LECTURE NOTES - V

« WATER RESOURCES »

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CHAPTER 5

HYDROLOGY

5.1. HYDROLOGIC CYCLE

Hydrology is the science which deals with the occurrence, distribution and movement of water on the earth, including that in the atmosphere and below the surface of earth. Water occurs in the atmosphere in the form of vapor, on the surface as water, snow or ice and below the surface as ground water occupying all the voids within the geologic stratum.

Except for the deep ground water, the total water supply of earth is in constant circulation from earth to atmosphere, and back to earth. The earth's circulatory system is known as the *hydrologic cycle*. Hydrologic cycle is the process of transfer of moisture from the atmosphere to the earth in the form of precipitation, conveyance of the precipitated water by streams and rivers to oceans and lakes, and evaporation of water back to the atmosphere. Fig. (5.1) illustrates schematically the complete hydrologic cycle.

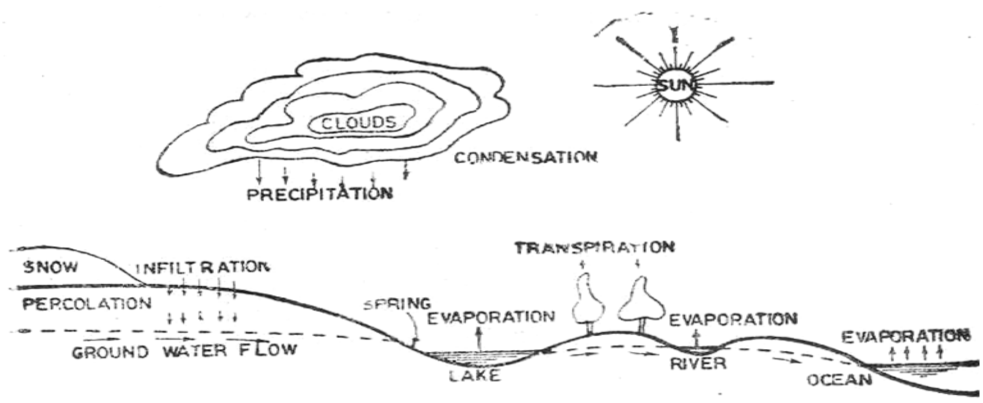


Figure 5.1. Hydrologic Cycle

The hydrologic cycle basically consists of the following processes:

A)

Evaporation (E) + Transpiration (T) = Evapotranspiration (ET)

The water from the surfaces of ocean, rivers, and lakes and also from the moist soil evaporates. The vapors are carried over the land by air in the form of clouds. *Transpiration* is the process of water being lost from the leaves of the plants. The total loss of evaporation and transpiration is called as *evapotranspiration*. Thus, evapotranspiration consists of:

i) Surface evaporation,
ii) Water surface evaporation from river surface and oceans,
iii) Evaporation from plants and leaves (transpiration), and
iv) Atmospheric evaporation.

B) Precipitation (P)

Precipitation may be defined as the fall of moisture from the atmosphere to the earth surface in any form. Precipitation may be in two forms:

i) Liquid precipitation as rainfall,
ii) Frozen precipitation as snow, hail, sleet, and freezing rain.

C) Infiltration (F)

A part of the precipitation falling on the earth's surface seeps into the soil by gravitation, capillary and molecular forces. This is called *infiltration*. Infiltrated water increases the soil moisture, produces subsurface flow, and moves into the deeper parts of the earth (percolates) to join the groundwater. It consists of;

i) Increase in soil moisture,
ii) Percolation to the groundwater.

D) Runoff (R)

Runoff is that portion of precipitation that is not evaporated. When moisture falls to the earth's surface as precipitation, a part of it is evaporated from the water surface, soil and vegetation and through transpiration by plant, another part of precipitation seeps into the soil as infiltration, and the remainder precipitation is available as runoff which ultimately runs to the ocean through surface and subsurface streams. Thus runoff may be classified as follows:

i) **Surface flow (runoff)**. Water flows over the land to reach the streams and rivers, which ultimately discharge the water to the sea.
ii) **Subsurface flow (runoff)**. A portion of precipitation infiltrates into surface soil and depending upon the geology of the basins runs as subsurface flow and reaches the streams and rivers.

Thus, the hydrologic cycle may be expressed by the *continuity equation* as:

$$\text{Precipitation} = \text{Evapotranspiration} + \text{Infiltration} + \text{Runoff}$$

$$P = ET + F + R$$

5.2. PRECIPITATION

Water falling on earth from atmosphere in liquid or solid form is called *precipitation*. The following are the essential requirements for precipitation to occur:

a) Some mechanism is required to cool the air sufficiently to cause condensation and droplet growth.
b) Condensation seeds are also necessary for formation of droplets. Such pieces of dust (of the order of microns) are always present in the atmosphere.
c) Large scale cooling is essential for significant amount of precipitation. This is achieved by lifting the air. Thus a meteorological phenomenon of lifting of air masses is essential to result precipitation.

5.2.1. Types of precipitation

Precipitation is often classified according to the factors responsible for lifting. Broadly speaking, there are 3 types of precipitation:

A) Cyclonic precipitation

Cyclonic precipitation results from lifting of air masses converging into low pressure area of cyclone. A border region between two adjacent air masses having different characteristics such as temperature and humidity is called a *front*. When a flow of warm and moist air meets cold air, the cold air being heavier, under run the warm air in the form of wedge forcing the warm air aloft. The lifted warm air mass cools down at high altitudes, causing precipitation. A front may be warm front or cold front depending upon whether there is active or passive ascent of warm air mass over cold air mass.

B) Convective precipitation

Convective precipitation is caused by natural rising of warmer lighter air in colder, denser surroundings. The difference in temperature may result from unequal heating at the surface, unequal cooling at the top of the air layer, or mechanical lifting when air is forced to pass over denser colder air masses. Convective precipitation is spotty, short duration, and heavy.

C) Orographic precipitation

A moist air mass will be cooled when it rises to pass a mountain range and produces orographic precipitation. This is seen on the slopes facing the sea, of mountains parallel to the coast, when moist air masses coming from the sea are lifted.

5.2.2. Precipitation Measurement

Precipitation is expressed as the *depth of precipitation*, defined as the height of water column that accumulates in a certain time interval on a horizontal plane, and is measured by *rain-gauge*. It is usually given in millimeters. 1 mm of precipitation is equal to 1 kg/m^2. Rainfall is measured by recording or non-recording instruments.

A) Non-recording pluviometers (rain-gauges):

Any cylinder with vertical sidewall can be used to measure the rainfall. Standard vessels must be used so that measurements are comparable and errors are of the same magnitude. Pluviometers do not give the variation of precipitation in time. They give only the total precipitation over a certain time interval.

B) Recording pluviographs (rain-gauges): These instruments record the variation of the precipitation depth with time on the paper. There are basically three types of pluviographs.

i) **Weighing gauge:** Rainfall is accumulated in a bucket. As the bucket gets heavier, it moves a pen on a rotating paper chart. This gives a curve showing the variation of precipitation depth with time.

ii) **Tipping-bucket gauge:** Rainfall entering the gauge accumulates in a very small bucket, which is emptied by tipping when it fills, moves a pen on a chart by a certain amount, and is replaced by another bucket. This type of gauge is less precise; the probability of error is higher.

iii) **Float-type gauge:** As the water level rises, a float moves a pen on a rotating chart. When the vessel is full, it is emptied rapidly by an automatic siphon.

iv) Radar: Microwave radar (wavelength 1-20 cm) can be used in precipitation measurement. Energy of the reflected waves is proportional to the size of rainfall drops, and therefore, to the intensity of precipitation.

Following are the advantages of recording type rain-gauge (pluviograph) over the non-recording (pluviometer) type:

1. Rainfall is recorded automatically and therefore, there is no necessity of any attendant.
2. The recording pluviograph also gives the *intensity* of rainfall at any time while the pluviometer gives the total rainfall in any particular interval of time.
3. As no attendant is required such rain-gauges can be installed in far-off places as well.
4. Possibility of human error is obviated.

5.2.2.1. Measurement Errors

Various errors may occur in the measurement of rainfall, in which case measurements do not correspond to the real values, and are usually smaller. There are basically two types of measurement error,

a) Wind error: Wind speed increases with the distance of the gauge above the ground, together with the ratio of precipitation that enters the gauge. They can be reduced by installing the gauges near the ground and far from the wind effect, and by using *windshields*.
b) Obstacle error: Another important cause of the errors is the reduction of the precipitation entering the gauge by high obstacles such as buildings and trees. Gauges must be placed at a distance of at least two times the height of such obstacles.

5.2.3. Analysis of Precipitation Records

A recording gauge provides a record of the precipitation depth as a function of time. Precipitation depth – time curve is called the *mass curve*. (Fig. 5.2)

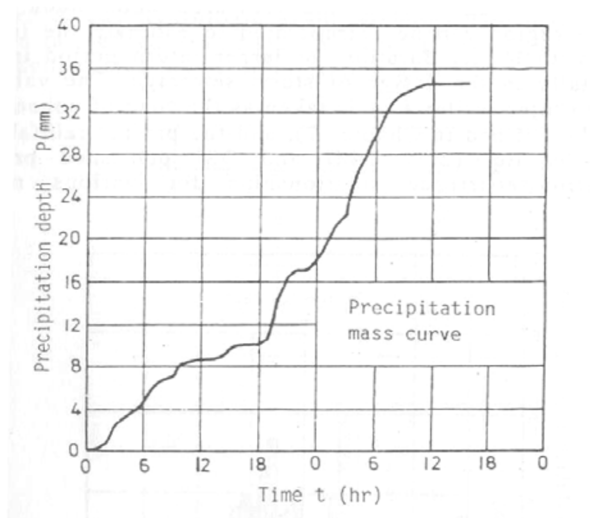


Figure 5.2. Precipitation Mass Curve (Bayazıt, 2001)

Precipitation depth in unit time is called *precipitation intensity*.

$$i = \frac{dP}{dt} \approx \frac{\Delta P}{\Delta t} \tag{5.1}$$

The curve showing the variation of precipitation intensity with time is called *hyetograph* and is usually drawn in steps. (Fig. 5.3). The time interval Δt is chosen with respect to the size of the region and usually in the range 1-6 hours. Precipitation with intensity less than

2.5 mm/hr is called light precipitation, 2.5-7.5 mm/hr as medium, and more than 7.5 mm/hr as heavy rain. Usually average intensity reduces as the duration increases.

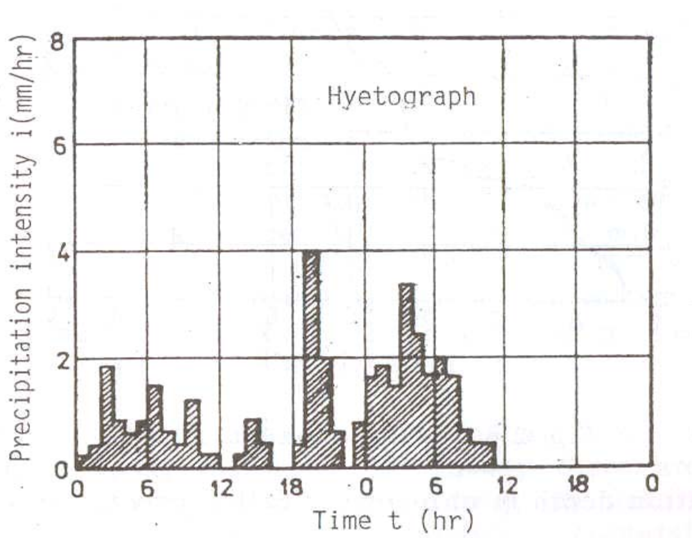


Figure 5.3. Hyetograph of the rainfall in Figure (5.2).
(Bayazıt, 2001)

5.2.4. Computation of Average Rainfall Depth over a Basin

In order to compute the average rainfall over a basin or catchment area, the rainfall is measured at a number of rain-gauge stations suitably located in the area. A network should be planned as to have a representative picture of the areal distribution of rainfall. World Meteorological Organization (WMO) recommends the optimum density of one gauge per 600-900 km^2 in plains, and one gauge per 100-250 km^2 in mountain regions, where the elevation difference must be less than 500 m.

If a basin or catchment area contains more than one gauge, the computation of average precipitation or rainfall depth may be done by the following methods.

5.2.4.1 Arithmetic Average Method

If the rainfall is uniformly distributed on its areal pattern, the simplest method of estimating average rainfall is to compute the average of the recorded rainfall values at various stations. Thus, if P_1, P_2, P_3,……, P_n are the precipitation values measured at n gauge stations, we have,

$$P_{av} = \frac{\sum_{i=1}^{n} P_i}{n} = \frac{P_1 + P_2 + ... + P_n}{n} \qquad (5.2)$$

This method can be used in regions smaller than 500 km^2 when the gauges are rather uniformly distributed.

5.2.4.2. Thiessen Polygon Method

Thiessen method is a more common method of weighing the rain-gauge observation with respect to the area. This method is more accurate than the arithmetic average method. The procedure to be followed in computing the average rainfall depth is;

i) Join the adjacent rain-gauge stations A, B, C, D,….. By straight lines.
ii) Draw the perpendicular bisectors of each of these lines.
iii) A *Thiessen Polygon* is thus constructed. The polygon formed by the perpendicular bisectors around a station encloses an area which is everywhere closer to that station than any other station. Find the area of each of these polygons.
iv) Multiply the area of each Thiessen polygon by the rainfall value of the enclosed station.
v) Find the total area (ΣA) of the basin.
vi) Compute the average precipitation depth from the equation;

$$P_{av} = \frac{\sum_{i=1}^{n} P_i A_i}{\sum A} \tag{5.3}$$

Thiessen polygon does not change in time, and is drawn only once. The method can be used in regions 500-5000 km^2 size. It considers the non-uniformity of the areal distribution of gauges.

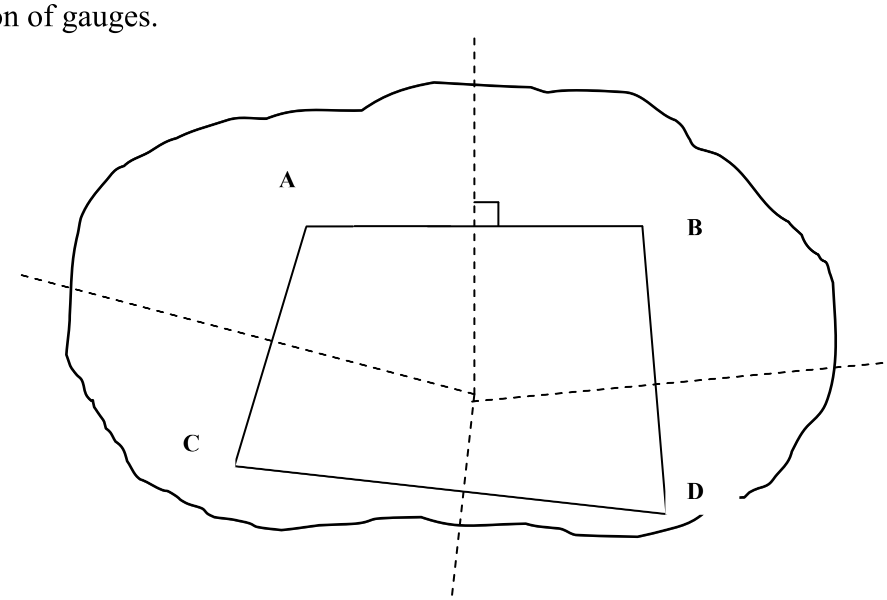


Figure 5.4. Thiessen Polygon

EXAMPLE 5.1: Calculate the average precipitation depth for the area given in Fig. (5.4) with four stations and rainfall depths given in Table (5.1).

Solution: The calculations are illustrated in Table (5.1).

Table 5.1. Thiessen Polygon Method

Rain-Gauge Station	Area of Thiessen Polygon A (km^2)	Precipitation Depth (mm)	A×P
A	45	31	1395
B	38	35	1330
C	30	33	990
D	40	25	1000
Sum	153	-	4715

$$P_{av} = \frac{\sum_{i=1}^{4} A_i P_i}{\sum A} = \frac{4715}{153} = 30.8 mm$$

5.2.4.3. Isohyetal Method

The basic assumption in the Thiessen polygon method is that a rain-gauge station best represents the area which is close to it. However, this may not be always valid, when the rainfall is controlled by topography or results from intense convection. The *Isohyetal* method is the most elaborate and accurate in such conditions.

An *isohyet* is a line, on a rainfall map of the basin, joining places of equal rainfall readings. An *isohyetal map* showing contours of equal rainfall represents a more accurate picture of the rainfall distribution over the basin. This method can be preferred for orographic precipitation. The computation steps to be followed for the application of this method are;

i) From the rainfall values recorded at various rain-gauge stations, the isohyetal map is prepared for the storm causing the rainfall over the area.
ii) Measure the areas enclosed between successive isohyets with the help of planimeter.
iii) Multiply each of these areas by the average rainfall between the isohyets.
iv) The average rainfall is then computed from the expression.

$$P_{av} = \frac{\sum_{i=1}^{n} \left[A_i \times \left(\frac{P_i + P_{i+1}}{2} \right) \right]}{\sum A} \tag{5.4}$$

EXAMPLE 5.2: Calculate the average rainfall depth for the area given with Isohyetal method.

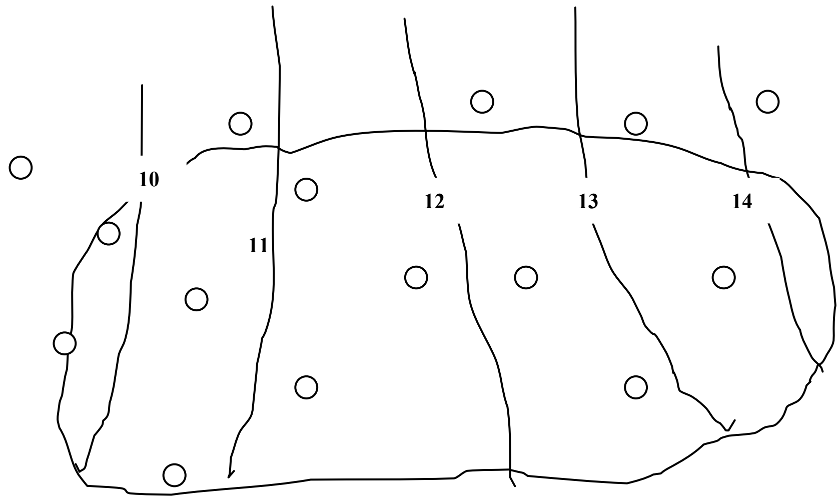


Figure 5.5. Isohyetal method

Calculations are illustrated in Table (5.2).

Table 5.2. Isohyetal Method

Isohyets (cm)	**Area between Isohyets A (km^2)**	**Average Precipitation** $\frac{1}{2}(P_1+P_2)$	**Product** $A\times\frac{(P_1+P_2)}{2}$
9	22	9.5	209
10	80	10.5	840
11	105	11.5	1208
12	98	12.5	1225
13	78	13.5	1053
14	16	14.5	232
15			
Sum	399		4767

$$P_{av} = \frac{\sum\left[A\times\left(\frac{P_1+P_2}{2}\right)\right]}{\sum A} = \frac{4767}{399} \cong 12cm$$

5.3. SURFACE RUNOFF

The runoff of a catchment area in any specified period is the total quantity of water draining into a stream or into a reservoir in that period. This can be expressed as a) centimeters of water depth over a region, or b) the total water volume in m^3 for given catchment.

The rainfall is disposed of in the following manner:

A) Basin recharge,
B) Evaporation,
C) Percolation down to the ground flow,
D) Direct runoff

A) Basin Recharge

i) Rain intercepted by leaves and stems of vegetation (*transpiration* and *interception*).
ii) Water held up in surface depressions, commonly known as the *depression storage*.
iii) Soil moisture held as capillary water in pore spaces of soil or as *hygroscopic water* absorbed on the surface of soil particles (*infiltration*).

B) Direct Runoff

Direct runoff is that water which reaches the stream shortly after it falls as rain. Direct runoff consists of:

i) Overland flow (*surface runoff*).
ii) *Subsurface flow*.

Surface flow is that portion of water travels across the ground surface to the nearest stream. However, if the soil is permeable, water percolates into it, and when it becomes saturated, flows laterally in the surface soil to a stream channel and this part of flow is called *subsurface flow*. The essential condition for subsurface flow is that the surface soil is permeable, but the subsoil is relatively impermeable so that water does not percolate deep to meet the groundwater.

C) Base Flow

If the subsoil is also permeable, water percolates deep downwards to meet the groundwater. Much of the low water flow of rivers is derived from this groundwater. Stream channels which are below the groundwater table are called *effluent streams*.

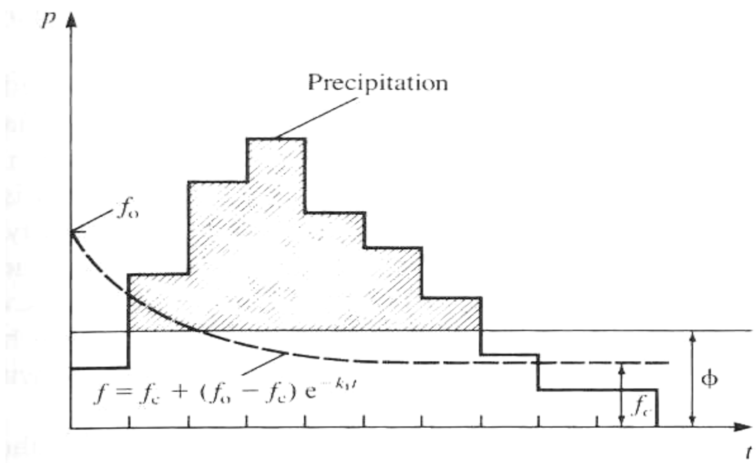


Figure 5.6. Illustration of Φ index and Horton's equation of infiltration

5.4. INFILTRATION

Infiltration is defined as the movement of water through the soil surface and into the soil. The capacity of any soil to absorb water from continuously falling rainfall goes on decreasing with time, until a minimum rate of infiltration is reached. At any instant, the *infiltration capacity* of a soil is the maximum rate at which water will enter the soil in a given condition. The *infiltration rate* is the rate at which water actually enters the soil during a storm, and is equal to the infiltration capacity or the rainfall rate, whichever less.

A basic formulation for the infiltration capacity as a function of time is Horton equation. The curve drawn by this equation is called *standard infiltration curve*.

$$f = f_c + (f_0 - f_c)e^{-kt} \tag{5.5}$$

where
f = Maximum infiltration rate at time t (infiltration capacity).
f_0 = Initial infiltration rate at t =0.
f_c = Minimum infiltration rate.
k = A constant.

An average infiltration capacity called *Φ index* has been widely used because of its simplicity. The Φ index is simply an average infiltration capacity that when applied to a particular rainfall

Computation of Φ index is done with the following way:

A horizontal line is drawn across the hyetograph such that the area between this line and hyetograph is equal to the direct runoff. (Fig. 5.6). The ordinate of the line is the Φ index. It is assumed that when the precipitation intensity exceeds the Φ index, the difference will become runoff.

EXAMPLE 5.3: A drainage basin has 3 km^2 area. The variation of the precipitation intensity with time has been given as;

$$i = \frac{3}{t^{0.5}}$$

where I is mm/hr and t is hour.

a) Derive the total rainfall depth equation,
b) Calculate the total rainfall depth for 30 minutes of rainfall.
c) Infiltration capacity is assumed to follow the Horton equation for this rainfall. If the initial infiltration capacity f_0 = 4 mm/hr, the limit capacity is f_c = 2 mm/hr and k = 0.5, calculate the total amount of water infiltrated during this rainfall.
d) Compute the direct runoff depth.

Solution:

a) Total rainfall equation can be derived as,

$$i = \frac{dp}{dt} = \frac{3}{t^{05}} \rightarrow dp = \frac{3}{t^{0.5}} dt$$

$$P = \int \frac{3}{t^{0.5}} dt \rightarrow P = 6\sqrt{t}$$

b) Total rainfall in 30 minutes is,

$$P = 6 \times \sqrt{\frac{30}{60}} = 4.24 mm$$

c) Total infiltrated water equation can be derived as,

$$f = f_c + (f_0 - f_c)e^{-kt} = \frac{dF}{dt}$$

$$f = 2 + (4-2) \times e^{-0.5t} = 2 + 2e^{-0.5t} = \frac{dF}{dt}$$

$$dF = \left(2 + 2e^{-0.5t}\right)dt$$

$$F = \int_{t=0}^{t=0.5} \left(2 + 2e^{-.5t}\right)dt = \left|2t - 4 \times e^{-0.5t}\right|_0^{0.5}$$

$$F = 2 \times 0.5 - 4 \times e^{-.25} - 0 + 4e^0$$

$$F = 1.88 mm$$

d) Direct runoff is,

$$R = P - F = 4.24 - 1.88 = 2.46mm$$

5.5. EVAPORATION AND EVAPOTRANSPIRATION

Evaporation from water and soil surfaces and transpiration through plants can account for significant volumes of water. Evaporation is the process by which water transforms into vapor. The process occurs at the water surface where molecules of water develop sufficient energy to escape bonds with the water and become vapor molecules in the air. Evaporation from a water body is a function of air and water temperatures, the moisture gradient at the water surface, and wind. Wind moves the moisture away from the water surface and, thus, increases the moisture gradient, increasing the rate of evaporation.

Evaporation pans are used to measure the evaporation from the water surface. The most common type is Class A evaporation pan. It has a surface of 1 m^2, and a depth of 25 cm. The pan is filled with water to a depth of 20 cm. The decrease water level is measured by a point gage, which gives the evaporation rate. In rainy days, the precipitation depth is measured and added to compute the evaporation. It is recommended to use Class A pan, multiplying the measured rate by the *pan coefficient* to obtain lake evaporation. The annual pan coefficient is around 0.7 for Class A pan.

Equation of continuity may also be used to calculate the evaporation from a water body such as lakes and reservoirs.

$$E = P + X - Y - F - \Delta S \tag{5.6}$$

Thus the evaporation rate E in a certain time interval can be computed using the information about precipitation P, inflow X, outflow Y, infiltration F, and the variation of the volume of water ΔS in the same interval.

EXAMPLE 5.4: Total area of land surface is 150×10^6 km^2, and area of oceans is 360×10^2 km^2. Average annual precipitation over the lands is 750 mm; average annual evaporation is 480 mm. For the oceans, average annual precipitation is 1070 mm. Find the average annual volume of water carried into the oceans by rivers, and the average annual evaporation from the oceans.

Solution: The long term of storage change will be ΔS = 0 for both lands and oceans. The equation of continuity is now X = Y.

For lands;

$$X = 0.75\times150\times10^{12} = 112.5\times10^{12} m^3$$
$$Y = 0.48\times150\times10^{12} + R = 72\times10^{12} + R(m^3)$$

Annual average volume of water that is carried by rivers into the oceans is,

$$R = (112.5 - 72) \times 10^2 = 40.5 \times 10^{12} m^3$$

For oceans,

$$X = 1.07 \times 360 \times 10^{12} + 40.5 \times 10^{12} = 425.7 \times 10^{12} m^3$$

Annual evaporation from oceans,

$$Y = X = 425.7 \times 10^{12} m^3$$

which is equivalent to the evaporation depth from the oceans,

$$E = \frac{425.7 \times 10^{12}}{360 \times 10^{12}} = 1183 mm$$

EXAMPLE 5.5: 500×10^6 of water has been stored in the reservoir of a dam in the beginning of September 2005. In this month, the river feeds the reservoir with average 20 m^3/s inflow. Monthly evaporation from the dam lake surface is 9×10^6 m^3 and no precipitation has been observed during this month. 50×10^6 of water has been extracted from the reservoir for the nearby city consumption. The reservoir volume has been measured as 480×10^6 at the end of September. Check if there is any infiltration to the soil from the reservoir bottom, if yes; compute the volume of infiltrated water.

Solution: Using Equ. (5.6),

Inflow volume is, $X = 20 \times 30 \times 86400 = 51.84 \times 10^6 m^3$

Outflow volume is, Y = 50×10^6 m^3

Precipitation is, P= 0,

Reservoir volume difference is, $\Delta S = (480 - 500) \times 10^6 = -20 \times 10^6 m^3$

Evaporation volume is, E = 9×10^6 m^3

$$E = P + X - Y - F - \Delta S$$

$$F = P + X - Y - E - \Delta S$$
$$F = 0 + 51.84 \times 10^6 - 50 \times 10^6 - 9 \times 10^6 + 20 \times 10^6$$
$$F = 12.84 \times 10^6 m^3$$

5.6. STREAMFLOW MEASUREMENT AND ANALYSIS OF DATA

It is important to determine the amount of surface runoff, which is required in various problems of water resources development. For example, the maximum discharge should be known in flood control projects, the discharge that is available for a certain number of days in a year should be known in hydropower projects. The branch of hydrology that deals with the streamflow measurements is called *hydrometry*.

The purpose of streamflow measurement is to determine the stage (water surface elevation) in a cross-section of a stream and the rate of flow (discharge, flow volume in unit time) along the time. The stage-discharge relationship (*rating curve*) of the gauging station is determined, and then only the water surface elevation (stage) is measured, and the corresponding discharge is read from the rating curve (Fig. 5.7).

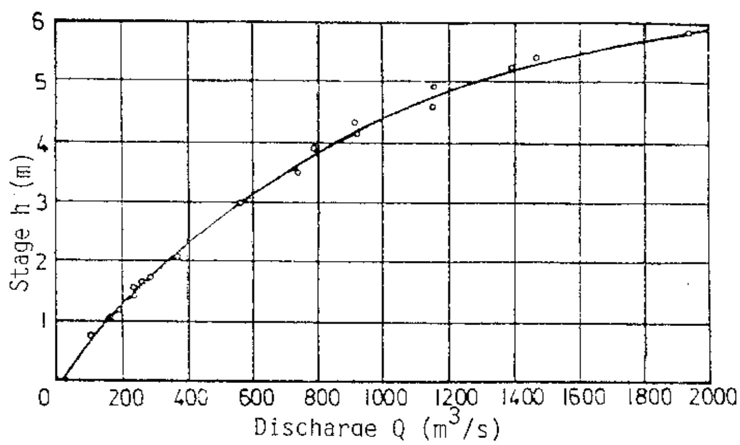


Figure 5.7. Rating curve (Bayazıt, 2001)

5.6.1. Measurement of Stage

The water surface elevation measured with respect to a certain datum is called the *stage*. Usually, it is measured with respect to the average sea level. Stage can be measured with recording gauges and non-recording gauges.

A. Non-recording gauges:

A *staff gauge*, a wooden or metal rod scaled in centimeters is commonly used to measure the stage. It can be attached to a bridge pier, a wall on the bank of the stream or any other structure. The water surface elevation is read on the staff gage at certain intervals. The zero of the gauge should be set such that the readings are always positive.

Non-recording gauges are usually read once a day (usually at 8:00) or two times a day (at 8:00 and 16:00). During the floods, readings are repeated every 1-6 hours.

B. Recording Gauges

The motion of a float on the surface of water in a stilling well connected to a stream by a pipe rotates a pulley by means of a wire attached to it (Fig. 5.8). As the pulley rotates, a pen moves on a rotating paper strip and records the variation of the stage in time. Recordings are transmitted by wireless, telephone, or input into a computer disk.

The advantage of recording gauges is the continuous recording of the stage, and the elimination of reading errors.

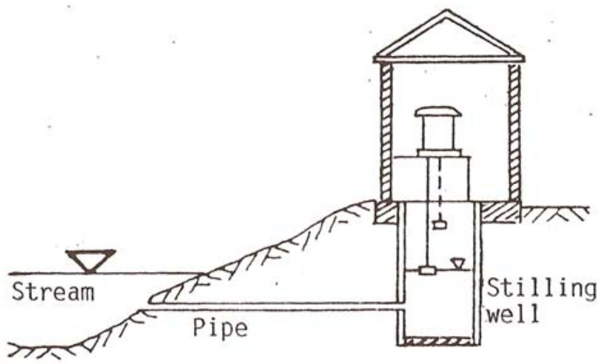


Figure 5.8. Stilling well and recording gage (Bayazıt, 2001)

5.6.2. Velocity and Discharge Measurements

The velocity at a point of the flow cross-section in a stream is measured by a *current meter*, which consists a propeller rotated by the flow around a horizontal or vertical axle, a tail piece and a weight to prevent the current meter to be moved by the flow. The rotation speed of the propeller is related to the flow velocity. The number of rotations in a minute, n is related to the velocity by (Bayazıt, 2001),

$$V = a + bn \qquad (5.7)$$

The coefficients a and b in Equ. (5.7) are given by the manufacturer for various range of n.

The average velocity along a vertical in the cross-section of the stream is determined by measuring the velocity by the current meter at a point 0.6 of the flow depth below the surface. If the depth is more than 0.5 m, the velocities measured at points 0.2 and 0.8 of the depth below the water surface are averaged (Fig. 5.9).

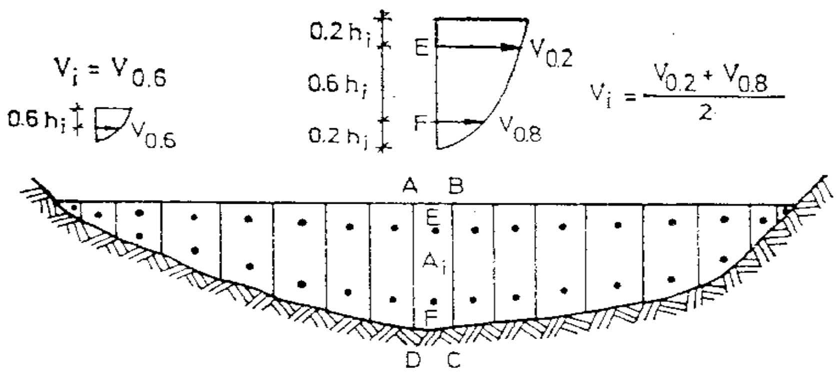


Figure 5.9. Measurement of the discharge by dividing the stream cross-section into strips. (Bayazıt, 2001)

The most common method to determine the discharge of a stream is to divide the cross-section into strips, to measure the average velocity V_i and the area A_i of each strip and then to compute the discharge as,

$$Q = \sum_{i=1}^{n} V_i A_i \qquad (5.8)$$

In a straight and uniform reach, the cross-section is divided into vertical strips (Fig. 5.9). Their number can be 10-30, depending on the width of the stream and regularity of the cross-section, such that not more than 10% of the discharge flows through any strip. For each strip (such as ABCD in the figure), the average velocity and depth along a vertical in the middle strip (such as EF) are measured. The discharge through each strip is computed, and the total discharge is found by Equ. (5.8) summing them up.

5.6.3. Rating Curve

Rating curve shows the stage-discharge relation of a stream cross-section. Rating curve is usually drawn with the stages along the vertical axis, and discharges along the horizontal axis. Logarithmic scale must be preferred because the rating curve approaches a straight line in this case.

A single valued relation between the stage and discharge must exit in a cross-section where the rating curve is obtained. Such a cross-section is called a *control section*. This relation may change in time for various reasons. In alluvial streams the rating curve changes by erosion and deposition at the moveable bed. The rating curve must be checked a couple of times in a year. This is required especially after the floods.

5.6.4. Analysis of Streamflow Records

5.6.4.1. Streamflow Gauging Network

In planning the network of streamflow gauging stations, their number and locations are optimized such that the data required precision are obtained an economically as possible. Three types of gauging stations can be installed;

a) **Base stations:** These are operated continuously. They are placed near the mouths of streams and on their main tributaries.

b) **Secondary stations:**

c) **Temporary (special purpose) stations:** These are operated for a certain period of time near the hydraulic structures to be built in the future.

World Meteorological Organization (WMO) recommends one gauging station for each 1000-2500 km^2 in plain regions, and one for each 300-1000 km^2 in mountainous regions where the elevation difference should not exceed 500 m.

5.6.4.2. Computation of Daily Flows

Daily flows are computed from the stage measurements on that day. Average stage of the day is found by the following equation at stations where the stage is measured once a day, where a, b, and c are the stages measured on the previous day, that day and the next day, respectively. (Bayazıt, 2001).

$$h = \frac{a}{18} + \frac{13b}{18} + \frac{4c}{18} \qquad (5.9)$$

When the stage is measured twice daily, the average stage is computed as,

$$h = \frac{a}{12} + \frac{5b}{12} + \frac{5c}{12} + \frac{d}{12} \qquad (5.10)$$

where a is the stage at 16:00 on the previous day, b and c are the stages of that day, and d is the stage at 8:00 next day. Having determined the daily average stage, the daily streamflow is found from the rating curve.

5.6.4.4. Hydrograph

The chronological record of flow is termed the *hydrograph*. It is basic data for all statistical analyses of the runoff of a drainage basin. The hydrograph reveals many aspects of the runoff characteristics of the basin including:

- The seasonal distribution of high and low flows.
- The character of flood flows, whether occurring in isolated flood rises or in a succession of floods rising above a high seasonal base and lasting several months.
- The influence of snow melt.
- The effect of valley storage.
- The contribution of groundwater flow.

The time unit used in compiling and analyzing the hydrograph will vary with its intended use. Annual discharges are usually of interest only in comparing sequences of high and low flow years. Monthly flows are the most useful unit in reservoir design for municipal water supply, irrigation development, and hydroelectric power. Hydrographs in units of a day or less are needed to develop design floods.

5.6.4.5. Flow-Duration Curve

If the flows for any unit time are arranged in descending order of time (without regard to chronological sequence), the percentage of time for which any magnitude is equaled or exceeded may be computed. The resulting array is called a *flow-duration curve* (Fig. 5.10).

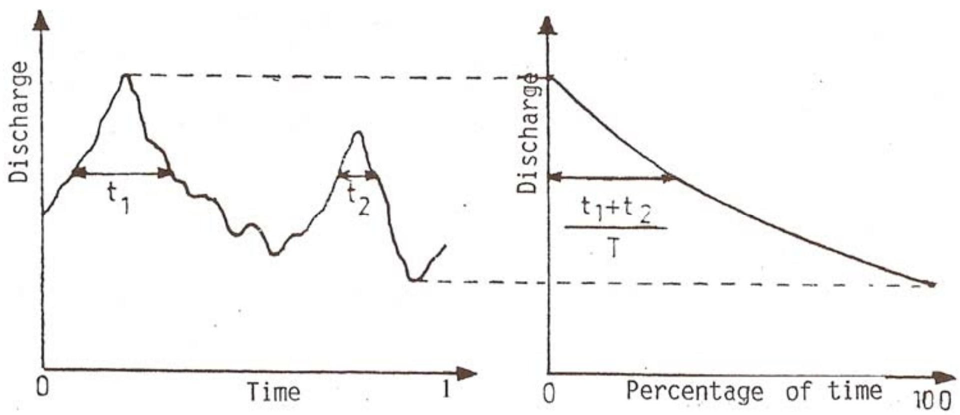


Figure 5.10. Determination of flow-duration curve (Bayazıt, 2001).

Such curves are useful in determining the relative variability of flow between two points in a river basin or between two basins. For example, if a stream is highly regulated, the curve will approach a horizontal line. The dependable flow is that corresponding to 100 percent of time. The relative variability of two flow records may be compared by converting the discharge scale in terms of a ratio to the mean. Any subarea under the curve represents the volume of annual runoff.

Flow-duration curves have been used to approximate the amount of storage needed to increase the dependable flow. For example, the horizontal line AB in Fig. (5.11) may represent a new dependable flow, and the required storage needed to obtain this flow is indicated by area ABC.

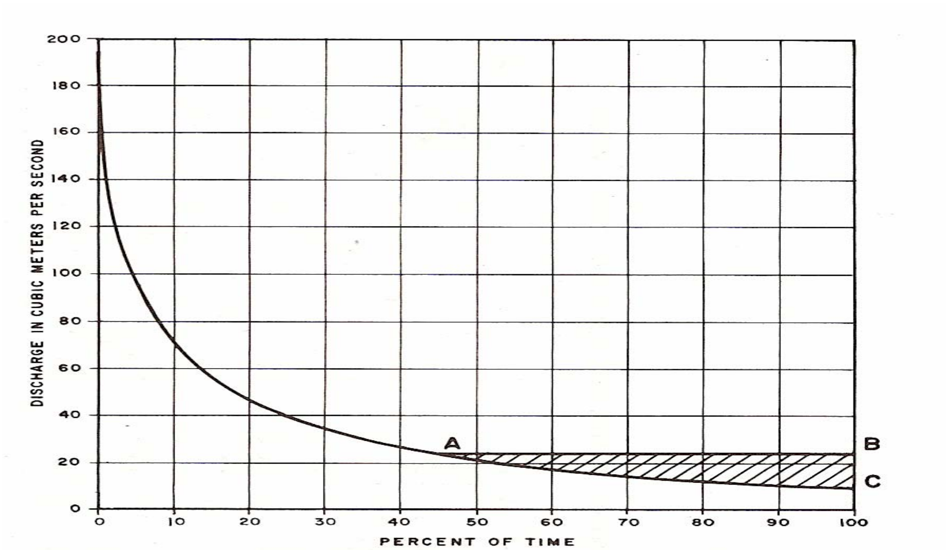


Figure 5.11. Duration curve of monthly discharges.

Power production values may be approximated from the duration curve by converting the discharge scale to kilowatts by multiplying by a selected head, efficiency and conversion factors. If the time scale is converted to hours in a year, a unit of are represents kilowatt-hours.

The flow-duration curve is particularly useful in combination with a sediment rating curve (river discharge versus the transported sediment load usually expressed in tons per day), to compute total sediment load to be expected in an average year.

5.6.4.6. Flow Mass Curve

Total flow volume from a certain initial time t = 0 up to time t can be computed as,

$$H = \int_0^t Q dt \tag{5.11}$$

In practice, the total volume is computed as,

$$H = \sum Q_i t_i \tag{5.12}$$

Q_i = the average discharge in time interval (month, year) Δt_i.

Flow mass curve is a plot of the cumulative runoff from the hydrograph against time. The time scale is the same as for the hydrograph and may be in days, months or years. The volume ordinate may be in m^3-days, m^3-months, m^3-years, etc. The slope of the mass curve is the derivative of the volume with respect to time or the rate of discharge.

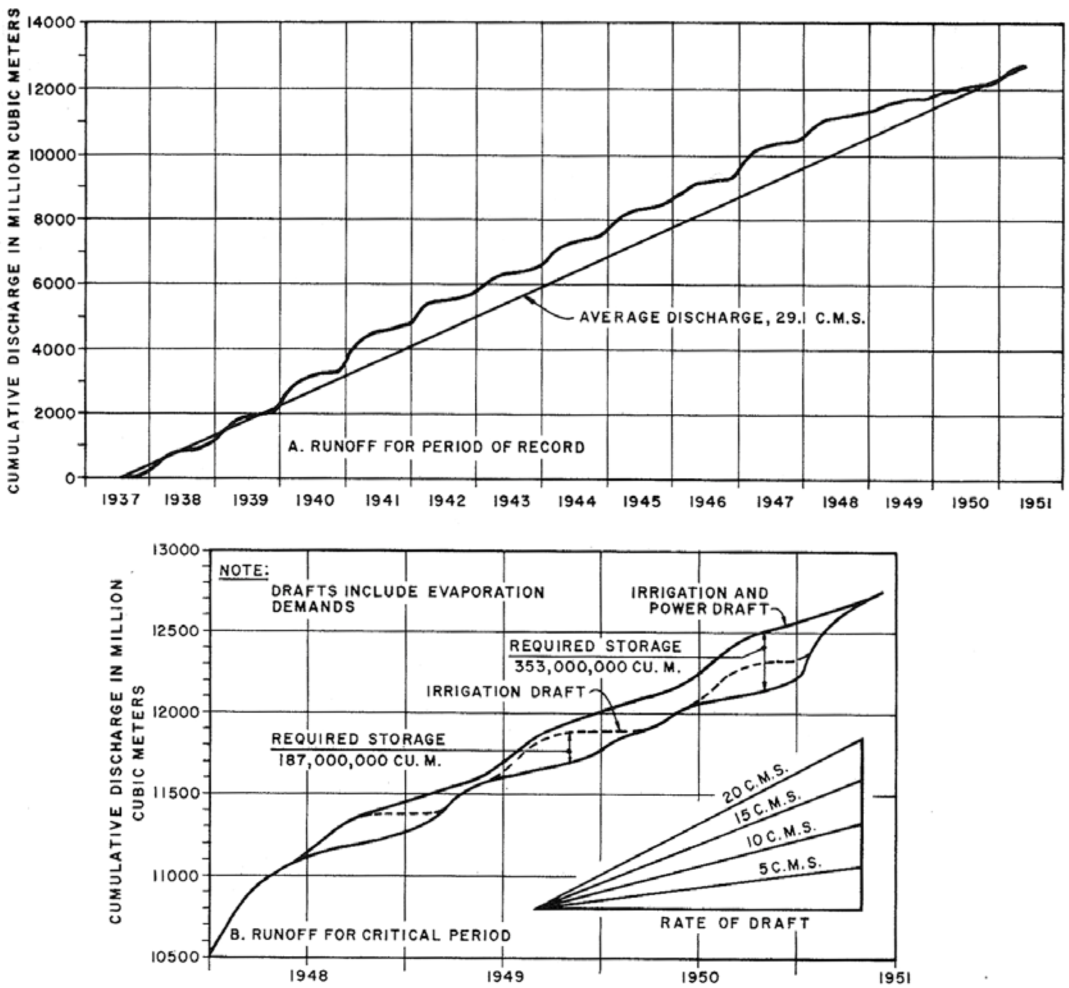


Figure 5.12. Analysis of runoff by mass curve

The mass curve usually has a wavy configuration (Fig. 5.12) in which the steeper segments represent high flow periods and flatter segments represent low flows. Uniform rates of withdrawal (draft) may be represented as tangent lines drawn from high points to intersect the curve at the next wave. The vertical distance between the draft line and the basic curve represents the cumulative difference between regulated outflow and natural inflow, or the *required storage*. If the draft line does not intersect the mass curve at the end of a year, it means that the reservoir does not refill with that rate of draft and regulation at the proposed draft rate will extend over two years or more. A typical mass curve is shown in Fig. (5.12).

In estimating storage requirements from the mass curve, it is not necessary to assume a constant rate of regulated flow. For example, if the draft rate to meet a demand for irrigation, water supply, or power varies from month to month, the draft line may be a curved or irregular line (Fig. 5.12b) and the maximum draft may not occur at the low point in the mass curve.

An allowance for evaporation should be applied to the mass curve analysis. If the water area does not change significantly during the annual cycle of use, an average correction for each calendar month can be subtracted from the inflow or added to the draft rates.

The ordinates of the flow mass curve increase continuously in time. The sum of the differences between the inflow and the yield (average flow) are drawn;

$$H_0 = \sum (Q_i - Q_{ave}) \Delta t_i \qquad (5.13)$$

Reservoir capacity is then vertical distance between the highest and lowest points of the curve.

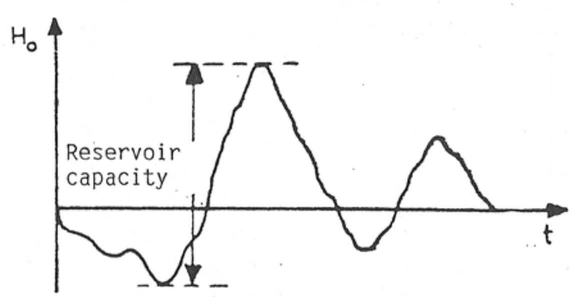


Figure 5.13. Flow mass curve derived using the differences of the discharges from the yield.

5.6.4.7. Storage-Draft Curve

The results of a mass-curve analysis can be plotted as a *storage-draft curve***.** His curve gives the storage needed to sustain various draft rates. Examples of storage-draft curves are shown in Fig. (5.14). Both irrigation requirements and combined irrigation and power requirements are illustrated. These curves were computed from the mass curve of Fig. (5.13).

If storage unlimited, the storage-draft curve will approach the available mean flow as asymptote. It is rarely possible to develop mean annual flow of a river basin. For most projects, some spillage will occur in years of runoff. To impound all flood flows will require an extensively large reservoir. Such a reservoir may not fill in many years, and probably could not be justified economically. The selected rate of regulated flow to be developed will depend on;

1. The demand of water users,
2. The available runoff,
3. The physical limits of the storage capacity,

4. The overall economies of the project.

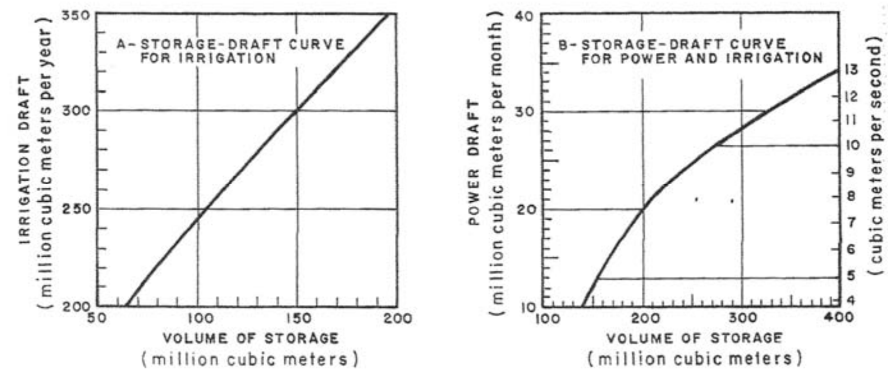


Figure 5.14. Storage-draft curves for multipurpose uses.

5.6.4.8. Selection of Design Flow

The hydrologic analyses, combined with economic analyses of costs and benefits for different heights of dam and reservoir capacity will lead to the selection of the reservoir capacity and the corresponding dependable flow that can be justified. The selected design flow may not necessarily be available 100 percent of the time. The propose water use may permit deficiencies at intervals, for example, a 15 percent shortage once in 10 years. Irrigation water supplies may permit greater deficiencies than those for urban and industrial use. Hydroelectric power plants, connected to large systems, may tolerate substantial water supply deficiencies.

5.6.4.9. Final Storage Selection

a) Evaporation Losses

Detailed evaluation of evaporation losses should be postponed until final operation and routing studies, when the actual variation in water area can be considered as well as the seasonal variation in evaporation.

Basic data on water surface evaporation may be obtained from records of pan evaporation. Such records overestimate lake evaporation and must be reduced by a *pan coefficient* which varies from 0.60 to 0.80 depending on the climate. The collection of evaporation records at a project site should be initiated in the planning stage. Evaporation corrections should be made on a monthly basis using actual past precipitation records at the project site if possible.

b) Power

Selection of an average flow alone will not permit determination of the benefits from a water resources development project without more detailed studies. Such studies require routing through the reservoir the entire record of flow (corrected for evaporation losses), on a month by month basis, using assumed patterns of use, outlet capacities and, in the case of power, turbine and generator capacities and efficiencies. The reservoir would normally be considered to be full at the start of the operation study, or at least full to normal pool.

For power benefits, the energy output will vary in accordance with the inflow, outflow, and change in storage and corresponding head, tailwater elevation, turbine capacity and plant efficiency. If the plant is a part of a system, the output may be subject to varying demands of the system load curve and whether the plant is to be used as a base load plant or a peaking plant. The routing study will indicate the necessary modifications to the head, storage, and even height of the dam to obtain maximum benefit.

c) Irrigation

Operation studies for irrigation use should be made using seasonal crop demands and selected outlet capacities. Short-term demands may indicate that the storage needed war greater than that required for uniform regulated flow (see Fig. 5.12). The proposed annual water use may be greater than that available 100 percent of the time, with the understanding that deficiencies can be tolerated in some years.

d) Water Supply

Operation studies for projects providing urban water supplies will be similar to those for irrigation projects in that there may be variations in the seasonal demand, especially where more than one source is available, or where there can be transfers to other regulation reservoirs. However, the degree of dependability of flow must be higher for urban water supply than for irrigation projects.

e) Flood Control

The storage allocated for flood control in single purpose or multipurpose projects is usually based on a definite design flood the control of which is needed for downstream protection. The required storage capacity is based on routing of the design flood inflow coincident with releases not to exceed downstream channel capacities.

Total Storage Requirement

The usable storage needed for single purpose projects can be readily determined as described in Sections (a) to (e). The total usable storage needed for multipurpose for multipurpose projects require more complex routing studies and numerous trials to obtain the most economic allocations.

In addition to the variable requirement for storage for downstream uses, the total storage may be increased for the following reasons:

- Minimum head on power installations.
- Allowance for the storage of sediments without loss of usable storage.
- Minimum area for recreation use, including seasonal requirements.

EXAMPLE 5.6: Monthly flow volumes feeding a reservoir are given in the table. Determine the storage capacity required to supply the mean annual flow volume yield.

Solution: Cumulative volumes are calculated and given in the table.

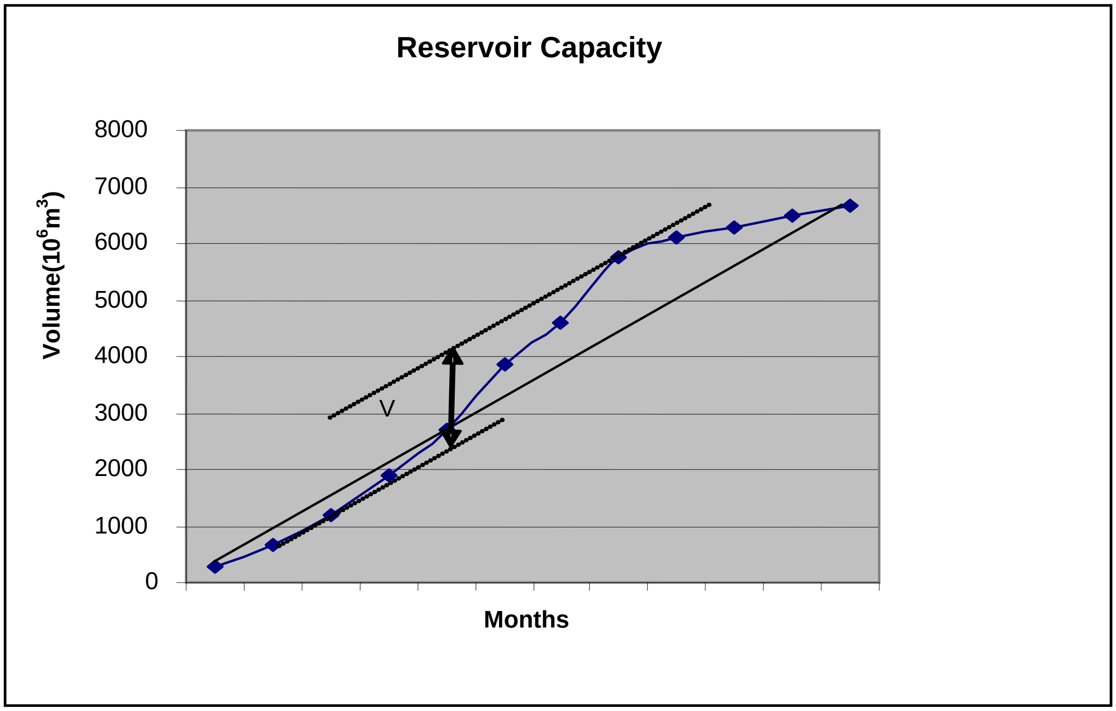
Month	Volume ($10^6 m^3$)	Cumulative Volume ($10^6 m^3$)
1	296	296
2	386	682
3	504	1186
4	714	1900
5	810	2710
6	1154	3864
7	746	4610
8	1158	5768
9	348	6116
10	150	6266
11	223	6489
12	182	6671

Total volume of flow feeding the reservoir is 6671×10^6 m^3. Annual mean discharge can be calculated as,

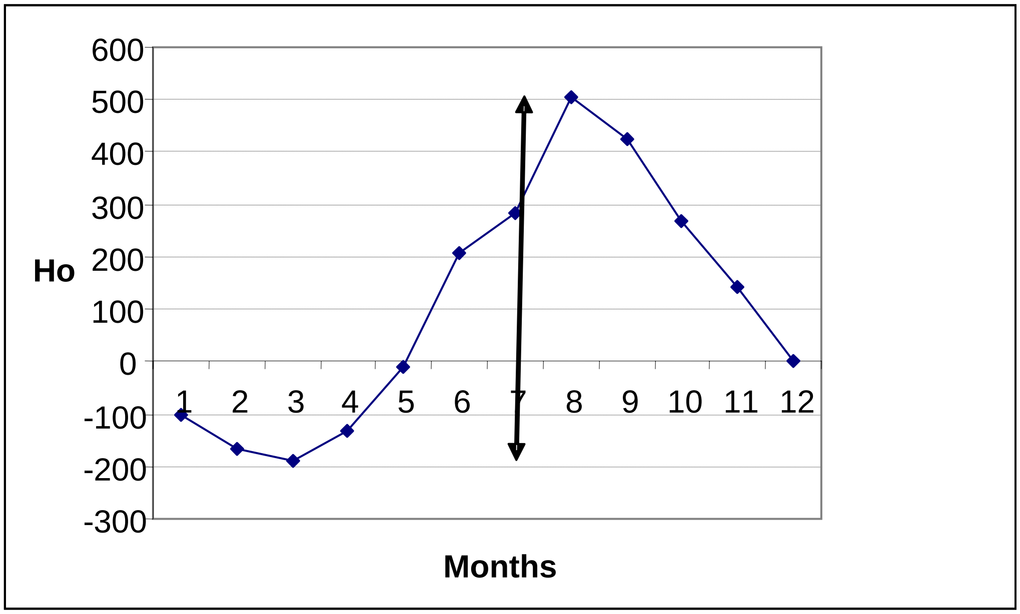
$$Q = \frac{6671\times10^6}{365\times86400} \cong 212\, m^3/s$$

The reservoir storage capacity required to obtain 212 m^3/s yield throughout the year is found by drawing tangents parallel to the average draft line from peak points. The vertical distance is 1800×10^6 m^3 is the required capacity of the reservoir.

The reservoir capacity to supply the annual mean discharge can be found out by using the sum of differences method using Equ. (5.13) as in table,



Month	Volume ($10^6 m^3$)	Flow (m^3/s)	H_0 (m^3/s)	ΣH_0 (m^3/s)
1	296	111	-101	-101
2	386	149	-63	-165
3	504	188	-24	-188
4	714	267	55	-134
5	810	335	123	-11
6	1154	431	219	208
7	746	288	76	284
8	1158	432	220	504
9	348	134	-78	426
10	150	56	-156	270
11	223	83	-129	142
12	182	70	-142	0



$$H_0 = \sum (Q_i - Q_{ave}) \Delta t_i$$

Reservoir Capacity = 504 – (-188) = 693 m^3/s

Volume = $692 \times 31 \times 86400 = 1853 \times 10^6 \, m^3$