

Chapter One

1. Introduction

The name discipline of Hydrology is derived from Greek words; "Hydro" means water and "logy" means science.

Hydro-logy: *the science that deals with the origin, distribution and properties of water on the earth including that in the atmosphere in the form of water vapor, on the surface as water, snow or ice, and beneath the surface as ground water. Also study about:*

- ✓ *The study of moving water found in rivers, open channels, lakes, and runoff across the open land surface.*
- ✓ *Important for transportation, irrigation, water supply, hydropower, etc.*
- ✓ *Ground water (below the surface).*
- ✓ *Marine water (in the oceans).*

Further emphasizes the degree of application this subject classified as:

- ✓ *Scientific hydrology: study to concern chiefly with academic aspect.*
- ✓ *Engineering hydrology: study to concern with engineering application.*

A good understanding of the hydrologic processes is important for the assessment of the water resources, their management and conservation on global and regional scales.

Knowledge of hydrology is essential for engineers dealing with:

- *water power engineering*
- *Highway engineering.*
- *Irrigation.*
- *Water supply engineering.*
- *inland navigation and*
- *Flood control etc.*

Applications of Engineering Hydrology

Hydrology finds its great Applications in the design of water resource development in engineering project those projects.

Some practical application of hydrology, hydrology is important for:

- ✓ ***Design of hydraulic structure***

Is important for estimation of the quantities of water to be handling at the site structure.

Design to provide best suitable shape and structure .so hydrology would answer for this question.

✓ **Municipal and industrial water supply**

The availability of water is important factor in locating the industrial and its has considerable effect on the growth of Municipal.

So hydrology would answer for this question whether the flow in the nearly stream is sufficient for such question to meet the need of Municipal city and indstriaies.

✓ **Hydropower development.**

Hydrology studies essential for planning of any water power development. So Hydrology determines the feasibility of runoff in river reliable predication is needed of absolute minimum daily flow that may be expected.

✓ **Irrigation and drainage.**

✓ **Flood control project.**

✓ **Watershed management and sediment control.**

1.2 Hydrologic cycle

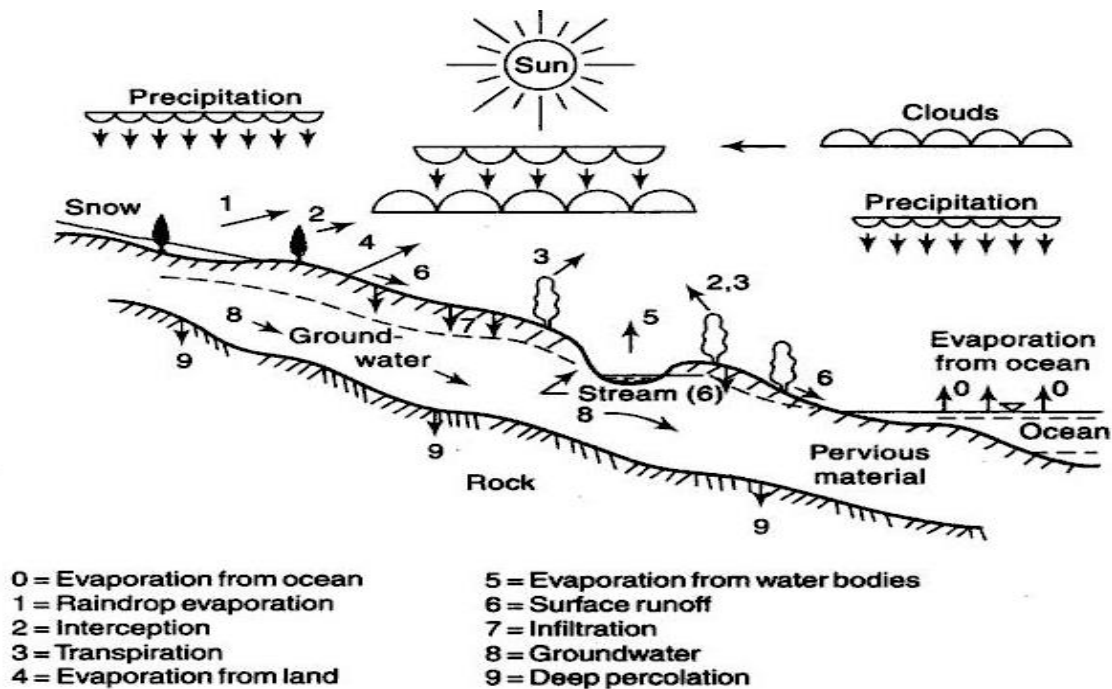
Water exists in earth atmosphere in the three phases:

1. Gaseous
2. Liquid
3. Solid form and circulate mainly planetary force.

The sun provides the energy for evaporation of open water bodies earth gravitational field and coriolous force contribute to the circulation of water.

The total amount of water on Earth is invariable. At the same time water is continuously renewed while circulating between oceans, land and atmosphere. All processes like evaporation, condensation, precipitation, interception, transpiration, infiltration, storage, runoff, groundwater flow, which keep water in motion constitute the hydrologic cycle. Those processes are stimulated by solar energy.

***Hydrologic cycle** is the dynamic movement of water that evaporates from the water bodies, condense in the atmosphere, form cloud fall as the rain, snow that contribute stream flow and recharge the groundwater. The schematic representation of Hydrologic cycle as follow:*



- ✓ The hydrologic cycle describes the **continuous re-circulating** transport of the waters of the earth, linking atmosphere, land and oceans.
- ✓ Water evaporates from the ocean surface, driven by energy from the **Sun**, and joins the atmosphere, moving inland as clouds. Once inland, atmospheric conditions act to condense and precipitate water onto the land surface, where, driven by **gravitational forces**, it returns to the ocean through river and streams.
- ✓ The process is quite **complex**, containing many sub-cycles.
- ✓ The quantification of the hydrologic cycle which is an open system can be represented by a **mass balance equation**, where inputs minus outputs are equal to the change in storage.
- ✓ It is a basic Hydrologic Principle or equation that may be applied either on global or regional scale

$$I - O = \Delta S$$

The main component of hydrologic cycle:

1) Transportation component:

- ❖ Precipitation.
- ❖ Evaporation.
- ❖ Transpiration.
- ❖ Infiltration.

❖ *Runoff.*

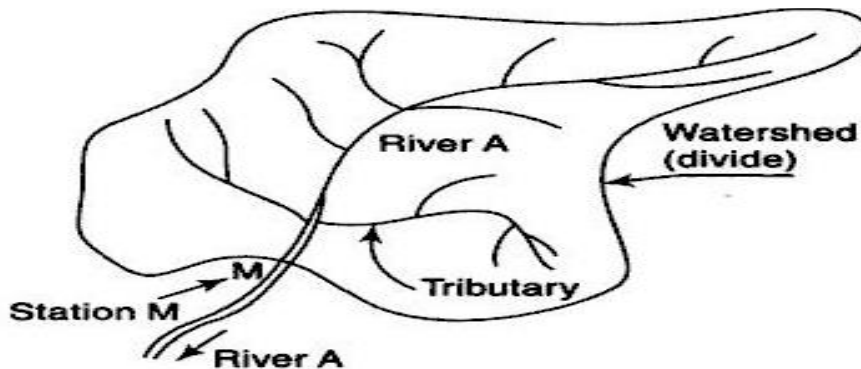
2) *Storage component:*

❖ *Storage of the land surface.*

❖ *Soil-moisture storage.*

❖ *Ground water storage.*

1.3 Catchment area (basin, drainage river, watershed): is an extent of land where water from rain or snow melt drains downhill into a body of water, such as a river, lake, reservoir, estuary, wetland, sea or ocean. In hydrology, catchment is a logical unit of focus for studying the movement of water within the hydrological cycle, because the majority of water that discharges from the catchment outlet originated as precipitation falling on the catchment. Catchment area is separated from neighborhood by the ridge is called divide (watershed).



$$\text{Total Precipitation} = \text{runoff} + \text{losses (R+L) or}$$

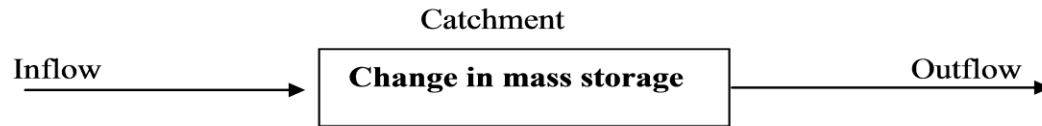
$$\text{Runoff} = \text{total precipitation} - \text{losses (Evaporation, Transpiration, Infiltration, Depreation storage, etc.)}$$

1.4 Water Budget/hydrologic Equation

The quantities of water going through the various paths of the hydrologic cycle can be described by the continuity equation known as **water budget equation or hydrologic equation**.

For a given problem area, say a catchment, in an interval of time Δt , the continuity equation for water in its various phases is written as.

Mass in flow – mass outflow = change in mass storage



If the density of the inflow, outflow and storage volumes are the same

$$V_i - V_o = \Delta S \quad (\text{Eq. 1})$$

Where

V_i = Inflow volume of water into the problem area during the time period,

V_o = Outflow volume to water from the problem area during the time period, and

ΔS = change in the storage of the water volume over and under the given area during the given period.

An expression of water budget equation of the catchment for time interval Δt is written as

$P - R - G - E - T = \Delta S$, Where P = precipitation, R = surface runoff, E = Evaporation, G = net groundwater, T = transpiration

For example, for an open water body, (i.e. a seas, lake or reservoir etc.),

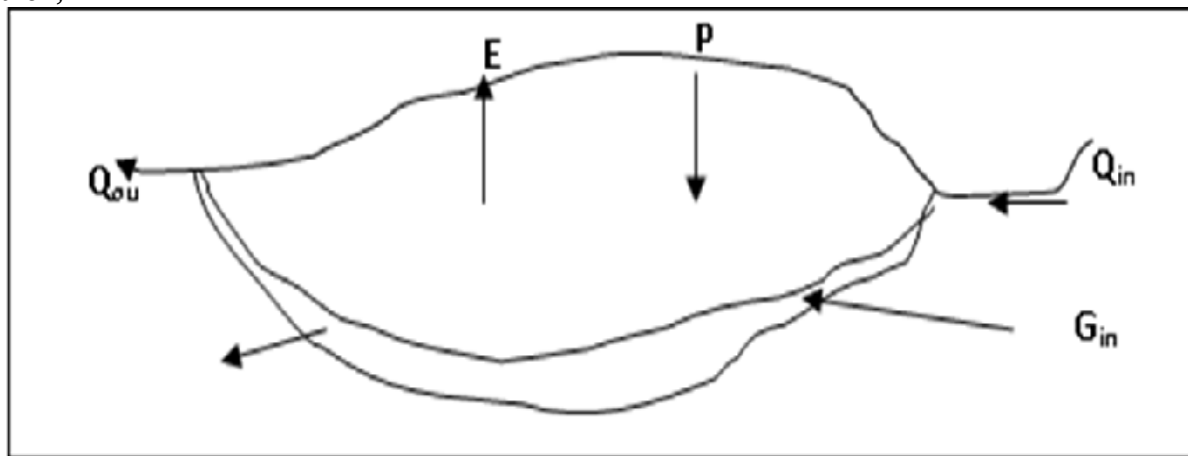
✓ The inputs of the system consist:

- ✚ the surface inflow Q_{in} ,
- ✚ the precipitation, P , and
- ✚ the sub-surface inflow, G_{in} ,

✓ The outputs of the system include:

- ✚ The surface runoff outflow, Q_{out} ,
- ✚ The evaporation, Transpiration from the water surface, E, T and
- ✚ Infiltration, percolation
- ✚ Any sub-surface outflow, G_{out} .

If the change in storage over the chosen time period is ΔS , which may be positive or negative, then,



$$Q_{in} - Q_{out} + P - E + G_{in} - G_{out} = \Delta S$$

Or

$$(Q_{in} + P + G_{in}) - (Q_{out} + E + G_{out}) = \Delta S$$

Example 1: a lake had a water surface elevation of 103.200 m above datum at the beginning of a certain month. In that month the lake received

- An average inflow of $6.0 \text{ m}^3/\text{s}$ from surface runoff sources. In the same period the outflow from the lake had an average value of $6.5 \text{ m}^3/\text{s}$. Further, in that month, the lake received a rainfall of 145 mm and the evaporation from the lake surface was estimated as 6.10cm.

- a) Write the water budget equation for the lake and calculate the water surface elevation of the lake at the end of the month.
- b) What is new water elevation the average lake surface area can be taken as 5000 ha. Assume that there is no contribution to or from the ground water storage.

Solution: In a time period t the water budget for the lake can be written as:

Assumption: no contribution to or from the ground water storage.

Input volume of lake – Output volume of lake = change in storage

Where:

I_{inflow} = average inflow rate = $6.0 \text{ m}^3/\text{s}$

O_{outflow} = average outflow rate = $6.5 \text{ m}^3/\text{s}$

P = precipitation = $145 \text{ mm} = 145 \times 10^{-3} \text{ m}$

E = evaporation = $6.10 \text{ cm} = 6.10 \times 10^{-2} \text{ m}$

A = surface area of the lake = $5000 \text{ ha} = 5000 \times 10^4 \text{ m}^2$.

Here: In one month: $\Delta t = 1 \text{ month} = 30 \times 24 \times 60 \times 60 = 2.592 \times 10^6 \text{ s} = 2.592 \text{ Msec}$.

A given surface elevation = 103.20 m

Step1:

Input volume of lake = $I_{\text{inflow}} \times \Delta t = 6.0 \text{ m}^3/\text{s} \times 2.592 \text{ M sec} = 15.552 \text{ Mm}^3$ (Mega = 10^6)

Input due to precipitation = $P \times A = 145 \times 10^{-3} \text{ m} \times 5000 \times 10^4 \text{ m}^2 = 7.25 \text{ Mm}^3$

Step2:

Output volume of lake = $O_{\text{outflow}} \times \Delta t = 6.5 \text{ m}^3/\text{s} \times 2.592 \text{ M sec} = 16.848 \text{ Mm}^3$

Output due to evaporation = $E \times A = 6.10 \times 10^{-2} \text{ m} \times 5000 \times 10^4 \text{ m}^2 = 3.05 \text{ Mm}^3$

Hence $\Delta S = (I_{\text{inflow}} \times \Delta t + P \times A) - (O_{\text{outflow}} \times \Delta t + E \times A)$

$$= (15.552 + 7.25) - (16.848 + 3.05) \text{ Mm}^3$$

$$= 2.904 \text{ Mm}^3$$

Change in elevation = $\Delta z = \Delta S / A = 2.904 \text{ Mm}^3 / 5000 \times 10^4 \text{ m}^2$

$$= 0.058 \text{ m}$$

New water surface elevation at the end of the month

$$= 103.200 \text{ m} + 0.058 \text{ m}$$

$$= 103.258 \text{ m above the datum level.}$$

Example 2: A small catchment of area 150 ha received a rainfall of 10.5 cm in 90 minutes due to a storm. At the outlet of the catchment, the stream draining the catchment was dry before the storm and experienced a runoff lasting for 10 hours with an average discharge value of $2.0 \text{ m}^3/\text{s}$. The stream was again dry after the runoff event.

a) What is the amount of water, which was not available to runoff due to combined effect of infiltration, evaporation and transpiration?

b) What is the ratio of runoff to precipitation?

Solution: The water budget equation for the catchment in a time Δt is:

$$P - R - G - E - T = \Delta S$$

$$\text{Total precipitation} = \text{runoff} + \text{Losses}$$

$$R = P - L \text{ where } L \text{ is losses} = \text{water is not available to runoff due to infiltration.}$$

In the present case take $t = \text{duration of the runoff} = 10 \text{ hours}$.

Note that the rainfall occurred in first 90 minutes and in the rest of 8.5 hours the precipitation was zero.

$$S = \text{change in the surface storage} = 0$$

$(G + E + T) = \text{water not available to runoff due to infiltration (causing addition to groundwater storage), evaporation and transpiration} = \text{Losses} = L$

It is reasonable to assume in this case that there was no contribution by ground water storage to the runoff in the stream.

a) Hence $P - R = L$

$$P = \text{Input due to precipitation in 10 hours}$$

$$150 \times 100 \times 100 \times (10.5/100) = 157,500$$

$$R = \text{runoff volume} = \text{outflow volume in catchment in 10 hours}$$

$$= 2.0 \times 10 \times 60 \times 60 = 72000 \text{ m}^3$$

Hence $L = 157500 - 72000 = 85,500 \text{ m}^3$

$$= \text{Volume of water not available to runoff}$$

b) $\text{Runoff/ rainfall} = 72000/ 157500 = 0.457$ (this ratio is known as runoff coefficient).

1.5 Variation of Water Distribution component on Earth

The "Blue Planet", as the Earth is called, is easily identified in the solar system due to its distinctive element: water.

Oceans and seas cover 71% of the planet's surface. The remaining 29% are land, but water can be found here as well in lakes and rivers, in the soil cover, underground and bound up in the composition of minerals of the Earth's crust and core. The [biosphere](#) contains water and cannot exist without it. Water is held in the [atmosphere](#) together with other gases.

Water exists in three states: liquid, solid (ice and snow) and gas (water vapour). Due to the energy supplied by the sun it is in permanent transformation from one state to another, and in constant motion between oceans, land, atmosphere and biosphere.

A reliable assessment of the water storage on Earth considers the amount of water as an average over a long period of time, contained in the [hydrosphere](#). Current estimations weigh up to 1386 million cubic kilometers of water that are divided as shown in Figure 1.1 and Table 1.1.

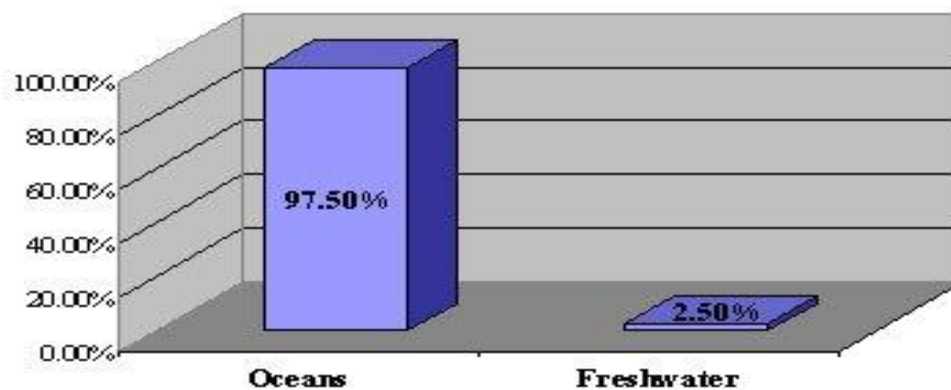


Figure 1.1 Distribution of water on Earth

Table 1.1. Distribution of freshwater on Earth

Component of freshwater	% of the hydrosphere content
Glaciers and Permanent Snow Cover	1.74 %
Groundwater	0.75 %
Freshwater Lakes	0.0066 %
Rivers	0.0002 %
Atmosphere	0.0009 %
Biosphere	0.0001 %

Freshwater is only 2.5% from the total, yet most of it is out of human reach. Freshwater usable by humans represents 0.3% of all water on Earth and is drawn from underground, lakes and rivers (Figure 1.2).

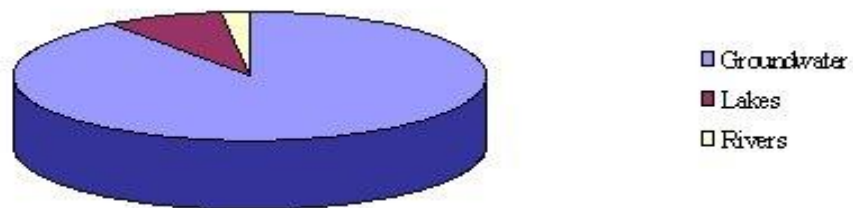


Figure 1.2 Freshwater available for human use (0.3 % of Earth's water)

Groundwater is the second largest storage of freshwater and the most used by humans. People in the arid and semi-arid regions, use groundwater exclusively for all their needs. Still, groundwater is not always within easy reach. The withdrawal of groundwater becomes difficult and expensive when it is confined over 800m depth.

The surface water bodies, as lakes and rivers, hold a very small amount of freshwater. Unlike groundwater it is easily accessible, but liable to pollution. At the same time, it is unevenly distributed with regard to continent surfaces and population. For example, 30 % of the world freshwater storage and 6 % of runoff are located alone.

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TABLE 10.2

Earth's Water Compartments

Compartment	Volume (1,000 km ³)	Percent of Total Water	Average Residence Time
Total	1,386,000	100	2,800 years
Oceans	1,338,000	96.5	3,000 to 30,000 years*
Ice and snow	24,364	1.76	1 to 100,000 years*
Saline groundwater	12,870	0.93	Days to thousands of years*
Fresh groundwater	10,530	0.76	Days to thousands of years*
Fresh lakes	91	0.007	1 to 500 years*
Saline lakes	85	0.006	1 to 1,000 years*
Soil moisture	16.5	0.001	2 weeks to 1 year*
Atmosphere	12.9	0.001	1 week
Marshes, wetlands	11.5	0.001	Months to years
Rivers, streams	2.12	0.0002	1 week to 1 month
Living organisms	1.12	0.0001	1 week

Source: Data from UNEP, 2002.

*Depends on depth and other factors.

Climatic Zones

Climate and Weather are the synonyms word.

The state of atmosphere with respect to temperature, humidity, wind, cloudiness etc. at the given time generally referred to as weather. The climate of region is aggregate of weather (Climate is the long-term weather patterns of a place).

✓ Weather describes what the atmosphere is like at a given time and place.

Scientists find the **climate** of an area by averaging **weather conditions over 30 years** or more.

A **climate zone** is an area that has similar average temperatures and precipitation throughout.

The global classification of climatic zones is:

- The tropical, temperate, and polar climate zones are based on distance from the equator.
- The **equator** is the imaginary line that divides Earth into its northern and southern hemispheres, or halves.
- An area's **latitude**, or distance from the equator, determines what climate zone it is in.

1. *Tropical climates are found near the equator. Tropical climates get different amounts of precipitation. The sun is directly overhead nearly all year. As a result, the area gets a lot of direct heat. The region on either side of equator between the tropics that the 23 1/2°N to 23 1/2° S of latitude and Cover more land area than any other climate (30% of Earth's land surface). Temperatures in tropical climates are typically greater than 18 °C.*
2. *Temperate Zone – The area between the tropical and polar zones, from about 23.5° to 66.5° north and 23.5° to 66.5° south latitudes.*

temperate climates are found in the middle latitudes. For most of the year, a temperate climate has temperatures between 10 °C and 18 °C. Most temperate climates have four seasons. Temperate climates get different amounts of precipitation.

3. ***Polar (cool) Zone – The areas near both poles, from about 66.5° to 90° north and 66.5° to 90° south latitudes.*** *Polar climates are farthest from the equator. They are found near Earth's poles. Polar climates get little precipitation. They are covered in snow and ice year-round. Temperatures in polar climates are typically less than 10 °C*

Here in table form

Climate Type	Boundaries	Comments
TROPICAL	Bounded on the north and south by the 18°C isotherm.	Temperatures are uniformly warm during the whole year and there is no true winter season.
TEMPERATE	Bounded on the poleward side by the 10°C isotherm and on the equator side by the 18°C isotherm.	Temperatures are high during the summer and low during the winter.
POLAR	Bounded on the equator side by the 10°C isotherm.	Temperatures are low during the whole year and there is no true summer; summers are warmer than winters.

In Ethiopia, the year may be divided into four weather season as given below:

1. **Kirmet or Meher (summer) season** - June, July and August are the summer season. Heavy rain falls in these three months.
2. **Belg (Autumn) season** - September, October and November are the spring season sometime known as the harvest season.
3. **Bega (Winter) season**- December, January and February are the dry season with frost in morning specially in January.
4. **Tseday (Spring) season** - March, April and May are the autumn season with occasional showers. May is the hottest month in Ethiopia.

The interaction of solar radiation with the atmosphere and the gravitational forces, together with the distribution of land and sea masses, produces an almost infinite variety of climates.

However, certain zones and belts of approximately uniform climates can be distinguished.

Chapter Two

Introduction

Precipitation is any form of moisture which falls to the earth. This includes rain, snow, hail and sleet. Precipitation occurs when water vapor cools. When the air reaches saturation point (also known as condensation point and dew point) the water vapor condenses and forms tiny droplets of water. These tiny droplets of water from clouds, Complex forces cause the water droplets to fall as rainfall (It happens as the result of warm, moist air being cooled, leading to condensation and in turn rain).

2.1 Meteorology

In hydrologic cycle water is transported in the air, over the land, and below the surface of the earth. Meteorology deals with the atmospheric phenomena.

*The word Meteorology is derived from two Greek word Meteors which mean **lofty (very high)** logos which mean science.*

Hydro Meteorology is the study of atmosphere process which affects water resource of the earth and interpreted to the hydraulic engineering.

Meteorology knowledge is important to:

- ✓ *Determine the probable the maximum precipitation used in spillway design.*
- ✓ *Design of dams and levee on the some hydrological problem area.*
- ✓ *Meteorology and Meteorology data play great role in design of such type of the structure.*

The nature of water is important present the aggregation state of:

- ✓ ***Solid :snow & ice***
- ✓ ***Liquid: pure water & solution.***
- ✓ ***Gaseous: vapor under different grade of pressure and saturation.***

Rain fall beings the predominate form of precipitation causing steam flow especially the flood in the majority of the river. Rain fall is used synonymously with respect precipitation

Conditions for Occurrence of Precipitation

1. Cooling of air masses.
2. Formation of clouds due to condensation
3. Growth of water droplets.
4. Accumulation of moisture.

TYPES OF PRECIPITATION

Moisture is always present in the atmosphere and there is no shortage of condensation nuclei in the present days due to rapid industrialization. Adiabatic cooling of the moist air through lifting is the main cause of condensation. Precipitation, normally classified according to the factors responsible for lifting the air mass, subsequent cooling. There are three type of Precipitation: (i) convective, (ii) orographic, (iii) cyclonic.

i) Convective

Unequal heating at the surface of earth is the main reason for this type of precipitation. In summer days air in contact with surface of the earth gets heated up, expands and rises due to lesser density. Surrounding air rushes to replace it and in turn gets heated up and rises. In the process, increasing quantities of water vapour are taken up by the air. When the air mass reaches to a great height, temperature falls below the dew point. At this stage condensation releases latent heat of 539 cal/g of water. This heat is added to the air at the height of condensation causing further heating to its upper air. This forces the air mass to move up. As more moist air from the surrounding joins the system, more energy is added. The vertical air currents develop tremendous velocities and dynamic cooling takes place. Depending on the moisture content, cooling and other factors, the precipitation intensity varies from light showers to cloud bursts amounting to 300 mm or more rainfall per hour. Such type of precipitation covers limited aerial extent and is normally found near equatorial zone. Sometimes strong upward wind currents exceeding 150 kmph freezes the rain drops to form hail. Multiple rise and fall of hail due to very strong upward currents may add to its size.

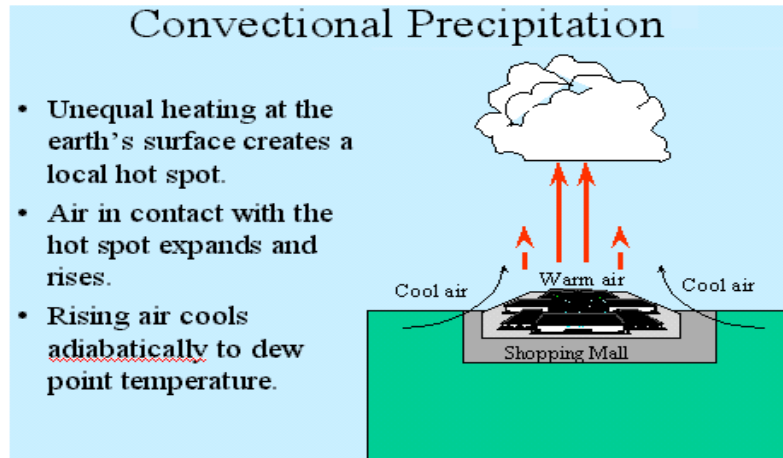


Fig 2.1 Convective Precipitation

ii) Orographic

Orographic or mountain-range barriers cause lifting of the air masses. Dynamic cooling takes place causing precipitation on the side of the blowing wind as shown in Fig. 2.2 Precipitation is normally heavier on the windward side and lighter on leeward side. Orographic precipitation gives medium to high intensity rainfall and continues for longer duration.

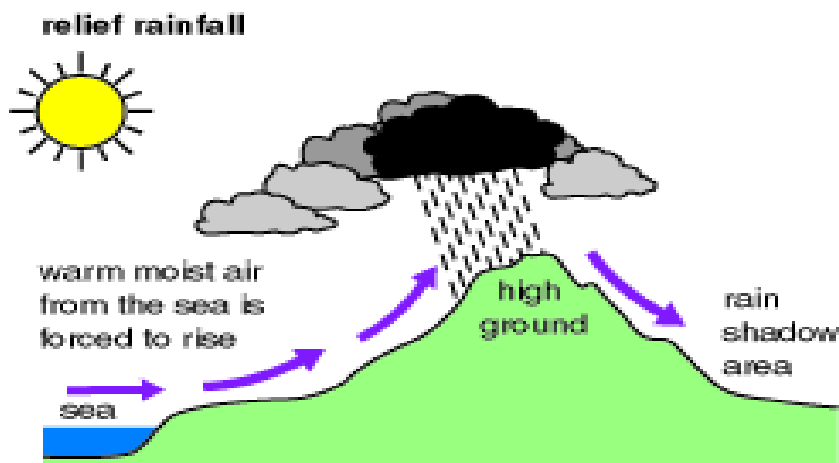


Fig. 2.2 Precipitation due to Orographic Features

iii) Cyclonic

A cyclone is a low pressure area surrounded by a larger high pressure area. When low pressure occurs in an area, especially over large water bodies, air from the surrounding rushes, causing the air at the low pressure zone to lift. This zone is surrounded by a very strong wind zone with wind speed sometimes exceeding 300 km/h. Aerial extent of the cyclone extends to a few hundred kilometers. The pressure distribution diagram for this zones in the form of Isobars (lines joining equal pressure points with respect to mean sea level) are closely spaced. There is steep decrease in pressure towards the eye.

2.2 Temporal and spatial variability of precipitation

Spatial: related to latitude.

- ✓ The equatorial zone (tropic belt) --world's max. RF
- ✓ Next to the tropics, low precipitation.
- ✓ further to poles the temperate and higher latitudes-- higher amounts of ppt
- ✓ finally the polar areas --very little precipitation

Temporal: related to seasonal distribution of ppt.

- ✓ tropical type -- 2 wet seasons (peaks in April and November) along
- ✓ the equator except trade wind and monsoon areas featuring 1 wet season,
- ✓ subtropical type featuring winter rain,
- ✓ temperate zone type characterized by rainfall throughout the year

MEASUREMENT OF PRECIPITATION

Information on rainfall (Precipitation) characteristics is essential for planning, design, and management of various hydraulic structures (flood protection works, urban sewers, etc.).

All forms of precipitation are expressed in terms of the vertical depth of water that would accumulate on a level surface.

One millimeter of precipitation represents the quantity of water needed to cover the land with a layer of water, taking into account that the water is not lost through the drainage, evaporation or absorption.

The simplest method of measuring precipitation is **Rain gauges**.

Rainfall measurements are important in the field of:

- ✓ *Highway designing.*
- ✓ *Hydropower generation.*
- ✓ *Irrigation*
- ✓ *Water way diversion.*
- ✓ *Flood control etc.*

The following standard settings have to be adopted while selecting a site for the rain gauge station and installing the rain gauge.

- *The site should be in an open space.*
- *A site that is sheltered from high winds.*
- *Should not be installed on the top or the side of the hill.*
- *A fence should be erected around the rain gauge station.*
- *The gauge must always be mounted firmly.*

Two kinds of rain gauges;

1. Non – recording type.

2. Recording type rain gauges.

- 1. Non - recording rain gauge:** - they are non-recording because they do not record the rain but only collect the rain. Is essentially consists of a circular area of 12.7cm (5 inches (127mm) diameter connected to funnel. Rim of collector is set in a horizontal plane at the height of 305mm (30.5cm) above the ground level.

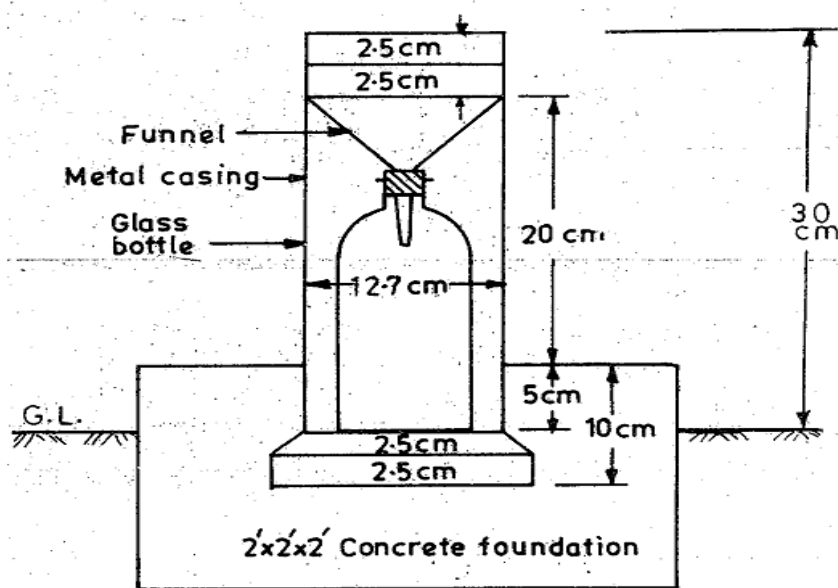


Fig. Symon's non-recording rain gauge.

The Properties of non Recording types of gauge:

- Rain collect in the bottle is taken and pour into graduated measured jar which is directly a depth of rainfall for day.
- Need observer at regular time and observer uses ruler to measure the depth of rainfall.
- Non recording gauge gives only total rainfall.

Recording type of rain gauge: These are rain gauges which can give a permanent, automatic rainfall record without any bottle recording. The gauge produces a record of cumulative rain Vs time in the form of a graph, which is known as mass curve of rain fallen.

The Properties of Recording types of gauge:

- Continuous Records at the rainfall over time.
- Gives all required information like duration, intensity and cumulative of rainfall.
- Commonly installed for the purpose for checking and calibration.
- Human errors are eliminated.

There are three types of recording gauges in common use.

- Tipping-bucket type
- Weighing type
- Floating type.

Reading assignment

2.3 Designing Rain Gauge Network

The density of rain gauge network depends on:

- (1) Purpose of the study;
- (2) Geographic configuration of the study region;

(3) Economic consideration. Therefore Rainfall data is the most important and fundamental data required for all hydrological investigations. Hence, one aims of an optimum density of gauges from which reasonable accurate information about the storm can be obtained. Towards this, the World Meteorology Organization (WMO) recommended the following densities.

- ✓ The flat regions of temperate, Mediterranean and tropical zones

Ideal-1 station for 600-900km²

Acceptable 1 station for 900-3000km²

- ✓ In mountainous regions of temperate, Mediterranean and tropical zones

Ideal-1 station for 100-250 km²

Acceptable 1 station for 25-1000km²

- ✓ In arid and polar regions: 1 station for 1500-10,000km² depending on the feasibility.

Statistics has been used in determining the optimum number of rain gauges (N) is required to be installed in the given catchments obtained by the following equation:

$$N = \left(\frac{C_v}{\varepsilon} \right)^2$$

$$C_v = \frac{100 * \sigma_{n-1}}{P_{av}}$$

$$\sigma_{n-1} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (P_i - P_{av})^2}$$

$$P_{av} = \frac{\sum_{i=1}^n P_i}{n}$$

Where N = optimal number of stations ε = allowable degree of (percentage) error in the estimate of the mean rainfall and C_v = coefficient of variation of the rainfall values at the existing n stations (%), n is number of station.

If $C_v < 10\%$ the existing station is sufficient. In case of $N > n$ the addition station are required in appropriate location of the basin.

Example 3: There are four rain gauge stations in the catchments of a river. The average annual rainfall values at these stations are 800, 620, 400 and 540 mm respectively. Determine

a) The optimum number of rain gauge in the catchments, if it is desired to limit of the error in the mean value in the catchments to 10%.

b) How many more gauge will then to be installed?

Solution

Station	Precipitation	Intensity	$p - p_{avg}$	$(p - p_{avg})^2$	ε
1	p_1	800	210	44100	10%
2	p_2	620	30	900	
3	p_3	400	-190	36100	
4	p_4	540	-50	2500	
n=4	total	2360		83600	
	average	590			

$$i) \quad P_{av} = \frac{\sum_{i=1}^n P_i}{n}$$

$$\begin{aligned} P_{average} &= (800 + 620 + 400 + 540) / 4 \\ &= 2360 / 4 \\ &= 590 \end{aligned}$$

$$ii) \quad \sigma_{n-1} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (P_i - P_{av})^2}$$

$$\begin{aligned} &= \sqrt{\frac{1}{4-1} (83600)} \\ &= 166.933 \end{aligned}$$

$$\begin{aligned} iii) \quad C_v &= \frac{100 * \sigma_{n-1}}{P_{av}} \\ &= 100 * 166.933 / 590 \\ &= 28.294 \end{aligned}$$

Hence a) Optimum number of rain gauge (N) is given by:

$$\begin{aligned} N &= \left(\frac{C_v}{\varepsilon} \right)^2 \\ &= (28.294/10)^2 \\ &= 8.004 \end{aligned}$$

b) The addition gauge is required to be installed:

$$\begin{aligned} &= 8 - \text{Estimated (4) gauge.} \\ &= 8 - 4 = 4 \end{aligned}$$

Conclusion: Optimum number of rain gauge for the catchments is hence 4 more addition station is needed.

Estimation of Missing Data

When undertaking an analysis of precipitation data from gauges where daily observations are made, it is often to find days when no observations are recorded at one or more gauges. These missing days may be isolated occurrences or extended over long periods. In order to compute precipitation totals and averages, one must estimate the missing values.

Several approaches are used to estimate the missing values. Station Average, Normal Ratio, Inverse Distance Weighting, and Regression methods are commonly used to fill the missing records.

1. Arithmetic Mean Method

In Station Average Method, the missing record is computed as the simple average of the values at the nearby gauges using this method only when the annual precipitation value at each of the neighboring gauges differs by less than 10% from that for the gauge with missing data.

At least three surrounding station data are available.

$$P_{avr} = \frac{P_1 + P_2 + P_3 + \dots + P_n}{n}$$

2. Normal Ratio method: Using this method only when the annual precipitation value at each of the neighboring gauges greater than 10% from that for the gauge with missing

data by weighing the precipitation at the neighboring stations by the ratios of normal annual precipitations.

Where: N_x = Annual-average precipitation at the gage with missing values.

$N_1, N_2, \dots, N_m$ = Annual average precipitation at neighboring gauges.

Example 4: The rain gauge station X was inoperative for a part of a month during which a storm occurred. The storm rainfall recorded at the three surrounding stations A, B and C was 75 mm, 59 mm and 86 mm, respectively. If the average annual rainfalls of the stations A, B, C and X are 750, 650, 850 and 750 mm respectively, estimate the storm rainfall of station X.

✓ The Maximum annual precipitation at stn c=850mm

✓ The minimum annual precipitation at stn b=650mm

The maximum difference of annual precipitation (D) =850-650=200mm

% of maximum difference of annual precipitation with respect to surrounding stn=

$(D / \text{Maximum annual precipitation}) * 100 = (200/850) * 100 = 23.52\%$

Solution: Because the difference in the average annual rainfall is more than 10% the normal ratio method will be used.

$$\begin{aligned} P_x &= \frac{N_x}{3} \left(\frac{P_A}{N_A} + \frac{P_B}{N_B} + \frac{P_C}{N_C} \right) \\ &= \frac{700}{3} \left(\frac{75}{750} + \frac{59}{650} + \frac{86}{850} \right) \\ &= 68.1 \text{ mm} \end{aligned}$$

3. The Inverse Distance Method weights the annual average values only by their distances, D^2 , from the gauge with the missing data and so does not require information about average annual precipitation at the gauges. Inverse Distance Method: This is the most acceptable method.

Where $D^2 = (\Delta X^2 + \Delta Y^2)$ is the distance of the station I in X and Y coordinates. Taking missing rainfall station at (0, 0) position. The missing value is estimated as:

$$P_x = \frac{\sum_{i=1}^n W_i P_i}{\sum_{i=1}^n W_i}$$

$$W_i = \frac{1}{D^2}$$

The value of W_i if the weights are inversely proportional to distance squared.

Example 5: In a river basin, a station A was inoperative during a storm, while stations B, C and D surrounding A were in operation, registering 12.3, 14.8 and 11.9 cm of precipitation. Mean annual precipitation at the four stations A, B, C and D are 1290, 1510, 1680 and 1375 mm respectively. Estimate the missing storm precipitation of station A. The coordinates of B, C and D are (6, -4), (8, -6) and (-4, 4), respectively, where as the coordinate of A is (0, 0).

2.4 Mean Area Depths of Precipitation

To convert the point rainfall values at various stations into an average value over a catchment, they are three methods that used Mean Area Depths of Precipitation over a catchment.

1. Arithmetical-mean method
2. Thiessen's polygon method
3. Isohyetal method.

Arithmetical-mean method: When the rainfall measured at various stations in a catchment show little variation over catchment area. Thus, if $P_1, P_2, \dots, P_i, \dots, P_n$ are the rainfall values in a given period in N stations within catchment then the value of the mean ppt. p over the catchment.

The method is simple and give good results if the precipitation measured at the various stations in a catchment show little variation.

Thiessen's polygon method (Non-uniform distribution of rain gauges): the rainfall recorded at each station is given a weight on the basis of an area closest to the station. The average rainfall over the catchment is computed by considering the precipitation from each gauge multiplied by the percentage of enclosed area by the Thiessen polygon. The total average areal rainfall is the

summation averages from all the stations. The Thiessen polygon method gives more accurate estimation than the simple arithmetic mean estimation as the method introduces a weighting factor on rational basis. Furthermore, rain gauge stations outside the catchment area can be considered effectively by this method.

Example 6 : Determining the average rainfall over the catchment by the Thiessen polygon method. The rainfall recorded at the various rain gauge stations and areas of the Thiessen polygons are marked on the plan.

$$P_{avr} = \frac{\sum_{i=1}^n A_i P_i}{\sum A_i}$$

$$= 1963.3/429$$

$$= 4.58 \text{ cm}$$

The Isohyetal method is the most accurate method of estimating areal rainfall. The method requires the preparation of the isohyetal map of the catchment from a network of gauging stations. Areas between the isohyets and the catchment boundary are measured. The areal rainfall is calculated from the product of the inter-isohyetal areas and the corresponding mean rainfall between the isohyets divided by the total catchment area.

Isohyets are the contours of equal rainfall depth.

Thus $P_1, P_2, P_3, \dots, P_n$ are values of isohyetal precipitation and $A_1, A_2, A_3, \dots, A_{n-1}$ are inter- Isohyetal area the mean rainfall over the catchment area calculated:

$$P_{avr} = \frac{A_1 * P_1 + A_2 \left(\frac{P_1 + P_2}{2} \right) + A_3 \left(\frac{P_2 + P_3}{2} \right) + \dots + A_{n-1} \left(\frac{P_{n-1} + P_n}{2} \right)}{A_1 + A_2 + A_3 + \dots + A_n}$$

$$= \frac{\sum_{i=1}^n P_{ij} A_{ij}}{\sum_{i=1}^n A_{ij}}$$

This method is most acceptable when the stations of the catchment are very large in number.

Procedure for Isohyetal Method:

1. *Draw isohyets (lines of equal rainfall) on the map.*
2. *Fill out the data table. First, find the average precipitation between isohyets. This will be the arithmetic average of the two isohyets. For example, between the 5 and 10 inch isohyets the average would be $(5+10)/2$ or 7.5 inches.*
3. *Find the area between the two isohyets by counting the number of boxes and use the scale to determine the areas.*
4. *Multiply the area between isohyets by the average precipitation (average isohyet). Sum these values.*
5. *Divide the above sum by the total area of the basin.*

Example 7: Isohyets due to the storm in a catchments are drawn in the fig and area of the catchment bounded by the Isohyets were tabulated as below.

<i>Isohyets(cm)</i>	<i>Isohyets area(km²)</i>
<i>Station-12.0</i>	<i>30</i>
<i>12.0-10.0</i>	<i>140</i>
<i>10.0-8.0</i>	<i>80</i>
<i>8.0-6.0</i>	<i>180</i>
<i>6.0-4.0</i>	<i>20</i>

Estimate the mean precipitation depth due to storm.

Solution:

<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>5</i>
<i>Isohyets</i>	<i>Average prec.(cm)</i>	<i>Isohyets area(km²)</i>	<i>Fraction of total area(A_i/450)</i>	<i>Total Depths of prec.(Col 2*Col 4)</i>
<i>Station-12.0</i>	<i>12</i>	<i>30</i>	<i>0.0667</i>	<i>0.800</i>
<i>12.0-10.0</i>	<i>11.0</i>	<i>140</i>	<i>0.3111</i>	<i>3.422</i>
<i>10.0-8.0</i>	<i>9.0</i>	<i>80</i>	<i>0.1778</i>	<i>1.600</i>
<i>8.0-6.0</i>	<i>7.0</i>	<i>180</i>	<i>0.4000</i>	<i>2.800</i>
<i>6.0-4.0</i>	<i>5.0</i>	<i>20</i>	<i>0.0444</i>	<i>0.222</i>
<i>Total Isohyets area=450km²</i>				<i>Total depths of prec.Σ=8.844</i>

Mean depth precipitation depth due to storm=8.84cm

2.5 Checking the Consistency of Point Measurements

If the conditions relevant to the recording of rain gauge station have undergone a significant change during the period of record, inconsistency would arise in the rainfall data of that station. This inconsistency would be felt from the time the significant change took place. Some of the common causes for inconsistency of record are:

1. Shifting of a rain gauge station to a new location.
2. The neighborhood of the station may have undergoing a marked change.
3. Change in the immediate environment due to damages due to deforestation, obstruction, etc.
4. Occurrence of observational error from a certain date both personal and instrumental.

The most common method of checking for inconsistency of a record is the Double-Mass Curve analysis (DMC). The curve is a plot on arithmetic graph paper, of cumulative precipitation collected at a gauge where measurement conditions may have changed significantly against the average of the cumulative precipitation for the same period of record collected at several gauges in the same region. The data is arranged in the reverse order, i.e., the latest record as the first entry and the oldest record as the last entry in the list. A change in proportionality between the measurements at the suspect station and those in the region is reflected in a change in the slope of the trend of the plotted points.

If a Double Mass Curve reveals a change in slope that is significant and is due to changed measurement conditions at a particular station, the values of the earlier period of the record should be adjusted to be consistent with latter period records before computation of areal averages. The adjustment is done by applying a correction factor K , on the records before the slope change given by the following relationship.

$$K = \frac{\text{Slope for period after slope change}}{\text{Slope for period before slope change}} = \frac{\text{corrected slope}}{\text{original slope}} = \frac{M_a}{M_o} = \frac{c}{a}$$

$$P_a = \left(\frac{M_a}{M_o} \right) P_o \quad \text{Where } P_a = \text{adjusted precipitation, } P_o = \text{original precipitation}$$

M_a = corrected slope, M_o = original slope

Chapter Three

Evaporation and Transpiration

3.1 Introductions

Evaporation occurs when water is converted in water vapor. The rate is controlled by the availability of energy at the evaporating surface and these with water vapor can into the atmosphere .Therefore

Evaporation

Evaporation is defined as the process by which liquid water changes into gaseous state as a result of heat energy transfer. Evaporation takes place at the free surface of water body and land surface at temperature lower than the boiling point of water. In a certain water body like a reservoir, lake, pond etc., the water molecules are in continuous motion with ranges of velocities. However, an increase in heat energy these water molecules will increase their velocity and kinetic energy as well. When the kinetic energy possessed by some of the molecules is sufficiently large, they escape from the water surface and join the atmosphere in the immediate neighborhood of the water surface. In the meantime, there are also water molecules within the vapor in the atmosphere and may penetrate the water surface. There is however, net escape of water molecules from the water surface.

Evaporation (E), from the hydrological point of view, is the process in which water from open water surfaces (oceans, seas, lakes and rivers), from uncovered soil and from surfaces covered by snow and glaciers goes into the atmosphere in vapor state. [Musy, 2001].or they are processes by which water is transformed from the liquid state to the gaseous state and is transferred to the atmosphere.

In case of vegetation growing in soil **transpiration** is defined as the part of total evaporation which enter the atmosphere from the soil though the plant. Or **Transpiration** is the process in which a fraction from the water assimilated by vegetation is set free into the atmosphere in vapor state.

Transpiration depended on

- ✓ Energy supply, wind
- ✓ Vapor pressure gradient

Transpiration rate is determined by: soil water content, ability of soil to conduct water into the root, etc. Transpiration rate is influenced by: crop characteristics, environmental aspect, cultural practice, etc.

Evaporation and transpiration are two important components of the hydrological cycle.

Evapotranspiration (ET) is the sum of those two processes, evaporation and transpiration. So the evapotranspiration is the total quantity of water, in the shape of vapor, transferred from atmosphere, hydrosphere, biosphere, lithosphere and anthroposphere.

$$ET = E_w + E_t + E_s + E_i + E_d + E_g$$

where:

ET evapotranspiration [unit of height] or [unit of volume / unit of time]

E_w evaporation from water surface [unit of height] or [unit of volume / unit of time]

E_t transpiration produced by the vegetation biological process [unit of height] or [unit of volume / unit of time]

E_s evaporation from soil surface without vegetation [unit of height] or [unit of volume / unit of time]

E_i evaporation of rainfall quantity intercepted by vegetal covering and also by constructions [unit of height] or [unit of volume / unit of time]

E_d evaporation of rainfall quantity accumulated in ground depressions without possibilities of infiltration [unit of height] or [unit of volume / unit of time]

E_g evaporation from snow and glacier surface [unit of height] or [unit of volume / unit of time]

Or Evaporation and transpiration vary in their sources from which the water is transformed. A combination of losses of water by evaporation together with transpiration from vegetation is known as Evapotranspiration. The estimation of Evaporation from open water bodies is frequently required in planning, design of many water resource projects. If you design a long canal in arid or semi-arid region due to serious consideration of Evaporation loss.

Important requirements for evaporation and transpiration process

- ✓ *Energy (direct solar radiation): required to change the state of water molecule from liquid to gaseous (vapor).*
- ✓ *Vapor pressure gradient (Driving force): to remove water vapor from evaporation surface (the difference between vapor pressure at the Evaporating surface and surrounding atmosphere ($e_s - e_a$)).*
- ✓ *When the number of water molecule that leave from water bodies as vapor is equal to the number of water molecule that fall back to after condensation, this process is saturation ($e_s - e_a$).*

Dalton (1802) establishes a law that expressed evaporation rate from water surface depending on the air saturation deficit and wind speed.

$$E = f(u) (e_s - e_a).$$

Where: E=Open water evaporation, mm/day

f(u)= wind speed function

e_s=saturation vapor pressure at water surface temperature, mmHg

e_a=actual vapor pressure, mmHg

Vapor pressure at the saturation state can be expressed by the relation:

$$e_s = 6.11 \exp\left(\frac{17.24T_m}{237.3 + T_m}\right)$$

Evaporation is continued three conditions should be satisfied:

- ✓ *There should be constant supply water*
- ✓ *There should be constant supply heat.*
- ✓ *There should be constant supply vapor deficit.*

3.2 Factors affecting evaporation

*Transfer of water into vapors requires energy known as **latent heat of vaporization**.*

1. *Meteorological factors: The meteorological factors that influence the evaporation process are it is supplied by solar radiation. The amount of radiation available for*

evaporation depends on: Latitude, Atmospheric (weather) conditions, Storage of heat in the water body, absorption by the atmosphere etc.

Rate of evaporation depends on the following Meteorological factors:

- *Temperature*
- *Wind speed*
- *Relative humidity*
- *Solar radiation*
- *Heat storage of water bodies*
- *Soluble salt content*

Temperature

Although there is no strong correlation between temperature and evaporation, there is generally an increase in evaporation rate with increasing temperature. Saturation vapor pressure of the air is dependent on air temperature with a direct relationship between them. Evaporation is dependent on the vapor pressure.

✓ Wind speed

Evaporation rate depends on the speed of the wind which is responsible to move the moisture away from the evaporating surface. Thus, evaporation increases with increase in wind speeds. The direction of the wind is however immaterial. Wind speed varies with elevation and generally speeds at a height of 2 m above the ground surface are used in estimation of evaporation. From the speed measured at height h, the wind speed at 2m can be estimated from:

$$U_2 = \frac{2.11 * U_h}{\log(66.7h - 5.3)}$$

In many stations wind speed is measured at a height of about 10 m above the ground surface and, speed at 2 m height can be estimated from: $U_2 \approx 0.75 * U_{10}$.

✓ Relative humidity

Evaporation highly depends on the air humidity. If the air becomes fully saturated with moisture, then evaporation ceases. Water content of the air or humidity is measured as water vapor pressure (kpa). The water vapor pressure at which the air is saturated with vapor is called

saturation vapor pressure e_s . The actual vapor pressure of the air is designated by e_a . Relative humidity is the ratio of actual to saturation vapor pressure.

$$RH = \frac{e_a}{e_s} * 100$$

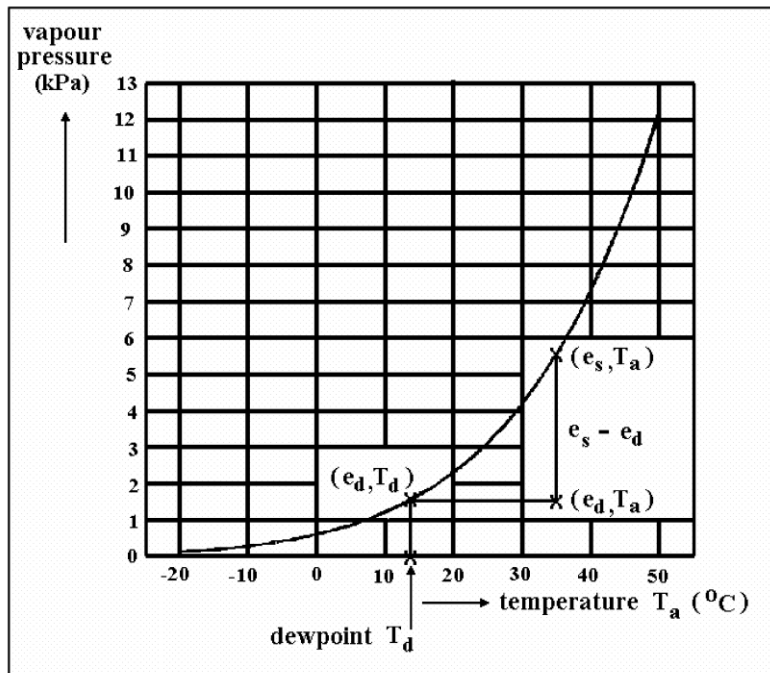


Fig: Relationship between saturation vapor pressure e_s and air temperature

When the air is fully saturated with water vapor, RH will be 100% at which evaporation stops.

With increasing RH, evaporation decreases.

✓ Solar radiation

The latent heat of vaporization required for evaporation is

$L = 2.45 * 10^6 \text{ J / kg}$. This heat or energy is directly or indirectly supplied from the sun.

Solar radiation is a dominant factor determining evaporation. Net radiation for evaporation is the difference between the incoming short wave radiation R_A and the fraction that is reflected back including the outgoing long wave radiation from the earth's surface.

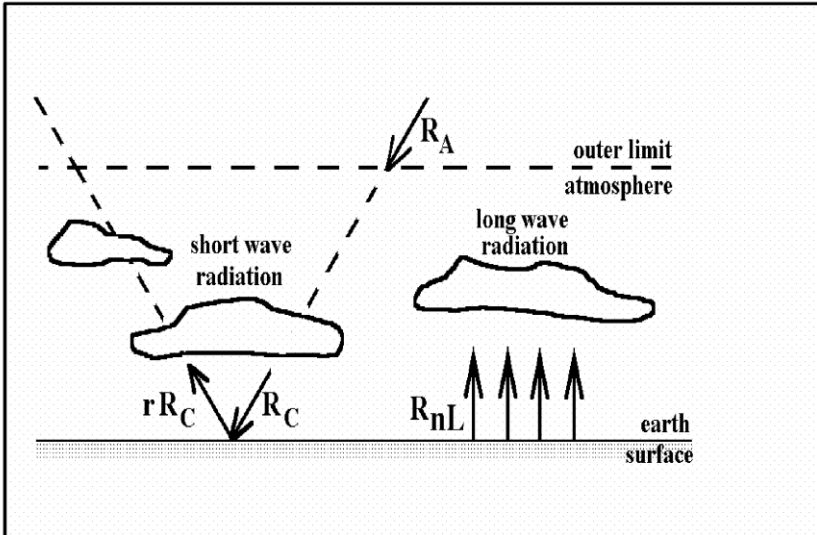


Fig: Radiation balance

The net short wave radiation is thus given by $R_s - r \cdot R_s = R_s(1-r)$ where r is Albedo or reflection coefficient.

Evaporating body	Value of r
Free water surface	0.06
Grass	0.22-0.25
Bare soil	0.10-0.30
Fresh snow	0.90

✓ **Heat storage of water bodies**

Seasonal variation of evaporation rate is affected by the heat storage capacity of the water bodies. Deep water bodies can store more heat for a long time than shallow water bodies.

✓ **Soluble salt content**

Presence of soluble salts in water reduces the rate of evaporation. For instance, evaporation from sea or ocean is about 3% less than that of fresh water.

2. **Physical factor:** The physical factors that have a major interference in the evaporation process are: the depth of the free water surface, the shape of the free water surface and the water salinity.

✓ **Depth of open water surface**

This characteristic plays an important role in energy storage. The essential difference between a shallow water surface and a deep-water surface results from the sensitivity of the shallow surface to seasonal climatic variations. A shallow water surface will follow closely meteorological variations, and the deep-water surface with an important temperature delay will present a different answer to climatic exchanges [Musy, 2001].

✓ **Shape of open water surface**

The nature of the evaporating surface affects evaporation by modifying the wind pattern. Over a rough, irregular surface, friction reduces the wind speed but tends to cause turbulence so that, with an induced vertical component of the wind, evaporation is enhanced.

✓ **Water salinity**

An increase of salinity concentration by 1% reduces the evaporation by 1% by reducing water pressure. This decreased pressure is directly proportional to the concentration of saline solution [Musy, 2001].

Transpiration

Transpiration is the process by which water is lost as vapors from the body of living plants. Water is normally taken up from the soil moisture by the roots of the plant and is lost through the leaf. All the factors affecting evaporation from open water surface also affect transpiration.

However there are two basic differences between evaporation and transpiration:

1. *Transpiration takes place only during daylight hours and is not the case for evaporation*
2. *Rate of transpiration depends on the growth stage of the plant*

3.3 Measurement Estimation of open water evaporation

Evaporation is of great importance in hydraulic and irrigation streams. Estimation of open water evaporation in reservoir planning is mandatory. In arid areas where water is a scarce resource, evaporation is a prime concern.

Evaporation from the pan is larger than open water evaporation from a water body due to the following reasons:

- Extra energy received from the sides of the pan
- Higher temperature over the pan
- Higher vapor pressure deficit over the pan

The rate of Evaporation from large water surface such as river, ponds reservoir, etc. can be determined by the following method:

1. Water budget method
2. Energy budget method
3. Empirical budget method

Water budget method

Is based on principle of inflow into the field is equal to out flow water from the same.

Sometimes known as the inflow–out flow method, which can give by the following expressions.

$$P + Q_i + -Q_g = E + Q_o + -Q_s$$

Energy budget method

It estimation on the principle of conservation of energy. This method is theoretical sound, but required a large number of hydro meteorological data which are not commonly available. The various energy based formula are as follow:

1. Penman formula(1948)

$$E = 0.89(1 - 0.52U_2)(e_s - e_a)$$

2. Meyer formula (1915).

$$E = c(e_s - e_a)(1 + U_9/16)$$

U_9 = mean wind velocity in km/hr at about 9m above the ground.

c = coefficient of the accounting for the other factor with the values of for 0.36 for the large deep water and 0.50 for small, shallow water

3. USSR formula

$$E = 4.57T + 43.3$$

4. Fritzerals equation

$$E = (0.4 + 0.124U)(e_s - e_a)$$

Empirical budget method

A large number of empirical equations are available to estimate the lake evaporation using commonly meteorological data.

Meyer formula (1915).

$$E = c(e_s - e_a)(1 + \frac{U_9}{16})$$

U_9 = mean wind velocity in km/hr at about 9m above the ground.

C = coefficient of the accounting for the other factor with the values of for 0.36 for the large deep water and 0.50 for small, shallow water

Rohwar's formula

Consider a correction for the effect of pressure in the addition to the the wind speed effect and given by:

$$E = 0.771(1.465 - 0.000732P_a)(0.44 + 0.0733U_a)(e_s - e_a)$$

P_a = mean barometric reading (mmHg)

U_o = mean wind velocity (km/hr) at the ground level which can be taken to be velocity at the height above the ground.

Table: Saturation vapor pressure of water

Temperature (°C)	Saturation vapor pressure e_s		Slope of plot between (1) and (2)
	mmHg)	mbar	
(1)	(2)	(3)	(4)
0.0	4.58	6.11	0.30
5.0	6.54	8.72	0.45
7.5	7.78	10.37	0.54
10.0	9.21	12.28	0.60
12.5	10.87	14.49	0.71
15.0	12.79	17.05	0.80
17.5	15.00	20.00	0.95
20.0	17.54	23.38	1.05

22.5	20.44	27.95	1.24
25.0	23.76	31.67	1.40
27.5	27.54	36.71	1.61
30.0	31.81	42.42	1.85
32.5	36.68	48.89	2.07
35.0	42.81	57.07	2.35
37.5	48.36	64.46	2.62
40.0	55.32	73.14	2.95
42.5	62.18	84.23	3.25
45.0	71.20	94.91	3.66

A reservoir with a surface area of 250 hectares had the following average values of climate parameters during a week: Water temperature = 20°C, Relative humidity = 40%, Wind velocity at 1.0 m above ground surface = 16 km/h. Estimate the average daily evaporation from the lake by using Meyer's formula.

Solution:

$$e_w = 17.54 \text{ mm of Hg} \quad e_a = 0.4 \times 17.54 = 7.02 \text{ mm of Hg}$$

$$u_9 = \text{wind velocity at a height of 9.0 m above ground} = u_1 \times (9)^{1/7} = 21.9 \text{ km/h}$$

By Meyer's Formula [Eq. (3.3)],

$$E_L = 0.36 (17.54 - 7.02) \left(1 + \frac{21.9}{16} \right) = 8.97 \text{ mm/day}$$

Table: Saturation Vapour Pressure of Water

Temperature (°C)	Saturation vapour pressure e_w (mm of Hg)	Λ (mm/°C)
0	4.58	0.30
5.0	6.54	0.45
7.5	7.78	0.54
10.0	9.21	0.60
12.5	10.87	0.71
15.0	12.79	0.80
17.5	15.00	0.95
20.0	17.54	1.05
22.5	20.44	1.24
25.0	23.76	1.40
27.5	27.54	1.61
30.0	31.82	1.85
32.5	36.68	2.07
35.0	42.81	2.35
37.5	48.36	2.62
40.0	55.32	2.95
45.0	71.20	3.66

Table: mean monthly solar radiation of at top of atmosphere H_a in mm of evaporable water/day.

North latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0°	14.5	15.0	15.2	14.7	13.9	13.4	13.5	14.2	14.9	15.0	14.6	14.3
10°	12.8	13.9	14.8	15.2	15.0	14.8	14.8	15.0	14.9	14.1	13.1	12.4
20°	10.8	12.3	13.9	15.2	15.7	15.8	15.7	15.3	14.4	12.9	11.2	10.3
30°	8.5	10.5	12.7	14.8	16.0	16.5	16.2	15.3	13.5	11.3	9.1	7.9
40°	6.0	8.3	11.0	13.9	15.9	16.7	16.3	14.8	12.2	9.3	6.7	5.4
50°	3.6	5.9	9.1	12.7	15.4	16.7	16.1	13.9	10.5	7.1	4.3	3.0

3.4 Computation of areal evaporation

The analytical method for determine the lake evaporation can be broadly classified into the three catogrose as.

- ✓ Water balance method
- ✓ Energy method
- ✓ Mass transfer (aerodynamic) method

Water balance method

It the simplest method of three analytical methods and least releable.it involves writing of hydrological continuity equation for the lake and determine the estimation of the other variable.

Consider the Daily average value for a lake, the continuity equation is written as:

$$P + V_{is} + V_{ig} = V_{os} + V_{og} + E_L + \Delta S + T_L$$

$$E_L = P + (V_i - V_{os}) + (V_{ig} - V_{og}) - T_L - \Delta S$$

Energy balance method

It is an application of the laws of conservation of energy. This method is widely used for estimating the amount of evaporation from a large body of water such as lakes, reservoirs etc. The available for the evaporation is determined by the incoming energy outgoing and energy stored in the water bodies over the known the interval of the water body.

Consider an evaporation pan of a circular tank containing water, in which the rate of evaporation is measured by the rate of fall of the water surface ($E_r = -dh/dt$). Based on the continuity and energy equation, one can derive the energy balance equation for evaporation as

$$E_r = \frac{1}{l_v \rho_w} (R_n - H_s - G)$$

If the sensible heat flux H_s (sensible heat loss to surroundings atmosphere to raise the temperature) and the ground heat flux G are both zero, then an evaporation rate E_r can be calculated as the rate at which all the incoming net radiation is

$$E_r = \frac{R_n}{l_v \rho_w}$$

Absorbed by evaporation:

where l_v = latent heat of vaporization (J/kg), [l_v (kJ/kg) = 2500 - 2.36 * T ($^{\circ}\text{C}$) up to 40 $^{\circ}\text{C}$]

ρ_w = water density (kg/m³)

R_n = net radiation (W/m²)

E_r = rate of evaporation (m/s)

Example Calculate by the energy method the evaporation rate from an open water surface, if the net radiation is 200 W/m² and the air temperature is 25 $^{\circ}\text{C}$, assuming no sensible heat or ground heat flux.

Solution: The latent heat of vaporization at 25 $^{\circ}\text{C}$ is $l_v = 2500 - 2.36 * 25 = 2441$ kJ/kg. Density of water at 25 $^{\circ}\text{C}$ is 997 kg/m³.

$$\begin{aligned} E_r &= \frac{R_n}{l_v \rho_w} \\ &= \frac{100}{2441 * 1000 * 997} \\ &= 8.22 * 10^{-8} \\ &= 8.22 * 10^{-8} * 1000 * 86400 \text{ mm/day} \\ &= 7.10 \text{ mm/day} \end{aligned}$$

3.5 Reservation evaporation methods for its reduction

The reduction of evaporation has great method economic importance especially in arid climate. The evaporation control is particular important ways to conserve water conservation because it usually required a new contraction and additional water become available without contraction delay.

3.5.1 Methods of reduce evaporation loss

Various methods available for reduce evaporation loss can be considered as:

(i) **REDUCTION OF SURFACE AREA** Since the volume of water lost by evaporation is directly proportional to the surface area of the water body, the reduction of surface area wherever feasible reduces evaporation losses. Measures like having deep reservoirs in place of wider ones and elimination of shallow areas can be considered under this category.

(ii) **MECHANICAL COVERS** Permanent roofs over the reservoir, temporary roofs and floating roofs such as rafts and light-weight floating particles can be adopted wherever feasible. Obviously these measures are limited to very small water bodies such as ponds, etc.

(iii) **CHEMICAL FILMS** This method consists of applying a thin chemical film on the water surface to reduce evaporation. Currently this is the only feasible method available for reduction of evaporation of reservoirs up to moderate size.

Certain chemicals such as *cetyl alcohol* (hexadecanol) and *stearyl alcohol* (octadecanol) form monomolecular layers on a water surface. These layers act as evaporation inhibitors by preventing the water molecules to escape past them. The thin film formed has the following desirable features:

1. The film is strong and flexible and does not break easily due to wave action.
2. If punctured due to the impact of raindrops or by birds, insects, etc., the film closes back soon after.
3. It is pervious to oxygen and carbon dioxide; the water quality is therefore not affected by its presence.
4. It is colourless, odourless and nontoxic.

Cetyl alcohol is found to be the most suitable chemical for use as an evaporation inhibitor. It is a white, waxy, crystalline solid and is available as lumps, flakes or powder. It can be applied to the water surface in the form of powder, emulsion or solution in mineral turpentine. Roughly about 3.5 N/hectare/day of cetyl alcohol is needed for effective action. The chemical is periodically replenished to make up the losses due to oxidation, wind sweep of the layer to the shore and its removal by birds and insects. Evaporation reduction can be achieved to a maximum if a film pressure of 4×10^{-2} N/m is maintained.

3.6 Measurement of Evapotranspiration

In a vegetative ground, both evaporation from the land surface and transpiration from plants take place at the same time. These two losses are combined together and are called *Evapotranspiration*.

Evapotranspiration occurs simultaneously and there is no easy way to distinguish.

Potential Evapotranspiration (PET): the rate at which the water, if the available would be remove from the wet soil and plant surface (unit depth of water per unit area).

Actual Evapotranspiration (AET): quantity of water actually removes from a surface due to the process of E and T.

Open water Evapotranspiration can be estimated in two important ways:

- Using experimenters field measurement and
- Using climatic approach evaporation equations methods

Experimenters field measurement:

Lysimeter: special watertight tank containing block of soil and set in the field of growing plant.

This method is important for the irrigation point of views are set up to enable the operate to measure

- ✓ Water balance
- ✓ Water added water retained by the soil
- ✓ Water lost through the all source
- ✓ Field experimental plot method: all elements all water budgets is known interval of time.

$ET = \text{Precipitation} + \text{Irrigation input} + \text{runoff} + \text{decreased soil storage} + \text{ground water loss}$

Using climatic approach evaporation

Some empirical and theoretical equations are derived on the basis of regional relationship between measured ET and climatic factor. The following methods are the combination of some empirical theoretical and analytical approach.

1. FAO Blenny –Criddle methods

$$PET_o = \sum K.F$$

$F = (0.46T + 0.812)$, (mm/days) K=monthly crop coefficient

2. FAO radiation methods

$$ET_o = c(w.R_s) \text{ (mm/days)}$$

3. FAO modified penman method

$$ET_o = c(w.R_s + (1-w)f(u)(e_s - e_a))$$

4. Hargreaves method

$$ET_o = 0.023 * R_a (T + 17.8) TD^{0.5}$$

5. *FAO Pan evaporation method*

$$ET_o = K_p * E_{pan}$$

6. *FAO Penman-Moneith method*

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} V_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34V_2)}$$

Where:

C in (1) = adjacent factor depended on the mean, sunshine hour and daytime wind estimation.

C in (2) = adjacent factor depended on the mean, sunshine hour and daytime wind condition.

C in (3) = adjacent factor depended to compensate of the day and night weather condition.

T=mean daily temp (°c) over the monthly consideration.

P= mean daily % of total annual day time hour obtained from the relevant table for a given month and latitude.

Rs=solar radiation in equivalent evaporation mm/day

w in (2)= temperature and latitude depending weighing factor.

w in (3)= temperature and weighing factor for the effect of radiation on PET.

(1-w)= temperature and elevation weighing factor for the effect of wind and humidity on PET.

Rn=net radiation in equivalent evaporation

f(u)= wind related function.

Ra=extraterisital radiation

TD=difference between max and min temperature.

Epan=pan evaporation.

Kpan=pan coefficient.

Rn=net radiation at crop surface (MJ/m²day).

G=soil heat flux (MJ/m²day)

V2=wind speed at 2m height (m/s)

= slope of vapor pressure curve (kPa/°C)

= hygrometric constant (kPa/°C)

- *900=conversion factor*

7. FAO-Penman¹ Method

Penman developed a theoretical formula based on the principles of both energy budget and mass-transfer approaches to calculate potential evapotranspiration. A simple energy budget neglecting all minor losses can be written as:

$$ET = \frac{(\Delta \times H + \gamma \times E_a)}{(\Delta + \gamma)}$$

Where H is the heat budget of an area with crops which is the net radiation in mm of evaporable water per day, ET the daily evaporation from free water surface in mm/day, γ is a constant (called psychrometric constant whose value is 0.49 mmHg/°C or 0.66 mb/°C, Δ the slope of the saturated vapor pressure vs. temperature curve at mean air

$$H = H_a(1 - r)(0.29 \cos \phi + 0.55n/N) - \sigma T_a^4 (0.56 - 0.092 \sqrt{e_a})(0.10 + 0.9n/N)$$

$$E_a = 0.002187(160 + u_2)(e_s - e_a) \text{ and } ET_o = \frac{(\Delta \cdot H + \gamma \cdot E_a)}{(\Delta + \gamma)}$$

T_a is the mean air temperature in °K = (273 + °C)

1. *Blanney-Criddle method*: proposed an empirical relation with which is used largely by irrigation engineers to calculate crop water requirement of various crop. Estimation of potential evapotranspiration (consumptive use) is carried out by correlating it with sunshine, temperature. Sunshine at place is depending on latitude of the place and varies month of year.

$$PET = \Sigma K.F$$

$$F = (0.0457T_M + 0.8128)P$$

Here K is the monthly crop coeff. to be determine from exponential data.

F the monthly consumptive use) factor PET = potential evapotranspiration in cm,
 T_M =mean monthly temp in °C, P = is monthly percentage of hour of bright Sunshine in year.

Table: Monthly day light hour's percentage (P) to be used by Blaney-Criddle Formula

Lat. °N	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
0	8.50	7.66	8.49	8.21	8.50	8.22	8.50	8.49	8.21	8.50	8.22	8.50
10	8.13	7.47	8.45	8.37	8.81	8.60	8.86	8.71	8.25	8.34	7.91	8.10
15	7.94	7.36	8.43	8.44	8.98	8.80	9.05	8.83	8.28	8.26	7.75	7.88
20	7.74	7.25	8.41	8.52	9.15	9.00	9.25	8.96	8.30	8.18	7.58	7.66
25	7.53	7.14	8.39	8.61	9.33	9.23	9.45	9.09	8.32	8.09	7.40	7.42
30	7.30	7.03	8.38	8.72	9.53	9.49	9.67	9.22	8.33	7.99	7.19	7.15
35	7.05	6.88	8.35	8.83	9.76	9.77	9.93	9.37	8.36	7.87	6.97	6.86
40	6.76	6.72	8.33	8.95	10.02	10.08	10.22	9.54	8.39	7.75	6.72	6.52
42	6.63	6.65	8.31	9.00	10.14	10.22	10.35	9.62	8.40	7.69	6.62	6.37
44	6.49	6.58	8.30	9.06	10.26	10.38	10.49	9.70	8.41	7.63	6.49	6.21
46	6.34	6.50	8.29	9.12	10.39	10.54	10.64	9.79	8.42	7.57	6.36	6.04
48	6.17	6.41	8.27	9.18	10.53	10.71	10.80	9.89	8.44	7.51	6.23	5.86
50	5.98	6.30	8.24	9.24	10.68	10.91	10.99	10.00	8.46	7.45	6.100	5.65

Use Blaney-Criddle method , estimate the consumptive use(PET)and net irrigation demands for the rice crop grown from Jan to march at the latitude of 22° from following data taken from nearly observatory, if the monthly crop coefficient of rise is 1.10 and 80% of effective rainfall use, the detailed information are given below.

month	Jan	Feb	Mar
Mean monthly temperature(°c)	12	16	24
Rainfall(mm)	8	20	16
Monthly day time hour@20°	7.74	7.25	8.41
Monthly day time hour@25°	7.53	7.14	8.39

Solution: for rice crop, monthly crop coeff. .K to be used in Blaney-Criddle method may be taken as 1.10 mean monthly Sunshine hour @ the latitude of 22° from Jan, Feb, and March where P (mean monthly Sunshine hour @ the latitude of 22°) can be calculated by interpolation techniques:

month	Mean monthly temp	Monthly %(p) of daytime hour from table	monthly consumptive use	K	PET=col4*col5	Effective RF at 80%(cm)	Depth of irrigation Col6-col7
col1	col2	col 3	col 4	col 5	col 6	col 7	col 8
jan	12	7.62	10.37	1.10	11.40	0.64	10.76
feb	16	7.20	11.12	1.10	12.23	1.60	10.63
march	24	8.40	16.04	1.10	17.64	1.28	16.36

F for col 4 jan = $0.0457T_m + 0.8128$)* P

= $0.0457*12 + 0.8128$)* $7.62 = 10.37\text{cm}$

F for col4 feb = $0.0457*16 + 0.8128$)* $7.20 = 11.12\text{cm}$

F for col4 mar = $0.0457*24 + 0.8128$)* $8.40 = 16.04\text{cm}$

Net irrigation demand = $10.76 + 10.63 + 16.36 = 37.75\text{cm}$

EXAMPLE: The following observatories were made for the conducting the water budget of a reservoir over the period of one month of 30days the given items are:

Average surface area = 10km^2	Rainfall = 10cm
Mean surface inflow = $10\text{m}^3/\text{s}$	Mean surface outflow = $15\text{m}^3/\text{s}$
Fall in reservoir level = 1.5m	Pan evaporation = 20cm
Pan evaporation coefficient = 0.70	

Estimate average seepage discharge during the month?

Solution: area of the reservoir = $10*10^6\text{m}^2$

Inflow items(m^3)	outflow items(m^3)
Surface inflow = $10*3600*24*30 = 25,920,000$	Surface outflow = $15*30*24*3600 = 38,880,000$
Rainfall = $(10/100)\text{m} * \text{area of reservoir}$ $(10/100)\text{m} * 10*10^6\text{m}^2 = 1,000,000\text{m}^3$	Evaporation = pan constant * pan evap * area of reservoir = $0.70 * (20/100)\text{m} * 10*10^6\text{m}^2 = 1,400,000$
Total inflow volume = $26,920,000\text{m}^3$	Total outflow volume = $40,280,000$

Total outflow volume - Total inflow volume = reduction of storage ($1.5\text{m} * 10*10^6\text{m}^2$)

$(40,280,000 + Se) - (26,920,000\text{m}^3) = 15,000,000$

$Se = 1,640,000 = 1.64\text{Mm}$

Mass transfer method and the energy balance approach

Using the mass transfer method and the energy balance approach, Penman derived an equation used for open water evaporation.

Penman equation

Penman in 1948 derived an equation for open water evaporation. His equation is given as:

$$E_o = \frac{C}{L} \frac{sR_N + c_p \rho_a (e_s - e_d) / r_a}{s + \gamma}$$

where

E_o	open water evaporation in mm.d ⁻¹
C	constant to convert units from kg.m ⁻² .s ⁻¹ to mm.d ⁻¹ ($C = 86400$)
R_N	net radiation at the earth's surface in W.m ⁻²
L	latent heat of vaporization ($L = 2.45 * 10^6$ J.kg ⁻¹)
s	slope of the temperature-saturation vapour pressure curve (kPa.K ⁻¹)
c_p	specific heat of air at constant pressure ($c_p = 1004.6$ J.kg ⁻¹ .K ⁻¹)
ρ_a	density of air ($\rho_a = 1.2047$ kg.m ⁻³ at sea level)
e_d	actual vapour pressure of the air at 2 m height in kPa
e_s	saturation vapour pressure for the air temperature at 2 m height in kPa
γ	psychrometric constant ($\gamma = 0.067$ kPa.K ⁻¹ at sea level)
r_a	aerodynamic resistance in s.m ⁻¹

The saturation vapor pressure can be determined from either the e_s versus temperature curve or from formula such as:

$$e_s = 0.6108 e^{\frac{17.27 T_a}{237.3 + T_a}}$$

in which T_a is daily mean temperature of the air in °C.

The aerodynamic resistance, r_a (s.m⁻¹) is a function of the wind speed, U_2 measured at a height of 2 m. Penman proposed the following expression for an open water surface

$$r_a = \frac{245}{0.54 U_2 + 0.5}$$

Net radiation R_N is estimated from

$$R_N = (1 - r) R_s - R_{n_L}$$

R_s data is often available, if not it can be estimated from the extraterrestrial radiation, R_A which can be obtained from the following tables for different latitudes.

$$R_s = (a + b \frac{n}{N})R_A$$

where the cloudiness n/N is defined as

$$\frac{n}{N} = \frac{\text{actual hours of sunshine}}{\text{possible hours of sunshine}}$$

and a and b are constants

n = actual sunshine hours per day

N = mean possible daily sunshine hours

The Netherlands	$R_s = (0.20 + 0.60 \frac{n}{N})R_A$
New Delhi	$R_s = (0.31 + 0.60 \frac{n}{N})R_A$
Singapore	$R_s = (0.21 + 0.48 \frac{n}{N})R_A$
General	$R_s = (0.25 + 0.50 \frac{n}{N})R_A$

Long wave radiation is emitted by the earth's surface, but also by water vapour and droplets (clouds!) in the air. The *net* outgoing long wave radiation R_{nL} (W.m^{-2}) may be estimated from the following empirical formula

$$R_{nL} = \sigma \frac{(273 + T_{\min})^4 + (273 + T_{\max})^4}{2} (0.34 - 0.139\sqrt{e_d}) (0.1 + 0.9 \frac{n}{N})$$

where σ is the Stefan-Boltzmann constant ($\sigma = 5.6745 \times 10^{-8} \text{ W.m}^{-2}.\text{K}^{-4}$), e_d is the actual vapour pressure of the air, and $T_{\min}$ and $T_{\max}$ are the minimum and maximum temperatures of the air in $^{\circ}\text{C}$, respectively.

	Lat	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
NORTHERN HEMISPHERE													
Equator	60	40	103	200	317	417	469	446	360	243	134	57	26
	52	91	157	252	357	440	475	457	389	292	192	111	74
	50	106	172	263	363	443	475	460	392	297	203	126	89
	40	177	240	317	395	455	477	466	420	346	266	194	160
	30	232	300	366	420	460	472	463	435	386	320	260	226
	20	309	354	400	435	449	452	452	440	412	369	323	297
	10	366	397	423	435	429	423	426	429	423	406	375	357
	0	415	429	435	420	397	383	389	409	426	429	417	409
	10	455	449	432	397	357	334	343	375	412	440	449	452
	20	489	457	415	357	306	277	289	332	389	437	469	483
	30	492	452	386	312	246	214	226	277	352	423	477	500
	40	495	432	349	254	183	149	160	217	306	395	472	509
	50	483	403	297	192	117	83	97	154	249	357	457	503
	60	472	360	237	123	51	26	37	89	186	309	432	500
SOUTHERN HEMISPHERE													

Shortwave radiation received at outer limits of the atmosphere, R_A , in W.m^{-2}

North Lats. South Lats.	Jan July	Feb. Aug.	Mar. Sept	Apr. Oct.	May Nov.	June Dec.	July Jan.	Aug. Feb.	Sept Mar.	Oct. Apr.	Nov. May	Dec. June
60	6.7	9.0	11.7	14.5	17.1	18.6	17.9	15.5	12.9	10.1	7.5	5.9
58	7.2	9.3	11.7	14.3	16.6	17.9	17.3	15.3	12.8	10.3	7.9	6.5
56	7.6	9.5	11.7	14.1	16.2	17.4	16.9	15.0	12.7	10.4	8.3	7.0
54	7.9	9.7	11.7	13.9	15.9	16.9	16.5	14.8	12.7	10.5	8.5	7.4
52	8.3	9.9	11.8	13.8	15.6	16.5	16.1	14.6	12.7	10.6	8.8	7.8
50	8.5	10.0	11.8	13.7	15.3	16.3	15.9	14.4	12.6	10.7	9.0	8.1
48	8.8	10.2	11.8	13.6	15.2	16.0	15.6	14.3	12.6	10.9	9.3	8.3
46	9.1	10.4	11.9	13.5	14.9	15.7	15.4	14.2	12.6	10.9	9.5	8.7
44	9.3	10.5	11.9	13.4	14.7	15.4	15.2	14.0	12.6	11.0	9.7	8.9
42	9.4	10.6	11.9	13.4	14.6	15.2	14.9	13.9	12.6	11.1	9.8	9.1
40	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.4	11.2	10.0	9.3
35	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.9	10.3	9.8
30	10.4	11.1	12.0	12.9	13.6	14.0	13.9	13.2	12.4	12.0	10.6	10.8
25	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	12.0	10.9	10.6
20	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	12.0	11.2	10.9
15	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	12.0	11.4	11.2
10	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	12.0	11.6	11.5
5	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
Equator 0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0

Mean daily duration of maximum sunshine hours, N

Thornth Waite method

This method uses;

- ✓ the mean daily temperature,
- ✓ latitude of the place
- ✓ the month of the year

$$PET = 1.62C \left(\frac{10T_m}{I} \right)^a$$

Where

PET = monthly Evapotranspiration or potential Evapotranspiration,

C = reduction factor (coefficient)

T_m = mean monthly temperature, ($^{\circ}C$)

a = constant,

The exponent a can be calculated as

$$a = 65.7 \cdot 10^{-8} |^3 - 77.3 \cdot 10^{-6} |^2 + 0.0179 | + 0.4921$$

I = the annual heat flux, given by

$$I = \sum_{m=1}^{12} \left(\frac{T_m}{5} \right)$$

Where

Assumed of each day has 12 hrs sunshine and each month has 30 days.

✚ **Jensen-Haise method(1963)**

Jensen and Haise proposed for computation of PET

$$PET = C_c (T - T_c) H_a$$

Where H_a = solar radiation in mm/day

The coefficient C_c calculated as

$$C_c = (1/C + 7.6 C_H)$$

$$C_H = (50 \text{ mbar} / (e_2 - e_1))$$

$C = 38 - (20^0 \cdot \text{Elevation (m)}) / 305$ Where $e_2 - e_1$ are the saturated vapor pressure at the maximum and minimum temperature for hottest month of the year respectively.

T = mean air temperature

$$T_c = -2.5 - 0.14(e_2 - e_1) - \frac{\text{catchment elevation (m)}}{550}$$