EVAPORATION FROM LAKES

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INTRODUCTION

Evaporation is one of the very significant components of the hydrologic cycle. Knowledge of evaporation rates is essential to estimate water availability in the water bodies such as lakes and reservoirs. Estimates of evaporation rates are also needed for various other purposes such as water resources planning and management, heat balance studies, temperature modeling etc. Inspite of its significance, however, precise estimation of evaporation from water bodies still remains one of the challenging tasks for the hydrologists and water resources engineers the world over. This is because evaporation is not so simple a process as it appears. It is a very complex process.

When the radiant energy is supplied to the lake water through the sun, kinetic energy of the water molecules is increased. When the water molecules attain enough kinetic energy, they escape from the water body overcoming the intermolecular forces and eject themselves into the atmosphere. The amount of energy expended by a unit mass of water while passing from liquid to vapour state at constant temperature, is called the heat of evaporation or the latent heat of vapourization. If external energy is not made available, energy is removed from the water body while evaporation is taking place resulting in lowering of water temperature. Thus, evaporation is indirectly a cooling process. Continuous supply of heat energy causes accumulation of more and more vapour molecules increasing the partial vapour pressure. This continues till the level of saturation vapour pressure is reached and water molecules are rejected in the form of condensation. If the vapour pressure of air above the free water surface is already equal to saturation vapur pressure, neither evaporation nor condensation takes place and it is said to be in equilibrium state. However, in practice an equilibrium stage never exists under normal conditions. This is because the atmosphere into which evaporation takes place, is infinite and various transport processes will also operate to transport the vapour in the atmosphere both parallel as well perpendicular to the lake water surface and prevent equilibrium from occurring.

FACTORS AFFECTING EVAPORATION

As stated earlier, evaporation is a very complex process. It involves complex interactions and interrelationships of number of meteorological and physical factors. These include radiation, temperature, humidity, wind and atmospheric pressure, water quality, size and shape etc. However, it is very difficult to quantitatively assess the relative importance of each of these factors. It varies from one climatic region to other, and also temporally. The variation in evaporation rates due to variation in these relationships need to be understood for a variety of climatic setting.

Temperature is often thought to be the only dominant factor deciding the evaporation rates, particularly for arid and semi arid regions. However, it is not the only factor deciding evaporation rates. For evaporation to occur, there should be availability of water, a source of energy to remove the water and a demand from surrounding air for water removal. The supply of energy is provided by solar radiation which has a close relationship with the evaporation. Where the radiation is high, evaporation is also high. The vapour pressure deficit (e_s-e_a) is an indicator of the actual evaporative demand of the air. As long as vapour pressure of water surface exceeds the vapour pressure of the air, evaporation continues. Vapour pressure of pure water is solely dependent on temperature. But most of the evaporation models use saturation vapour pressure of air as equivalent of vapour pressure of water, as water temperature data are generally not available. Actual vapour pressure of air, which denotes the partial pressure exerted by water vapour present in air, is a function of temperature and humidity together, the maximum vapour pressure that is thermodynamically stable is called the saturation vapour pressure. Wind is another important factor in the process of evaporation. It ensures the continuity in demand of air for water removal. If there was no wind, air would soon get saturated with water vapour and evaporation would cease. Thus, higher the wind velocity higher is the evaporation. However, there is an upper bound called critical velocity, beyond which any increase in wind speed does not change the evaporation rate.

Other factors influencing evaporation include atmospheric pressure, sunshine hours, water quality and geometry of water body. Evaporation has an opposite relationship with atmospheric pressure. Decrease in atmospheric pressure increases the evaporation and vice-versa. This is because vapour pressure of air also decreases with atmospheric pressure thereby increasing the vapour pressure deficit. Water quality, particularly dissolved solids, decreases the vapour pressure of water and reduces evaporation. The decrease is of the order of one percent for every one percent increase in salinity. Turbidity, also indirectly affects the evaporation through alteration of albedo, but the effect is known to be very little. The geometry of the water body is important when volume of water lost and not the rate of evaporation are important. However, size of the water body would affect the evaporation rates also, in the sense that air moving over large surface would gradually increase its water content thereby loosing its water holding capacity.

VARIABILITY OF EVAPORATION

Evaporation rates vary with region and also temporally within a region. For example, in Japan it has been observed that the annual variation of evaporation is greater in autumn and winter seasons, from September to March, than in spring and summer seasons. The pattern of monthly evaporation is also not always consistent from year to year. Studies have also shown that evaporation rate varies across a lake, in case of large lakes. Also, there are seasonal, intra-seasonal and inter-annual variations in lake evaporation. The spatial and temporal variations in evaporation estimates are due to the variation in interrelationships and relative significance of the various controlling factors, as pointed out earlier. Studies show that for shallow lakes, sensible and latent heat flux, and the energy storage in the lake may vary considerably across the lake. Similarly, wind speed and stability of thermal stratification have shown to strongly affect the evaporation from some lakes. It has been observed in a study that evaporation from the shallow lake is found to be higher than the deep lake in winter and summer, but in autumn and summer, the situation reversed. The evaporation from the shallow lake has been observed to be directly related to the amount of incoming short wave radiation while the lag in evaporation at the deeper lake has been a function of seasonal heat storage. Thus, the thermal regime of the lake must be considered to accurately estimate the seasonal evaporation rates from a deep lake. Studies of relative importance of various routine meteorological variables in evaporation and Evapotranspiration, carried out using using routine meteorological data using factor analysis approach, indicate that relative humidity, temperature and wind speed are the most important factors that influence the evaporation and evapotranspiration process, in that order, while rainfall and sunshine duration have less influence. However, again the results may vary from region to region. Some studies which have also included radiation data indicate that that evaporation rates are more sensitive to the values of outgoing and incoming long-long-wave radiation, followed by air and water surface temperatures. These studies further indicate that the rest parameters do not significantly affect the evaporation rates except for the effect of air vapour pressure on lower evaporation rates which are quite significant. It has been further observed that the net radiation during spring and early summer is utilized mainly for the lake's heating and therefore, for rising lake's temperature and is stored in the lake as thermal energy. Reversely during autumn, even though air temperature and net radiation continuously decrease, evaporation rates are high because lake releases the energy stored in its volume, in the form of latent heat, and in a minor proportion, as sensible heat. This discussion makes it aptly clear that evaporation is a very complex process and roles of different factors vary locally and temporally. Further, it has been reported that the role of controlling factors in evaporation variability has been found to vary with the type of data also. As such, any conclusions on the relative effect of controlling meteorological factors must also be qualified in terms of the time period considered.

EVAPORATION ESTIMATION

Evaporation research started with the pioneering work of Dalton in 1802 who observed that evaporation rate is closely related to vapour pressure difference between the evaporating surface and the surrounding air. This led to the classical Dalton equation, also called aerodynamic equation. However, systematic evaporation research can be traced back to another pioneering work; that of Penman in 1948. Penman adopted the best features of the mass transfer and energy balance methods and derived an equation to estimate open surface evaporation from routinely observed meteorological data. A number of methods and models have since been developed to estimate evaporation from the open water surface which are being used for lakes.

The various models of evaporation can be classified into different categories such as energy balance models, water balance models, mass transfer models, combination models, pan evaporation models, equilibrium temperature models and empirical models Besides the models that have specifically been developed for the purpose of open water surface evaporation estimation, it is a common practice to use models developed for potential evapotranspiration (PET) estimation, for estimating the lake evaporation. Most of these models are intended for use in climates similar to where they were developed and have a wide range of data requirement. The data requirement of these models varies from a single parameter as in certain temperature and radiation based empirical models, to the complex energy budget models that require a large number of measurements.

Theoretically the water balance appears to be the most realistic model. However, although the water balance equation looks simple, its practical application poses many difficulties causing errors in estimation of different components. The errors in lake water balance components are mainly due to errors of measurement and errors of regionalization. Water balance models are, therefore, not considered accurate. The energy balance methods, such as the Bowen-ratio energy budget (BREB) method, are considered to be the most accurate of all the available methods. However, extensive data and instrumentation requirements, associated costs and the requirement of precision in data, often limit their use. In such cases, the combination methods, typified by the Penman model, are used as the standard method for estimation of evaporation.

In situations where observed data are limited, recourse is taken to more simplistic methods. Mass transfer methods, also called aerodynamic methods, are hence more popular. They are simple to use and also have a lesser data requirement. They are based on the concept of eddy motion transfer of water vapour from an evaporating surface. A number of empirical and semi empirical models based on the mass transfer approach have been developed. Most of the mass transfer equations are Dalton type which can be written in the form:

$$E= (a+bU)(e_w-e_a) \qquad ....(1)$$

where, e_w and e_a are vapour pressures of water and air and, u is the wind speed. An improved version of the mass transfer method is the bulk aerodynamic method which is based on the following equation:

$$E=a+NU^n e_{sw}-e_a) \qquad .... (2)$$

where, e_{sw} is saturation vapour pressure calculated from water surface temperature, e_a is vapour pressure of the air above water surface, 'a' and 'n' are constants for a given water body, N is mass transfer coefficient and U is wind speed.

Although satisfactory results have been achieved with the mass-transfer in some studies, in most cases estimates of mass transfer has been observed to vary considerably than the more precise energy balance method. Thus, despite their popularity, mass transfer based equations have limited universal applicability. This is mainly because the mass transfer coefficients vary from region to region and have to be locally calibrated.

Use of pan data is another very popular method as there is an element of observed evaporation in the data. The method is discussed in some details in next section. If even the pan data are not available and only some limited meteorological data are available, empirical models that use parameters such as only temperature or solar radiation are also used. A number of such models have been developed. Examples of these include models by Stephans and Stewart, Jansen and Haise, Kohler and Parmele, Priestly and Taylor, Stewart and Rouse etc. However, although it is a common practice to use these models for other regions also, mainly because of their very limited data requirements, they need to be evaluated before adopting them for a region. If the results are not satisfactory, it is required to calibrate them locally or to develop a region specific model.

PAN METHOD AND PAN COEFFCIENTS

Pan method is one of the most popular methods because of its simplicity. This method is used not only for the estimation of evaporation from open water surfaces but also for reference crop evapotranspiration estimation. Different types of pans are available. The Class A pan is used most widely throughout the world, for measurement of evaporation India Meteorological Department has also adopted USWB class `A' pan for measurement of evaporation in different parts of the country. The Class-A evaporation pan is 122 cm in diameter and has a depth of 25 cm. It is placed on a level ground. The pan is mounted on a wooden frame raised 15 cm above the level ground to allow free circulation of air beneath it. It is covered with mesh to prevent birds or animals drinking from it. Evaporation is measured daily as the depth of water (in mm) that evaporates from the pan. The measurement day begins with the pan filled to exactly 5 cm from the pan top. At the end of 24 hours, the amount of water to refill the pan to exactly 5 cms from its top is measured. Refilling is done with a cylinder specially calibrated for the purpose. If any precipitation occurs in the 24-hour period, it is taken into account in calculating the evaporation. Sometimes precipitation is greater than evaporation, and measured increments of water must be dipped from the pan. The most common and obvious error is during heavy rainfall events which cause the pan to overflow. Fig. 1 below shows a view of the evaporation pan used in the experiment.

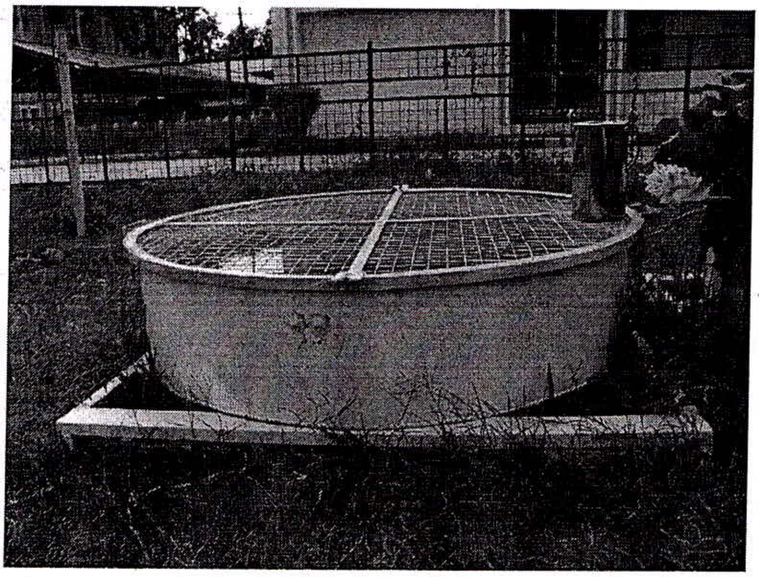

Fig. 1: A view of the Class A evaporation pan used in the study

The thermodynamics of a pan is different than water bodies like lakes and reservoirs. Sensible heat transfer from sides and bottom of the pan is appreciable while for lakes and reservoirs heat through the bottom is almost zero. Consequently a coefficient has to be applied to pan data for converting it into the water surface evaporation. This coefficient, called pan coefficient (K_p) is the ratio between observed pan evaporation to the evaporation from water surface. It has been reported that annual pan coefficient values for US Class-A pan are scattered around 0.77.

Commonly, annual pan coefficients are applied even for monthly and seasonal time scales or, monthly and seasonal coefficients derived in some other investigations are used. There is also a tendency to use a uniform coefficient of 0.7 for all time scales, particularly in design problems. Most of the State Irrigation Departments in India also use a uniform value of 0.7. However, pan coefficients are observed to be different for different regions and are also different for different time scales. The monthly pan coefficient has been observed to differ from the commonly used coefficient of 0.7 by more than 100%. The coefficient is dependent on local climate and physical conditions, and should be determined locally from a standard method such as the Penman method. Abtew (2001) proposed monthly values of K_p for Lake Okeechobee, located in subtropical South Florida. The values ranged from 0.64 for January to 0.91 for June. Alvarez et al. (2007) derived pan coefficients for irrigation water reservoirs in south Eastern Spain. Monthly K_p values were observed to vary significantly throughout the year. The variation was found to be $0.5< K_p <1.5$ for deep waters and $0.8< K_p <1.2$ for shallow waters.

PENMAN METHOD

No method exists for direct measurement of actual lake evaporation. It has to be determined indirectly. As has been said earlier, the energy balance method is considered to be by far the most accurate method. However, due to the requirement of exhaustive data, which is mostly not available, it is generally not possible to employ the energy balance method. So Penman combination method is generally used for the purpose. It is a universally accepted method, as it is based on the sound combination of the principles of mass and energy transfer. Estimates obtained from the modified Penman method have been found to agree closely with the energy budget values. Moreover, the data requirement of the Penman method is also relatively easily met than the energy balance methods, as it uses the routinely observed meteorological data. For example, it uses air temperature data instead of water temperature which is generally not available. For evapotranspiration studies, The Penman-Monteith method has been recognized as standard method of ET estimation by Food and Agricultural organization of the United Nations. This method was originally developed for estimating potential evapotranspiration but is widely used for estimating open water surface evaporation like lake evaporation. The evaporation obtained by this method is considered as the actual evaporation.

The modified Penman combination equation is:

$$E = \frac{\frac{\Delta}{\Delta+\gamma}*(R_n - G) + \frac{\gamma}{\Delta+\gamma}*6.43*(1.0+0.53*U_2)*(e_s - e_a)}{\lambda} \qquad \text{...... (3)}$$

where,

E	=	potential evaporation [mmd^{-1}];
R_n	=	net radiation [$MJm^{-2}d^{-1}$];
G	=	heat flux density [$MJm^{-2}d^{-1}$];
U_2	=	wind speed measured at 2 m above the ground [ms^{-1}];
e_s	=	saturated vapour pressure at air temperature [kPa];
e_a	=	actual vapour pressure at air temperature [kPa];
Δ	=	slope of saturation vapour–pressure-temperature curve [kPa^0C^{-1}];
Υ	=	psychrometric constant [kPa^0C^{-1}]; and

λ = latent heat of vapourization [$MJkg^{-1}$]

The details of the Penman Method are available in most standard textbooks of Hydrology and water resources.

IMPACT OF MACROPHYTES ON LAKE EVAPORATION

Most of the shallow lakes and ponds in tropics show presence of macrophytes due to heavy pollution. Macrophytes like the water hyacinth have become a menace for many a lakes all over the world, particularly in the tropical and sub-tropical countries. A number of workers have shown that presence of aquatic plants in general enhance water loss. The evapotranspiration to open-water evaporation ratio (ET/E) for aquatic plants can be more than 1.4 and sometimes even more than 13.0. Common water hyacinth (*Eichhornia crasspies*) is particularly known to cause heavy evapotranspiration losses. The rate of water loss due to water hyacinth is found to be much more than the open water evaporation. Different studies have shown different rates of variation ranging from 1.8 times to 13 times more. The rates are found to vary from region to region. Some researchers have observed that the ratio between evapotranspiration and free water evaporation decreases with increasing amount of solar energy and increases with increasing vapour pressure deficit. Further, it has also been demonstrated that evapotranspiration by aquatic plants is also influenced by plant canopy characteristics and nutrient availability.