Module
2
The Science of Surface and Ground Water

Lesson
1
Precipitation And Evapotranspiration

Instructional Objectives

On completion of this lesson, the student shall learn:

1. The role of precipitation and evapotranspiration with the hydrologic cycle.
2. The factors that cause precipitation.
3. The means of measuring rainfall.
4. The way rain varies in time and space.
5. The methods to calculate average rainfall over an area.
6. What are Depth – Area – Duration curves.
7. What are the Intensity – Duration – Frequency curves.
8. The causes of anomalous rainfall record and its connective measures.
9. What are Probable Maximum Precipitation (PMP) and Standard Project Storm (SPS).
10. What are Actual and Potential evapotranspiration.
11. How can direct measurement of evapotranspiration be made.
12. How can evapotranspiration be estimated based on climatological data.

2.1.0 Introduction

Precipitation is any form of solid or liquid water that falls from the atmosphere to the earth's surface. Rain, drizzle, hail and snow are examples of precipitation. In India, rain is the most common form of precipitation.

Evapotranspiration is the process which returns water to the atmosphere and thus completes the hydrologic cycle. Evapotranspiration consists of two parts, Evaporation and Transpiration. Evaporation is the loss of water molecules from soil masses and water bodies. Transpiration is the loss of water from plants in the form of vapour. We proceed on to discuss precipitation, and its most important component in India context, the rainfall.

2.1.1 Causes of precipitation

For the formation of clouds and subsequent precipitation, it is for necessary that the moist air masses to cool in order to condense. This is generally accomplished by adiabatic cooling of moist air through a process of being lifted to higher altitudes. The precipitation types can be categorized as.

- **Frontal precipitation**
  This is the precipitation that is caused by the expansion of air on ascent along or near a frontal surface.

- **Convective precipitation**
  Precipitation caused by the upward movement of air which is warmer than its surroundings. This precipitation is generally showery nature with rapid changes of intensities.

- **Orographic precipitation**
  Precipitation caused by the air masses which strike the mountain barriers and rise up, causing condensation and precipitation. The greatest amount of precipitation will fall on the windward side of the barrier and little amount of precipitation will fall on leave ward side.

For the Indian climate, the south-west monsoon is the principal rainy season when over 75% of the annual rainfall is received over a major portion of the country. Excepting the south-eastern part of the Indian peninsula and Jammu and Kashmir, for the rest of the country the south-west monsoon is the principal source of rain.

From the point of view of water resources engineering, it is essential to quantify rainfall over space and time and extract necessary analytical information.

2.1.2 Regional rainfall characteristics

Rain falling over a region is neither uniformly distributed nor is it constant over time. You might have experienced the sound of falling rain on a cloudy day approaching from distance. Gradually, the rain seems to surround you and after a good shower, it appears to recede. It is really difficult to predict when and how much of rain would fall. However it is possible to measure the amount of rain falling at any point and measurements from different point gives an idea of the rainfall pattern within an area.

In India, the rainfall is predominantly dictated by the monsoon climate. The monsoon in India arises from the reversal of the prevailing wind direction from Southwest to Northeast and results in three distinct seasons during the course of the year. The Southwest monsoon brings heavy rains over most of the country between June and October, and is referred to commonly as the 'wet' season. Moisture laden winds sweep in from the Indian Ocean as low-pressure areas develop over the subcontinent and release their moisture in the form of heavy rainfall. Most of the annual rainfall in India comes at this time with the exception of in Tamil Nadu, which receives over half of its rain during the Northeast monsoon from October to November.

The retreating monsoon brings relatively cool and dry weather to most of India as drier air from the Asian interior flows over the subcontinent. From

November until February, temperatures remain cool and precipitation low. In northern India it can become quite cold, with snow occurring in the Himalayas as weak cyclonic storms from the west settle over the mountains. Between March and June, the temperature and humidity begin to rise steadily in anticipation of the Southwest monsoon. This pre-monsoonal period is often seen as a third distinct season although the post-monsoon in October also presents unique characteristics in the form of slightly cooler temperatures and occasional light drizzling rain. These transitional periods are also associated with the arrival of cyclonic tropical storms that batter the coastal areas of India with high winds, intense rain and wave activity.

Rainfall and temperature vary greatly depending on season and geographic location. Further, the timing and intensity of the monsoon is highly unpredictable. This results in a vastly unequal and unpredictable distribution over time and space. In general, the northern half of the subcontinent sees greater extremes in temperature and rainfall with the former decreasing towards the north and the latter towards the west. Rainfall in the Thar Desert and areas of Rajasthan can be as low as 200mm per year, whereas on the Shillong Plateau in the Northeast, average annual rainfall can exceed 10,000 mm per year. The extreme southern portion of the country sees less variation in temperature and rainfall. In Kerala, the total annual rainfall is of the order of 3,000 mm.

In this lecture, we discuss about rainfall measurement and interpretation of the data.

2.1.3 Measurement of rainfall

One can measure the rain falling at a place by placing a measuring cylinder graduated in a length scale, commonly in mm. In this way, we are not measuring the volume of water that is stored in the cylinder, but the 'depth' of rainfall. The cylinder can be of any diameter, and we would expect the same 'depth' even for large diameter cylinders provided the rain that is falling is uniformly distributed in space.

Now think of a cylinder with a diameter as large as a town, or a district or a catchment of a river. Naturally, the rain falling on the entire area at any time would not be the same and what one would get would be an 'average depth'. Hence, to record the spatial variation of rain falling over an area, it is better to record the rain at a point using a standard sized measuring cylinder.

In practice, rain is mostly measured with the ***standard non-recording rain gauge*** the details of which are given in Bureau of Indian Standards code IS 4989: 2002. The rainfall variation at a point with time is measured with a ***recording rain-gauge***, the details of which may be found in IS 8389: 2003. Modern technology has helped to develop Radars, which measures rainfall over an entire region. However, this method is rather costly compared to the conventional recording and non-recording rain gauges which can be monitored easily with cheap labour.

2.1.4 Variation of rainfall

Rainfall measurement is commonly used to estimate the amount of water falling over the land surface, part of which infiltrates into the soil and part of which flows down to a stream or river. For a scientific study of the hydrologic cycle, a correlation is sought, between the amount of water falling within a catchment, the portion of which that adds to the ground water and the part that appears as streamflow. Some of the water that has fallen would evaporate or be extracted from the ground by plants.

FIGURE 1. A hypothetical catchment showing four raing gauge stations

In Figure 1, a catchment of a river is shown with four rain gauges, for which an assumed recorded value of rainfall depth have been shown in the table.

		Time (in hours)				Total
		First	Second	Third	Fourth	Rainfall
Rain(mm)	A	15	10	3	2	30
	B	12	15	8	5	40
	C	8	10	6	4	28
	D	5	8	2	2	17

It is on the basis of these discrete measurements of rainfall that an estimation of the average amount of rainfall that has probably fallen over a catchment has to be made. Three methods are commonly used, which are discussed in the following section.

2.1.5 Average rainfall depth

The time of rainfall record can vary and may typically range from 1 minute to 1 day for non – recording gauges, Recording gauges, on the other hand, continuously record the rainfall and may do so from 1 day 1 week, depending on the make of instrument. For any time duration, the average depth of rainfall falling over a catchment can be found by the following three methods.

- The Arithmetic Mean Method
- The Thiessen Polygon Method
- The Isohyetal Method

Arithmetic Mean Method

The simplest of all is the Arithmetic Mean Method, which taken an average of all the rainfall depths as shown in Figure 2.

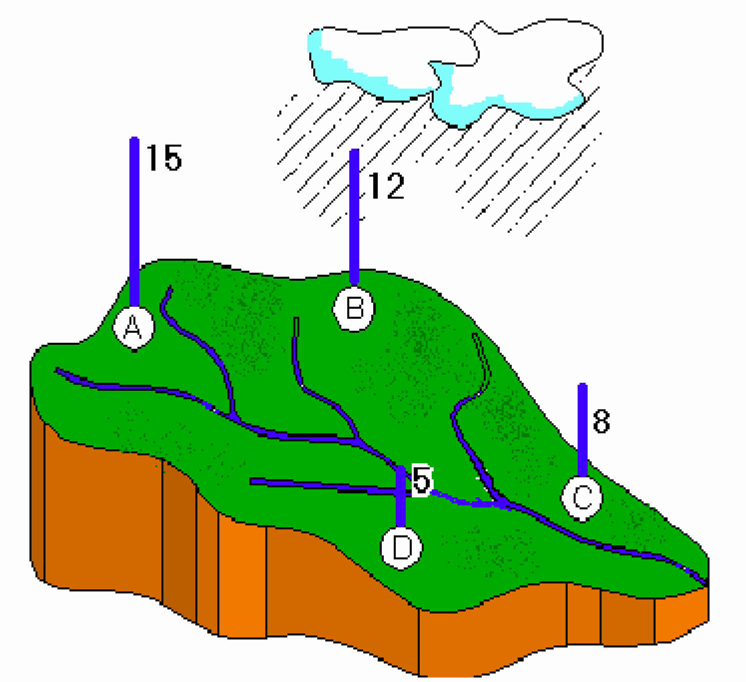

FIGURE 2. Representation of the rainfall recorded in the four rain gauges (values in mm)

Average rainfall as the arithmetic mean of all the records of the four rain gauges, as shown below:

$$\frac{15+12+8+5}{4} = 10.0\,\text{mm}$$

The Theissen polygon method

This method, first proposed by Thiessen in 1911, considers the representative area for each rain gauge. These could also be thought of as the areas of influence of each rain gauge, as shown in Figure 3.

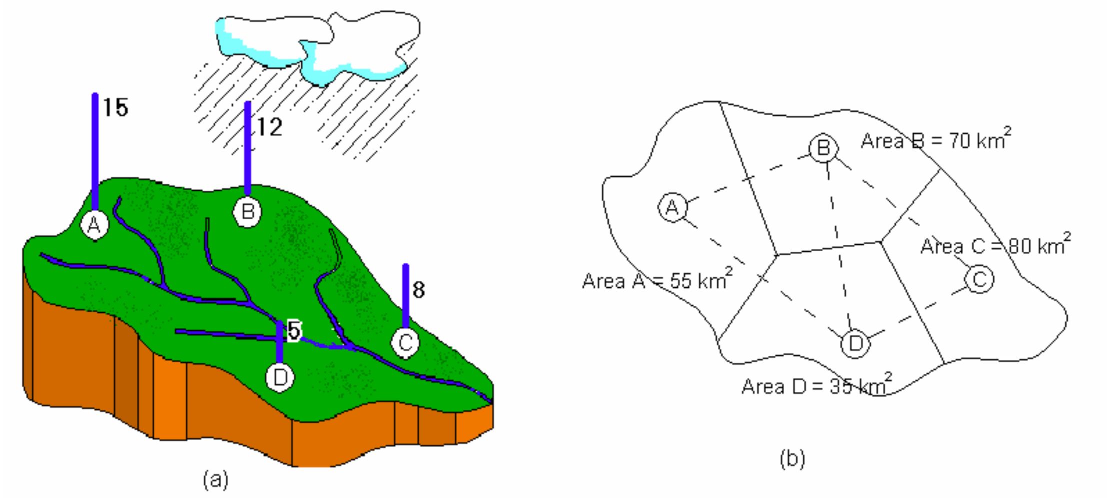

FIGURE 3. Rainfall measurement by Thiessen Polygon method. (a) Rainfall recorded; (b) Areas of influences

These areas are found out using a method consisting of the following three steps:

1. Joining the rain gauge station locations by straight lines to form triangles
2. Bisecting the edges of the triangles to form the so-called "Thiessen polygons"
3. Calculate the area enclosed around each rain gauge station bounded by the polygon edges (and the catchment boundary, wherever appropriate) to find the area of influence corresponding to the rain gauge.

For the given example, the "weighted" average rainfall over the catchment is determined as,

$$\frac{65\times15+70\times12+35\times8+80\times5}{(55+70+35+80)}=10.40\text{ mm}$$

The Isohyetal method

This is considered as one of the most accurate methods, but it is dependent on the skill and experience of the analyst. The method requires the plotting of ***isohyets*** as shown in the figure and calculating the areas enclosed either between the isohyets or between an isohyet and the catchment boundary. The areas may be measured with a ***planimeter*** if the catchment map is drawn to a scale.

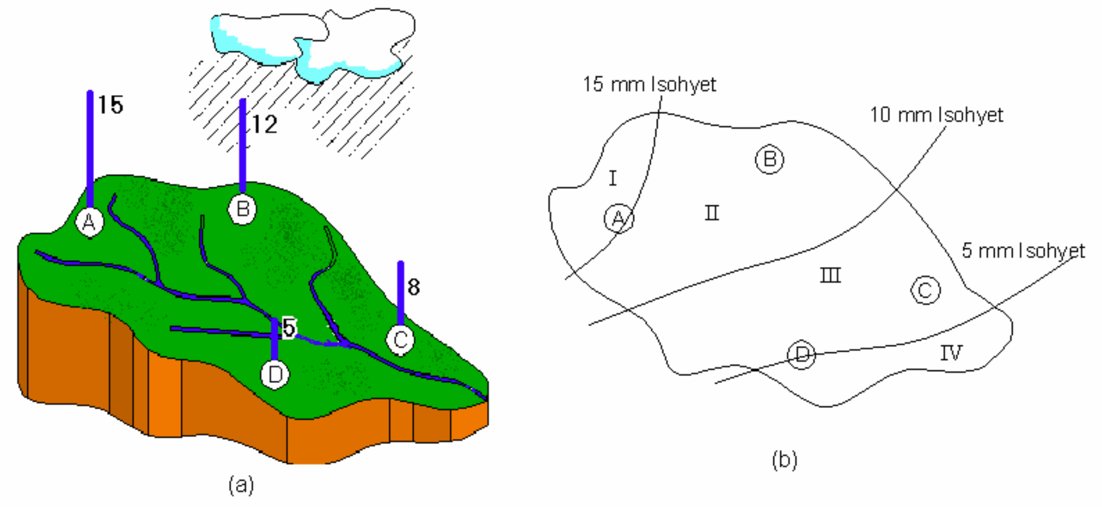

FIGURE 4. Rainfall measurement by the Isohyetal method. (a) Recorded rainfall; (b) Isohyets and the areas enclosed bewteen two consecutive isohyets.

For the problem shown in Figure 4, the following may be assumed to be the areas enclosed between two consecutive isohyets and are calculated as under:

Area I = 40 km^2
Area II = 80 km^2
Area III = 70 km^2
Area IV = 50 km^2
Total catchment area = 240 km^2

The areas II and III fall between two isohyets each. Hence, these areas may be thought of as corresponding to the following rainfall depths:

Area II : Corresponds to (10 + 15)/2 = 12.5 mm rainfall depth
Area III : Corresponds to (5 + 10)/2 = 7.5 mm rainfall depth

For Area I, we would expect rainfall to be more than 15mm but since there is no record, a rainfall depth of 15mm is accepted. Similarly, for Area IV, a rainfall depth of 5mm has to be taken.

Hence, the average precipitation by the isohyetal method is calculated to be

$$\frac{40\times15+80\times12.5+70\times7.5+50\times5}{240}$$

= 9.89 mm

Please note the following terms used in this section:

Isohyets: Lines drawn on a map passing through places having equal amount of rainfall recorded during the same period at these places (these lines are drawn after giving consideration to the topography of the region).

Planimeter: This is a drafting instrument used to measure the area of a graphically represented planar region.

2.1.6 Mean rainfall

This is the average or representative rainfall at a place. The mean annual rainfall is determined by averaging the total rainfall of several consecutive years at a place. Since the annual rainfall varies at the station over the years, a record number of years are required to get a correct estimate.

Similarly, the mean monthly rainfall at a place is determined by averaging the monthly total rainfall for several consecutive years. For example, the mean rainfall along with the mean number of rainy days for New Delhi (as obtained from World Meteorological Organisation – WMO) is as follows:

Month	Mean Total Rainfall (mm)	Mean Number of Rain Days
Jan	20.3	1.7
Feb	15.0	1.3
Mar	15.8	1.2
Apr	6.7	0.9
May	17.5	1.4
Jun	54.9	3.6
Jul	231.5	10.0
Aug	258.7	11.3
Sep	127.8	5.4
Oct	36.3	1.6
Nov	5.0	0.1
Dec	7.8	0.6

In comparison, that for the city of Kolkata, obtained from the same source, is as follows:

Month	Mean Total Rainfall (mm)	Mean Number of Rain Days
Jan	16.8	0.9
Feb	22.9	1.5
Mar	32.8	2.3
Apr	47.7	3.0
May	101.7	5.9
Jun	259.9	12.3
Jul	331.8	16.8
Aug	328.8	17.2
Sep	295.9	13.4

Oct	151.3	7.4
Nov	17.2	1.1
Dec	7.4	0.4

2.1.7 Depth-Area-Duration curves

In designing structures for water resources, one has to know the areal spread of rainfall within watershed. However, it is often required to know the amount of high rainfall that may be expected over the catchment. It may be observed that usually a storm event would start with a heavy downpour and may gradually reduce as time passes. Hence, the rainfall depth is not proportional to the time duration of rainfall observation. Similarly, rainfall over a small area may be more or less uniform. But if the area is large, then due to the variation of rain falling in different parts, the average rainfall would be less than that recorded over a small portion below the high rain fall occurring within the area. Due to these facts, a Depth-Area-Duration (DAD) analysis is carried out based on records of several storms on an area and, the maximum areal precipitation for different durations corresponding to different areal extents.

The result of a DAD analysis is the DAD curves which would look as shown in Figure 5.

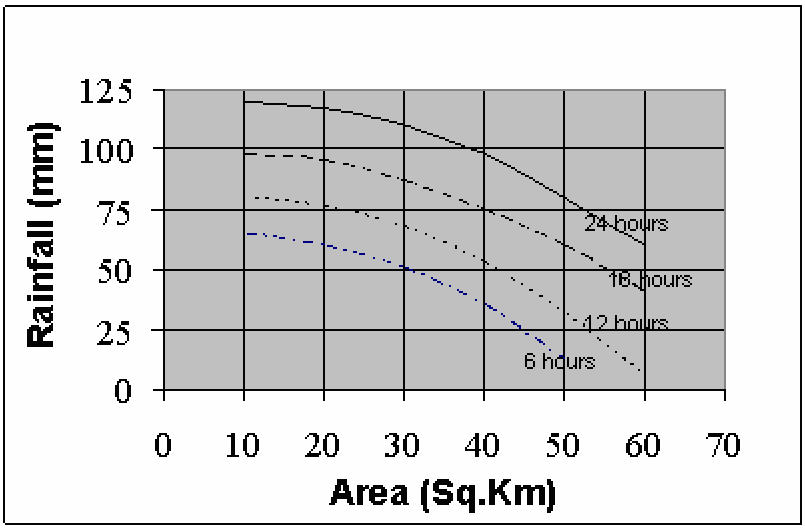

FIGURE 5. A typical Depth-Area-Duration (DAD) curve

2.1.8 Intensity-Duration-Frequency curves

The analysis of continuous rainfall events, usually lasting for periods of less than a day, requires the evaluation of rainfall intensities. The assessment of such values may be made from records of several part storms over the area and presented in a graphical form as shown in Figure 6.

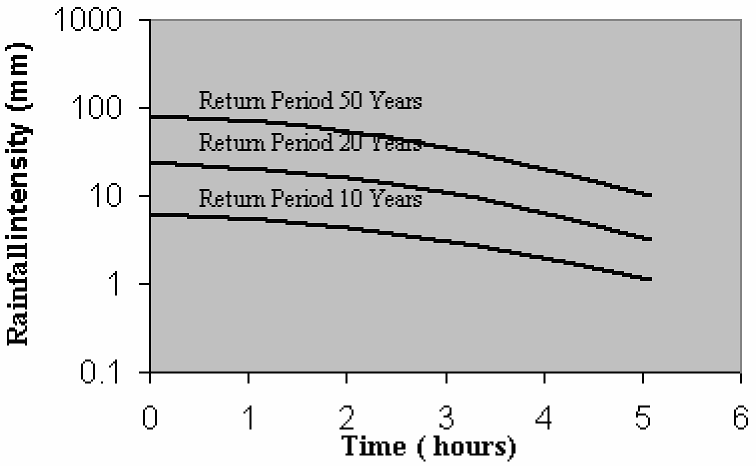

FIGURE 6. A typical rainfall intensity-duration-frequency (IDF) curve

Two new concepts are introduced here, which are:

- **Rainfall intensity**
  This is the amount of rainfall for a given rainfall event recorded at a station divided by the time of record, counted from the beginning of the event.

- **Return period**
  This is the time interval after which a storm of given magnitude is likely to recur. This is determined by analyzing past rainfalls from several events recorded at a station. A related term, the frequency of the rainfall event (also called the storm event) is the inverse of the return period. Often this amount is multiplied by 100 and expressed as a percentage. Frequency (expressed as percentage) of a rainfall of a given magnitude means the number of times the given event may be expected to be equaled or exceeded in 100 years.

2.1.9 Analysis for anomalous rainfall records

Rainfall recorded at various rain gauges within a catchment should be monitored regularly for any anomalies. For example of a number of recording rain gauges located nearby, one may have stopped functioning at a certain point of time, thus breaking the record of the gauge from that time onwards. Sometimes, a perfectly working recording rain gauge might have been shifted to a neighbourhood location, causing a different trend in the recorded rainfall compared to the past data. Such difference in trend of recorded rainfall can also be brought about by a change in the neighbourhood or a change in the ecosystem, etc. These two major types of anomalies in rainfall are categorized as

- Missing rainfall record
- Inconsistency in rainfall record

Missing rainfall record

The rainfall record at a certain station may become discontinued due to operational reasons. One way of approximating the missing rainfall record would be using the records of the three rain gauge stations closet to the affected station by the "Normal Ratio Method" as given below:

$$P_4 = \frac{1}{3}\left[\frac{N_4}{N_1}P_1 + \frac{N_4}{N_2}P_2 + \frac{N_4}{N_3}P_3\right] \qquad (1)$$

Where P_4 is the precipitation at the missing location, N_1, N_2, N_3 and N_4 are the normal annual precipitation of the four stations and P_1, P_2 and P_3 are the rainfalls recorded at the three stations 1, 2 and 3 respectively.

Inconsistency in rainfall record

This may arise due to change in location of rain gauge, its degree of exposure to rainfall or change in instrument, etc. The consistency check for a rainfall record is done by comparing the accumulated annual (or seasonal) precipitation of the suspected station with that of a standard or reference station using a double mass curve as shown in Figure 7.

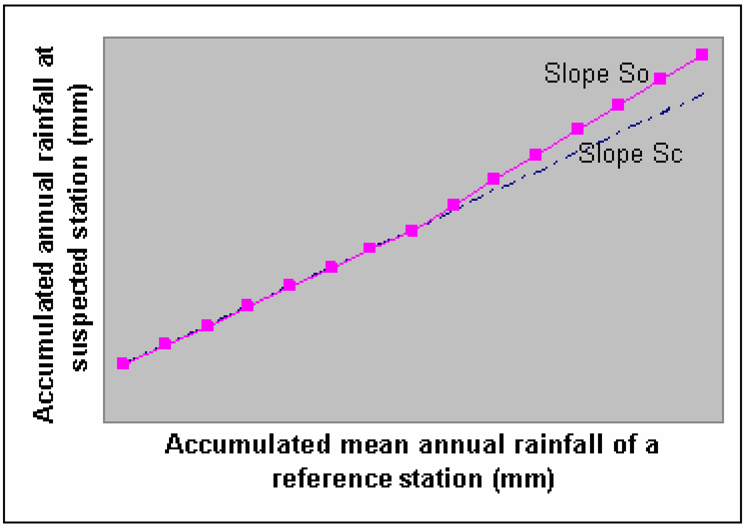

FIGURE 7. A typical example of inconsistent rainfall record

From the calculated slopes S_0 and S_c from the plotted graph, we may write

$$P_c = P_0 \left(\frac{S_c}{S_0} \right) \tag{2}$$

Where P_c and P_0 are the corrected and original rainfalls at suspected station at any time. S_c and S_0 are the corrected and original slopes of the double mass-curve.

2.1.10 Probable extreme rainfall events

Two values of extreme rainfall events are important from the point of view of water resources engineering. These are:

Probable Maximum Precipitation (PMP)

This is the amount of rainfall over a region which cannot be exceeded over at that place. The PMP is obtained by studying all the storms that have occurred over the region and maximizing them for the most critical atmospheric conditions. The PMP will of course vary over the Earth's surface according to the local climatic factors. Naturally, it would be expected to be much higher in the hot humid equatorial regions than in the colder regions of the mid-latitudes when the atmospheric is not able to hold as much moisture. PMP also varies within India, between the extremes of the dry deserts of Rajasthan to the ever humid regions of South Meghalaya plateau.

Standard Project Storm (SPS)

This is the storm which is reasonably capable of occurring over the basin under consideration, and is generally the heaviest rainstorm, which has occurred in the region of the basin during the period of rainfall records. It is not maximized for the most critical atmospheric conditions but it may be transposed from an adjacent region to the catchment under considerations.

The methods to obtain ***PMP*** and ***SPS*** are involved and the interested reader mayfind help in text books on hydrology, such as the following:

- Mutreja, K N (1995) Applied Hydrology, Tata McGraw Hill
- Subramanya, K (2002) Engineering Hydrology, Tata McGraw Hill

2.1.11 Evapotranspiration

As discussed earlier, evapotranspiration consists of evaporation from soil and water bodies and loss of water from plant leaves, which is called transpiration. It is a major component of the hydrologic cycle and its information is needed to design irrigation projects and for managing water quality and other environmental concerns. In urban development, evapotranspiration calculations are used to determine safe yields from aquifers and to plan for flood control. The term consumptive use is also sometimes used to denote the loss of water molecules to atmosphere by evapotranspiration. For a given set of atmospheric conditions, evapotranspiration depends on the availability of water. If sufficient moisture is always available to completely meet the needs of vegetation fully covering the area, the resulting evapotranspiration is called potential evapotranspiration (PET). The real evapotranspiration occurring in a specific situation is called actual evapotranspiration (AET).

2.1.12 Measurement of evapotranspiration

There are several methods available for measuring evaporation or evapotranspiration, some of which are given in the following sub-sections.

2.1.12.1 Potential Evapotranspiration (PET)

- **Pan evaporation**

The evaporation rate from pans filled with water is easily obtained. In the absence of rain, the amount of water evaporated during a period (mm/day) corresponds with the decrease in water depth in that period. Pans provide a measurement of the integrated effect of radiation, wind, temperature and humidity on the evaporation from an open water surface. Although the pan responds in a similar fashion to the same climatic factors affecting crop transpiration, several factors produce significant differences in loss of water from a water surface and from a cropped surface. Reflection of solar radiation from water in the shallow pan might be different from the assumed 23% for the grass reference surface. Storage of heat within the pan can be appreciable and may cause significant evaporation during the night while most crops transpire only during the daytime. There are also differences in turbulence, temperature and humidity of the air immediately above the respective surfaces. Heat transfer through the sides of the pan occurs and affects the energy balance.

Notwithstanding the difference between pan-evaporation and the evapotranspiration of cropped surfaces, the use of pans to predict ET_o for periods of 10 days or longer may be warranted. The pan evaporation is related to the reference evapotranspiration by an empirically derived pan coefficient:

$$ET_o = K_p \, E_{pan}$$

Where

ET_o reference evapotranspiration [mm/day],
K_p pan coefficient [-],
E_{pan} pan evaporation [mm/day].

- **Evapotranspiration gauges**

  The modified Bellani plate atmometer has been offered as an alternative and simpler technique to combination-based equations to estimate evapotranspiration (ET) rate from green grass surface.

2.1.12.2 Actual Evapotranspiration (AET)

- **Simple methods**
  - Soil water depletion method

    Evapotranspiration can be measured by using soil water depletion method. This method is usually suitable for areas where soil is fairly uniform. Soil moisture measured at various time intervals. Evapotranspiration can be measured from the difference of soil moisture at various time levels.

  - Water balance method

    The method is essentially a book-keeping procedure which estimates the balance between the inflow and outflow of water. In a standard soil water balance calculation, the volume of water required to saturate the soil is expressed as an equivalent depth of water and is called the soil water deficit. The soil water balance can be represented by:

$$Ea = P - Gr + \Delta S - Ro$$

Where, Gr = recharge;
P = precipitation;
Ea = actual evapotranspiration;
ΔS = change in soil water storage; and
Ro = run-off.

- **Complex methods**
  - Lysimeters

    A lysimeter is a special watertight tank containing a block of soil and set in a field of growing plants. The plants grown in the lysimeter are the same as in the surrounding field. Evapotranspiration is estimated in terms of the amount of water required to maintain constant moisture conditions within the tank measured either volumetrically or gravimetrically through an arrangement made in the lysimeter. Lysimeters should be designed to accurately reproduce the soil conditions, moisture content, type and size of the vegetation of the surrounding area. They should be so hurried that the soil is at the same level inside and outside the container. Lysimeter studies are time-consuming and expensive.

  - Energy balance method

    The energy balance consists of four major components: net radiation input, energy exchange with soil, energy exchange to heat the air (sensible heat) and energy exchange to evaporate water (latent energy). Latent energy is thus the budget involved in the process of evapotranspiration:

Net Radiation -Ground Heat Flux = Sensible Heat + Latent Energy

The energy balance method of determining Evapotranspiration can be used for hourly values during daylight hours but accurate night time values are difficult to obtain. Eddy diffusion equations can be used and combinations of these procedures can be used also to calculate evapotranspiration. The method used is governed often by the data available, the accuracy needed, and the computational capability.

- Mass transfer method
  This is one of the analytical methods for the determination of lake evaporation. This method is based on theories of turbulent mass transfer in boundary layer to calculate the mass water vapour transfer from the surface to the surrounding atmosphere.

2.1.13 Estimation of Evapotranspiration

The lack of reliable measured data from field in actual projects has given rise to a number of methods to predict Potential Evapotranspiration (PET) using climatological data. The more commonly used methods to estimate evapotranspiration are the following:

- Blaney-Criddle method
- Modified Penman Method
- Jansen-Haise method
- Hargreaves method
- Thornwaite method

Some of the more popular of these methods have been discussed in detail in lesson 5.4 “Estimating irrigation demand”. Interested readers may consult Modi, P N (2000) Water Resources Engineering for detailed discussions on this issue.