al.(1955, 1959) have developed graphical solutions for estimating lake evaporation from pan values and have described the distributions of pan coefficient and lake evaporation over the United States. Kchler (1954) reported that annual lake evaporation could probably be estimated to within 10-15%, provided lake depth and climatic regime are considered in selecting the coefficient. This method can produce a useful first approximation of annual lake

Table – 6 Pan coefficients for a Class A pan. (From Hughes 1967, Kohler 1954, Ficke 1972, U.S. Geological Survey 1958.)

LOCATION	TIME OF YEAR	MEAN COEFFICIENT	RANGE OF THE COEFFICIENT
Fort Collins, CO	Apr.-Nov.	0.70	0.60-0.82
L. Elsinore, CA	All year	0.77	0.63-0.97
Texas	All year	0.68	
Florida	All year	0.81	0.69-0.91
L. Hefner, OK	All year	0.69	0.35-1.32
L. Mead, AZ	All year	0.60	
Salton Sea, CA	All year	0.50	0.31-0.83
Pretty Lake, IN	All year	0.70	0.50-0.90

evaporation and be used to predict evaporation from proposed reservoirs.

It is not advisable to use the annual C_e value for the estimation of monthly or seasonal evaporation in the absence of knowledge about seasonal variation of C_e for given climatic conditions. The difference between Pan and lake will vary through the year because of seasonal differences in radiation, air temperature, wind velocity and heat storage within the larger body of water. Therefore, a Pan coefficient which varies through the year must be applied to measurements of Pan evaporation in order to estimate evaporation from lakes and reservoirs for shorter durations. Seasonal variations Pan coefficients have been discussed by Nordenson (1963), Australian Water Resources Council (1970) and Venkataraman & Krishnamurthy (1973). Variations of seasonal Pan coefficients for shallow lakes at 8 locations in India are presented in Table (7) (Venkataraman & Krishnamurthy 1973). The seasonal value of pan coefficient generally remains around 0.70 in summer and 0.90 in winter season.

Ferguson and Znamensky (1981) suggested a refinement of equation (29) by taking into account the difference in water surface temperatures between the lake and evaporimeter for estimating daily or monthly evaporation.

$$E = C_e' \frac{\overline{e^*_L} - \overline{e_Z}}{\overline{e^*_p} - \overline{e_Z}} E_p \qquad \ldots(30)$$

where

C_e' = coefficient which depends mainly on the type of evaporimeter and slightly on the lake area.

$\overline{e^*_L}$ mean saturation vapour pressure at the lake surface temperature.

TABLE - 7

Ratios of Evaporation from Mesh covered Class A Pan to Shallow Lake Evaporation.

Sl. No.	Month / Station	Jan.	Feb.	March	Apr.	May	June	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
1.	DELHI	1·00	1·00	0·90	0·75	0·70	0·70	0·75	0·90	0·95	0·90	1·00	1·10
2.	JODHPUR	1·20	1·10	0·95	0·80	0·70	0·70	0·80	0·90	0·90	1·00	1·10	1·20
3.	AHMEDA-BAD	0·90	0·80	0·75	0·75	0·60	0·65	0·75	1·00	0·90	0·90	0·85	0·90
4.	CALCUTTA	0·90	0·80	0·75	0·65	0·60	0·75	0·90	0·90	0·90	0·90	1·00	1·00
5.	NAGPUR	1·00	0·90	0·90	0·80	0·70	0·75	0·90	1·00	1·00	1·00	1·00	1·00
6.	POONA	1·00	0·85	0·80	0·75	0·70	0·75	1·00	1·00	1·00	1·00	0·90	1·00
7.	MADRAS	0·90	0·90	0·80	0·85	0·85	0·85	0·80	0·90	0·95	1·00	0·90	0·90
8.	TRIVANDRUM	0·90	0·80	0·80	0·85	0·90	1·00	1·00	1·00	1·00	1·00	1·00	1·00

$\overline{e}_p^*$ mean saturation vapour pressure corresponding to the pan water temperature.

$\overline{e}_Z$ = mean vapour pressure measured at height z over the lake.

This equation has been developed in various ways. For a Class A pan, $Z = 4m$, and using daily averages of vapour pressure, a value of $C'_e=0.7$ was obtained.

2.5 Comparison of various Evaporation Estimation Methods

Some interesting studies in Europe and the U.S.A.comparing techniques of estimating evaporation can be found in the literature (Antal et al.,1973; Keijman and Koopmans, 1973; Ficke, 1972; Winter, 1981 etc). Gangopadhyaya et al.(1966) reported many examples of comparative studies of various types of pans and tanks done world over. It was reported that the GGI-3000 pan and the class A pan showed as much as 10 percent and 35 percent less evaporation respectively for a given month of the year when compared to the control tank. Winter (1981) observed that evaporation from a rinsed floating pan differed from class A pan by 14 to 29 percent on a monthly basis, and 22 percent for a six-month period. 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 and Koopmans (1973) compared the energy budget, mass transfer, panman and pan coefficient methods in lake studies conducted at Flevo, the Netherlands using 13 periods of seven days average duration, 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.

It will be interesting to examine the results of comparative studies of estimating lake evaporation made by several workers as reported in Table (^{8}) cited from Winter (1981). The evaporation estimates as obtained by various method have been compared with the Energy Budget method and the comparison has been made for the period during which energy budget calculations were done. Since the energy budget is supposed to be the most accurate method, the comparison has been done against that. However, it is interesting to note that the estimated errors in selected terms of given equations, or in evaporation itself are generally judged against other methods of evaporation, which in themselves may contain errors. It is evident from the table (8) that less accurate results are obtained for shorter time periods e.g.weekly or daily as compared to longer periods of a month of more. It could also be inferred from the table that mass transfer method provides relatively better estimates of evaporation as compared to other methods used. Ficke (1972) reported that the energy budget estimates tend to be lower than other methods during spring and autumn low rate seasons and higher during the summer high rate season. Since these average out, so seasonal totals are the same. He stated that the spring time and short term energy budget data are perhaps less reliable as compared to mass transfer data. In an attempt of 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 co-axial graphical technique using climatologically derived estimates of radiation term also seems to be adequate.

TABLE-8 Summary of Comparisons of Evaporation Calculated by Different Methods (values are the percent of difference between evaporation calculated by the given methods from that calculated by the energy budget method).

Lake	Water Budget	Mass Transfer	Class A Pan (uncorrected)[1]	Class A Pan (corrected)[2]	Computed Class A Pan (uncorrected)[3]	Computed Class A Pan (corrected)[4]	GGI-3000 Pan	Period	Length of Study
Mead (Arizona-Nevada)	----	2.00-27.40	----	0-22.20	----	----	----	4 Weeks	12 March 52-28 September 53
Harbeck, *et al.*, 1958)	----	10.00	----	7.20	----	----	----	Mean of Periods	
	----	1.10	----	4.70	----	----	----	Total	
Salton Sea (California)	0-36.70	0.90-46.40	Several Hundred	----	----	----	----	2 Weeks	9 January 61-8 January 63
(Hughes, 1967)	10.95	13.13	----	----	----	----	----	1961 Mean of Periods	
	14.65	13.59	----	----	----	----	----	1962 Mean of Periods	
	5.00	3.80	----	----	----	----	----	1961 Total	
	1.20	0.60	----	----	----	----	----	1962 Total	
Salton Sea (California)	1.40-40.40	0.20-24.20	----	----	----	----	----	Monthly	August 67-December 68
(Sturrock, 1977)	13.39	8.23	----	----	----	----	----	Mean of Periods	
	2.90	0.30	----	----	----	----	----	Total	
Pretty (Indiana)	3.50-46.90	0.20-39.30	0-70.20	0.50-68.10	0.90-37.50	0.80-51.10	----	2 Weeks	April 63-September 65
(Ficke, 1972)	16.22	14.89	15.77	18.07	14.75	13.10	----	Mean of Periods	
	9.80	9.40	25.80	18.90	4.50	2.80	----	1964 Total	
	4.30	2.70	27.00	28.70	0.00	2.30	----	1965 Total	
Velen (Sweden)	4.00	----	----	2.00	----	----	22	June and July	June 71-September 71
(Rodhe, 1973)	8.00	----	----	36.00	----	----	51	August	
	35.00	----	----	54.00	----	----	32	September	
	8.00	----	----	15.00	----	----	29	Total	

[1] From Class A pan data at National Weather Service stations.

[2] Corrected for advection and energy storage.

[3] Computed by method described by Kohler, *et al.* (1959).

[4] Same as 3, but corrected for advection and energy storage.

The comparison of different methods of estimating evaporation in terms of the data requirement, instrumentation needed and their relative suitability for specific conditions has been tabulated in table -9.

It is clear that there are several alternatives of estimating reservoir evaporation ranging from fairly accurate techniques requiring sophisticated instruments (like in energy budget method) to relatively less accurate methods using conventional instruments and existing evaporation pans. The energy budget technique supposed to be the most accurate method wherein the errors in estimating the evaporation range about 10 percent and 15 percent for annual and monthly estimates respectively. But it requires extensive instrumentation & frequent surveys of water body making it a comparatively expensive deal. The mass transfer method is another alternative which provides relatively better estimates of evaporation using routinely observed meteorological and reservoirs water level fluctuation data. The estimation of mass transfer coefficient, N is the only limitation of this method. However this could also provide relatively compromising results even when, N is worked out from the surface area of a water body as suggested by Harbeck (1962). The data of pan evaporation using suitable pan coefficient can be made with caution.

TABLE - 9

Method of Estimation	Data Requirement	Instrumentation Required	Remarks
Water Budget Method	Inflow, outflow, seepage, change in storage and precipitation in the reservoir	For measuring water level, inflow and outflows. Rain gauge for measuring precipitation	Estimation of incorrect seepage makes the method inefficient
Energy Budget Method	Water surface temperature, air temperature, air and water surface vapour pressures, relative humidity sunshine hours data, latitude and longitude of the place. Inflow, outflow and storage data.	Pyrheliometer for measuring solar radiation and reflectivity of the surface, hydrothermograph or psychrometer to determine relative humidity and vapour pressure of the air, staff for measuring water level, and instrumenation for inflows and outflows.	Method involves not only installation of costly instruments but also careful measurement of various parameters.
Mass Transfer Method	Wind velocity, air and water surface vapour pressures For determination of mass transfer coefficient, N : Inflow, outflow and change in storage is required as shown in Fig.(4).	Graduated staff placed in the centre of the lake and system of instruments for measuring inflows and outflows	Method is suitable only for small ponds and shallow lakes for the periods where there are no inflows and outflows.
Penman Method	Same data are required as in cases of water budget and energy budget methods	Same as in cases of energy budget and water budget.	Sunshine hours, and wind velocity observation must be taken carefully.
Pan Evaporation Method	Pan evaporation value corrected for precipitation.	U.S. Class-A pan evaporimeter.	Sensible heat transfer through walls results in geographical variations of pan coefficient, therefore, method is suitable for estimation of annual evaporation losses.

3.0 PROBLEM DEFINITION

The review of literature indicates that the energy budget method provides the most accurate estimates of reservoir evaporation but at the same time requires extensive instrumentation and frequent thermal surveys of water body which are mostly not available in the field. Therefore an alternative approach is required to compute reservoir evaporation depending upon the routinely observed meteorological and reservoir water level fluctuation data. Therefore, in view of data availability of Bhadre reservoir project, district Shimoga in Karnataka, method of mass transfer using mean daily meteorological parameters (e.g.wind velocity, air temp.,relative humidity, air vapour press. etc.) and reservoir water level fluctuation data, the estimation of evaporation have been made for selected periods for the year 1979. The Penman method has been also used for the same period for estimating evaporation by deriving values of some climatological data from standard tables and considering sunshine hours data of nearby station with suitable adjustments.

4.0 METHODOLOGY

The estimation of reservoir evaporation has been done with a very limited set up of mean daily meteorological data and daily reservoir water level fluctuation & inflow, outflow data. The estimates of evaporation have been made for few selected period for which there was no inflow, using the mass transfer method, just to illustrate the use of this approach for the field users. The estimates of evaporation have been also made using Penman method by taking the values of few meteorological parameters from available standard tables and using sunshine hours data of Bellary station with suitable modification as an illustrative example only.

4.1 Estimation of Evaporation by mass transfer method

Calculation of evaporation (cm/day) from Bhadra reservoir project ($13^{\circ}42'N$), Karnataka, by mass transfer method for the period of Jan. 1979 to May 1979 , using equations:

$$E = f(u)\ (e_s - e_a) \qquad ...(15)$$

$$f(u) = a + Nu^n \qquad ...(16)$$

$$\Delta h = E + S \qquad ..(17)$$

Here $f(u)$ = coefficient of proportionality, often called the wind function.

e_s = vapour pressure of water surface (mb)

e_a = vapour pressure of the air (mb)

a and n= constants for a given water body. Generally, n is assumed to be unity & a is assumed zero, while computing evaporation from lakes.

u wind speed(km/day)

Δh net change of water surface elevation adjusted for surface inflow and outflow and for precipitation onto the lake surface. An elevation volume curve or table for the lake is needed for the adjustment. During the period of no surface inflow or outflow, this is simply the fall of the water surface, which can be evaluated through repeated observations of water level on a graduated staff set in the reservoir.

E evaporation (cm/day)

S net ground water seepage (cm/day)

A - Data(obtained from W.R.D.O.& P.W.D., Karnataka for 1-31 March, 1979).

1. Mean daily air temperature =26.4°C.
2. Mean daily relative humidity %=83
3. Mean daily vapour pressure of the air= 32.4 mb
4. Wind speed (daily mean)=4.2 kmph
5. Net change of water surface elevation, Δh=1.45 cm/day

B - Solving equation (15), (16) and (17)

(i) $$e_s = 100 \times \frac{e_a}{R.H\%} = \frac{32.4 \times 100}{83} = 39.04 \text{ mb}$$

(ii) $$u = 4.2 \text{ kmph} = 4.2 \times 24 = 100.8 \text{ km/day}$$

(iii) $$u\,(e_s - e_a) = 100.8\,(39.04 - 32.4)$$
$$= 668.92 \left(\frac{\text{Km}}{\text{day}} \times \text{mb}\right)$$

Similar procedure is adopted for Jan.to May 79.

Table - 10

Month	$u(e_s-e_a)$ km/day xmb (1)	h(cm/day) (2)	$E=Nu(e_s-e_a)$ cm/day (3)	Pan Evaporation cm/day (4)	Pan Coefficient (5)
Jan.79	253.7	1.086	0.123	0.33	0.37
Feb.79	356.08	1.305	0.172	0.38	0.45
March 79	668.92	1.45	0.323	0.54	0.60
April 79	921.4	1.35	0.45	0.57	0.79
May 79	1200.0	1.68	0.58	0.59	0.98

C - Fitting a straight line (Fig. 8) using least square method in the graph $u(e_s-e_a)$ V/S $\triangle h$, we get seepage, S(1.045 cm/day) by reading intercept on Y-axis and slope of the line gives the values of mass transfer coefficient, N(0.0004835).

$S = 1.045$ cm/day and

$N = 0.0004835$

Putting these values in equation (15), (16) and (17), we get

$$\triangle h = 1.045 + 0.0004835\, u\, (e_s-e_a) \qquad \ldots(31)$$

Multiplying column (1) of table (10) by N we get daily mean evaporation, E in cm/day as shown in column (3) of table (10) for the months during Jan.79 to May 79.

Dividing column (3) by column (4) we get column (5) that is pan coefficient.

D - For obtaining N equation (18) can also be used i.e.

$N = 0.000169(A)^{0.5}$

A = area in sq.km

or we can write

$N = 0.000272\ (A)^{0.5}$

where A is surface area in sq.miles.

Calculating N by the above equation we get evaporation E, as shown in table 11.

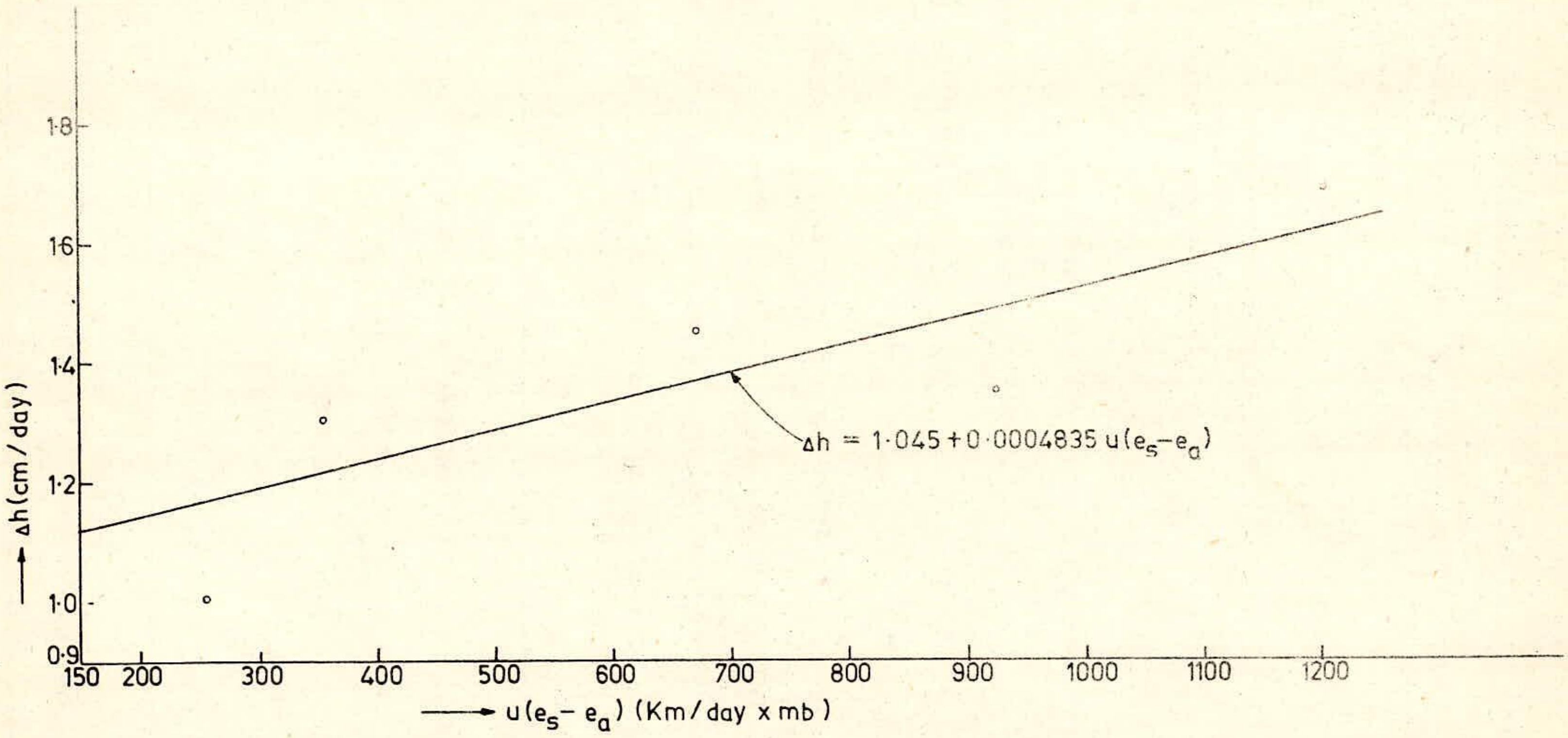


FIG. 8 PLOT OF MEASURED CHANGE OF WATER LEVEL AGAINST $u(e_s - e_a)$ FOR BHADRA RESERVOIR PROJECT (DATA FROM W.R.D.O. AND P.W.D.)

Table -11

Months	N	Column 1 $u(e_s-e_a)$ of table 10	$E = Nu(e_s-e_a)$ cm/day
January	0.00174	253.7	0.44
February	0.00168	356.08	0.60
March	0.00160	668.92	1.07
April	0.00147	921.4	1.35
May	0.00136	1200.0	1.63

4.2 Estimation of Evaporation by Penman Method

Estimation of Evaporation from open water surface E_o(mm/day) for Bhadra Reservoir Project (13°42'N), Karnataka, using Penman Formula given in equation (23) for the period of Jan.79 to May 79.

A - Data	Period March 1-31,1979
1. Mean daily air temp.(°c)	26.4
2. Mean daily relative humidity(%)	83
3. Mean daily vapour pressure of air, e_2 or e_a(mb)	32.4
4. Mean sunshine hours(hr/day)	6.5
5. Possible sunshine hours, N(from Tab.3)	12.16
6. Value of n/N	0.534
7. Wind speed(km/day)	4.2 x 24 =100.8
8. Extra terrestrial radiation I_o in (mm/day)(from table-1)	14.95
9. Reflection coefficient	0.06

B - Solving expression

$$Q_{rs} = (1-\alpha)I_o(a+b\frac{n}{N})$$

10. $(1-\alpha)$ $=(1-0.06)=0.94$

11. $I_o(a+b\frac{n}{N})$ (taking a & b from table-2)

$= 14.95\ (0.18 + 0.62 \times 0.534)$ $=7.65$

12. Q_{rs} = Item Nos (10 x 11) = 0.94×7.65 $=7.19$ mm/day

C - Solving expression of equation (13)

$$Q_{lw} = \sigma T_2^4\ (0.56 - 0.08\sqrt{e_2})\ (0.10+0.9\ n/N)$$

13. σT_2^4 (from table-12) $=16.34$

Also e_2 or e_a is 32.4 mb

14. $\sigma T_2^4\ (0.56 - 0.08\sqrt{e_2})(0.10+0.9\ n/N)$

$= 16.34\ (0.56 - 0.08\sqrt{32.4})(0.10 + 0.9 \times 0.534)$

$=0.992$ mm/day

D- From equation (14), $Q_n = Q_{rs} - Q_{lw}$

$= 7.19 - 0.992$ $=6.198$ mm/day

E - $e_{sa} = \frac{e_2}{R.H.\%} \times 100 = \frac{32.4}{83} \times 100$ $= 39.036$ mb

F - Solving equation (22)

$$E_a = (0.013 + 0.0001\ u_2)(e_{sa}-e_a)$$

$= (0.013 + 0.001 \times 100.8)(39.036-32.4)$

$= 0.153$ cm/day $=1.53$ mm/day

G - Solving equation (23)

$$E_o = \frac{Q_n \frac{\Delta}{r} + E_a}{\frac{\Delta}{\gamma} + 1}$$

$\frac{\Delta}{\gamma}$ from (table -5) $=2.958$

Therefore $E_o = \frac{6.198 \times 2.958 + 1.53}{2.958 + 1}$ $=5.018$ mm/day

similarly estimating evaporation for other months as shown in table(13)

TABLE 12 Values of σT_a^4 for various temperatures when computing evapotranspiration by the Penman method (after Criddle)

Temperature (*°K*)	σT_a^4 (*mm water/day*)
270	10.73
275	11.51
280	12.40
285	13.20
290	14.26
295	15.30
300	16.34
305	17.46
310	18.60
315	19.85
320	21.15
325	22.50

Note: Heat of vaporization was assumed to be constant at 590 cal/gm of water.

(*Israelsen and Hansen*, 1962)

Table 13

Months	Evaporation estimated by Penman method(mm/day)	Pan Evaporation mm/day	Pan Coefficient
January 1979	3.29	3.3	0.99
February 1979	3.98	3.8	1.05
March 1979	5.018	5.4	0.92
April 1979	5.1	5.7	0.89
May 1979	5.2	5.9	0.88

5.0 RESULTS AND DISCUSSION

5.1 The estimated value of evaporation from Bhadra Reservoir Project, obtained by using mass transfer method are given in table (10). In order to use mass transfer method daily mean data of periods for which there was no inflow, have been used so as to find out the change in daily mean reservoir level by subtracting measured outflows. Using this value the mean daily evaporation have been calculated for that month and this was considered as the mean daily evaporation for that particular month. Since the water surface temperature data were not available the air temperature data have been used alongwith relative humidity and vapour pressure of the air. These simplifications and assumptions have been made in order to overcome the paucity of data and to illustrate the procedure for estimating reservoir evaporation to field engineers and also to suggest as to what probelms are encountered and how the data deficiency could be improved in future. The value of evaporation obtained by mass transfer method do not appear to be accurate and generally point towards a lower value. Moreover the variation of pan coefficient do not appear to be appropriate as the values of pan coefficients are less in winter and more in summer which is against the normally reported trend. These descripancies may be attributed to the paucity of data in absence of which the values of reservoir levels of only few days (generally 5 to 24 days, Jan.and Feb.having the lowest such days of the order of 5 to 7 days) when inflow were observed to be zero. This may be the reason for relatively higher descripancies specially in the month of January and February for which using the daily reservoir fluctuation value of only 5 to 7 days, the mean daily evaporation of the respective months have been calculated. Therefore, the values of evaporation thus obtained could only be considered as indicative and suggestive values and may not be considered as accurate one. However, by using the required data reliable estimates of evaporation can be made by adopting the procedure discussed in the report. This method can be used to determine the average daily seepage rate from a reservoir under the given conditions. Once having obtained this value of seepage rate it could be deducted from corrected water level fluctuation, Δh to compute evaporation for similar situation.

5.2 The Penman method has also been used for the same period for Bhadra Reservoir Project for estimating evaporation by deriving values of same climatological data from standard tables and considering sunshine hours data of nearby station with suitable adjustments. Sunshine data of Bellary have been adjusted suitably as the cloudiness is more pronounced at Bhadra Reservoir project in comparison to Bellary. Therefore adjusted sunshine data have been used on adhoc basis just as an illustrative example and also to get some idea about its comparison with the estimates made by mass transfer method. The evaporation estimates obtained by Penman method appear to be relatively more reliable and in this method pan coefficient is also relatively more in winter period (i.e.0.99) as compared to that of summer period (0.88).

The average evaporation value estimated by this method ranges between 3.3 to 5.2 from Jan 79 to May 79 while pan coefficient ranges between 0.99 to 0.88 from Jan.79 to May 79.

6.0 CONCLUSIONS

Evaporation losses from the lakes and reservoir water surfaces is an important consideration in planning and design of such structures specially in arid and semi arid regions and drought prone areas. It is clear that there are several alternatives of estimating reservoir evaporation ranging from fairly accurate techniques requiring sophisticated instrumentation (like energy budget method in which errors in estimating evaporation losses ranges about 10 to 15%) to relatively less accurate method using conventional instruments and existing pan evaporimeters. It is also evident from the studies conducted in India and elsewhere that less accurate results are obtained for shorter time periods(e.g.weekly or daily) as compared to larger periods of a month or more. The mean daily evaporation for Bhadra Reservoir Project using mass transfer method are to be 0.123, 0.172, 0.323, 0.45 and 0.58 cm/day for the month of Jan.,Feb.,March, April and May 1979 respectively. The value of evaporation obtained by mass transfer method do not appear to be accurate and generally point towards a lower value. Moreover the variation of pan coefficients are less in winter and more in summer which is against the normally reported trend. Therefore the values of evaporation thus obtained could only be considered as indicative and suggestive values and may not be considered as accurate one. However by using the required data reliable estimates of evaporation can be made by adopting the procedure discussed in the report.

The evaporation losses estimated by Penman method for Bhadra reservoir project, using derived value of some climatological data from standard tables and considering suitably adjusted sunshine hours data of nearby Bellary station, are 0.33, 0.38, 0.54, 0.57 and 0.59 cm/day for the months of Jan.,Feb.,March, April & May respectively. These evaporation estimates made by Penman method appear to be relatively more reliable and in this method pan coefficient is also relatively more in winter period (i.e.0.99) as compared to that of summer period (0.88).

It is suggested that the observatories located near the dam site may be equiped with sunshine recorders and net radiometers to measure actual sunshine hours and net radiation. Since water surface temperature data is required for the mass transfer method, the provisions for measurement of the water surface temperature may also be made. In order to carry out reservoir evaporation studies and viz a viz reservoir water balance studies at few selected reservoirs provisions for floating pan evaporimeter and floating platform type hydrometeorological observatory are suggested.

REFERENCES

1. Albertson, M.L., 1948.Analysis of Evaporation is a Boundary-Layer Phenomenon. Ph.D.Dissertation, University of Lowa, Ames, Lowa.

2. Anderson, E.R., L.J.Anderson, and J.J.Mariano, 1950, A Review of Evaporation Theory and Development of Instrumentation. U.S. Navy Electronics Laboratory, Report 159, 71 pp.

3. Anderson, E.R.(1954) Energy budget studies; U.S.Geological survey professional paper 269.

4. Antal, E.S.Baranyi and E.Toth, 1973. Comparison of Calculation Method for Evaporation Using Lake Balaton as an Example. Hydrology of Lakes, Helsinki Symposium, International Association of Hydrological Sciences, Publication 109, pp.220-224.

5. Australian Water Resources Council, (1970a). Evaporation from Water Storages Canbera, Dept. of National Development, Hydrologic Ser.No.4,81p.

6. Australian Water Resources Council.1970b. Estimating Evapotranspiration an evaluation of techniques. Canbera, Dept. of National Development Hydrologic Ser.No.5.

7. Betson, A.R.,Jr.,W.P.James, and J.W.Rouse, Jr.1978. Evapotranspiration from Water Hyacinth in Texas Reservoirs. Water Resources Bulletin 14(4); 919-930.

8. Black, J.N., Bonython, C.W. and Prescott, J.A.(1954) solar radiation and the duration of sunshine; Quarterly Journal of the Royal Meteorological Society, Vol.80, pp.231-235.

9. Bowen, I.S.,"The Ratio of Heat Losses by Conduction and by Evaporation from any water surface", physical Review, Vol.27, 1926, pp.779-787.

10. Bruin De, H.A.R., A Simple Model for shallow lake evaporation, Jour. of Applied Meteorology, American Meteo. Soc., 0021-8952/ 78/pp.1132-1134, 1978.

11. Chang, J.H.(1968) climate and agriculture an ecological survey, Aldine, Chicago, 296 pp.

12. Dalton, J., 1802.Experimental Essays on Evaporation. Manchester Literary Philosophical Society Proceedings 5:536-602.

13. Davis, J.A., and C.D.Allen, 1973: Equilibrium, potential and actual evaporation from cropped surfaces in southern Ontario.J. Appl.Metor.,12, 649-657.

14. Doorenbos, J. and Pruilt, W.C.(1945), Guidelines for predicting crop water requirements, Irr.and Drainage Paper 24, FAO, Rome 197p

15. Ferguson, H.L.; den Hartog, G.1975.Meteorological studies of Evaporation at Pench lake, Ontario.Hydrological sotudies on a small basin on the Canadian Shield-A final summary of the Pench Lake Evaporation study, 1965-74, Vol.2, P.417-447. Chalk River, Ontario, Stomic Energy of Canada Limited, Chalk River Nuclear laboratories (AECL-5041).

16. Ferguson, H.L. and Znamensky, V.A.,1981,'Methods of computation of the water balance of lakes and reservoirs' Vol.I Methodology Unesco Publications.

17. Ficke, J.F.1972, Comparison of Evaporation Computation Methods, Pretty Lake, La Grange County, Northeastern Indiana, U.S.Geological Survey Professional paper 686-A, 49 pp.

18. Gangopadhyaya, M.,G.E.Harbeck, Jr.T.J.Nordenson, M.H.anar. and V.A.Uryvaev, 1966, Measurement and Estimation of Evaporation and Evapotranspiration. W.M.O., Technical Note 83, 121 pp.

19. Gangopadhyaya, M., Dotar, S.V. and George, C.J.(1970).On the global solar radiation, climate and evapotranspiration estimates in India. Indian J.Met.Geophys., 23-30.

20. Gunaji, N.N., 1968. Evaporation investigations at Elephant Butte Reservoir in New Mexico. In Geochemistry, Precipitation, Evaporation, Soil Moisture, Hydrometry. General Assembly of Eern, International Association of Scientific Hydrology 78:308-325

21. Harbeck, G.E.,& Meyers, J.S.,'Present day Evaporation Measurement Techniques', Proc. of ASCE, Hydr.,Div.Vol.96, No.HY7, July 1970, pp.1381-1387.

22. Harbeck, G.E.,Jr.,1962. A practical Field Technique for Measuring Reservoir Evaporation Utilizing Mass-Transfer Theory.U.S. Geological Survey Professional Paper 272-E, pp.101-105.

23. Harbeck, G.E., Jr.,M.A.Kohler, G.E.Koberg, et al.,1958.Water Loss Investigation. Lake Mead Studies, U.S.Geological Survey professional paper 298, 100 pp.

24. Hounam, C.E.,1973.Comparison Between Pan and Lake Evaporation. World Meteorological Organisation, Technical Note 126, 52 pp.

25. Hoy, R.D., Stephens, S.K.1977.Field study of evaporation-analysis of data from Eucumbene, Cataract, Manton and Mundaring. Canbewa, Australian Water Resources Council, (Tech.Paper No.21).

26. Hughes, G.H.,1967. Analysis of Techniques Used to Measure Evaporation From Salton Sea, California U.S.Geological Survey Professional Paper 272-H, 176 pp.

27. Israelson, O.W. and Hansen, V.E.(1962). Irrigation principles and practices. John Wiley and Sons, New York 447p.

28. Jobson, H.E.(1972) Effect of Using Averaged Data on the Computed Evaporation. Water Resources Research 8(2):513-518.

29. Jukka Jarvinen (1978), Estimating lake Evapn.with floating evaporimeters and with water Budget', Nordic Hydrology, 9.pp121-130.

30. Keijman, J.Q. and R.W.R.Koopmans, 1973, A Comparison of several Methods of Estimating the Evaporation of Lake Flevo.Hydrology of Lakes, Helsinki Sympsoium International Assoc.of Hydrological Sciences, Pub.109: 205-232.

31. Kohler, M.A.,1954.Lake and Pan Evaporation in water loss investigations, Lake Hefner Studies Technical Report.U.S.Geological Survey Survey Professional Paper 269, 138 pp.

32. Kohler, M.A., T.J.Nordenson, and W.E.Fox, Evaporation from Pans and Lakes, U.S.Weather Bur.Res.Pap.38, 1955.

33. Kohler, M.A.,T.J.Nordenson, and D.R.Baker, Evaporation maps for the United State, u.S.Weather Bur.Tech.Paper 37, 1959.

34. Lamoreux, W.W.(1962) Modern evaporation formula adopted to computer use, Monthly Weather Review, Vol.90, pp.26-28.

35. Langbein, W.B.,Hains, C.H. and Cullers R.C.(1951) Hydrology of stock water reservoirs in Arizona; U.S.Geological Survey Circular 10.

36. Linsley, K.R., Kohler, M.A. & Paulhus H.L., Hydrology for Engineers 1975, Second Edition, McGraw Hill Publications.

37. Marciano, J.J. and G.E.Harbeck, Jr.,1954.Mass-transfer studies in Water-Loss Investigations; Lake Hefrer studies Technical Report U.S.Geological Survey Professional paper 269, pp.46-70.

38. Mckay, G.A.sow stichling, W.(1961).Evaporation computations for prainic reservoirs; National Research Council of Canada, Proc. of Hydrology Symposium No.2, Evaporation, pp.135-167.

39. Mehndiratta, K.R. and Hoon, R.N., Evaporation Losses from the Bhakra Reservoir and the Reservoirs Effect on the Local Climatic Conditions. Jour. of Irrigation and Power, CBIP, Vol.30, No.3, July 1973, pp.227-236.

40. Meyboom, P.(1967) Mass transfer studies to determine the groundwater regime of permanent lakes in hummocky moraine of Western Canada; Jour of Hydrology, Vol.5, pp.117-142.

41. Mukammal, E.I., and H.H.Neuman, 1977: Application of Priestlay-Tayer evaporation model to assess the influence of soil moisoture on the evaporation from a large weighting lysimeter and class A pan.Boundary-layer, Meteor, 12, 243-256.

42. Nordenson, T.J.(1963).Appraisal of seasonal variation in pan coefficients. IASH, Berkeley Assembly,p.279-286 (IASH Publ.No.62).

43. Penman, H.L.'Natural Evaporation from Open Water, Bare Soil and Grass', Proc.Roy.Soc.London A.193 pp.120-145.

44. Phillips, K.N. and Van Den burgh, A.S.(1971) Hydrology & geochemistry of Abort, Summer and Goose Lake and closed-basin lakes in South Central Oregon; U.S.Geological Survey Professional Paper 502-B.

45. Prandtl, L., 1905. On Fluid Motions with very small friction. Proc. of the Third Mathematical Congress. Heidelberg, 1904.

46. Priestley, C.H.B., and R.J.Taylor, 1972: On the Assessment of Surface heat flux and evaporation using large scale parameters, Mon.Wea.Rev.,100, 81-92.

47. Roberts, W.J. and Stall J.B.(1966) Computing lake evaporation in Illinois, Water Resources Research, Vol.2, pp.205-208.

48. Stewart, R.B., and W.R.Rouse, 1977, Substantiation of the Priestley-Taylor parameter α = 1.26 for potential evaporation in high latitudes. J.Appl.Meteor., 16, 649-650.

49. Stewart, R.B., and W.R.Rouse, 1976; A simple method for determining the evaporation from shallow lakes and ponds. Water Resources Research.,12, 623-628.

50. Sturrock, A.M., 1978. Evaporation and Radiation Measurements at Salton Sea, California. U.S.Geological Survey Water-Supply paper 2053, 26 pp.

51. Turk, L.J.(1970) Evaporation of brine: a field study on Bonneville Sact Flats, Utah; Water Resources Research, Vol.6 pp.1209-1215.

52. Turner, J.G.(1966) Evaporation study in a humid region, Lake Michie, North Carolina; U.S.Geological Survey professional paper 272-G.

53. U.S.Geological Survey (1958) Water loss investigations Lake Hefer Studies; U.S.Geological Survey professional paper 298.

54. Venkataraman, S. & Krishnamurthy, V.1973, Annual Evaporation losses from large reservoir, Irrigation and Power Jour., Jan.1973 pp.59-66.

55. Winter, Thomas. C.(1981),"Uncertainties in Estimating the Water Balance of Lakes" Water Resources Bulletin, Vol.17, No.1, pp.82-115.

55. Yonts, W.L., G.L.Giese, and E.F.Hubbard, 1973. Evaporation from Lake Michie, N.Carolina 1961-71. U.S.Geological Survey Water Resources Investigations 38-73, 27 pp.