ESTIMATION OF POTENTIAL EVAPORATION FROM WATER SURFACE USING METREOLOGICAL DATA

Master Thesis

Aziz Ul Haq MUJAHID

Eskisehir, 2019

ESTIMATION OF POTENTIAL EVAPORATION FROM WATER SURFACE USING METREOLOGICAL DATA

Aziz Ul Haq MUJAHID

MASTER THESIS

HYDRAULICS/CIVIL ENGINEERING DEPT.

Prof. Dr. Mustafa TOMBUL

Eskisehir

Anadolu University

Graduate School of Sciences

March 2019

FINAL APPROVAL FOR THESIS

This thesis titled "ESTIMATION OF POTENTIAL EVAPORATION FROM WATER SURFACE USING METREOLOGICAL DATA" has been prepared and submitted by Aziz Ul Haq Mujahid in partial fulfillment of the requirements in "Anadolu University Directive on Graduate Education and Examination" for the Degree of Master of Science in Hydraulics Department has been examined and approved on 20.03.2019

Committee Members	**Title, Name and Surname**	**Signature**
Member (Supervisor)	Prof. Dr. Mustafa TOMBUL	
Member	Assoc. Prof. Dr. Hakan ŞİRİN	
Member	Assist. Prof. Dr. Hasan TOZLUK	

Prof. Dr. Ersin YÜCEL

Director of Graduate School of Sciences

ABSTRACT

ESTIMATION OF POTENTIAL EVAPORATION FROM WATER SURFACE USING METREOLOGICAL DATA

Aziz Ul Haq MUJAHID

Department of Civil Engineering

Programme in Hydraulics

Anadolu University, Graduate School of Sciences, March 2019

Supervisor: Prof. Dr. Mustafa TOMBUL

This research consists of two parts. In the first part, the significance of five evaporation rate governing factors i.e. radiation, temperature, vapor pressure deficit, and relative humidity were evaluated using daily metrological data, for the Atatürk dam, Turkey and their impact on the evaporation rate were established using standardization method. It was established that the effect of these leading factors varied with the time-scale. For the precise management of water balance in rapidly diminishing water resources such as channels, lakes and water reservoirs, it is important to know the rate of evaporation from the water surface. Due to the difficulty in measuring the evaporation from the water surfaces experimentally, different methods and techniques are developed and suggested for its determination. Evaporation from the reservoir of Ataturk dam, located in south-east Turkey on Euphrates river was estimated using different methods and their robustness and vigorousness were tested. Evaporation was calculated using Penmen-Monteith combination equation. Penmen-Monteith model for evaporation is considered to be the standard model for estimating evaporation. Measurements of climatological parameters enabled estimation of energy balance components. Other radiations and temperature-based methods were tested and evaluated in accordance with the Penman-Monteith method.

Keywords: Open water surface, Evaporation, Euphrates, Mass-transfer-based, Potential evaporation, Radiation-based, Turkey, Temperature-based

ÖZET

METROLOJİK VERİLERİ KULLANARAK SU YÜZEYİNDEN POTANSİYEL BUHARLAŞMANIN TAHMİNİ

Aziz Ul Haq MUJAHID

İnşaat Mühendisliği Anabilim Dalı, Hidrolik Bilim Dalı

Anadolu Üniversitesi, Fen Bilimleri Enstitüsü, Mart 2019

Danışman: Prof. Dr. Mustafa TOMBUL

Bu araştırma iki bölümden oluşmaktadır. İlk bölümde; radyasyon, sıcaklık, buhar basıncı açığı, rüzgâr hızı ve bağıl nem gibi beş buharlaşma oranını belirleyen faktörün önemi günlük metrolojik veriler kullanılarak değerlendirilmiştir. Atatürk Barajı’nın, Türkiye için buharlaşma oranı üzerindeki etkileri standardizasyon yöntemi kullanılarak belirlenmiştir. Bu öncü faktörlerin etkisinin zamanla değiştiği tespit edilmiştir. Kanallar, göller ve su rezervuarları gibi hızla azalan su kaynaklarındaki su dengesinin hassas yönetimi için, su yüzeyinden buharlaşma oranını bilmek önemlidir. Buharlaşmanın su yüzeylerinden deneysel olarak ölçülmesindeki zorluk nedeniyle, belirlenmesi için farklı yöntemler ve teknikler geliştirilmiş ve önerilmiştir. Türkiye’nin güney doğusundaki Fırat Nehri’nde bulunan Atatürk Barajı’nın rezervuarından buharlaşma farklı yöntemler kullanılarak tahmin edilip, sağlamlıkları ve dinçlikleri test edilmiştir. Buharlaşma, Penman-Monteith kombinasyon denklemi kullanılarak hesaplanmıştır. Penman-Monteith modelinin buharlaşmayı tahmin etmek için standart model olarak kabul edilmektedir. Klimatolojik parametrelerin ölçülmesi, enerji dengesi bileşenlerinin tahmin edilmesini sağlamıştır. Diğer radyasyonlar ve sıcaklık tabanlı yöntemler Penman-Monteith yöntemine göre test edilip değerlendirilmiştir.

Anahtar Sözcükler: Açık su yüzeyi, Buharlaşma, Fırat, Kütle transferi-bazlı, Potansiyel Buharlaşma, Radyasyon-bazlı, Türkiye, Sıcaklık-bazlı

ACKNOWLEDGEMENT

I would first like to thank my thesis advisor Prof. Dr. Mustafa TOMBUL The door to Prof. Tombul office was always open whenever I ran into a trouble spot or had a question about my research or writing. He consistently allowed this paper to be my own work but steered me in the right the direction whenever he thought I needed it.

Aziz Ul Haq MUJAHID

20/03/2019

STATEMENT OF COMPLIANCE WITH ETHICAL PRINCIPLES AND RULES

I hereby truthfully declare that this thesis is an original work prepared by me; that I have behaved in accordance with the scientific ethical principles and rules throughout the stages of preparation, data collection, analysis and presentation of my work; that I have cited the sources of all the data and information that could be obtained within the scope of this study, and included these sources in the references section; and that this study has been scanned for plagiarism with "scientific plagiarism detection program" used by Anadolu University, and that "it does not have any plagiarism" whatsoever. I also declare that, if a case contrary to my declaration is detected in my work at any time, I hereby express my consent to all the ethical and legal consequences that are involved.

Aziz Ul Haq Mujahid

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

CFSR	:Climate Forecast System Reanalysis
CISL	:Computational and Information Systems Laboratory
DOE	:Department of Energy
ECMWF	:European Centre for Medium-Range Weather Forecasts
EHM	:Hamon Equation
EHG	:Hargreaves Equation
EJH	:Jensen-Haise Equation
EMJH	:Modified Jensen-Haise Equation
EPT	:Turc Equation
EPM	:Penman-Monteith Equation
EPT	:Priestly-Taylor Equation
ERK	:Romanenko Equation
ETHW	:Thornthwaite Equation
FAO	:Food and Agriculture Organization
Ha	:Hectare
NCAR	:National Centers for Atmospheric Research
NCEP	:National Centers for Environmental Predictions
NSE	:Nash Sutcliffe Efficiency
PPT Rate	:Precipitation Rate
RDA	:Research Data Archive
Strat. + Conv.	:Stratiform plus convective forms of precipitation
VPD	:Vapor Pressure Deficit
VPG	:Vapor Pressure Gradients
PC	:Pan Coefficients

SVP :Saturated Vapor Pressure

AVP :Actual Vapor Pressure

LIST OF SYMBOLS

α: Priestly-Taylor Coefficient = 1.26

α_s: Shortwave Albedo

β: Bowen Ratio

γ: Psychometric Coefficient [kPa °C^{-1}]

Δ: Slope of Vapor Pressure Curve [kPa °C^{-1}; mbar °C^{-1}]

Δ_w: Slope of the Vapor pressure curve at Wet bulb Temperature [kPa °C^{-1}; mbar °C^{-1}]

ε: molecular weight of water vapor to dry air ratio

ρ: Water Density

ρ_a: Air Density

τ: Constant of Time

$\lambda f(u)$: Wind Function [MJ Kg-1]

λE: Flux of latent heat [MJ Kg-1]

σ: Constant of Stefan-Boltzmann = 4.9 x 10^{-9} (MJ m^{-2} ºC^{-4} d^{-1})

c: Specific Heat of Water = 0.0042 [MJ Kg^{-1} °C^{-1}]

CH: Hargreaves Coefficient

c_p: Specific Heat of Air Temperature = 0.001013 [MJ Kg^{-1} °C^{-1}]

d: Number of Days in each Month

e_a: Actual Vapor Pressure [kPa]

e_d: Saturated Vapor Pressure [kPa]

ET: Evaporation or Evapotranspiration

G: Soil Heat flux [MJ m-2 day-1]

I: Annual Heat Index

i: Monthly Thornthwaite Heat Index

k: von Karman’s Constant

L↓: Inbound (incoming) long-wave radiation

$L\uparrow$, Outbound (outgoing) long-wave radiation

N: Change in heat Storage

N_s: Theoretical Sunshine Hours

P: Atmospheric Pressure [MPa; mbar]

Q_{ri}: Rate of surface inflow

Q_{ro}: Rate of surface outflow

Q_{gi}: Rate of inflow of groundwater and seepage

Q_{go}: Outflow rate of groundwater and seepage

RH: Relative Humidity [%]

R_n: Net Radiation [cal cm^{-2} day^{-1}; MJ m^{-2} day^{-1}; mm day^{-1}]

R_s: Total Solar Radiation [cal cm^{-2} day^{-1}; MJ m^{-2} day^{-1}; mm day^{-1}]

R_a: Extraterrestrial radiation [cal cm^{-2} day^{-1}; MJ m^{-2} day^{-1}; mm day^{-1}]

r_a: Aerodynamic Resistance [°C]

r_2: Coefficient of Determination

T: Air Temperature [°C]

T_a: Mean daily temperature of air [°C]

T_{max} and T_{min}: Minimum and Maximum Temperature [°C]

T_{Wet}: Temperature of Wet Bulb [°C]

T_{Dew}: Temperature of Dew Point [°C]

T_e: Equilibrium Temperature [°C]

u: Speed of Wind [m s^{-1}]

u_2: Measured at 2m the speed of Wind [m s^{-1}]

z_o: Momentum and water vapor roughness length (m)

z_r: Height of measurement above surface [m]

1. INTRODUCTION

Evaporation is an important part the central process of hydrological cycle. The water transformation into vapors and its rise to the atmosphere constitutes an important step in hydrological cycle. (Figure 1.1) shows the water cycle and its basic components.

The moisture is transferred to the atmosphere from the earth's surface, through the process of evaporation. This process of evaporation comprises of vaporization of molecules of water molecules, form soil, water and snow surfaces. The moisture in the atmosphere is replenish through this process which the precipitation has extracted from the atmosphere, the evaporation also equalizes the temperature of the atmosphere. Solar radiation helps the in vaporization of water molecules as in large water bodies such as ocean and lakes the absorbed amount of solar radiation is significant, which in return heats the water molecules turning them to vapors. As these vapors rises back to the atmosphere and condenses the heat is then exchanged back to the atmosphere thus making a process which keeps the heat in equilibrium.

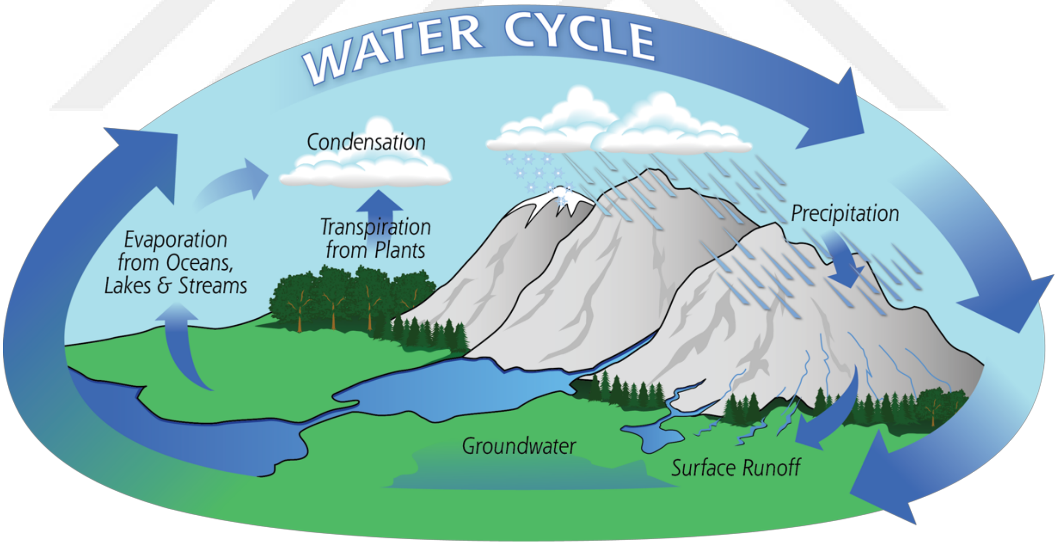


Figure 1.1. *Water Cycle*

Open water evaporation estimates are increasing more and more for numerous Environmental activities to function and operate, mainly Ecology and management of water resources. The approximations from studies on evaporation are increasingly used in modelling work and for water balance studies and still waters management. The call for such estimates is likely to raise in the near future driven by the loss of water and mismanagement of water resources resulting in water losses of higher degrees and also due to the fact that the water resources are depleting at a faster rate than previously expected. The estimates from these studies can help in managing the water sources in a more efficient way.

Estimating open water evaporation is done through different methods, which vary among the regions and sometime within the same regions; a commonly implemented best model or method is not available. Furthermore, the accuracy of estimates produced by the currently defined or known methods has sometimes disparity among the results (as they are usually raw and focus of uncertainties which are great) and their importance in the estimations and calculations which are used as a foundation for the taking the decisions. To assess the disparity in numerical terms is important and should be made possible permitting it to be considered in the making of decisions.

Evaporation from open water surfaces or wet surface is the net outcome of the effects of the net radiation, water body surface and the air temperature, wind and humidity also take the major role in the whole process of evaporation.

Measurement of evaporation for some localities can be easily done by imitating the water body properties such as pan evaporation method which is successful and the results it yields also are satisfactory enough and for some particular localities the results obtained from the pan can be generalized to the water reservoir using empirical factors and using appropriate conversion factors. For localities where no such particular estimates are computed, and the evaporation is not measured, analytical and empirical methods based on the meteorological data can be applied solely reliant on the accessibility of data.

1.1. Literature Review

A variety of methods (equations) have been proposed for the calculation of evaporation and evapotranspiration within the scope of the studies carried out due to differences in the type of climate data, environmental conditions. When the studies on evaporation and evapotranspiration are examined, it is seen that most of the studies progress in two scopes. The first one is the study of the calculation equations for estimation of evaporation and evapotranspiration by establishing a relationship between meteorological variables and the evaporation measured using pans. The purpose of this study is the application of these models, methods and equations for the study region, the consistency of the equation and its comparisons.

Studies in this scope include, in general, (i) Temperature Based Hargreaves (Hargreaves & Samani, 1985), Hamon (D. Haith & L. Shoenaker, 1987), Thornthwaite (Charles Warren Thornthwaite, 1948) (Temperature-based), (Romanenko, 1961) (Humidity-based) and (Priestly & Taylor, 1972), (Turc, 1961) and (M. Jensen & Haise, 1963a) (Radiation-based) and (H. L. Penman, 1948) (Combination Equation) .

2. EVAPORATION FROM OPEN WATER

An introduction to the evaporation process, open water surfaces potential evaporation and the factors and influencers that affects and disturbs the process.

2.1. Evaporation

¨Loss of water in excess of condensation from the water surface, wet soil or snow to the atmosphere ¨ is the general definition of the term Evaporation accepted. The conversion of liquid water to vapors due to the influence of external factors is defined as evaporation. The rate of evaporation is controlled by the availability of energy such as radiation and temperature etc. which heats the water body resulting in the excitement of water molecules thus making them leave the water surface and escape and mix into the atmosphere.

Water molecules comprising of a given mass are in constant motion as the kinetic theory of matter explains that all matter be composed of molecules in motion when the temperature is above absolute zero I.e. -273°C. When water surfaces are exposed to constant energy sources such as radiation and temperature (from sun light) etc. the water molecules energy is increased as a part of the radiation and temperature is absorbed by the water body while some of it is reflected back. As the water body absorbs sufficient energy from the radiation and temperature thus enabling the water molecules to escape the water body due to the energy present in the molecules.

The continued transfer requires a constant supply of energy from external factors such as wind, radiation, air and water temperatures, atmospheric pressure, quality of the water and water vapor in the adjoining air to the water surface saturated layer. These are some of the factors affecting the evaporation from a surface. Solar radiation takes the lead in effecting the evaporation thus evaporation varies with season, sky conditions (cloudiness, clear sky etc.), latitude, and time of day. Despite the knowledge of these controlling factors, the determination of their relative effectiveness is difficult due to the interrelations.

2.2. Effect Of Metrological Factors On Evaporation

The effect of meteorological factors on open water evaporation is considered to be effective enough to have an enough qualitative effect on the evaporation and demography of the water.

2.2.1. Net radiation

Radiation is one of the key elements which governs the rate of evaporation. The amount of radiation that is absorbed by the body is generally one of the leading influencers governing the rate of annual evaporation.

The radiation is classified as the longwave and the shortwave radiation.

1. Shortwave radiation

When the radiation energy is transmitted in the form of visible or ultraviolent radiation it is recognized as the Shortwave radiation. A huge proportion of energy of radiation is transferred in the form of shortwave as the energy radiation form of the sun is visible light, thus making the solar radiation a shortwave type of radiation. The wave lengths of shortwave radiation are smaller. The energy radiated from sun that enters our atmosphere is in the form of ultraviolent and visible light carrying comparatively more energy.

2. Longwave radiation

When the form of energy transfer is infrared light then it is considered as the longwave radiation. It is carried by the infrared lights has a lower energy levels as compared to shortwave radiation. The main type of longwave radiation is thermal radiation.

When the energy from the sun, as the sun is extremely hot and an energy source, it has a lot of energy to give off, when that energy in the shortwave radiation form, enters the Earth's atmosphere, surface and clouds absorb the solar energy. A large portion of longwave radiation is reflected back due to low level of energy it carries but in contrast the reflected back shortwave radiation percentage is small while a huge portion of the energy is absorbed. (Figure 2.1) shows the radiation balance. The solar radiation instance at the topmost layer of the atmosphere, S_O, a part of which I-e S_t, reaches the body directly without any obstruction by the atmosphere. Now a part of the solar radiation is obstructed and scattered by the clouds and atmospheric particles, I-e S_d, it reaches the body in the scattered form. The total reflection from the body is the sum of S_d and S_t, while a reflection coefficient, or shortwave albedo I-e α_s is used. For a water generally, a value of 0.08 is used as the reflection coefficient but it depends of transitory influencers such as the direction and solar beam angle. So, the total reflection from the water body is the sum of $(S_t+S_d)\alpha_s$. 0.08 is used as the reflection coefficient value, commonly used for water indicates that only 8% of the solar radiation is reflected back from that striking the water body to the atmosphere while 92% of the radiation is taken by the body. However, the wavelength plays a significant part in this process as throughout the thickness of the water column the radiation is absorbed, the penetration of water body to a certain thickness by the radiation depends on the radiation wavelength. Accordingly, blue light having a shorter wavelength penetrate a column up to tens of meters of clear water while the same water body if being strike by a near-infrared radiation it is only able to penetrate less than a meter. The net shortwave radiation, S_n, is the sum of S_d and S_t captured by the waterbody minus the losses due to reflection I-e $(S_t+S_d)\alpha_s$.

$$\boldsymbol{S_n = (1 - \alpha_s)(S_d + S_t)} \tag{2.1}$$

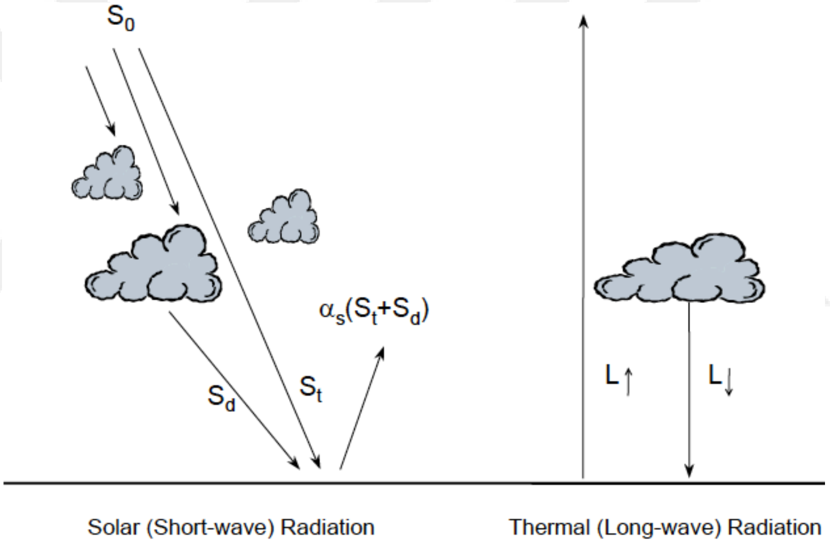


Figure 2.1. *Radiation Classification (Finch & Hall, 2001)*

The waterbody surface and the atmosphere exchange a significant quantity of radiant energy in the arrangement of longwave radiation (thermal). The dominant source of the longwave incoming radiation, L↓, is the earth itself as the shortwave length radiation, radiated by the sun is absorbed by the earth' surface, clouds and remitted at longer wavelengths. In Figure 2.1 the emitted outgoing radiation from the surface of the body of water is longwave radiation.

R_n, reflects net radiation, which the difference among solar radiation (shortwave) reflected and absorbed by the surface, plus the difference between absorbed and reflected thermal (longwave) radiation:

$$\mathbf{R_n = (1 - \alpha_s)(S_d + S_t) + (L_\uparrow - L_\downarrow)} \tag{2.2}$$

2.2.2. Humidity

Humidity affects the rate of evaporation to a certain extent although no proper extent of the effect is defined yet. Humidity is the presence of the water vapors in the air. Two different types of humidity are defined:

1. **Absolute humidity**

   At a particular temperature the amount of water vapor over the amount of dry air in a certain air volume is known as absolute humidity.

2. **Relative humidity**

   Depending upon the current temperature, ratio of current of absolute humidity to the highest possible humidity, is the relative humidity.

Except with a change in mass of air, throughout the day, the variation in absolute humidity is very minor. But, relative humidity changes more frequently and, as a change in the value of relative humidity is in increasing trend, there will be a decrease in the transfer of water molecules from the surface. The RH relates with the air temperature, if the air temperature decreases the relative humidity increases consequently resulting in dropping of evaporation rate (Romanenko, 1961).

2.2.3. Diffusion process

The continuous diffusion of molecules of water from the surface of an open water into immobile air adjacent to the water surface, the air will approach a point where any further diffusion will not take place as the air will be saturated. If there is no air movement or wind, the evaporation will come to a standstill point as the air will be not able to take any further water molecules diffused from the water surface. Therefore, the rate of evaporation is affected to a greater degree by turbulent and tempestuous movement of air. Wind speed and the surface roughness of water body are the turbulence degree and is strongly associated to these two factors. If in mean temperature of air an appropriate gradient exists far from the surface of water, by convective turbulence the frictional air turbulence can be enhanced.

2.2.4. Wind speed

The degree of water evaporation is affected to certain degree by the speed of wind over the water surface. The airborne water particles already diffused from the water body are swept away by the blowing wind, thus reducing the humidity of air above the surface of water as an outcome more molecules of water can diffuse into the adjacent air above the surface. Although, only up to a critical value the positivity of relationship between wind speed and evaporation rate exists. Thus, the determination of the maximum evaporation rate is by the availability of energy and humidity (Linsley & Kohler, 1982).

2.2.5. Temperature

Temperature provides the energy required by the molecules to escape the body of water and mix into the atmosphere. Higher the temperature is higher will be the energy provided to the molecules. This leads the way for temperature to be one of the controlling or important metrological parameter in governing the rate of evaporation. The interrelation of the temperature and other metrological factors makes it hard to evaluate the unique influence of temperature on the evaporation but according (Linsley & Kohler, 1982), if all other meteorological factors including radiation were to remain unchanged the evaporation rate will be in-complete harmony with the temperature. Sing and Xu in their assessment of the metrological parameters with reference to evaporation found out that the evaporation is affected by temperature in a proportional way not only for shorter periods of time but for longer periods too such as monthly evaporation (Xu & Singh, 1998).

2.3. Influence Of Water Body Properties On Evaporation

The properties of water body lead a significant part in defining the rate of evaporation. Although, some properties may have a smaller effect compare to others, but the overall result is quietly altered by the water body properties.

2.3.1. Water depth

The heat storage capacity of a water body is largely determined by its depth which in terms has a considerable effect on the seasonal distribution of evaporation rate. In shallow water bodies the temperature of the water body has no considerable variation with the seasonal temperature and the maximum rate of evaporation can be recorded in summer and minimum in winter. But for deep water bodies where the water column depth is more than 4.5 m, the incoming solar radiation warms the water body during the seasons of summer and spring but during the seasons of winter and autumn the stored heat energy is released as the incoming solar radiation decreases. The effect of heat storage due to water depth can be disregarded for shallow bodies of water where the depth of water column is less than 0.5 m and the effect of water body heat storage maximum level is reached as the seasonal evaporation rate stops to variate once the depth of the water column increases past 4.5 as very small percentage of the inbound solar radiation is able to penetrate below this depth.

Although the change in annual evaporation is affected to a very small extent as the seasonal variations is evaporation rate tends to cancel out the effect from one year to the other due to the annual energy input is approximately constant.

2.3.2. Thermal stratification

A function of the water body surface area is known as thermal Stratification. In deep, large bodies of water stratification occurs but not at low altitudes but in mid and high latitude. Stratification is one of the possible reasons for the accentuation of the time lag among the rate of evaporation and radiation. As the water density has a dependency on the temperature, it is one of the key factors (at 4°C, water has maximum density).

In early spring, most of the large water, mild water bodies show a distribution of nearly uniform nature of temperature with the depth. Mostly large but mild water bodies in the times of early spring, a nearly uniform distribution of temperature exhibits with the depth (homeothermic conditions). But with the progress of time and increase in temperature, the water bodies receive more heat at a more rapid frequency. At the start, the body still remains homeothermic because the additional heat conveyed to the water body is transferred to the deeper layer of the water column by the currents and turbulence induced by the wind. With the further increase in temperature, the heating of the water body continues to rise, but at a certain point the receiving temperature exceeds the degree of transmission to the subterranean layers, resulting in the higher temperature of the water body surface than the deeper layers. As the heating endures, a point of inflection begins to develop in the temperature depth profile resulting in a well-mixed, blended epilimnion or surface layer, with the formation of comparatively intense gradient at its lowest boundary with the metalimnion. Gradient of Maximum temperature plane is called the thermocline. The thermocline slowly and gradually descends into the lake, during the remaining heating period. The formation of thermocline results in the relative independence of the deeper regions of the lake from the changes in surface conditions.

In autumn, when the water body attains maximum heat content, the movement rate of thermocline to the deeper layer of the body of water increases, increases in the movement of thermocline in often called turnover. Convective mixing due to decrease in the surface temperature amplifies the wind mixing resulting in an increase density. As the well-mixed epilimnion continues to cool further, the thermocline continues to move down rapidly, until homeothermic conditions are attained again.

In winter the stratification can be ‘reversed’ specially in mainland climates, but a much thinner cooler is formed than of summer epilimnion. Enough cooling may result in the freeze over of the water body while the temperature of the subterranean water layers is retained between the 2-4°C range. A temperature larger than 4°C results in only a single turnover I.e. only in Autumn. Generally large water bodies in tropical climate with high temperatures rarely stratifies.

Heat storage results in the lower water than temperatures of air through the summer season and in winter opposite to that of summer. Thus, stratification results in a variable evaporation rate from large water bodies, with sometimes a higher rate in winter than in summer. Although, the stratification does increase the evaporation rate but in winter when the temperature drops a significant evaporation rate is achieved due to the stratification.

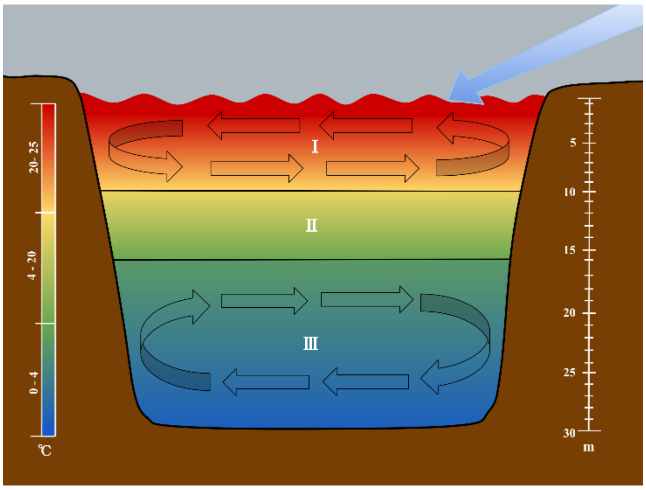


Figure 2.2. *Stratification of Lake; I. The Epilimnion, II. The Metalimnion, III. The Hypolimnion*

2.3.3. Size of surface

At a constant speed of wind, the evaporation is associated to the relative humidity and size of the surface of the body of water. The larger the water body is the greater the rate of evaporation is. Although, the depth of evaporated water decreases with the increase in the surface area but as with a large surface area the upper layer of the water body more energy with more potential to evaporate. Due to the bigger water body surface area as the wind moves across the surface changing the humidity level. There will be independence of air humidity to the distance it has covered from the boundary if water body is large enough and rate of evaporation will be in agreement to the available energy amount. On the contrary, bodies of water with small surface area, such as evaporation pans, a constant evaporation rate is maintained which is high, due to the little influence of temperature or humidity. The humidity of incoming air from the edge or boundary of the body of water has a considerable consequence on the rate of evaporation from different size water bodies.

As the wind moves from the edges of the water body, the speed of wind tends to increase due to the smoother surface of the water. As a result, an increment in the evaporation rate is made which have a tendency to counter the decline trend in the rate of evaporation which is the result of decrease in the relative humidity (Condie & Webster, 1997).

2.3.4. Rainfall

No considerable effect of rainfall on evaporation rate is yet established. Rainfall may change the heat balance of the water body if falls directly, but the change is sufficiently small and neglected as the rainfall volume is considerably minor in comparison with the body of water, so is the difference and variation in temperature.

2.3.5. Inflow and outflow

The water inflow and outflow from the water body may have effect on heat stored in the water body. If the inflow and outflow volume is similar to that of body of water and the inflow water temperature is substantially diverse than the body water temperature, then contribution to stored heat is may be a considerable.

2.3.6. Vegetation

The presence of protuberant vegetation may affect the evaporation rate. Notable effects of vegetation can be seen as the canopy of vegetation can shade the surface of water consequently blocking the heat reaching the surface of water resulting in reduction of the heat gained by the body. A decrease or increase (in case of dense canopy or sparse canopy) in the aerodynamic roughness of the surface is also a direct result of the vegetation.

The higher albedo of the vegetation can also contribute to the reduction in water loss as the required energy for transpiration may then not be available (Eisenlohr Jr, 1966). The shore surrounding the body of water and the vegetation on the it may also have an effect on the evaporation, but the effect is mostly local, around the edges. The effect is due to the turbulence of the offshore winds due to the presence of the clump of trees. Although the effect will be quite local but the influence on total evaporation is only reliant on the size of body of water (H. Penman, 1963).

2.3.7. Turbidity and bottom reflectance

The water body short-wave albedo can be increased due to the presence of the suspended particulate matter. Turbid water lakes tend to reflect a greater amount of the inbound solar radiation in comparison to that from clear water. The effect of turbidity can be quite significant in hyper-turbid lakes as the turbid lakes can have a high albedo like 0.2, compared to that of the clear water 0.08.

For water bodies with deeper water columns the albedo of the subterranean part of the body of water if high can influence the absorption of the radiation energy resulting in lower energy level of the water body. If the albedo is smaller more radiation energy is captivated by the substrate which by conductions heats the body.

2.3.8. Salinity

Saline water vapor pressure is lower, due to this the evaporation rate decreases almost at a proportional rate with an increase in salinity. For example, 1 percent increase in the salinity can reduce the evaporation rate by 1 percent. From fresh water bodies the effect is not considerable enough to be considered (Straskraba, 1980).

3. METHODLOGY

For evaporation estimation, a large number of methods and models are narrated in literature. These methods and models can be categorized into seven types as following;

- The equilibrium temperature method,
- Pan evaporation,
- Bulk transfer models,
- Combination models,
- Energy budget models,
- Empirical factors and
- Mass balance.

The review of these models and methods and their relevance are discussed in this chapter. Although not all possible methods and models are discussed and included in this study due to their impracticality (e.g. Bowen Ration, eddy correlation or micrometeorological measurements (Brutsaert, 1982)).

3.1. Pan Evaporation

Measuring of evaporation using pans of water goes back to 18th century. As they evaporation of open water is measured in observable way, it is easy to comprehend their intuitive demand. However, the use of data from pans except in specific circumstances is difficult despite numerous studies. One of these studies and reviews is done by Hounam (Hounam, 1973), from measurement of pan evaporations he carried a review for estimation of lake evaporation.

3.1.1. Measurements

US Class A pan is one of the widely used pan around the world. The pan is an iron tank and galvanized with a 1.207 m^2 dia. and having a depth of 0.25 m (Figure 3.1(a)). For the air to circulate around and under the pan it is mounted on an open wooden frame. The level of water is kept below the rim at 50 mm. Using a hook gauge the level is measured daily. Water temperature is measured by a thermometer while the wind speed above the rim at a height of 150 mm is observed and measured using a three-cup. Previous 24 hours rainfall recorded must be added .

One of the pans used by UK Meteorological office is known as the Symons Pan. It is a Galvanized water tank having area of 1.83 m^2 and 0.61 m deep (Figure 3.1(b)). With the water level set to the level of the ground, and with rim 100 mm above the ground it is set in the ground. The color of the interior is black painted. A hook gauge with a Vernier scale attached to it is used for daily measurements. Previous 24 hours rainfall recorded must be added .

Another evaporation pan, whose use is initiated worldwide is the USSR GGI-3000 pan. Cylindrical in shape with a conical base, the tank has a smaller surface area (0.3 m^2 and 0.618 m diameter) relative to the other pans but the depth is same as that of Symons pan I.e. (0.60-0.685 m) (Figure 3.1(c)). The tank is set in the ground with the rim leaning above the surface at about 75 mm. The pan is painted white. (Shaw, 2014)

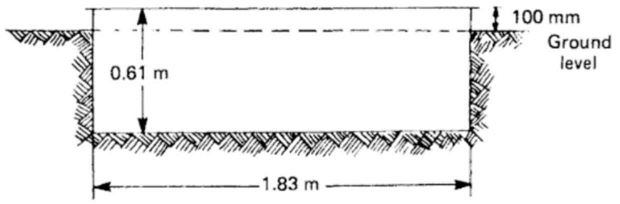
3.1.2. Measurement error and its sources

If enclosed by a drier surface, an improvement will be seen in the evaporation from the pan, this effect is known as the Oasis Effect. The surrounding area will be providing extra energy for evaporation of water in the pan which will be transferred horizontally from the drier surface. This transfer of energy will result in an evaporation rate in pan which will be higher than that from a water body.

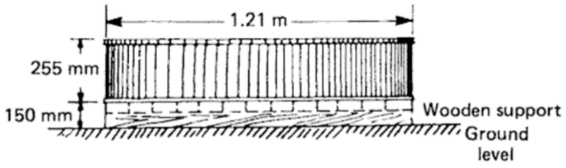
The US Class A pan is exposed to direct sunlight, the sides of the pan are hit by the sun directly making the pan hotter and consequently increasing the evaporation. The pans sunken in the ground doesn’t have this problem but conversely, because of the transfer of heat from the soil surrounding the sunken pans incline to the overestimation of evaporation. Another difficulty in sunken pans is the detection of leakage.

Sunken pans are also vulnerable to splashing in and out. The pans may be used as a drinking water source of in summer by the wildlife. When tried to solve this problem by providing a mesh cover for the pan, a significant decrease in the evaporation rate was recorded.

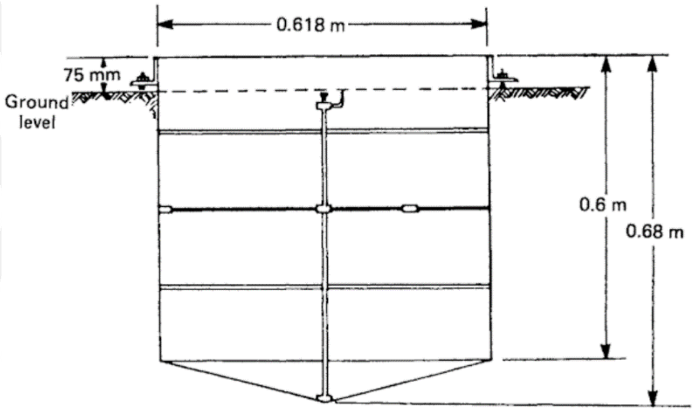
A careful maintenance of all the pans is necessary despite their apparent simplicity. Periodic re-painting and regular cleaning are necessary. Also, the water levels must be kept to the prescribed level.



(a) UK British Standard tank



(b) US Class A pan



(c) USSR GGI-3000 tank

Figure 3.1. *Different types of Pans*

Another major impact on the measurement is the sitting of the pan. For example, lower evaporation rates may be recorded from grass sited pans than the bare soil sited because the in the case of bare soil the movement of air over the pan will be drier. (Richard G Allen, Pereira, Raes, Smith, & J Fao, 1998). The evaporation rates can differ around 20% (Finch & Hall, 2001).

3.1.3. Data analysis

The measurements from the pan can hardly ever be used without changing as evaporation estimates because between the water body and pan there is differences of size, and air overlying. (Winter, 1981) in his study suggested that the data used from the pans can result in considerable error if the location of the pan is set at a substantial distance away from the water body.

Coefficients of Pan (PC) and Pan conversions; are the two approaches used to help in transformation of the estimation of the evaporation from the pan to that of a water body.

PC is the ratio of the sum total of evaporation measured from a large water body to that from an evaporation pan. In literature, quite a few numbers of coefficients are reported but most of them are applied to the US Class A pan, every pan type has specific of these coefficients. The pan type, location of the measurements and water body nature has association with the pan coefficients. Furthermore, the coefficients may vary with time.

A comparison of the evaporation from 16 ha near London and that from US Class A and Symons pan over a period of seven year was done by Lapworth (Lapworth, 1965). The evaporation from the reservoir was calculated using water balance. In his study, for annual totals, 1.1 and 0.7 were the pan coefficient for the Symons pan and US Class A pan respectively. At Farmoor reservoir in Oxfordshire, a value 0.94 and 0.78 respectively was reported by Crowe for a seven-month study period (Crowe, 1974). Also, (Lapworth, 1965) found a monthly variation which was strong, in the pan coefficient variating between the values 0.47 and 1.18, in his study for US Class A pan (Lapworth, 1965). In an another hypothetical study by Winter (1981), 50% error for application of pan coefficients, 10% for measurement errors and 15% for areal averaging was suggested.

Pan Conversion, to achieve the pan conversions bulk mass transfer method equation for the pan and lake were considered, and their ratio resulted in achieving the pan conversion:

$$\bar{E} = K\frac{(\bar{e}_s^* - \bar{e})}{(\bar{e}_p - \bar{e})}\bar{E}_p \tag{2.2}$$

$\bar{E}$; the rate of mean evaporation (water body), $\bar{E}_p$; the rate of mean evaporation (pan), , $\bar{e}_s^*$; the mean air SVP at the temperature of water surface, $\bar{e}_p$; mean air SVP at the temperature of pan surface, K; an empirical constant and $\bar{e}$; the mean air VP at reference height.

3.2. Mass Balance

A method simple in principle for measuring open water evaporation. States that evaporation from a water body or reservoir is calculated or measured as the inflow and outflow difference and change in stored volume of water, I.e.

$$E = P + \frac{(Q_{ri}+Q_{gi})-(Q_{ro}+Q_{go})-dV/dt}{A_s} \tag{2.3}$$

where E, the evaporation rate , P, the precipitation mean rate for the selected period of time, Q_{ri} and Q_{ro}, the surface inflow and outflow rate respectively, Q_{go} and Q_{gi}, the groundwater plus seepage outflux rate and the groundwater plus seepage influx rate respectively, while V is the stored water stored and area of the surface is represented by A_s.

The comparative standing of these terms is decided by and depends on the hydrological setting and physiography of the region. The relative magnitudes of the equation terms are the what the feasibility of explaining evaporation depends on mainly. Whenever, the inherited error in the measurement is of the same order of magnitude as the evaporation, obtaining a reliable estimate becomes very difficult, resulting in making this method unsuitable for water bodies with large flows passing through.

Detailed study and investigation of Hefner Lake (having a surface are of 13.8 km^2, Oklahoma, USA) by (G. Harbeck, Kohler, & Koberg, 1954) over a 16-month period. Result of the estimation from the study showed that the monthly estimate error was fewer than 5%. The 5% monthly estimate error is the maximum accuracy that must be accepted that can reached possibly by the use of this method.

Results from over an seven-month assessment period from a reservoir in Oxfordshire, the Farmoor reservoir during it commissioning, are reported by (Crowe, 1974), but no details or valuation of the accurateness is given. Estimation of evaporation over a long period of seven years by (Lapworth, 1965), from a reservoir near London having an area of 16 hectare. An assumption regarding seepages was made as they were considered insignificant and were neglected. Rainfall as an exception measured at site with rain gauges, no influxes and outfluxes over the study period.

3.2.1. Measurements

One or more rain gauges are required for precipitation estimation, as the water body or reservoir size decided the number. Commonly, gauges are set on the neighboring land and observation are taken from there. As properties of water and land surfaces differ, these differences are particular over divider of the inbound energy by the land between latent and sensible heat flux into the atmosphere. A consequence of this difference is that the reservoir or body of water have its own micro-climate that is distinct than that on the land, as a difference in the climate now, a significant difference in precipitation can be observed on the water body than that on the land.

Large water bodies surface discharge can be measured to a reasonable accuracy. Although, the less accurately known flow is the surface inflow. Generally, measured flows are only the flows of major water courses and flood water inflows maybe large is unmeasured. If flow is seasonal, through the summer surface inflow may be minor in contrast to the evaporation, to be estimated with practical and acceptable accuracy through this time period. The evaporation losses should be comparable to the inflow and outflow volumes, in order to achieve a tolerable error. On Colorado River, the Franklin D. R. Lake, studied by (Gangopadhaya, Harbeck, Nordenson, Omar, & Uryvaev, 1966) shows that the uncertainty was ten times the quantity of evaporation, due to the error in measuring outflow. in their study of Lake Hefner over 16-month period, evaporation was 10% lesser than the measured influxes and discharges.

Inflow and discharge of groundwater with seepage volume are generally unknown. In some cases, possible assumption of their negligibility is acceptable. The measurements and results are further complicated if groundwater storage takes place in the banks formed on the sides of water bodies (the material constituting the side and edges of the water body, water can be briefly amassed in the vacuums of these materials). (Gangopadhaya et al., 1966) in their study observed that the capacity of total storage can be increased due to water accumulation by as much as 12% with the resulting error in the evaporation estimation if this is neglected.

Mass balance method is unlikely to be practical for an estimation period shorter than a month due to the possible error.

3.3. Energy Budget

In this method, as the name suggests, it is assumed that evaporation from a reservoir is an energy component that is necessary for the completion of the energy budget, if rest of the components and factors energy budget of the water bodies are identified I.e. it will be the outstanding component. The required heat for the conversion of liquid water into vapor (known as latent heat of Vaporization, λ) and the water molecules in the form of vapor, their energy (vapor molecules of water's energy) advected and carried from the body. λ , the latent heat of vaporization is from 2.5 to 2.4 MJ kg^{-1} ranging between 0 to 40 ° C for liquid water.

The water body's energy budget is given by:

$$N = S(1 - \propto_s) + L_{\downarrow}(1 - \propto_l) - L_{\uparrow} - \lambda E - c(T_s - T_b)E - H + F_{in} - F_{out} + F_{p-}\, G \quad (2.4)$$

where N represents the variation in the energy storage, the long-wave radiation loss from the water is represented by L↑, λE, the flux of latent heat (rate of evaporation in units of energy flux; λ is the latent heat of vaporization and E in mass units is the evaporation rate), S is the incident short-wave while L↓ is the incident long-wave radiation respectively, and αS and αL are the short and long-wave albedos (reflectivity's), specific heat of water is c, Ts, evaporated water temperature, and Tb is the temperature of arbitrary base, H is the sensible heat flux, F_{in} and F_{out} are the heat fluctuations related with water flows from and to the water body, F_P denotes precipitation associated heat influx, and G symbolizes the conduction heat that occurs among water and its substrate. The unit is energy per unit water surface area, for all the energy components.

Net radiation, R_n is given by the three radiation terms together (Equation. 2.1). so rewriting Equation. (2.4) gives

$$\lambda E + c(T_s - T_b)E = R_n - H + N + F_{in} - F_{out} + F_{p-}\, G \quad (2.5)$$

In general, the term "sensible heat" (sum of energy that is used in heating the air directly) is difficult to be determined easily, thus excluded from the Equation (2.5) using the Bowen coefficient, β. The ratio between the sensible and latent heat fluxes is known as the Bowen ratio, expressed as:

$$\beta = \frac{H}{\lambda E} = \frac{c_p \phi (T_s - T_a)}{\varepsilon_m \lambda (e_s^* - e)} \quad (2.6)$$

Whereas c_p denotes at constant pressure the specific heat of air, φ represents the atmospheric pressure, T_s and T_a represents the water surface and air temperatures at a reference height respectively, ε_m stands for the molecular weight of water to that of dry air ratio, and e_s^* and e denotes the air SVP at the temperature of water surface and at the reference height air vapor pressure respectively. The term $\varphi / \varepsilon\lambda$ is also identified as the psychometric coefficient, γ. (Brutsaert, 1982) has given details concerning the physics of evaporation including the Bowen ratio and many other characteristics.

Substituting $H = \beta\lambda E$, from (Equation 2.6), into Equation (2.5) results in the evaporation rate equation,

$$E = \frac{R_n + N + F_{in} - F_{out} + F_{p -} G}{\lambda(1+\beta) + c(T_s - T_b)} \tag{2.7}$$

The variance between the evaporated water temperature and temperature of an arbitrary base (correction term) is represented by the second term of the denominator.

Sometimes, terms F_{in}, F_{out}, and G, can be ignored by choosing the average time. In fact, the energy content in a reservoir is mainly determined by the change in energy from the surface, rather than by inputs, including the water-substrate interface as well as precipitation and discharges (Henderson-Sellers, 1986). A certainty of this happening is when the inflow outflow amount of water to and from the reservoir is less than in volume or the reservoir or water body temperature are close to that of in and outfluxes. Hence, if the arbitrary base temperature and temperature of the water surface are equal I.e. $T_b = T_s$ energy budget becomes,

$$E = \frac{R_n + N}{\lambda(1+\beta)} \tag{2.8}$$

This is occasionally indicated to as the reduced equation of energy budget ((Dos Reis & Dias, 1998) and (Simon & Mero, 1985)).

This method involves determination, either by estimation or measurement, the terms and parameters in whichever Equation. (2.7) or (2.8).

3.3.1. Measurements

Energy balance method is considered to be the most accurate for evaporation rate estimation after measuring direct evaporation. ((Hoy & Stephens, 1977) quoted by (Assouline, 1993)). Therefore, most of the times testing and calibration of other methods are done with this method taken as the reference or standard. Water body size and timescale defines the accuracy. Due to the heat accumulation, to achieve adequate accuracy at different temperature, for larger water bodies or reservoirs, it takes longer, or longer gap is needed between measurements and observations of the temperature profile. In a typical study on Hefner Lake (Anderson, 1954), in evaporation estimation an accurateness of 5% was achieved for different time-scale that included periods of one week or longer but a decrease was seen for time-scale that were shorter than one week. (Stewart & Rouse, 1976) hypothesized that lakes which are shallow (commonly 0.6 m), that the accuracy of model is adequate enough that it can be taken as standard and other models or methods can be tested against it.

Energy balance method has its own drawbacks, as the number of observations and measurements in this method is not only large, but their frequency and the difficulty in performing some of them. Due to these facts, the methods become expensive and the feasibility of its use drops in term of a more comprehensive equation. A study on Lake Hefner by (Anderson, 1954), Lake Mendota, Wisconsin by (Stauffer, 1991), and (Sturrock, Winter, & Rosenberry, 1992) did a comparative study of Lake Williams in northern Minnesota and, most recently, the evaporation from lakes in Florida two in number (Sacks, Lee, & Radell, 1994).

Measurements and observations of micrometeorology, surface and core water temperatures are needed to be done at a point characterizing the conditions or over the reservoir or body of water. It is usually done using an offshore anchored raft instrument (for example, (Anderson, 1954)), but at the same time, measurements were carried out on land, and sometimes on data from remote weather stations, for ease of maintenance and cost. For the determination of effects on evaporation estimates due to the usage of different data sources studies are conducted (e.g. (Keijman, 1974)).

The main influences affecting the amount of inbound solar radiation (R_s) are absorption, scattering in the atmosphere and reflection, and the type and quantity of clouds as well in addition to the latitude of the area and season are considered significant. The albedo effects the radiation reflected which in turn depends upon to a certain extent on solar angle and amount of cloudiness. The longwave radiation $L\downarrow$, radiated by the atmosphere, its calculation is done from humidity and temperature vertical nature profiles. Though, sometimes finding of data as such is difficult and missing, leaving Stefan-Boltzmann ratio to calculate it using the following formula,

$$L_{\downarrow} = \varepsilon \sigma T_a^4 \tag{2.9}$$

Near the surface temperature of the air is denoted by T_a , σ represent the Stefan-Boltzmann constant and the emissivity of clear sky is denoted by ε, from near the surface humidity and temperature which can calculated. The effect of cloudiness is same for R_S and $L_{\downarrow}$. From the water surface the losses of long-wave radiation can also be calculated using suitable surface approximates for the emissivity and temperature. (Stannard & Rosenberry, 1991) discovered in their work that the inbound radiation measurement and modeling of outbound radiation led to overestimation of the total radiation of the lake compared to directly measured values. A possible cause of this is the radiation difference between the lake and the measured location at a distance of 4.5 km. Measured or estimated, the integration of radiation amount is done to obtain the duration estimates in correspondence to other measurements.

The heat accumulation or storage, N is calculated using the following equation:

$$N = \rho c d \frac{\Delta T_w}{\Delta t} \tag{2.10}$$

where density is denoted by ρ, specific heat represented by c, d is depth and ΔT_w is variation in geo-spatial mean temperature of the water body or reservoir in Δt, time steps. For well-mixed reservoirs and small lakes, the surface temperature can help in approximation of T_w, (Keijman, 1974). But this give birth to questions as appropriate surface temperature values; in steady and serene circumstances with higher amount of solar radiation, geo-spatial change in surface temperature over smaller time periods can be large. But the necessity of conducting thermal surveys which comprises of temperature profiles alongside depth, observed and measured almost perfectly at a satisfactory number of stations in order to yield a decent average. The exclusive study of Lake Hefner study, taken as an example, 16 stations were the focus of observations, which were conducted at weekly intervals and while one of two stations the observation were done at daily intervals (Anderson, 1954), whereas observations at Williams Lake took place every 16 weeks (Sturrock et al., 1992). The choice of a suitable time period or interval based on the size of the reservoir may cause the N value to be negligible.

3.3.2. Errors

The eddy correlation equipment established on the lakes was used for direct measurements to compare the evaporation assessment using energy balance (Sene, Gash,

& McNeil, 1991), (Stannard & Rosenberry, 1991) and (Assouline, 1993). It shows that the hourly or day-to-day evaporation amounts for deep lakes are influenced mainly by stability of wind and atmosphere, while the required energy is provided from the stored heat in the lake. As a result, the evaporation estimates by method of energy balance for deep lakes may be incorrect in a short time. It was founded by Assouline (1993) that the average daily evaporation rate estimated by the energy balance method for high wind speeds and sensible temperatures was having a value of 2.8 mm day^{-1} compared to evaporation measured by eddy correlation which was 4.1 mm day^{-1}. Although, when observations were made with less advection and lower wind speeds, agreement much closer was found. For longer period of times the obtained evaporation estimates through eddy correlation and energy budget, a much closer rates of evaporation are obtained. An accuracy of 5% of evaporation estimates was given for Lake Hefner by (1954).

3.4. Bulk or Mass Transfer

(Sene et al., 1991) has derived a modest form of the bulk transfer equation. According to his form

$$E = Cu(e_s^* - e) \tag{2.11}$$

where C denotes the mass transfer coefficient (MTC), u represents the wind speed and e_s^* - e is the saturated vapor pressure gradient. MTC can be considered as the total drag coefficient; the amalgamation of friction of skin and resulting force from the wind slowing in the flow direction. If the surface is uniform, calculation of C through theoretical means can also done over the surface, hence shows that C is a function of the surface roughness which is affected by the speed of wind, and stability of atmosphere (Brutsaert, 1982). Despite significant scatter in results, the value of the MTC is usually determined and calculated for marine surfaces (Brutsaert, 1982). In most domestic water bodies, smooth surface conditions are not met, and for obtaining a theoretical solution of the heat transfer and evaporation equations, more restrictive assumptions are required (Brutsaert, 1982). The value of coefficient, C, is the reflection of the transport characteristics of a particular reservoir or water body, determined by its vegetation cover, geometry, use of land, topography and surrounding area's climate. In addition, the MTC value has the specificity of the metrological observations recording site characteristics; e.g. The observation of wind speed at a height of 2m will be incorrect to be used with observation of wind speed at 10m, even the site conditions are same. Thus, resulting in no universal value of C that can applied to every reservoir or water body. Although, hydrologists have attempted for the production of generally acceptable and applicable value. (G. E. Harbeck, 1962) suggested and provided an expression of MTC that incorporated and combined the area of the reservoir or water body. From Shuttleworth (Maidment, 1993) works the transfer equation with proper units is:

$$E = 2.909 A_s^{-0.05}\, u_2 (e_s^* - e) \qquad (2.12)$$

where A_s, area of the water surface in m^2, and u_2 is the wind speed observation at 2 m above the surface. Appropriate for lakes in a relatively dry area of 50 m < $A_s^{0.5}$ <100 km. For pans in the 0.5 m < $A_s^{0.5}$ <5 m range, an identical expression also proposed by Shuttleworth taking work of (Brutsaert & Yu, 1968) as basis:

$$E = 3..623 A_s^{-0.066}\, u_2 (e_s^* - e) \qquad (2.13)$$

The dependence of MTC upon the reservoir or water body size which is a weak inverse dependency, shows a reduction in the efficiency effect of the turbulent and uneven transfer over smooth water surfaces (Maidment, 1993). Although, increase in transfer in large reservoirs or bodies of water is indicated in some observations. Taking the work and observations of (Venalainen, Heikinheimo, & Tourula, 1998) as an example, his work on two Swedish lakes, using eddy correlation and direct metrological measurements, he stated and concluded that the evaporation from the larger water body (lake) was greater than that from the smaller lake. This was attributed or linked to the outcome of amplified speed of wind more than recompensing the adverse effects of the increase in air humidity relative to the greater distance traveled over water by air.

3.4.1. Measurements

Once the value of the term C, is been determined, at a height same as that used in the determination of C, vapor pressure and wind speed are to be measured routinely. The measurements and observations should be done over the water body, in order to represent the conditions which dominates water body surface, except if the water body is closer than a few meters. In addition, for the determination of e_s^* the mean temperature of the water surface should also be measured.

If work of (Stauffer, 1991) is taken as an example for the daily or hourly time-scale estimates, effects of atmospheric stability should also be taken into account but if the estimates are for long term the atmospheric stability effect can generally be neglected.

The use of functional forms other than this, few of which includes air temperature are also reported in literature. Using data from North Western Canada, 13 mass transfer equations were tested by (Xu & Singh, 1997), which were transformed into a form more simple or generalized. At four different sites pan evaporation data was compared with evaporation estimate for monthly time-scale, with each equation calibrated for the sites. In general, good agreement between the results estimated and measurement was found but only for the calibrated sites, but the equations failed to yield satisfactory results for the uncalibrated sites. The inadequacy and limitation of the pan evaporation estimates was demonstrated and the results were inconsistent with the results and observation produced by (Venalainen et al., 1998) from his study on the two lakes in Sweden. The inconsistency is due to the fact that for the time-scales longer than day, the prime control over the evaporation was that of humidity rather than that of wind speed.

3.4.2. Errors

Due to inconsistency in the results from the evaporation estimation over the Lake Kinneret, Israel, (Simon & Mero, 1985) gave up the use mass transfer model. Not only the discrepancy in the estimation but also the transfer coefficients estimates were largely scattered. But on the other hand (Sacks et al., 1994) succeeded in finding acceptable agreement between the mass-transfer estimated evaporation and energy-budget estimated evaporation for monthly time-scale (commonly, within 8%) when applied to a deep lake in Florida, but larger error was recorded (24% mean monthly estimates) when applied to a shallower lake also found in Florida. No improvement whatsoever was recorded even with coefficient of mass transfer correction (Stauffer, 1991). An assessment by (Sacks et al., 1994) suggests that smoothing effect which the differences might be, the use of long-term continued average vapor pressure gradients can be a cause of it (soothing effect); the sensitivity shown by this method to the error and inaccuracies in the VPG is one of the leading problems identified. Furthermore, the usage of coefficient of mass transfer (G. E. Harbeck, 1962) form I.e. (Equation 2.12) resulted in underestimation, with an underestimation of 14% from the shallow lake while that from the deeper lake was 27%. Furthermore, this finding was not in line with the findings of (Sturrock et al., 1992), who discovered that the use of Harbeck recommended method resulted in over estimation of evaporation than that of energy budget. Although, no clear argument and reasons are been put forwarded to explain these inconsistencies and disagreements.

3.5. Combination Equations Method

3.5.1. The equations of Penman and Priestly-Taylor

Penman equation (H. L. Penman, 1948) has outclassed all the other methods used for evaporation estimation from either vegetation or water in the last fifty years. Even its application in different places it was successful due to its physical basis. A table presented by (Linacre, 1993) in his work shows the comparison of estimates by Penman applied to an extensive variety of reservoirs around the world for monthly or annual time-scales. The measured to estimated evaporation ratio mean value was 0.99 with 0.12 value for standard deviation. Energy balance and mass transfer approaches were combined by Penman and disregarded the surface temperature need in order to acquire equation for evaporation from open water in per day in mm:

$$E = \frac{\Delta R'_n}{\Delta + \gamma} + \frac{\gamma f(u)(e_a^* - e)}{\Delta + \gamma} \tag{2.14}$$

where R'_n denotes the net radiation in units of (mm day^{-1}) which is corresponding depth of water, Δ represents the saturated vapor pressure-temperature curve slope and psychometric coefficient is denoted by γ. Later, into a more familiar form it was transformed by Penman recognized as Penman E_T, which is the short-watered vegetation expected evaporation rate. Form modified for open water (Equation 2.14) have no regard for storage of heat and there was no anticipation of its use for water bodies that are deeper with or without the factor of horizontal transfer (advected) of energy components. For the incorporation of advected energy R'_n was to be replaced by A, the energy available, which incorporates any advected energy that goes into the water excluding the energy that follows the path into storage and net radiation.

Analysis of data gathered over land surface that were large, widespread and saturated and oceans by (Priestley & Taylor, 1972) and discovered that values of evaporation were tailored using

$$E = \alpha \frac{\Delta A}{\Delta + \gamma} \tag{2.15}$$

A is the available energy and constant α, takes into account the evaporation besides the equilibrium term, the evaporation due to lack of humidity. The equation is now accepted as Priestly and Taylor equation. A mean value of the constant α, was established by Priestly and Taylor as 1.26 from the examination of the data which is later confirmed by successive studies. Flevo Lake in Netherland, having an area of 460 km^2 and average depth of 3 m considered as shallow and large lake, analysis by (de Bruin & Keijman, 1979) using the Priestly and Taylor equation on aforementioned lake, respectable results were obtained as the results by Priestly and Taylor equation were in respectable agreement with energy and water budget methods estimates for daily evaporation for the early autumn and summer season with the value of constant taken as 1.25. Although, in the value of the constant α, a daily change was also found, the daily alternation in the constant was attributed to the change in the water and air temperature differences and furthermore, recommended that it can be anticipated from many lakes that can produce such conditions and environments which in turn produces such change. In the value of constant α, the indication of seasonality was also discovered, of the same amount as the daily discrepancy in evaporation. This change or discrepancy is the outcome of specific evaporation taking place even when zero energy was available. Evaporation estimated by means of the following formula and that from energy budget calculation were close to each other when assessed by de Bruin and Keijman:

$$E = \frac{\Delta A}{\lambda(0.85\Delta + 0.63\gamma)} \tag{2.16}$$

Relationship among the constant α, and β and a relationship empirical in nature $\beta = 0.63\gamma\ \Delta - 0.15$ is specified by (Hicks & Hess, 1977) which they derived from Priestly and Taylor equation.

Heat storage and net radiation were replaced by the use of inbound solar radiation linear function and then a different form of the Equation. (2.15) was derived by (Stewart & Rouse, 1976). *a* and *b*, function parameters, regression was used to find them, and a necessity is that they are explicit to the corresponding lakes. But the equation resulted is matching and alike to the equation by (Makkink, 1957) who formulated it for the estimation of well-watered grasses evaporation:

$$E = a\frac{\Delta}{\Delta + \gamma}S + b \tag{2.17}$$

In comparison with other methods, Priestly-Taylor equation has the disadvantage as it is particularly important to measure and record the values of $R_n{}'$ and N; generally, its measurement and recording is high costly or impossible to make enough N observations for a water body of larger size. The combination of Priestly and Taylor equation and Penman by (De Bruin, 1978) succeeded in overcoming this hurdle, consequently abolishing the term of energy to get the relationship.

$$E = \left(\frac{\alpha}{\alpha-1}\right)\left(\frac{\gamma}{\Delta+\gamma}\right) f(u)(e_a^* - e) \tag{2.18}$$

Measurement of temperature of air, wind speed at a height of 2 m and lack of moisture (humidity deficit) are the requirements of this formula. At the middle of Flevo Lake, time-average input data taken as the base or foundation for the verification of the wind function proposed by (Sweers, 1976) and used by de Bruin method and evaporation for different time periods was calculated. He received a respectable agreement of data for 10 or more days with estimates based on the energy budget method. The variable nature of Priestly-Taylor coefficient for time periods of a day or less, was also discovered by him.

3.5.2. The Penman-Monteith equation

Penman-Monteith (J. Monteith, 1965) equation is a further wide-ranging method of combination equation. To describe the phenomenon of water vapor evaporation from the sub-stomatal and lower voids of plants. Evaporation rate in its essentiality is found from the equations of diffusion instantaneous solution for water vapor and heat , and the equation of energy balance. When the same equation is used for water,

$$E = \frac{1}{\lambda}\left[\frac{\Delta A + \frac{\rho C_p (e_a^* - e)}{r_a}}{\Delta + \gamma}\right] \tag{2.19}$$

where r_a, is the representation of aerodynamic resistance which is the resistance encountered by the molecules of water while their movement to a reference height in atmosphere from the surface of water, and proportionality to the wind speed is inverse. Physical basis and foundations of this equation is same as that of Penman equation except for the calibration of coefficients is not done experimentally, as used by the Penman in its naturality for the wind function. Consequently, a better description and explanation of the process of evaporation is given by this method and provided the availability of necessary and essential data, should be preferred over other methods. The available energy, A should be inclusive of the supply of net energy and heat storage to the reservoir. Another requirement for precise estimations is that the value of the r_a, the aerodynamic drag, takes into account the surface roughness effect, water body size and the stability of the atmosphere.

3.5.3. Measurements

Combinational equations require the values of temperature of air, net radiation, wind speed and vapor pressure. The requirement of input parameters is lesser for simpler, derivative methods, such as the equation of Priestley-Taylor. There is no requirement of surface temperature values like that in energy and mass balance methods. Although, for accurate estimates of evaporation, the time interval during which evaporation estimates are required, heat storage should be estimated or measured in water, unless heat storage is negligible. A simplified version of the Penman equation was derived by (Linacre, 1993), for which only the data of temperature of air dew point and wind speed is required. Two different approaches were put forwarded by Linacre for predicting solar radiation, in of these approaches, for cloudiness substitute indictor rainfall is taken, and the other approach accounts altitude, remoteness from sea and for distance from latitude and change and variation in temperatures. This method when used only with monthly or longer averaged input data, estimates from Australia, United States and Copenhagen received a good agreement (within 5%) with evaporation rates measured.

3.5.4. Errors

Earlier discussed other methods, the evaporation estimates and calculations, uncertainties are greater for water bodies that are deep due to a greater heat accumulation component. For water bodies that are larger in size, the surface energy change which is dependent of the atmospheric stability which should be considered of significant importance for time periods of a day or shorter, mainly determines the heat storage or accumulation component. When a certain depth is reached in the water bodies, phenomenon of stratification begins to take place and hydrodynamic models and measured or observed temperature profiles determines the heat storage.

But, in climates of tropical nature, the temperature of water for lakes can be almost persistent and constant all over the year, so any variation in the heat storage will be insignificant and can be ignored (Sene et al., 1991).

Based on data collected from the literature, (Linacre, 1993) indicates that Penman’s equation is estimated at about 8% of the possible monthly or annual estimate of evaporation using monthly data.

The Priestley-Taylor equation (2.15) was tested by (Stewart & Rouse, 1976) on a small (105 m^2) shallow (mean depth 0.6 m) using the data obtained from the lake and half an hour and daily evaporation estimates by the energy method found a good fit with the evaporation. Their analysis showed that at about 5% evaporation could be estimated. Makkink formula (Equation 2.17) was also tested by them and observed that the equation provided evaporation estimates within 10% accuracy at two-week or monthly breaks.

As the necessity of knowing and observing the term *N,* was eliminated and abolished by De Bruin model, but the variation in the Priestly and Taylor coefficient α, is the reflection of its effect. As evaporation is quite sensitive to change and variation in this parameter, the selection of an adequate value is required otherwise consequence of this will be in the shape of large errors in the estimation. Also, to the VPD the sensitivity of this model is observed.

3.6. The Method Of Equilibrium Temperature

A more thorough assessment of heat transfer methods on the water body surface, contributed convenient models. The only data requirement different than that of Penman is the water heat storage computed within the models. Concept and idea of equilibrium temperature was introduced by (Edinger, Duttweiler, & Geyer, 1968). Meteorological data determined time constant was linked with the equilibrium temperature, towards which the net heat exchange drives the water temperature I.e. the net heat exchange rates approaches zero when the water attains the equilibrium temperature. It opens the possibility of deriving an expression for a well-mixed water body temperature as time and water-depth function. After assessing water body temperature, its use for the assessment or estimation of sensible and evaporative heat fluxes, the loss of long-wave radiation from the water body and the storage and accumulation of heat.

An alike method was also used by (Keijman, 1974) who then estimated the evaporation from Lake Flevo (a shallow lake) using heat storage, calculated in the Penman equation (Equation 2.16). A marginally different method is used by (De Bruin, 1982) for water temperature expression, which also uses an equilibrium temperature, which was constant and equal to the mean of Keijman value. Extended over several years for two reservoirs of distinct depth in Netherland, standard ten-day meteorological data (ground-based) was used by Bruin in his work which later achieved an acceptable agreement between predicted and measured water temperatures. (Fraedrich, Behlau, Kerath, & Weber, 1977) extended similar type of work, they considered the inflow and outflow advected energy into the reservoir and its effect. In surface-transfer and mechanism forced by hydrology response, imitation of the energetics of the water body is allowed by the two distinctive related time and temperature constants. A large but shallow reservoir was taken as the water body where the model was applied and upward longwave radiation and water temperatures, predicted and simulated averages (monthly) were in a good agreement. Energy accumulation term was also calculated using the water temperature, which was then later used in the combination equations (Equation 2.16, 2.17) for the evaporation estimation and the estimates given by Penman was good than Priestly-Taylor equation.

3.6.1. Measurements

(Keijman, 1974) in addition to the wet bulb and dry air average temperatures (daily) values, wind speed jointly with duration of sunshine were measured around the lake which paves the way for the calculation of net radiation, a requirement for driving the model. He also compared the effect of data gathered from the center of Lake Flevo with the data collected at two stations around the lake. Decent results were obtained if the downwind side station data was used. In order to run and drive the more complex model, monthly average weather data was used by (Fraedrich et al., 1977) in collaboration with the temperature and rates of the discharge and influx.

3.6.2. Errors

In the literature, little has been reported about errors related to this model. (De Bruin, 1978) succeeded in providing an acceptable agreement for reservoir surface temperatures between the predicted and measured values. (Keijman, 1974) also reported a good and acceptable agreement which was reflected in the estimate of evaporation (daily) by the standard and lower error (0.6 mm) when Penman equation was used. E_{PM} estimates are better with this method than that of equation of E_{PT}.

3.7. Empirical Factors

Evaporation operational estimates, for some time factors that are empirical in nature were used to convert the estimates or measurements of evaporation which were done for a particular kind of land surface to those of another. They have the same function as that of the pan coefficients and are comparable in nature.

Although any method could be a source of reference evaporation, in practice these were combined equations. The reason behind the selection of the combination equations is that the meteorological data used by these equations are easily accessible and their reliability in predicting evaporation is proven.

(H. L. Penman, 1948) studies lead to factors that are used for finding or converting to open water surface evaporation, with the same weather conditions for both evaporations, from the abundant water-fed grass:

March-April (Spring) 1.43

May-Aug. (Mid-Summer) 1.25

Sept.– Oct. (Autumn) 1.43

Nov.– Feb. (Mid-Winter) 1.67

Measured evaporation values were obtained for a region in the south of England (Rothamsted experimental station) using cylinders having depth of 0.76 m and 1.83 m, therefore outside of these circumstances the use of these factors must be considered carefully. Penman evaporation model was calibrated using water evaporation measurements and therefore for reference evaporation the use of these factors is limited to be used only when this model is applied.

List of crop coefficients (empirical factor) given by (Doorenbos & Pruitt, 1984) that permit one to evaporation estimation from an extensive variety of land surfaces from a number of evaporations of a time series calculated using the Penman model (1948) for grasslands but the modified version. Wind function variation is included in this change. For open water evaporation the given factors are:

Strong wind in Humid environment – 1.15

Light to Moderate wind in Humid environment – 1.1

Strong wind in Dry environment – 1.2

Light to Moderate wind in dry environment – 1.15

Evaporation estimation from Penman-Monteith, (R. G. P. Allen, L. S. Raes, D. Smith, M., 1998) put forwarded crop coefficients, approximating a 70 s m^{-1} surface resistance and a 0.12 m hypothetical crop height (can also be considered as corresponding to grass short in height and supplied freely with water). In a humid climate or in tropical regions and in water bodies not deeper than 2 meters, the coefficient given for water bodies is 1.05. In a mild climate, two coefficients were given to reservoirs with no more turbidity than m. In the case of heat evacuation of the reservoir, it is recommended for autumn and winter to have a value of 1.25, and 0.65 for the spring and summer when the reservoir collects heat. In the use of these coefficients caution was recommended by (Richard G Allen et al.) and no justification or explanation was given for them. The Metrological Office Rainfall Evaporation Calculation System (MORECS) version of the PM, the resistance of bulk canopy of grass is continuously changing throughout the year, for the yearly cycle simulation, and therefore no full complying of the version given by (Richard G Allen et al., 1998) is corresponded.

3.7.1. Sources of errors

Potential errors found in the pan coefficients sustained by using these coefficients with evaporation pans data and empirical factors are very resembling in nature

Unavoidable error genetic in nature in the measurement and observation of metrological data are found which is turns is used for reference evaporation calculation. Net radiation is the leading influencing variable which is derived generally from the hours of sunshine or inbound solar radiation. Although, in the case of the inbound solar radiation, an accuracy of around ±5% can be achieved with usage of modern instrumentation. A general assessment of solar radiation values measured directly and that from sunshine hours recorders, an accuracy of about 5% are reliably attained with the exception in the days of winter when the sky is covered with heavy clouds and incident radiation is at its lowest.

In calculation of the reference evaporation the conditions in the reservoir in terms of metrology must be reflected in the data (meteorological) used for the calculation. The quantification of error is difficult that can be the result of failing to fulfil the aforementioned condition but about 10% error is estimated. The use of meteorological data should not be remote and should be close to the study area otherwise the overall topography and properties of the water body and the land cover around the water body will not be reflected properly.

The use of improper and inadequate coefficient for the water body which is the focus of the study will be probably the core cause of the error. For each specific water body exclusive coefficients should be determined which must variate during the year, this must be done in order to achieve accuracy of highest level. Feasibility of this in practicality is very low and therefore the coefficients should be trusted ideally only when the conditions and circumstances for which they were determined are same as that for which they are intended to be used. Specifically, an error approximately equals to 30% in total evaporation for less than a year time scales are due to the discrepancy in depth of water and most probably the surface areas. The change in weather conditions from one year to another will lead to potential errors if the same empirical factors are used continuously. A likely error of approximately 15 or 20% is expected in monthly assessments. Furthermore, the development of the empirical factor should only be for specific sources such as Penman-Monteith or Priestly-Taylor potential evaporation. For example, if similar set of empirical factors are used for the estimates of potential evaporation from the Penman model (1948), and from the application of Penman-Monteith by MORECS, it is likely to cause discrepancies of about 30% in evaporation from open water.

Therefore, the accuracy and precision are about 30% for estimates of annual time-scale while for monthly time-scale estimated evaporation the degree of accuracy is about 50%, for open water evaporation.

4. ANALYSIS, RESULT AND DISCUSSION

In the management of the water resources including reservoirs, lakes channels etc. one of the main complications is the assessment of all the components of water budget. Management and design of water resources systems requires extensive information of the variation and magnitude of losses due to evaporation. Although, being this much important, for the estimation and calculation of evaporation there are a number of methods used. The experimentally method or on-site calculation or estimation of evaporation rate is pan-evaporation. Due to the difficulty faced in calculation the evaporation experimentally several hydrologists presented and developed equations to calculate and estimate the evaporation to the possible accuracies. These methods are based on the different metrological parameters which have a direct effect on evaporation. Although, not all of these equations are as robust and rigor but there use in different climate conditions or the for the climatic conditions of the areas for which they are extensively tested, does yield satisfactory results. The multitude of methods for the estimation can be grouped based on the climatological parameters they use. The methods and equations used in this study are Hargreaves, Hamon, Thornthwaite (Temperature-based), Romanenko (Humidity-based) and Priestly-Taylor, Turc and Jensen-Haise (Radiation-based). The difficulty arises incorrectly selecting the appropriate method for the study since extensive variety of types of data is required and range of proficiency and knowhow is required to use the equations properly.

According to the recommendations of FAO (R. G. Allen, Smith, Pereira, & Perrier, 1994a; R. G. Allen, Smith, Perrier, & Pereira, 1994b; R. G. P. Allen, L. S. Raes, D. Smith, M., 1998) for the selected empirical equations, as an assessment standard the Penman-Monteith equation was used. This study includes a discussion in detail of present methods, comparison, and evaluation of the nominated models with the calibrated values in accordance to the location of the empirical constants taking place in these equations. Finally, the predictive ability of the equations is discussed, and the overall applicability of these equations is examined for the study region.

4.1. Study Region and Data

Ataturk dam is situated on the Euphrates south-east of Turkey in Bozova. The Ataturk dam reservoir is the 3rd largest reservoir in Turkey, surpassed by Van lake and Tuz Lake. The reservoir has an area of 847 km^2 with a capacity of 48.7 cubic kilometers of water. The metrological data was obtained from Globalweather.Tamu.edu ("Global Weather Data for SWAT," 2019). The location data was for coordinates of 37.65-38.47NE, 37.62-38.43SW, as the climatological station in the requirement of the Global weather exist in between the above-mentioned coordinates. Several hydrometeorological parameters, including temperature of air, solar radiation, relative humidity, and wind speed, are obtained for the time period 2000-2013. The data selected was daily which were later subsequently integrated for use in this study into monthly values. (Table 4.2) has the main climatic parameters with their monthly averages and the quantity of evaporation.

4.1.1. Use of CFSR data in the study

The use of Climate Forecast System Reanalysis (CFSR) is done in various studies. One of the detail assessments of CFSR data is done by (Fuka et al., 2014). The study aims at establishing an acceptable environment for the usage of CFSR data. The CFSR data results for the streamflow were compared with the measured stream flow and nearest weather station results. The results yielded were more than satisfying as the results from CFSR data were almost as good or had better streamflow predications as the weather

Table 4.1. *Reanalysis datasets available from the NCAR, CISL, RDA*

Reanalysis dataset (CISL ID)	Date range	Time step (h)	PPT field	Res	Coverage
CEP/NCAR (ds090.0)	1948–2010	6	PPT Rate	2.5° (~290 km)	Global
NCEP/DOE R2 (ds091.0)	1979–2012	6	PPT Rate	1.875° (~209 km)	Global
NCEP N. American Regional (ds608.0)	1979–2012	3	PPT Rate	~0.25° (~32 km)	North America
NCEP 51-Year Hydrological (ds607.0)	1948–1998	3	Total PPT	0.125° (~15 km)	Continental USA
ECMWF 15 Year (ds115.5)	1979–1993	6	Strat. + Conv. PPT	1.125° (~130 km)	Global
ECMWF 40 Year (ds117.0)	1957–2002	6	Strat. + Conv. PPT	1.125° (~130 km)	Global
ECMWF Interim (ds627.0)	1979–2012	6	Strat. + Conv. PPT	0.703° (~82 km)	Global
CFSR (ds093.1)	1979-present	1	PPT Rate	0.3125° (~38 km)	Global
Japanese 25-Year (ds625.0)	1979–2011	6	Total PPT	1.125° (~130 km)	Global

near to study location. Another assessment for the use of CFSR data is done for the Blue Nile River (Dile & Srinivasan, 2014). Dile and Srinivasan concluded that the usage of CFSR weather resulted in satisfactory output (NSE ≥ 0.5).

The CFSR dataset contains of weather forecasts for hourly timescale produced by the National Weather Service's (NCEP) Global Forecast System. Every 6 h (analysis hours = 0000, 0600, 1200 and 1800 UTC) forecast models are reinitialized using satellite-derived information and data from the network of global weather station.

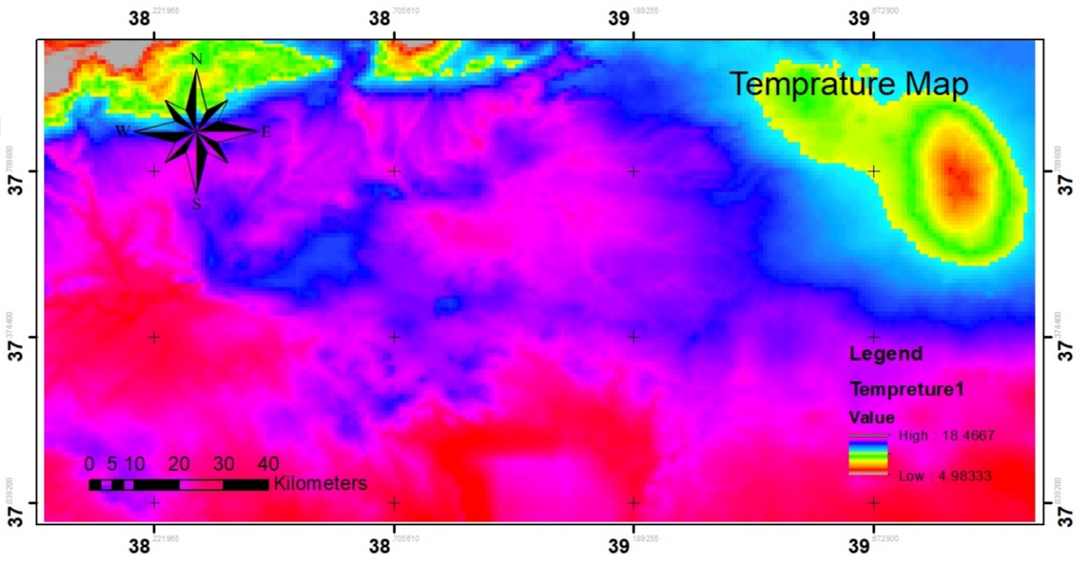


Figure 4.1. *Temperature record for the Bozova district and relative area for the year 1979-2010*

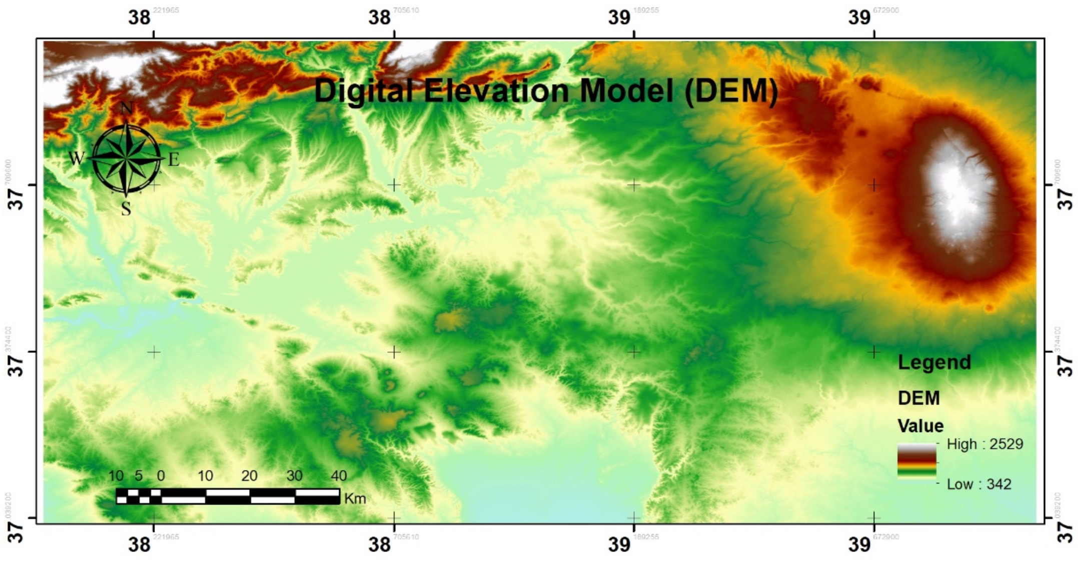


Figure 4.2. *Digital Elevation Model of the Bozova district and relative area*

The CFSR comprises both types of data I.e. data forecasted, previous analysis hour prediction, and the data from the assessment employed to reinitialize the forecast models, at each analysis hour. 38 km is the horizontal resolution of the CFSR (Table 4.1);(Saha et al., 2014).

The studies mentioned above were used as the basis for the CFSR weather data use for this study. As the accessibility of weather data from the station in Turkey is not easy, the use of CFSR is a valuable option for the hydrological prediction not only in Turkey but in areas lacking the stations or the availability of data or the ease of access to the data.

4.2. Evaporation Dependency on Metrological Variables

For a better comparative and reasonable evaluation, dimensionless quantities are preferred. The standardized values of each variable were calculated and related to each other by using the transformation in this study,

$$\boldsymbol{Z_i = (X_i - \mu)/\sigma} \tag{4.1}$$

where x represents the variate, i is the i^{th} value, $\boldsymbol{\mu}$ denotes the mean of x and $\boldsymbol{\sigma}$ is the standard deviation of x (Xu & Singh, 1998). To the daily and monthly values, a similar transformation was applied.

A variation in the air temperature role is observed with the time-scale. As at the daily-scale (Figure 4.3) shows how the role of air temperature affects the evaporation. As a result of depth of water, the influence of heat storage capacity on the distribution of evaporation in seasons can be significant, which is too large extent determined by the water body depth. The water body tends to store heat and the heat exchange occurs in early days of spring and late winter, due to this phenomenon the evaporation has still considerable rate when the temperatures are low. This heat storage and exchange property of a body greatly affect the rate of evaporation, especially when estimating potential evaporation from large water bodies with greater depths than 4.5 m (Finch & Hall, 2001). The effect of heat storage can generally be disregarded for shallow bodies of water having a depth of 1 m or less, but the effect influences to its maximum once the depth of water column in water bodies increases beyond 4.5 m. In the daily evaporation estimate from the body, there is a notable difference in late winter and spring (days 0-50) and early autumn (days 250-300). This difference is a clear indication of the heat storage and transfer of heat energy among the environment and body of water thus affecting the evaporation rate. Although, at the monthly scale, between evaporation and air temperature, a lag of almost one month is seen especially in late winter (and early spring) and early autumn.

Table 4.2. *Monthly averages of the key metrological parameters and evaporation for Ataturk Dam Reservoir on Euphrates, Turkey*

Month	Temperature (ºC)	Vapor Pressure Deficit (kPa)	Wind Speed (m/s)	Radiation (MJ m^{-2} d^{-1})	Relative Humidity (%)	E_{PM}^{*} (mm day^{-1})
January	3.43	0.02	1.84	3.17	78.82	1.478
February	3.78	0.02	1.84	4.57	81.12	2.389
March	7.79	0.03	1.78	6.84	72.88	3.440
April	12.98	0.07	1.71	9.05	60.19	4.444
May	19.05	0.14	1.80	10.65	43.36	5.147
June	25.33	0.26	2.12	11.25	28.03	5.486
July	29.64	0.36	2.33	10.83	23.95	5.707
August	30.90	0.39	2.18	9.22	23.92	5.334
September	26.95	0.30	1.99	6.70	28.37	4.413
October	20.78	0.17	1.62	4.04	39.69	3.430
November	12.83	0.07	1.66	2.49	60.11	2.468
December	6.43	0.03	1.68	2.37	71.17	1.799

[*] Evaporation estimated using Penman-Monteith Equation

As the water evaporation rate is affected to a certain level by the speed of wind over the water surface. The airborne water particles already diffused from the water body are swept away by the blowing wind, thus reducing the air humidity above the water surface, as a result, more molecules of water can diffuse into the adjacent air above the surface. Although, only up to a critical value the positivity of the relationship between wind speed and evaporation rate exists.

(Figure 4.4) shows the effect of wind speed on evaporation for monthly and daily time-scale. No proper relation can be established between wind speed and evaporation as the effect is reduced with an increase in time scale. The effect transforms from one shape to another in a monthly timescale graph. Though, with the increases in the time-scale a decrease

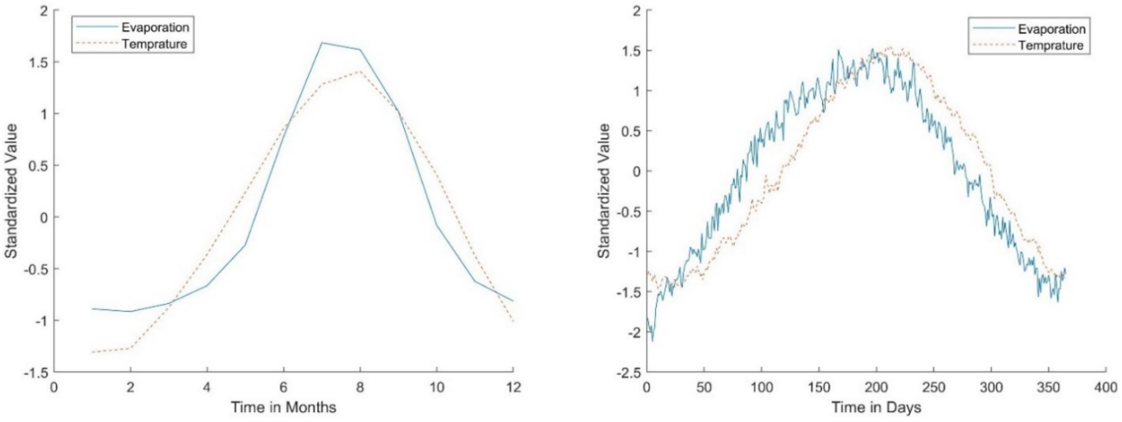


Figure 4.3. *Evaporation dependency on temperature of air at different time-scales (yearly values are averaged to monthly values for the period 2000-2013)*

in the dependence of evaporation on wind speed is recorded. In the daily time-scale the effect of wind is inverse in the spring season and then again becomes in agreement in the summer season but again in winter, the wind starts losing its effect on wind speed.

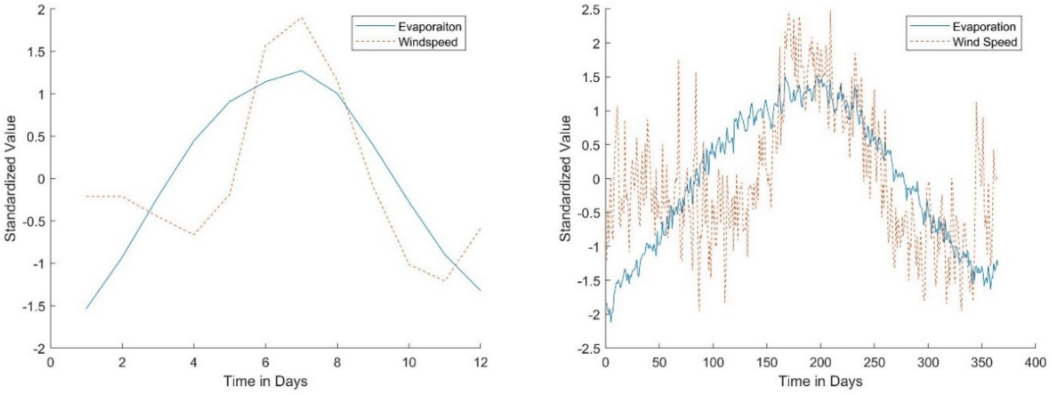


Figure 4.4. *Evaporation dependency on speed of wind at different time-scales (yearly values are averaged to monthly values for the period 2000-2013)*

For time steps that are lengthier than a day, the speed of wind is not that significant as according to Linsley and Kohler "For a considerable amount of time over a shallow lake if every other metrological element is kept constant alongside radiation exchange, the temperature of water and rate of evaporation would become constant. Then suddenly if the wind speed were doubled, transitorily the rate of evaporation rate would also become twofold. The increased evaporation rate would begin to draw heat from the water immediately at a rate more rapid than what could be replaced by conduction and radiation. But after some time, the temperature of the water body would reach a new, lesser equilibrium value, and consequently the diminishing of evaporation rate will take place accordingly. A variation of 10% in the speed of wind will alter evaporation only 1 to 3% on a long-term basis, while other metrological factors remain influencers” (Linsley & Kohler, 1982).

(Figure 4.5) shows the dependence of evaporation on radiation for various time-scales.

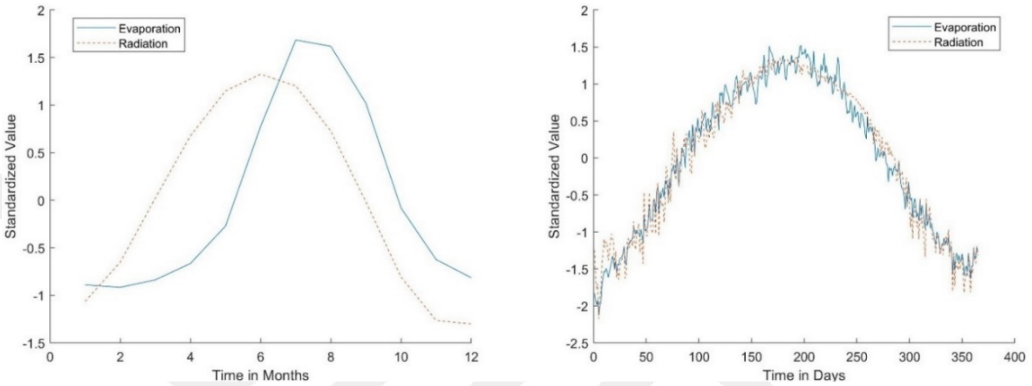


Figure 4.5. *Total solar radiation effect on evaporation at different time-scales (yearly values are averaged to monthly values for the period 2000-2013)*

Almost a perfect symmetrical agreement between evaporation rate and radiation can be found in the daily time-scale. Not only in the daily time-scale, the agreement is good but also at the monthly time-scale there is a symmetry found. Although a lag of a month in the effect can be noted in the monthly time-scale. The lag can be a consequence of the heat energy storage capacity of the body of water. As the water body tends to store more heat energy if the depth increases from a certain level.

Relative humidity, in general, is a good indicator of evaporation (Figure 4.6). The effect of humidity is almost same in both time-scales i.e. daily and monthly. An inverse relation can be noted from the graphs as in the summer when the relative humidity drops an increase in the evaporation rate is recorded and vice-versa. There is no clear indication of the difference in the effect of relative humidity on evaporation in different time-scales.

(Figure 4.7) shows that the vapor pressure deficit (VPD) irrespective of the time-scale remains an important driving parameter of evaporation with time-scales varying from monthly to daily.

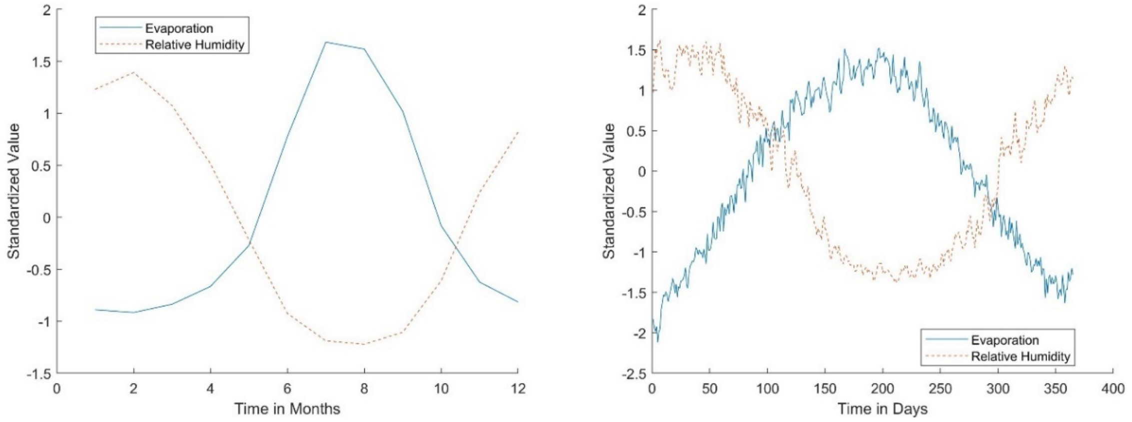


Figure 4.6. *Relative Humidity effect on evaporation at different time-scales (yearly values are averaged to monthly values for the period 2000-2013)*

VPD remains more of a controlling factor in monthly time-scale but in the daily time-scale, the agreement between these two isn't that much fragmented either. The VPD is an important feature in the of evaporation rate determination, that is why evaporation estimation mass transfer methods are primarily founded on the VPD, give usually respectable assessments for different time-scales (Xu & Singh, 1998).

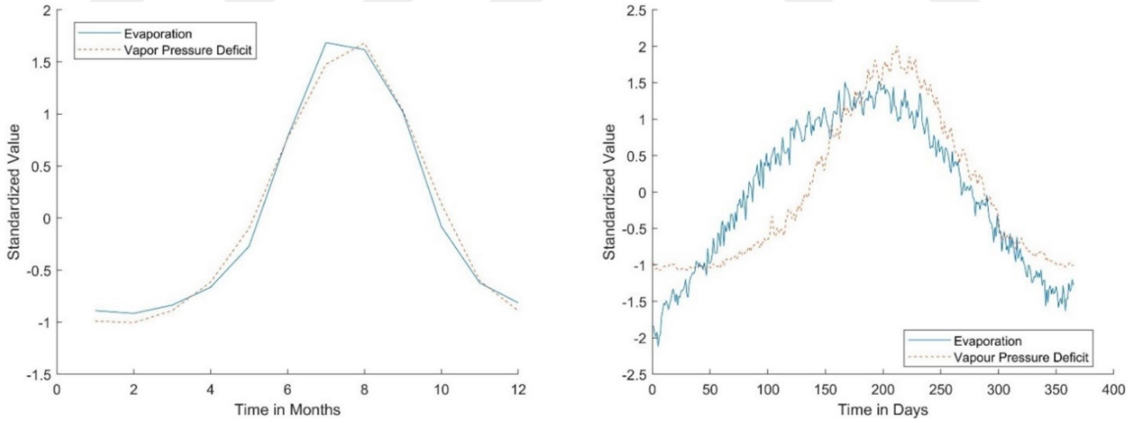


Figure 4.7. *Vapor Pressure Deficit effect on evaporation at different time-scales (yearly values are averaged to monthly values for the period 2000-2013)*

The development of different evaporation methods and equations over time make it difficult to choose the best of these equations. An analysis of these studies can show the close to the original result, but these results and the best method selected based on these results are only confined to the area. Although, Penman-Monteith (PM) equation has shown that the results obtained from it, are closer to original evaporation and since in PM equation the combination of Mass transfer and energy balance are in almost perfect relation.

Table 4.3. *Correlation Between Metrological parameters and Evaporation*

	Evaporation	Temperature	Relative Humidity	VPD	Wind Speed	Radiation
Evaporation	1.00	0.90	-0.84	0.84	0.59	0.97
N	365	365	365	365	365	365
Temperature	0.90	1.00	-0.98	0.97	0.57	0.82
N	365	365	365	365	365	365
Relative Humidity	-0.84	-0.98	1.00	-0.95	-0.52	-0.75
N	365	365	365	365	365	365
VPD	0.84	0.97	-0.95	1.00	0.67	0.76
N	365	365	365	365	365	365
Wind Speed	0.59	0.57	-0.52	0.67	1.00	0.57
N	365	365	365	365	365	365
Radiation	0.97	0.82	-0.75	0.76	0.57	1.00
N	365	365	365	365	365	365

4.3. Comparison of Different Methods

4.3.1. Temperature based models

i. Hargreaves equation:

(Hargreaves & Samani, 1985) expressed The Hargreaves equation as

$$ET_o = CH * 0.408 * R_a * (T_a + 17.8)\left(\sqrt{T_{max} - T_{min}}\right) \quad (4.2)$$

where T_a is the mean temperature of air [°C] for daily time-scale, T_{max} and T_{min} represent maximum and minimum temperature of air [°C] also for daily time-scale, and extraterrestrial radiation is R_a [MJ m^{-2} day^{-1}]. CH is the Hargreaves coefficient while 0.408 is the inverse of vaporization latent heat flux at 20 °C, converting the extraterrestrial radiation units form MJ m^{-2} day^{-1} to mm day^{-1}(R. G. P. Allen, L. S. Raes, D. Smith, M., 1998). The value of CH in Equation. (4.2) can be fixed to 0.0023, without calibration for locality, reimbursing for error in the basic Hargreaves equations (Hargreaves, 1994). But for the study area the locally calibrated value for the CH is taken as 0.0020. The Hargreaves method is accepted as a temperature-based method but according to (Xu & Singh, 2000) Hargreaves is a radiation-based equation. Although the main variables required for the aforementioned Hargreaves method Equation. (4.2) are given in (Table 4.5), no radiation data whatsoever is required as the extraterrestrial radiation can be computed latitude, time and date of day function (R. G. P. Allen, L. S. Raes, D. Smith, M., 1998).

In the Hargreaves equation, mean temperature of air is calculated as an average of maximum and minimum temperature of air while from the information of the time of the year and locaiton, R_a can be computed. Hence, the continuous measurement required of only parameter is the temperature of air.

ii. Hamon equation:

Hamon equation developed by Hamon in 1956 (D. Haith & L. Shoenaker, 1987).

$$\boldsymbol{PET = k \times 0.165 \times 216.7 \times N \times \left(\frac{e_s}{T_a + 273.3}\right)} \tag{4.3}$$

Where k is a proportionality coefficient having a value of 1^1 (unitless).N, theatrical sunshine hours while e_s is the saturated vapor pressure. Although, the potential evaporation calculated using Hamon is reliable, the evaporation rates in summer are overestimated while in winter they are underestimated.

iii. Thornthwaite equation:

Thornthwaite equation is based on temperature (C. W. Thornthwaite, 1948) with daylight hours adjustment being made.

$$\boldsymbol{PET_{non-corrected} = 16 \times \left(\frac{10 \times Ta}{I}\right)^{\alpha}} \tag{4.4}$$

$$\boldsymbol{\alpha = 675 \times 10^{-9} \times I^3 - 771 \times 10^{-7} \times I^2 + 1792 \times 10^{-5} \times I + 0.49239}$$

$$\boldsymbol{i = \left(\frac{t}{5}\right)^{1.514}}$$

$$\boldsymbol{I = \sum_{i=1}^{12} i}$$

T_a is the mean temperature. Attained values are further revised according to the month real length and the theoretical sunshine hours for the interested latitude, with the help of the following formula:

$$\boldsymbol{PET = PET_{non-corrected} \times \left(\frac{N}{12}\right) \times \left(\frac{d}{30}\right)} \tag{4.5}$$

N represent the theoretical hours of sunshine while **d** is the number of actual days in each month.

By different authors, many different equations were formularized and used in their studies, due to the wide-range inconsistencies in the collection procedures and standards of metrological data. There is Variation in the performance of the empirical equations from one location to another. In humid locations the evaporation rate estimated by Hargreaves and Blaney-Criddle, in the result of the comparative study done by Jensen (M. E. Jensen, Burman, & Allen, 1990), the result are fairly closed to the measured ET. In a more recent study conducted by Sing and Xu (Xu & Singh, 2001), the Hargreaves and Blaney-Criddle methods gave improved results with than others with the locally determined constant values, which are in accordance with results from Jensen's. Thus, one of these two methods were selected to be used in this study as a representation of the temperature-based methods. The use of Thornthwaite in the study is because that it is one of the oldest methods used for the estimation of Evaporation.

4.3.2. Radiation based models

i. Turc method

Under the wide-ranging climatic settings of western Europe, Turc calculated ET, it is in millimeters per day (Turc, 1961).

$$\boldsymbol{ET = 0.013 \times \frac{T}{T+15}(R_s + 50) \quad for \quad RH \geq 50} \tag{4.6}$$

$$\boldsymbol{ET = 0.013 \times \frac{T}{T+15}(R_s + 50)\left(1 + \frac{50-RH}{70}\right) \quad for \quad RH < 50} \tag{4.7}$$

where T denotes the average temperature of air in ºC, R_s is the total solar radiation in cal/cm^2/day, and RH represents the relative humidity in percent.

ii. Priestly and Taylor

A simplified and basic version of the combination equation was proposed by (Priestly & Taylor, 1972). They analyzed data composed from the widespread wet land surfaces and oceans.

$$\boldsymbol{ET = \frac{1}{\lambda} \times \frac{\Delta}{\Delta+\gamma} \times R_n \times \propto} \tag{4.8}$$

λ is the latent heat of vaporization ≈ 2.4644 (MJ Kg^{-1}), ET is the rate of evaporation in mm day^{-1}, Δ is the temperature-saturation vapor curve of water slope at temperature of air, R_n is the net radiation, γ is known as psychometric constant (kPa $^oC^{-1}$) and α is the coefficient known as Priestly-Taylor coefficient.

Average value for the coefficient $\alpha = 1.26$ was founded by Priestley and Taylor from their assessment on the data and there has been succeeding validation by other studies of this value (Finch & Hall, 2001). Flevo Lake in Netherland, having an area of 460 km^2 and average depth of 3 m considered as shallow and large lake, analysis by (de Bruin & Keijman, 1979) using the Priestly and Taylor equation on aforementioned lake, respectable results were obtained as the results by Priestly and Taylor equation were in respectable agreement with energy and water budget methods estimates for daily evaporation for the early autumn and summer season with the value of constant taken as 1.25.

iii. Jensen and Haise

(M. Jensen & Haise, 1963b) presented the following equation for the estimation of evaporation,

$$\boldsymbol{E = (0.025T_a + 0.08)\frac{R_s}{28.6}} \qquad (4.9)$$

T_a and R_s are same for the other equations. A problem identified with the Jensen and Haise equation is that generally in spring the estimation of evaporation is underestimated while in summers the evaporation rate is overestimated. The over and underestimations are because of the less weight given to radiation while the temperature is given more weight (Feddesl & Lenselink, 1994).

In a study conducted by (Xu & Singh, 2000), the evaluation of radiation based equations eight in number was performed. The study determined that with appropriately selected and locally calibrated values for the constants for the equations results in a more efficient results. From the aforementioned study the Priestly-Taylor and Turc equation was selected as the locally calibrated constant results in far better results.

4.3.3. Humidity based equation

i. Romanenko

Developed by Romanenko in 1961, is based on humidity (Romanenko, 1961). The equation bases were founded on the relative humidity and mean temperature relationship.

$$\boldsymbol{PET = 0.018(25 + T_a)^2(100 - RH)} \qquad (4.10)$$

where T_a and RH are same as that for other equations. The calculated potential evaporation is in mm month^{-1}.

4.3.4. Combination equation (Mass transfer and energy budget)

i. Penman-Monteith equation

Developed by Penman in 1948 (H. L. Penman, 1948) and later modified by Monteith in 1965 (J. Monteith, 1965). The modification by Monteith introduces better consistency in term of physical uniformity into the aerodynamic parameter of the Penman model by integrating the idea of resistance, specifically, in the aerodynamic resistance, $\mathbf{r_a}$, to formulate the Penman-Monteith model. The equation in the form for evaporation from water and daily rate of evaporation the equation is:

$$\boldsymbol{\lambda E} = \frac{\Delta(\boldsymbol{R_n} - \boldsymbol{N}) + \frac{\mathbf{86400}\boldsymbol{\rho_a c_p (e_s - e_a) d}}{\boldsymbol{r_a}}}{\Delta + \boldsymbol{\gamma d}} \qquad (4.11)$$

where c_p represents air specific heat = 0.001013 (MJ kg^{-1} ^{o}C^{-1}) and ρ_a denotes air density = 1 (kg m^{-3}). 86400 are the number of seconds in a day is a constant which is needed for the consistency of different terms unit in the equation.

Monteith introduced the variable, **d**, (J. L. Monteith, 1981), for the purpose of correction as the use of the temperature of air, rather than the temperature of surface while calculating outgoing component of long-wave net radiation.

$$\boldsymbol{d} = \frac{\mathbf{1} + \mathbf{4}\boldsymbol{\sigma}(\boldsymbol{T_a} + \mathbf{273.13})^{\mathbf{4}}\boldsymbol{r_a}}{\mathbf{86400}\boldsymbol{\rho_a c_p}} \qquad (4.12)$$

4.4. Daily and Monthly Values

As the evaporation rates calculated using equations given in (Table 4.4) having units in mm day^{-1}, except for Romanenko and Thornthwaite. The evaporation values from Penman-Monteith are then averaged for mm month^{-1}. A general relation between the evaporation rates estimated by methods having units in mm month^{-1} is given in (Figure 4.8). Thornthwaite and Romanenko equations calculates the estimation rates in mm month^{-1}, for a better assessment and their relation and difference with the standard equation of Penman-Monteith, the calculated value of evaporation rate using Penman-Monteith (PM) is converted[1] to mm month^{-1} as generally the rates of evaporation calculated using PM equation the values are in mm day^{-1}.

---

[1] A standard value of 30.437 is used to convert mm day^{-1} to mm month^{-1}

In (Table 4.7) the monthly estimated values for Thornthwaite and Romanenko are given with percent error with the estimation done using the Penman-Monteith equation. As Romanenko is based on humidity, in areas with large open water reservoirs such as lakes and basins the result from the Romanenko is more reliable with comparatively less error being recorded. (Figure 4.8) and (Table 4.7) shows the percentage of error recorded in the calculation of evaporation estimates using Thornthwaite and Romanenko.

Table 4.4. *Equations for calculation of evaporation or potential evaporation used in this study.*

Methods	Type	Equation	Unit
Hargreaves	T-based*	$ET_o = 0.0023(T_a + 17.8)(\sqrt{T_{max} - T_{min}})R_a$	mm day^{-1}
Hamon	T-based	$PET = k \times 0.165 \times 216.7 \times N \times \left(\frac{e_s}{T_a + 273.3}\right)$	mm day^{-1}
Thornthwaite	T-based	$PET_{non-corrected} = 16 \times \left(\frac{10 \times Ta}{I}\right)^{\alpha}$	mm month^{-1}
Turc	R-based*	$ET = 0.013 * \frac{T}{T + 15}(R_s + 50) \quad for \quad RH \geq 50$	mm day^{-1}
Priestly- Taylor	R-based	$ET = \frac{1}{\lambda} * \frac{\Delta}{\Delta + \gamma} * R_n * \propto$	mm day^{-1}
Jensen-Haise	R-based	$E = (0.025T_a + 0.08)\frac{R_s}{28.6}$	mm day^{-1}
Romanenko	H-based*	$PET = 0.018(25 + T_a)^2(100 - RH)$	mm month^{-1}
Penman-Monteith	Combination*	$E = \frac{\Delta(R_n - N) + \frac{86400\rho_a c_p(e_s - e_a)d}{r_a}}{\Delta + \gamma d}$	mm day^{-1}

*T-based means temperature-based methods, *R-based means radiation-based methods, *H-based means humidity-based model, *Combination equations: Equations based on Energy budget and mass Transfer Equations

The error in using Thornthwaite gets to a certain extreme in winter as the evaporation is highly underestimated in those months but in summer, a more reliable result is obtained while error in Romanenko estimation method is comparatively low than Thornthwaite. Starting from Autumn the error in Romanenko equation starts to drop and reaches its lower point in the severe winter. The reason of the drop is the surge in the humidity in the region in winter and autumn seasons.

Thornthwaite is solely based on temperature with a correction being applied for theoretical sunshine hours for the latitude of interest and real length of the month. The high percentage of error is due to the only use of temperature in an area where the effect of other parameters on evaporation is not negligible.

Table 4.5. *Requirements of the equations used in this study*

Method	Temperature	Relative Humidity	Wind Speed	Vapor Pressure	Daylight Hours	Radiation
Temperature Based						
Hargreaves	R[2]	-	-	-	-	-
Hamon	R	-	-	-	R	-
Thornthwaite	R	-	-	-	R	-
Radiation-Based						
Turc	R	-	-	-	-	R
Priestly and Taylor	R	-	-	-	-	R
Jensen and Haise	R	-	-	-	-	R
Humidity-Based						
Romanenko	R	R	-	-	-	-
Energy Budget and Mass Transfer Equation						
Penman-Monteith[3]	R	R	R	R	-	R

Table 4.6. *Generalized form of evaporation equations*

Generalized equation form[a]	Original Equation	Original Constants
$ET = a(T + b)\frac{Rs}{\lambda}$	(Hargreaves & Samani, 1985)	a = 0.0023, b = 17.8
$ET = a\left(\frac{e_s}{T_a + 273.13}\right)N \times k \times 216.7 + b$	(D. A. Haith & L. L. Shoenaker, 1987)	a = 0.165, b = 0
$ET = a\left(\frac{10 \times T_a}{I}\right)^{\alpha}$	(C. W. Thornthwaite, 1948)	a = 16
$ET = a(T + b)\frac{Rs}{\lambda}$	(M. Jensen & Haise, 1963b)	a = 0, b = 0.08
$ET = a \times \frac{R_n}{\lambda} \times \frac{\Delta}{\Delta + \gamma}$	(Priestly & Taylor, 1972)	a = 1.26
$PET = a(25 + T_a)^2(100 - RH)$	(Romanenko, 1961)	a = 0.018

---

[2] Requirement of the meteorological parameter

[3] Developed in 1948 by Penman, modified by Monteith in 1965

$ET = a \times \frac{T}{T+15}(R_s+50)+b \quad for \quad RH \geq 50$ $ET = a \times \frac{T}{T+15}(R_s+50)\left(1+\frac{50-RH}{70}\right)+b \quad for \quad RH < 50$	(Turc, 1961)	a = 0.013, b = 0

[a] a and b are variables to be estimated.

Table 4.7. *Monthly estimated evaporation rates and relative error for selected methods*

Season	Month	E_{PM}	E_{THW}	(%) Error	E_{RK}	(%) Error
Winter	January	45.83	9.53	-79.20	49.54	8.10
	February	66.88	11.45	-82.88	41.38	-38.12
Spring	March	107.37	35.09	-67.31	57.43	-46.51
	April	133.61	96.13	-28.05	85.83	-35.76
	May	159.64	104.71	-34.41	122.77	-23.09
Summer	June	165.03	173.50	5.13	158.50	-3.96
	July	176.58	183.76	4.07	171.80	-2.71
	August	164.08	182.87	11.45	173.48	5.73
Autumn	September	131.31	123.85	-5.68	167.63	27.66
	October	104.47	70.88	-32.16	142.63	36.52
	November	73.09	73.16	0.08	99.70	36.40
Winter	December	55.63	20.68	-62.83	70.41	26.58

E_{PM} = Penmen-Monteith (mm month^{-1}), E_{RK} = Romanenko (mm month^{-1}), E_{THW} = Thornthwaite (mm month^{-1})

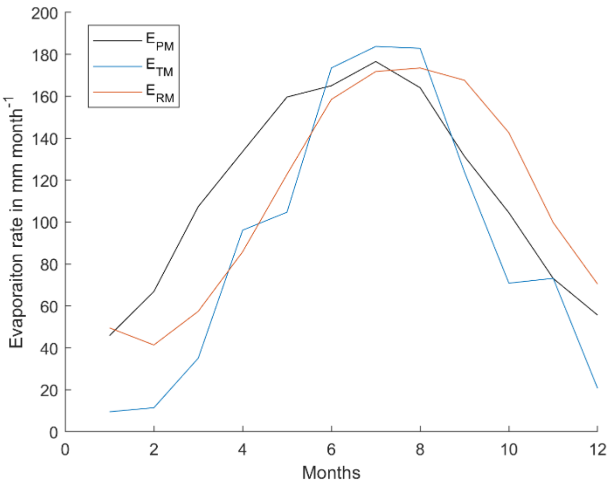


Figure 4.8. *Variation in evaporation estimates for ETM = Thornthwaite and ERM = Romanenko against EPM = Penman-Monteith*

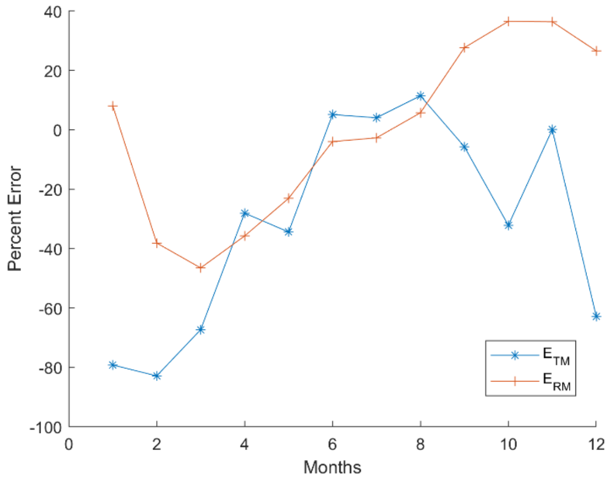


Figure 4.9. *Variation of percentage error in evaporation estimates for ETM=Thornthwaite and ERM=Romanenko*

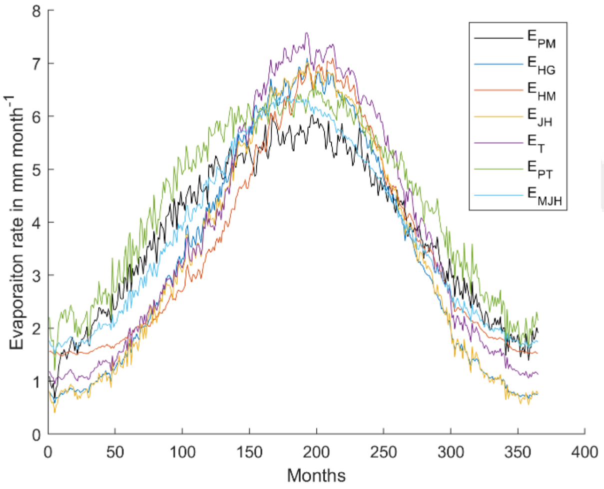


Figure 4.10. *Variation of evaporation rates for daily time-scale estimated using different equations (EPM=Penmen-Monteith, EHG=Hargreaves, EHM=Hamon, EJH=Jensen-Haise, EPT=Priestly-Taylor, ET=Turc and EMJH=Modified Jensen-Haise)*

For instance, in (Figure 4.10) the graph line of Hamon estimations is comparatively lower and closer to the standard Penmen-Monteith except for the summer season while E_{JH} and E_{T} have comparatively a sharp rise at the mid-spring which reaches the highest point in summer when temperatures are at the highest points. The radiation-based methods such as E_{PT}, E_{JH} and E_{T} (E_{JH} = Jensen and Haise, E_{PT} = Priestly and Taylor and E_{T} = Turc) all together have overestimated the evaporation in summers to a much greater extent as compared to the temperature-based methods such as E_{HG} and E_{HM} (E_{HG} = Hargreaves, E_{HM} = Hamon) but except for E_{PT} all of the defined methods have underestimated the evaporation in winter and spring seasons. The relative error of each method is given in (Figure 4.11) and (Table 4.8) The error in Priestly and Taylor is positive, which means that the E_{PT} is overestimated for the specific conditions of the region. In winter the E_{PT} is much overestimated with a relatively closer result in summer.

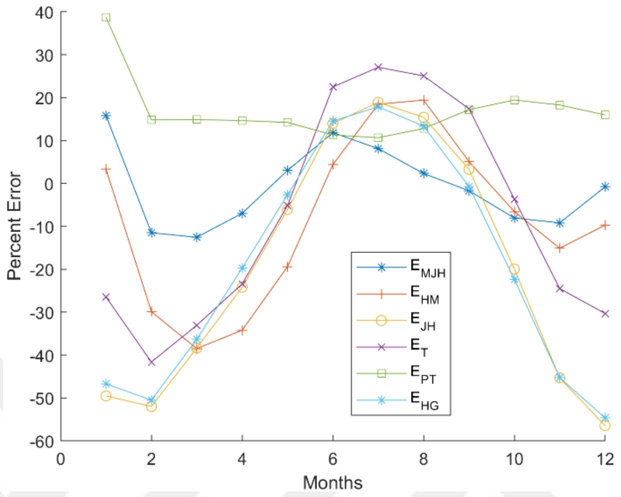


Figure 4.11. *Variation of percentage error in evaporation estimates using Hargreaves, Hamon, Jensen-Haise, Priestly-Taylor, Turc and Modified Jensen-Haise methods*

4.5. Correlation Between Evaporation Methods

The computed values as mentioned before were averaged to mean daily evaporation rate for a month. The computed values for fourteen years (2000-2013) from the different methods given in (Table 4.7) and (Table 4.8) were analyzed with E_{PM} equation estimated values using a linear regression equation.

$$Y = mX + c \tag{4.13}$$

Where E_{PM} is represented by Y and X is the evaporation rates calculated using equations based on Temperature (Hargreaves, Hamon, and Thornthwaite), Humidity (Romanenko) and Radiation (Turc, Priestly and Taylor and Jensen and Haise). While slope and intercept are represented by, m and c, respectively. The results of regression together between E_{PM} and the evaporation calculated and estimated from other methods are presented in (Figure 4.14) and (Figure 4.15).

It is seen from the (Figure 4.14) and (Figure 4.15) that the selected model resulted in significant error. In these regression equations either the slopes values are expressively different from 1 (Turc, Hargreaves) or the values of intercepts are considerably different from 0 (Romanenko, Jensen-Haise) or in some cases both (Thornthwaite, Hamon). This study shows that radiation-based Priestly-Taylor method best fits the measured data when the constant for the equations are locally calibrated. Underestimation and overestimation of the evaporation was found when the original constants were used. For example, when the original constant value for the Thornthwaite equation was used the evaporation was greatly underestimated while when the original constant for the Priestly-Taylor was used, the evaporation was greatly overestimated for the whole year.

Table 4.8. *Daily estimated evaporation rates and relative error for selected methods*

Season	Month	E_{PM}	E_{HG}	(%) Error	E_{HM}	(%) Error	E_{JH}	(%) Error	E_{PT}	(%) Error	E_{T}	(%) Error
Winter	January	1.48	0.79	-46.71	1.53	3.31	0.68	-54.11	2.05	38.70	0.68	-26.47
	February	2.39	1.18	-50.48	1.68	-29.87	1.06	-55.70	2.74	14.85	1.06	-41.63
Spring	March	3.46	2.21	-36.31	2.13	-38.49	2.04	-41.17	3.98	14.89	2.04	-33.04
	April	4.45	3.58	-19.71	2.93	-34.20	3.32	-25.55	5.11	14.64	3.32	-23.43
	May	5.15	5.01	-2.65	4.15	-19.40	4.85	-5.84	5.88	14.22	4.85	-5.16
Summer	June	5.50	6.30	14.55	5.74	4.39	6.38	15.94	6.12	11.30	6.38	22.48
	July	5.70	6.71	17.85	6.75	18.46	6.94	21.78	6.30	10.66	6.94	27.06
	August	5.29	6.00	13.34	6.32	19.41	6.26	18.19	5.97	12.80	6.26	25.07
Autumn	September	4.38	4.34	-0.73	4.60	5.11	4.59	4.81	5.13	17.20	4.59	17.40
	October	3.37	2.62	-22.34	3.15	-6.55	2.70	-20.02	4.03	19.44	2.70	-3.67
	November	2.44	1.33	-45.26	2.07	-15.08	1.29	-47.09	2.88	18.29	1.29	-24.50
Winter	December	1.79	0.81	-54.64	1.62	-9.74	0.73	-59.50	2.08	15.96	0.73	-30.31

E_{PM} = Penmen-Monteith (mm day^{-1}), E_{HG} = Hargreaves (mm day^{-1}), E_{HM} = Hamon(mm day^{-1}), E_{JH} = Jensen and Haise(mm day^{-1}), E_{PT} = Priestly and Taylor (mm day^{-1}), E_{T} = Turc (mm day^{-1}).

Furthermore, for intercept, **c**, higher values are detected between the E_{PM} and temperature-based methods relation. The intercept values for the radiation-based methods are also higher except for Priestly and Taylor. But humidity-based equation i.e. Romanenko has performed considerably well in reference to its counterpart I.e. Thornthwaite.

The values of the original constant of the empirical formulae were not used in this research, but necessary changes were made to the equations in order to get satisfactory results. Change were made to the models for the robustness testing purpose of the for the specific climatic conditions. Due to the inconsistency of the original constant, the model's outcomes are questionable. The use of original constant values of the empirical formulae which are applicable to certain climatic conditions or for which they were specially developed such as for Priestly and Taylor equation the value of α = 1.25 was used by de Bruin for the evaporation from a lake in Netherland with shallow depth properties (de Bruin & Keijman, 1979), results in questionable outcomes if used everywhere else. The models will fail to calculate the evaporation to a certain accuracy, either the evaporation rates are overestimated or underestimated to a very high error.

Table 4.9. *Locally Calibrated constant values for the equations*

Generalized equation form[a]	Original Equation	Original Constants	Locally Calibrated Constants
$ET = a(T+b)\frac{Rs}{\lambda}$	(Hargreaves & Samani, 1985)	a = 0.0023, b = 17.8	a = 0.0020, b = 18.4
$ET = a\left(\frac{e_s}{T_a + 273.13}\right)N * k * 216.7 + b$	(D. A. Haith & L. L. Shoenaker, 1987)	a = 0.165, b = 0	a = 0.145, b = 0.8
$ET = a(T+b)\frac{Rs}{28.6}$	(M. Jensen & Haise, 1963b)	a = 0.025, b = 0.08	a = 0.013, b = 0.16
$ET = a * \frac{R_n}{\lambda} * \frac{\Delta}{\Delta + \gamma}$	(Priestly & Taylor, 1972)	a = 1.26	a = 1.26
$PET = a(25 + T_a)^2(100 - RH)$	(Romanenko, 1961)	a = 0.018	a = 0.0023
$ET = a * \frac{T}{T+15}(R_s + 50) + b \quad for \;\; RH \geq 50$ $ET = a * \frac{T}{T+15}(R_s + 50)\left(1 + \frac{50 - RH}{70}\right) + b \quad for \;\; RH < 50$	(Turc, 1961)	a = 0.013, b = 0	a = 0.009, b = 0.7
$ET = a\left(\frac{10 \times T_a}{I}\right)^{\alpha}$	(C. W. Thornthwaite, 1948)	a = 16	a[4] = 58.5 (Jan-Feb) 38 (March-April) 18.5 (May-June) 14.8 (July-Oct) 42 (Nov-Dec)

A systematic underestimation can be found in the winter season for temperature-based equations (Figure 4.11) while except for E_{PT} the radiation-based models also

---

[4] The single constant in Thornthwaite equation was replaced by five seasonal or monthly constants.

underestimated in winter. While the same equations with the modified constant of the empirical formulae have overestimated in the summer season. For Hamon equation, a seasonal lag can be noted for the particular conditions.

4.6. Modification of Jensen-Haise Equation

Jensen -Haise equation was modified with the addition of daylight hour term and maximum temperature. The modification resulted in reducing the extra weight of the temperature term. Jensen-Haise equation as stated earlier underestimates in winter and over estimates in summer. The daylight term reduces the over and underestimation of the evaporation in both seasons as in the equation the evaporation rate is dependent on the daylight hours with the max temperature recorded in a day. The modified equation is:

$$\boldsymbol{E = 0.14 \times \left(\frac{N}{T_{max}} \times T_a + 0.12\right)\frac{R_s}{24\times Lambda} + 1.16} \tag{4.14}$$

N denotes the hours of theoretical sunshine while T_{max} represents the maximum daily temperature. The modified equation constants were calibrated for the region. Although, to generalize the equation to other region further study is required.

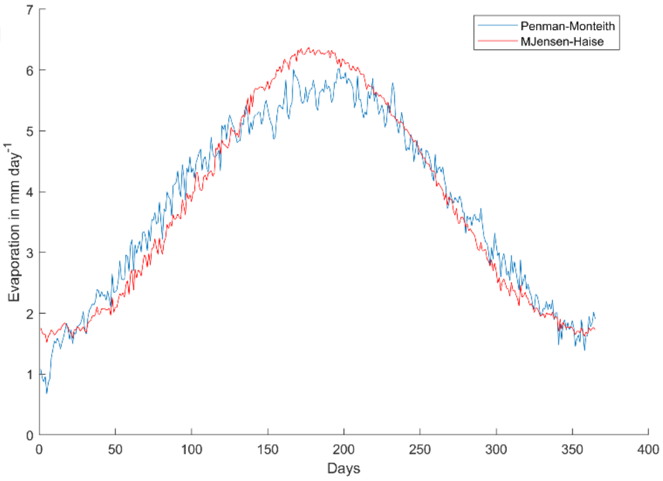


Figure 4.12. *Variation of evaporation rates for daily time step estimated using Modified Jensen-Haise equation*

The estimated values of evaporation and percent for the Modified Jensen-Haise equation is given in (Table 4.10).

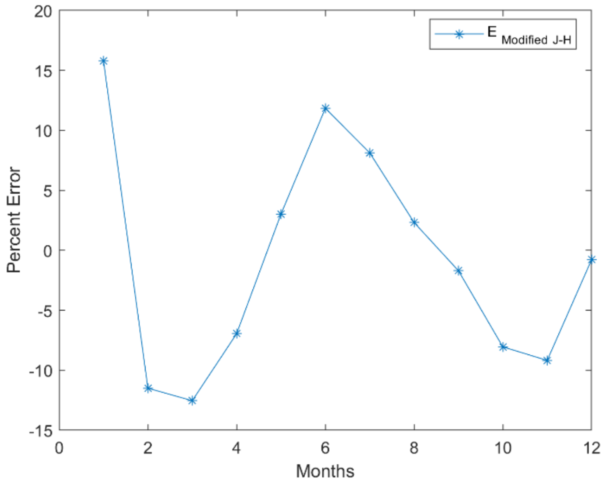


Figure 4.13. *Percentage error in estimates of evaporation using Modified Jensen and Haise equation*

Table 4.10. *Daily estimated evaporation rates and relative error for Modified Jensen-Haise methods*

Season	Month	E_{PM}	E_{MJH}	(%) Error
Winter	January	1.48	1.71	15.80
	February	2.39	2.11	-11.50
Spring	March	3.46	3.03	-12.54
	April	4.45	4.14	-6.96
	May	5.15	5.31	3.02
Summer	June	5.50	6.15	11.84
	July	5.70	6.16	8.12
	August	5.29	5.42	2.32
Autumn	September	4.38	4.30	-1.71
	October	3.37	3.10	-8.05
	November	2.44	2.21	-9.18
Winter	December	1.79	1.78	-0.79

The analysis for the Modified Jensen-Haise equation in graphical form is given in (Figure 4.12) and (Figure 4.13). In (Figure 4.12) the variation in daily evaporation and the difference between the standard Penman-Monteith equation is shown while (Figure 4.13) shows the percent error.

The Nash Sutcliff efficiency and coefficient of determination (r^2) are given in (Table 4.11).

Table 4.11. *Co-relation and NSE values for the model*

Based on	Model	r^2	Slope	Intercept	n	NSE
Radiation	Jensen and Haise	0.92	0.65	1.59	365	0.57
	Turc	0.88	0.62	1.45	365	0.55
	Priestly-Taylor	0.98	0.93	-0.26	365	0.83
Temperature	Hargreaves	0.93	0.66	1.54	365	0.61
	Hamon	0.81	0.71	1.25	365	0.55
	Thornthwaite	0.75	0.54	72.73	12	0.29
Humidity	Romanenko	0.64	0.94	32.86	12	0.55
Special Equation	Modified Jensen-Haise	0.95	1.08	-0.32	365	0.93

4.7. Results Discussion

In the first part of the study, the dependency of the parameters on the evaporation was analyzed. An image of the estimation rate driving parameters effect on the evaporation was created. As from the analysis, the effect of the individual factors was analyzed.

For wind, no clear relationship could be established with evaporation rate but as mentioned by (Linsley & Kohler, 1982) the effect of wind is limited to a small time-scale let's say shorter than a day. And as for humidity, the evaporation rate has shown an inverse relation for both time-scales. In summer when the air is less humid the evaporation rate increases but in winter when the humidity of the area is high a decrease in the evaporation is recorded.

For the monthly time-scales, a complete agreement with the evaporation of vapor pressure deficit is observed in its effect. The vapor pressure deficit has an extensive effect on evaporation and that too in complete harmony. For radiation on the longer time-scale i.e. monthly, the effect has a lag of almost a month.

The evaporation rates lead the radiation by almost one month. It can be established that as the water body has a large volume the radiation energy directly doesn't affect the evaporation rate but after a period of time when the energy is gained by the body the evaporation rate starts to increase. The effect of temperature in the longer-time scale is little different than that of vapor pressure deficit. As for temperature effect, when the temperature is lower in winter, yet notable evaporation was recorded due to the heat storage strength of the water body.

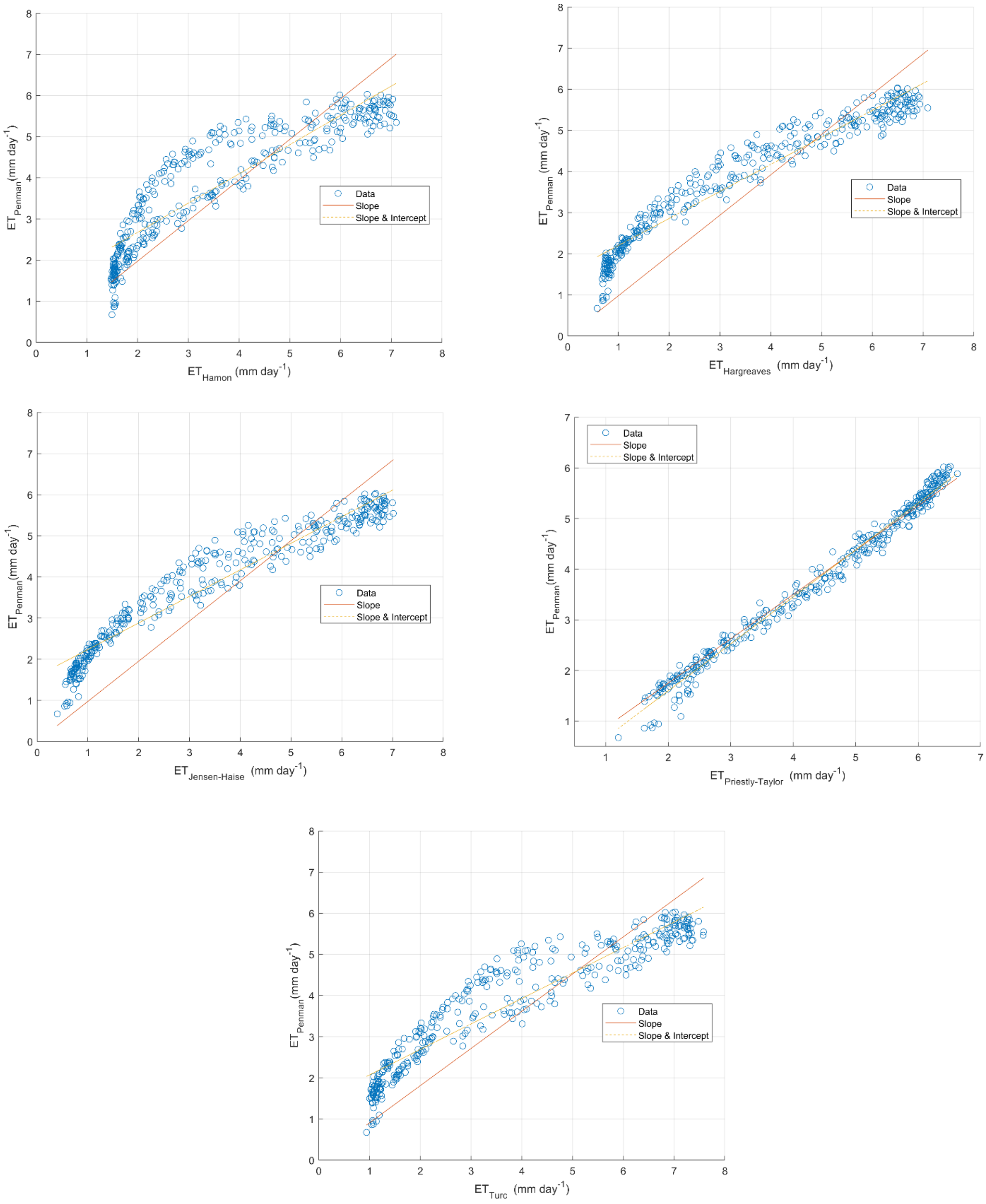


Figure 4.14. *Comparison of EPM with estimated ET for the Priestly and Taylor equation, Jensen and Haise equation, Hargreaves equation, Hamon equation, and Turc equation.*

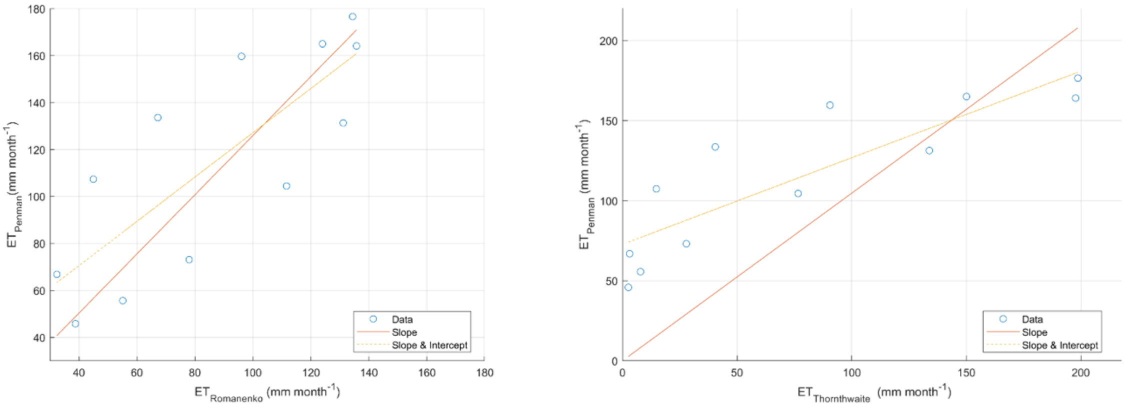


Figure 4.15. *Comparison of EPM with estimated ET for the Romanenko equation and Thornthwaite equation.*

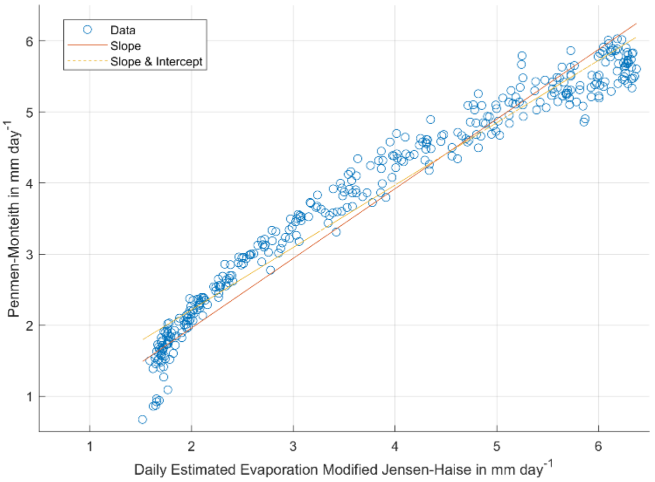


Figure 4.16. *Comparison of EPM with estimated ET for the Modified Jensen-Haise equation.*

In the 2nd part of the study, a comparative analysis was done. Daily[5] evaporation from Penmen-Monteith method and seven other empirical methods i.e., Jensen-Haise, Turc, Priestly-Taylor, Romanenko, Thornthwaite, Hamon and Hargreaves was estimated. Modification was done to the empirical constants of the equations for the local calibration. Monthly evaporation values computed from Romanenko and Thornthwaite, were compared with Penman-Monteith values (Figure 4.8) while the percent error form of these equations is given in (Figure 4.9). A visual analysis of these graphs shows that the percent error is high for both these methods. For Romanenko a seasonal variation in the error can be observed. In winter the estimation of evaporation tries to remain parallel to that of E_{PM} but in summer the evaporation starts to be underestimated but for

---

[5] And Monthly evaporation rates for Romanenko and Thornthwaite Models

Thornthwaite the underestimation error in winter is quite large. For both equations, the original constant values were not used, for Romanenko constant value of 0.0023 while Thornthwaite equation was calibrated using five seasonal or monthly constants I.e. 58.5 (Jan-Feb), 38 (March-April), 18.5 (May-June), 14.8 (July-Oct), 42 (Nov-Dec).

The rest of the methods which are calculated in mm day^{-1} are given in (Figure 4.11) while the percent error of these methods is given in (Figure 4.11). A visual analysis of the graph shows that most of the methods have overestimated in summer and underestimated in winter. Priestly-Taylor's overestimation is the highest among all models in winter while Turc followed by Jensen-Haise, have overestimated the evaporation in summer for a significant period of time. Although, in mean overestimation, Priestly-Taylor have the highest value as for the selected time period a constant overestimation is observed. The temperature-based models except for Thornthwaite have comparatively performed well with satisfactory result.

The Turc, Hargreaves and Jensen-Haise have performed almost the same in the winter with disagreement starting in the summer season. Among all the temperature-based models Hargreaves has comparatively performed well in the current conditions while Thornthwaite been the worst with an unacceptable Nash Sutcliff efficiency of 0.29. The empirical constant used for these equations were changed and the original values for these equations were not used i.e. for Hargreaves coefficient value of ***0.0020*** and ***18.4***. In original form of the Hamon equation only one constant is used I.e. ***0.165***, in order to overcome the high intercept value in the regression equation and balance the underestimation in winter a second constant was deemed necessary, calibration led to the value of ***a = 0.145, b = 0.8*** for the second constant. For Jensen & Haise ***0.013*** and ***0.16***, for Turc ***0.009*** while another constant was added with calibration a value of ***b = 0.7*** was achieved, and for Priestly-Taylor coefficient I.e. ***a = 0.82*** was used. The use of the original empirical constants did result in higher errors as most of the constants were designed for areas with different climatic attitude than study area in this work.

Whereas the determination coefficient is concerned, Priestly-Taylor and Hargreaves have the highest value with $r^2 = 0.98$ and 0.93 respectively. While the lowest value of the determination coefficient is observed for Romanenko I.e. 0.64. To check the seasonality of the estimation errors for the equations, mean monthly averaged values for the 14 years are taken into consideration as shown in (Figure 4.17).

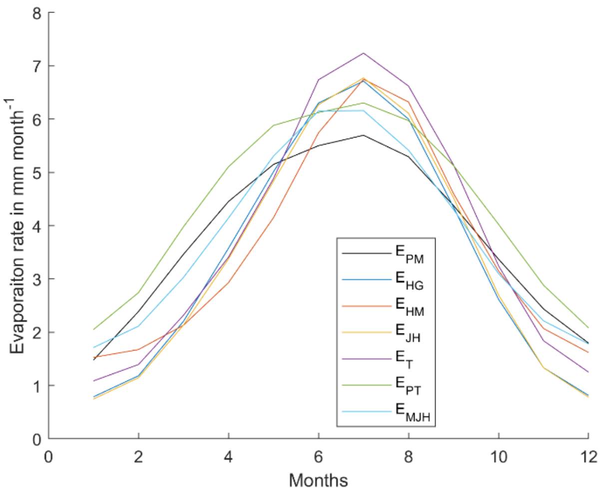


Figure 4.17. *Variation of evaporation rates for monthly time step estimated using different equations(EPM=Penmen-Monteith, EHG=Hargreaves, EHM=Hamon, EJH=Jensen-Haise, EPT=Priestly-Taylor and ET=Turc, EMJH=Modified Jensen-Haise)*

In winter season the Priestly and Taylor has overestimated the evaporation while all the other models have underestimated. While the overestimation of Priestly and Taylor model is continued for the whole year, other models' underestimation doesn't have the same trend. Except for Priestly and Taylor, all other models tends to only overestimate the estimation for summer while followed by drop-in autumn while reaching to its lowest point in winter again.

4.8. Conclusion

As recommended by FAO, The Penman-Monteith method was taken as a standard (R. G. P. Allen, L. S. Raes, D. Smith, M., 1998) in evaluating the methods. Five major metrological parameters that lead the control over evaporation i.e. air temperature, wind speed, radiation, relative humidity, and vapor pressure deficit, were compared at different time scales (daily and monthly) against evaporation calculated from Penman-Monteith equation. It is concluded that the role of these parameters changes with the scale of time. Humidity is inversely related to evaporation at all time-scales while temperature and vapor pressure deficit has a good correlation in all time-scales. A lag between radiation and evaporation was noticed in the monthly time-scale. The co-relation of speed of wind with evaporation in comparison with other factors, is the least.

The results in this study are only for the locally calibrated constants as the results from the original constants were quite unsatisfactory for posting. The result of the comparison of different methods against Penman-Monteith shows that if the models are properly calibrated locally the estimates are satisfactory. For different seasons the models have either overestimated or underestimated the evaporation. The seasonal variability in the models is a result of the non-consideration of some seasonal factors. Another reason which defines the lack of relation between the methods is the heat storage capacity and equilibrium temperature. The heat storage capacity of the water body was not taken into consideration by any of the models. The models failed to yield quality estimates if no calibration was done for climatological parameters and usage of air temperature instead of water body temperature.

The temperature-based models i.e. Hargreaves and Hamon yield a more satisfactory result when compared to the estimates given by radiation-based methods except for the Priestly-Taylor. The only humidity-based method used in this study i.e. Romanenko yields a satisfactory result too for the same climate conditions. Romanenko shows a greater correlation with Penman-Monteith estimates and a conclusion was made that, as Romanenko model is based on humidity, in areas with large open water bodies such as lakes and basins the result from the Romanenko is more reliable with comparatively less error being recorded due to high humidity but when in summer the humidity level drops, the level of error starts to increase.

The modification to the Jensen-Haise method resulted in an improve estimation of the evaporation. The addition of the daylight term with the max temperature actually reduces the extra weightage given to the temperature term. As most of the evaporation is done during the day time and the big amount of radiation and temperature is also received during this period so, the inclusion of the daylight term resulted in an extensive efficiency of the method. Although, this method is only developed for this particular study region but for generalization of the constants more work and research are required over a course of further reservoirs.

More work is required to calibrate empirical constants for different climate conditions as the use of original constant will not yield a satisfactory result such as the use of Priestly and Taylor coefficient resulted in overestimation of evaporation throughout the selected time period, while if calibrated, the result would have been different as shown in previous studies (Xu & Singh, 2002).

As for this study when the model’s constants were locally calibrated, satisfactory results were achieved. The most improvement was shown by Priestly-Taylor equation. Although, the equation still overestimates but the percentage of error reduces significantly.

REFERENCES

Allen, R. G., Pereira, L. S., Raes, D., Smith, M., & J Fao. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *300*(9), D05109.

Allen, R. G., Smith, M., Pereira, L. S., & Perrier, A. (1994). An Update for the Calculation of Reference Evaporation. *ICID Bull*, 35-92(b).

Allen, R. G., Smith, M., Perrier, A., & Pereira, L. S. (1994). An Update for the Definition of Reference Evaporation. *ICID Bull*, 1-33(a).

Allen, R. G. P., L. S. Raes, D. Smith, M. (1998). Crop evapotranspiration - Guidelines for computing crop water requirements. *FAO Irrigation and Drainage*, Paper 56.

Anderson, E. R. (1954). Energy-budget studies. *Waterloss investigations: Lake Hefner studies. Tech. Rep. US Geol. Surv. Prof. Pap, 269*, 71-119.

Assouline, S. (1993). Estimation of lake hydrologic budget terms using the simultaneous solution of water, heat, and salt balances and a Kalman filtering approach: Application to Lake Kinneret. *Water Resources Research, 29*(9), 3041-3048.

Brutsaert, W. (1982). Evaporation into the Atmosphere: theory, History and Applications. Holland. D. In: Reidel Publishing Co., Dordrecht, 299pp.

Brutsaert, W., & Yu, S. L. (1968). Mass transfer aspects of pan evaporation. *Journal of Applied Meteorology, 7*(4), 563-566.

Condie, S. A., & Webster, I. T. (1997). The influence of wind stress, temperature, and humidity gradients on evaporation from reservoirs. *Water Resources Research, 33*(12), 2813-2822.

Crowe, P. J. (1974). The Farmoor source works in operation. . *J.Instn Wat.Env.Man, 28* 101-124.

De Bruin, H. (1978). A simple model for shallow lake evaporation. *Journal of Applied Meteorology, 17*(8), 1132-1134.

De Bruin, H. (1982). Temperature and energy balance of a water reservoir determined from standard weather data of a land station. *Journal of Hydrology, 59*(3-4), 261-274.

de Bruin, H. A. R., & Keijman, J. Q. (1979). The Priestley-Taylor evaporation model applied to a Large, Shallow Lake in the Netherlands. *Journal of Applied Meteorology*, 898-903.

Dile, Y. T., & Srinivasan, R. (2014). Evaluation of CFSR climate data for hydrologic prediction in data-scarce watersheds: an application in the Blue Nile River Basin. *JAWRA Journal of the American Water Resources Association, 50*(5), 1226-1241.

Doorenbos, J., & Pruitt, W. O. (1984). Guidelines for predicting crop water requirements. *Food and Agriculture organization., 24*.

Dos Reis, R. J., & Dias, N. L. s. (1998). Multi-season lake evaporation: energy-budget estimates and CRLE model assessment with limited meteorological observations. *Journal of Hydrology, 208*(3-4), 135-147.

Edinger, J. E., Duttweiler, D. W., & Geyer, J. C. (1968). The Response of Water Temperatures to Meteorological Conditions. *Water Resources Research, 4*(5), 1137-1143. doi:10.1029/WR004i005p01137

Eisenlohr Jr, W. S. (1966). Determining the Water Balance of a Lake Containing Vegetation.

Feddesl, R. A., & Lenselink, K. J. (1994). Evapotranspiration. In H. P. Ritzema (Ed.), *Drainage Principles and Applications* (Second Edition ed., pp. 145-172). Netherland: ILRI Publication.

Finch, J. W., & Hall, R. L. (2001). *Estimation of Open Water*. Retrieved from Bristol:

Fraedrich, K., Behlau, A., Kerath, G., & Weber, G. (1977). A simple model for estimating the evaporation from a shallow water reservoir. *Tellus, 29*(5), 428-434.

Fuka, D. R., Walter, M. T., MacAlister, C., Degaetano, A. T., Steenhuis, T. S., & Easton, Z. M. (2014). Using the Climate Forecast System Reanalysis as weather input data for watershed models. *HYDROLOGICAL PROCESSES, 28*(22), 5613-5623.

Gangopadhaya, M., Harbeck, G. E., Nordenson, T. J., Omar, M. H., & Uryvaev, V. A. (1966). *Measurement and estimation of evaporation and evapotranspiration: .* Retrieved from

Global Weather Data for SWAT. (2019). *Texas A&M University*. Retrieved from https://globalweather.tamu.edu/

Haith, D., & Shoenaker, L. (1987). Generalized watershed loading functions for stream flow nutrients. *Water Resources Bulletin, 23*(3), 471-478.

Haith, D. A., & Shoenaker, L. L. (1987). Generalized Watershed Loading Functions for Stream Flow Nutrients 1. *JAWRA Journal of the American Water Resources Association, 23*(3), 471-478.

Harbeck, G., Kohler, M., & Koberg, G. (1954). Water loss investigations: Lake Hefner studies. *"Technical Report."*.

Harbeck, G. E. (1962). *A practical field technique for measuring reservoir evaporation utilizing mass-transfer theory* (Vol. 272): US Government Printing Office.

Hargreaves, G. H. (1994). Defending and using reference evapotranspiration. *Journal of Irrigation and Drainage engineering*, 1132-1139.

Hargreaves, G. H., & Samani, Z. A. (1985). Estimating potential evapotranspiration. *Journal of Irrigation Drainage Engineering*, 225-230.

Henderson-Sellers, B. (1986). Calculating the surface energy balance for lake and reservoir modeling: A review. *Reviews of Geophysics, 24*(3), 625-649.

Hicks, B., & Hess, G. (1977). On the Bowen ratio and surface temperature at sea. *Journal of physical oceanography, 7*(1), 141-145.

Hounam, C. E. (1973). *Comparison between pan and lake evaporation*. Geneva: World Meteorological Organization.

Hoy, R., & Stephens, S. (1977). Field study of evaporation, Research Project 6815. *ACT, Department of Natural Resources, Australian Water Resources Council*.

Jensen, M., & Haise, H. (1963a). Estimating evapotranspiration from solar radiation. *Journal of the Irrigation and Drainage Division*, 15-41.

Jensen, M., & Haise, H. (1963b). Estimating evapotranspiration from solar radiation. *Journal of the Irrigation and Drainage Division*, 15-41.

Jensen, M. E., Burman, R. D., & Allen, R. G. (1990). *Evapotranspiration and irrigation water requirements*.

Keijman, J. (1974). The estimation of the energy balance of a lake from simple weather data. *Boundary-Layer Meteorology, 7*(3), 399-407.

Lapworth, C. (1965). Evaporation from a reservoir near London. *Journal of the Institution of Water and Environmental Management, 19*, 163-181.

Linacre, E. T. (1993). Data-sparse estimation of lake evaporation, using a simplified Penman equation. *Agricultural and Forest Meteorology, 64*(3-4), 237-256.

Linsley, R. K. J., & Kohler, M. A., Paulhus, J. L. H. (1982). *Hydrology for engineers*. Newyork: McGraw-Hill.

Maidment, D. R. (1993). *Handbook of hydrology* (Vol. 9780070): McGraw-Hill New York.

Makkink, G. (1957). Ekzameno de la formulo de Penman. *Netherland J. Agric. Sci., 5*, 290-305.

Monteith, J. (1965). Evaporation and enviro Biology, vol. 19. In: University Press, Cambridge.

Monteith, J. L. (1981). Evaporation and surface temperature. *Quarterly Journal of the Royal Meteorological Society*, 1-27.

Penman, H. (1963). Vegetation and Hydrology, Commonwealth Agric. *Bureau. Farnham Royal*.

Penman, H. L. (1948). Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society of London. Series A. Mathematical Physical Sciences, 193*(1032), 120-145.

Priestley, C. H. B., & Taylor, R. J. M. w. r. (1972). On the assessment of surface heat flux and evaporation using large-scale parameters. *100*(2), 81-92.

Priestly, C. H. B., & Taylor, R. J. (1972). On the Assessment of Surface Heat Flux and Evaporation Using Large-Scale Parameters. *Monthly Weather Review*, 81-92.

Romanenko, V. A. (1961). Computation of the Autumn Soil Moisture Using a Universal Relationship for a Large Area. *Ukrainian Hydrometeorological Research Institute, Kiev*.

Sacks, L., Lee, T., & Radell, M. (1994). Comparison of energy-budget evaporation losses from two morphometrically different Florida seepage lakes. *Journal of Hydrology, 156*(1-4), 311-334.

Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., . . . Becker, E. (2014). The NCEP Climate Forecast System Version 2. *27*(6), 2185-2208. doi:10.1175/jcli-d-12-00823.1

Sene, K., Gash, J., & McNeil, D. (1991). Evaporation from a tropical lake: comparison of theory with direct measurements. *Journal of Hydrology, 127*(1-4), 193-217.

Shaw, E. (2014). *Hydrology in Practice*: CRC Press.

Simon, E., & Mero, F. (1985). A simplified procedure for the evaluation of the Lake Kinneret evaporation. *Journal of Hydrology, 78*(3-4), 291-304.

Stannard, D. I., & Rosenberry, D. O. (1991). A comparison of short-term measurements of lake evaporation using eddy correlation and energy budget methods. *Journal of Hydrology, 122*(1-4), 15-22.

Stauffer, R. E. (1991). Testing lake energy budget models under varying atmospheric stability conditions. *Journal of Hydrology, 128*(1-4), 115-135.

Stewart, R. B., & Rouse, W. R. (1976). A simple method for determining the evaporation from shallow lakes and ponds. *Water Resources Research, 12*(4), 623-628.

Straskraba, M. (1980). The effects of physical variables on freshwater production: analyses based on models. *The functioning of freshwater ecosystems*, 13-84.

Sturrock, A., Winter, T., & Rosenberry, D. (1992). Energy budget evaporation from Williams Lake: a closed lake in north central Minnesota. *Water Resources Research, 28*(6), 1605-1617.

Sweers, H. (1976). A nomogram to estimate the heat-exchange coefficient at the air-water interface as a function of wind speed and temperature; a critical survey of some literature. *Journal of Hydrology, 30*, 375-401.

Thornthwaite, C. W. (1948). An Approach toward a Rational Classification of Climate. *Geographical Review*, 55-94.

Thornthwaite, C. W. (1948). *An approach toward a rational classification of climate* (Vol. 66): LWW.

Turc, L. (1961). Estimation of irrigation water requirements, potential evapotranspiration: a simple climatic formula evolved up to date. *Annals of Agronomy*, 13-49.

Venalainen, A., Heikinheimo, M., & Tourula, T. (1998). Latent heat flux from small sheltered lakes. *Boundary-Layer Meteorology, 86*(3), 355-377.

Winter, T. C. (1981). Uncertainties in estimating the water balance of lakes 1. *JAWRA Journal of the American Water Resources Association, 17*(1), 82-115.

Xu, C.-Y., & Singh, V. P. (1997). Evaluation and generalization of 13 mass-transfer equations for determining free water evaporation. *HYDROLOGICAL PROCESSES, 11*(3), 311-323.

Xu, C.-Y., & Singh, V. P. (1998). Dependence of evaporation on meteorological variables at different time-scales and intercomparison of estimation methods. *HYDROLOGICAL PROCESSES*, 429-442.

Xu, C.-Y., & Singh, V. P. (2000). Evaluation and generalization of radiation-based methods for calculating evaporation. *HYDROLOGICAL PROCESSES*(14), 339-349.

Xu, C.-Y., & Singh, V. P. (2001). Evaluation and generalization of temperature-based methods for calculating evaporation. *HYDROLOGICAL PROCESSES, 15*(2), 305-319.

Xu, C.-Y., & Singh, V. P. (2002). Cross Comparison of Empirical Equations for Calculating Potential Evapotranspiration with Data from Switzerland. *Water Resources Management*, 197-219.

CURRICULUM VITAE

Name/Surname : Aziz Ul Haq Mujahid
Foreign Language : English, Pushto
Birth Place and Year : Afghanistan/1995
Email Address : Haq753@gmail.com

Education History:

- 2016, CECOS University, Civil Engineering Dept.

Awards:

- 2016, 1st Prize, Best Final Year Project, Seismic Design and Retrofitting of Existing Buildings, Peshawar, Pakistan