2
Hydrology

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2.1. INTRODUCTION

The hydro-power plays a very important role in the development of the country as it provides power at cheapest rate being perpetual source of energy. Nearly 20% of the total world power is generated using hydro-plants. There are some fortunate countries in the world where 90% of the nation's power requirement is met by hydro power. There are few countries like Russia and Nepal where vast hydro resources are yet to be harnessed. As per the estimate of the World Power Organization, the world hydro-potential is roughly 5000 GW whereas only 200 GW is presently developed (4% only). Many more hydro-plants are included in coming plan of the Government of India.

Rain falling upon the earth's surface has potential energy relative to oceans towards which it flows. This energy can be converted into shaft work passing through hydraulic prime mover and ultimately into electrical energy. The shaft power developed by the water passing through the prime-mover is given by

$$\text{kW (power)} = \frac{mgH}{1000} \times \eta_h \times \eta_m \times \eta_g$$

where m = Rate of water flow in kg/sec, H = Height of fall in metres.
and η_h = Hydraulic efficiency of prime mover
and η_m and η_g are mechanical and generating efficiencies

$$\text{kW} = \frac{mgH}{1000} \times \eta_{overall}$$

where $\eta_{overall} = \eta_h\ \eta_m\ \eta_g$.

The quantity of water available and head are equally important in the generation of power. The available head depends upon the selection of site for hydraulic power plant. The site of the power plant is always selected for the highest available head when other things are in favour of site selection.

The quantity of water available at the selected site depends upon the hydrological cycle of nature. The quantity of water available can be determined from the study of rainfall and run-off in that area or rainfall and run-off decides the site for the power plant. As the availability of water depends on the natural phenomenon of rain, the maximum capacity of hydraulic generating plant is usually fixed on the basis of minimum quantity of water available. Usually storage reservoirs are constructed for such plants in order to store the water during peak periods of run-off and supply the same during off-peak periods of run-off.

The study of rainfall and run-off is very important for the students before going to the study of hydro-power engineering. This study helps in the design of dams, spillways and so on.

Hydrology. The science which deals with rainfall and run-off is known as hydrology. The evaporation of the water from the surfaces of river and oceans and its precipitation on the earth is known as hydrological cycle. The distribution of precipitation on the earth surface and beneath the earth is calculated with the help of hydrological considerations.

Water is evaporated from plants, rivers, oceans and carried with the air in the form of vapour which is known as clouds. When the vapours in the atmosphere are cooled below dew point temperature, it falls in the form of water or snow depending on the atmospheric temperature. This evaporation and precipitation is a natural continuous process and therefore constitutes a perennial source of energy. Processes of evaporation and precipitation are shown in Fig. (2.1).

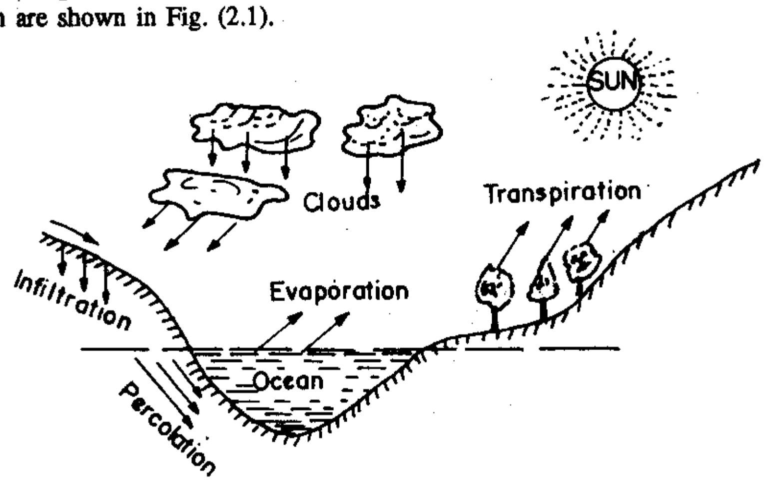


Fig. 2.1. Hydrological cycle.

Most of the water resource projects are multi-purpose projects as irrigation, navigation, flood control and generation of electric power. The problems in the design of multi-purpose projects usually are how much water is needed and how much is available ? These are the most difficult problems to answer of all the design problems because it involves social, economic and engineering aspects.

The design of the project whether it is multi-purpose or single purpose depends upon the availability of water. Peak rates of flow are the basis of design of projects to control the excess water (flood control) while volume of flow during longer periods of time is of interest in designing projects for use of water (irrigation or power generation or both). The answer to this question is found through the application of hydrology, the study of the occurrence and distribution of the natural waters on the earth.

Many projects are designed to control the flood, irrigation and power generation if the quantity of water available is sufficient for the required purpose and site is as per requirements. Many projects are designed only for irrigation purposes or power generation purposes. The flood control is one of the considerations in the design of the project whether it is designed for power generation or irrigation as it cannot be avoided.

The design of multipurpose projects is always difficult compared with the single purpose projects because the requirements from multi-purpose are varied. The study in this book is strictly limited to single purpose plant for power generation as it is the main purpose of the present text.

2.2. RAINFALL AND ITS MEASUREMENT

The "rainfall", known as "precipitation", is the natural process of converting atmospheric vapour into water.

During summer, the evaporation loss from free water surface is considerably large and this evaporated water finds room in the air mass. The water holding capacity of air in the form of vapour is also considerably large in hot weather. When this highly moist air mass cools down by some means below the dew point temperature, the water vapour from the air precipitates in the form of water and reaches the earth known as rainfall.

Rainfall in general sense is defined as the total condensation of moisture from the atmosphere that reaches the earth, including all forms of rains, ice and snow. The rate of rainfall is expressed in centimetres of water during a given period of time. One centimetre rainfall is defined as follows : when the quantity of water collected on a certain plain area due to rainfall becomes one centimetre in height, one centimetre of rainfall is said to occur. It is assumed that there are no losses due to evaporation, seepage and whatsoever and there is no run-off also during the accumulation of water.

The rainfall varies widely from one part of the world to another, ranging from desert regions of Rajasthan to the hills of Assam where the average annual rainfall is over 1140 cm. In some regions, the seasonal variation is very slight and monthly rainfalls are relatively uniform. In other regions, the seasonal variation is wide and monthly rainfalls also differ widely. The monthly rainfalls at four places are shown in Fig. 2.2. At Armagh, the mean monthly rainfall varies little throughout the year as shown in Fig. 2.2. (*a*), and it may be regarded as notable for uniform distribution throughout the year. This uniform distribution of mean monthly rainfall is, a characteristic in the eastern part of Great Britain and Maryland. The seasonal variation is more strongly marked, over much of the world as shown in Fig. 2.2. (*b*), (*c*) and (*d*), and is quite stable many times. At Kosti, the mean annual rainfall (40 cm) is not great but seasonal variation is extreme as five months of the year are rainless. At Calicut, the annual rainfall is much heavier but dry season is not completely dry. In some equatorial zones, there are two wet seasons which occur at different times of year as shown in Fig. 2.2. (*d*).

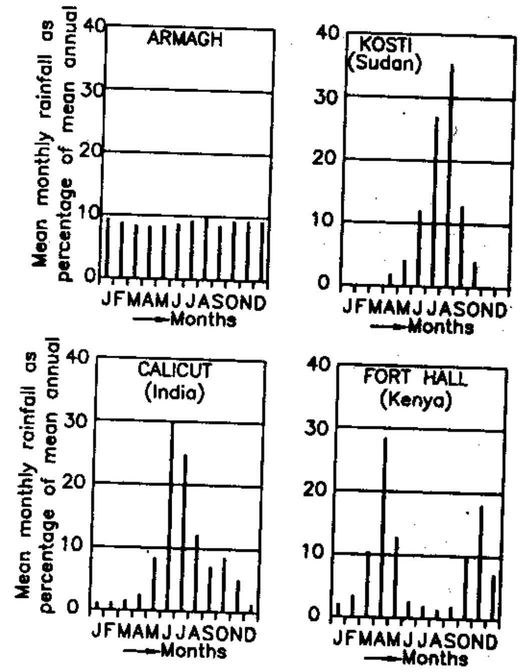


Fig. 2.2. Specific monthly distribution of rainfall at four different places.

The annual rainfall at any given stations varies irregularly from year to year. The range of this variation marks the reliability of the rainfall and is of great importance in the design of storage reservoirs. Fig. 2.3 shows the annual rainfalls for 30 years at Armagh and Kosti and indicates the erratic nature of year to year variations. The reliability of rainfall depends mostly upon the period selected for consideration. The monthly rainfall is much less reliable than the annual rainfall. The zones of India having different rainfall values are shown in Fig. 2.4 on the map of India.

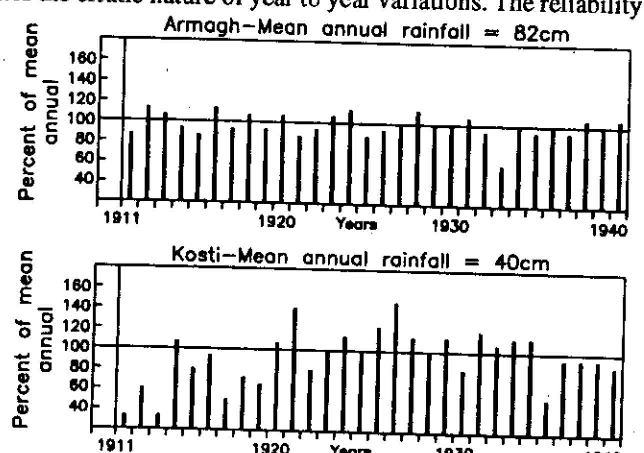


Fig. 2.3. Variations of annual rainfall for 30 years.

Intensity of Rainfall. The intensity of rainfall is expressed as an amount of precipitation in a stated period. The intensity of rainfall varies widely from minute to minute during heavy rain storm and can only be measured with a continuously recording gauge. Intense rainfall is usually of limited extent and duration. The greater the area under consideration, the smaller the average intensity. Like-wise, the longer the duration of rainstorm, the smaller the average rainfall intensity.

The relation between the area of a rainstorm and its average intensity is important in assessing the amount of rain which may be expected to fall upon a catchment area within a given period. The intensity of rainfall is equally important in the design of spillways during heavy rain periods.

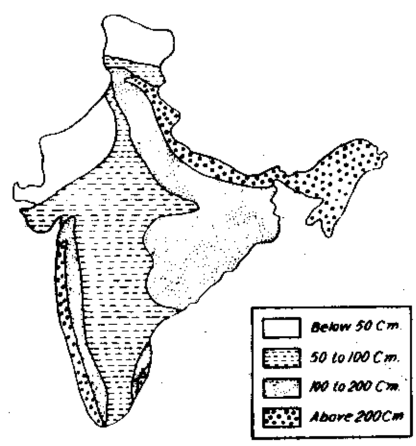


Fig. 2.4. Yearly rainfall in India in centimetres.

The intensity of rainfall is given by the following formula :

I (Intensity in inches/hr)

$= \dfrac{R}{T + C}$ where T is the duration of rainstorm in hours and R and C are the constants quoted by different authorities for different areas in the world. The intensity also depends upon the area selected for the measurement.

Measurement of rainfall. All forms of precipitation are measured on the basis of vertical depth of water which would accumulate on the level surface if all the precipitation remained where it fell. The rainfall is generally measured with the help of rain-gauges. Rain-gauges are mainly of two types :

1. Non-recording type. If the water from the rainfall is collected before the losses take place, then the depth of the water over the small area can be accurately determined to find out the rainfall in mm. The area selected for setting the gauge should represent the large area whose meteorological characteristics are the same. The non-recording gauge usually consists of a standard funnel discharging into a receiver large enough to hold the maximum possible day's rainfall. The funnel and receiver are placed in a metal casing with suitable packings. At regular intervals, the water is collected into a measuring vessel which is so calibrated in relation to the area of the funnel mouth that directly reads the rainfall in cm or mm. The interval used for measuring the rainfall generally depends upon the intensity of rainfall. The arrangement of the rain-gauge is shown in Fig. 2.5. The base of the gauge is permanently fixed in the concrete block at a site where rainfall is to be measured. The precaution is taken during fixing to level perfectly. The gauge is fixed in the block in such a way that the top of the gauge will be 30 cm above the natural surface level. The gauging station is generally protected by wire fencing with gate.

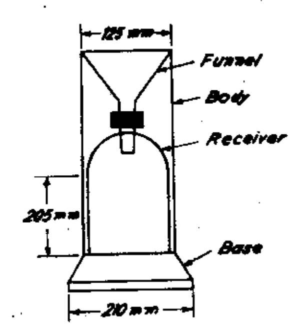


Fig. 2.5. Non-recording Type Gauge.

2. Recording type. The recording type gauge is shown in Fig. 2.6, A standard funnel is provided on the top of rectangular box as shown in Fig. 2.6 A float is adjusted in the same box. The float is connected to a pin point by means of a float rod. The pin point touches the graph paper mounted on a rotating drum as shown in Fig. 2.6. The rotating drum is kept rotating continuously with the help of electric motor. The drum makes generally one rotation during 24 hours. When the rainfall occurs, water passes into the

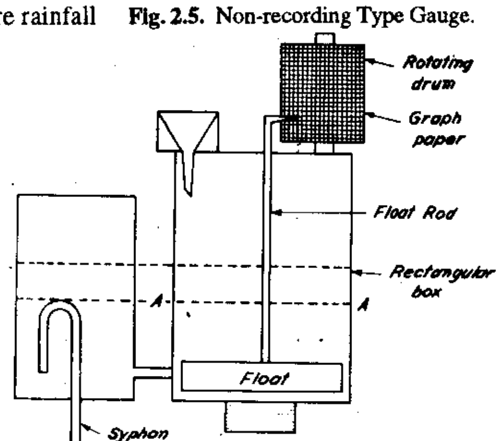


Fig. 2.6. Recording Type Gauge.

rectangular box. The float rises as the water level in the box rises. As the float rises, the pin point moves up on the graph paper to plot the mass curve (cumulative rainfall) of rainfall.

When the box gets filled to a level shown by *AA* the siphon starts working and all the collected water is drained out from the box. The graph on the rotating drum gives the mass-curve of the rainfall.

Weighing type recording gauge is commonly used for field work instead of floating type, because they record rain as well as snow. In this type of gauge, the precipitation passes through a collector into a bucket which is supported on the platform of a spring balance. The movement of balance is transmitted by means of suitable levers and links to a recording pen. The chart on the drum shows the accumulated precipitation. Recording type gauges are generally preferred in remote areas (forest) where daily going is not possible. This gauge also records the exact duration of heavy rainstorm and variations of rainfall intensity.

The number of gauges used for hydro-electric purposes should be as numerous as possible and should be carefully distributed over the catchment area and also over the adjacent territory, if possible.

There is no definite rule for determining the number of gauges necessary to cover the considered area. The desirable "gauge density" depends upon the size and configuration of the catchment area and upon the uniformity of its rainfall distribution. The rain gauges should be distributed over the catchment area in such a manner which will cover fairly various belts of rainfall and will cover as wide range of altitude as possible. One gauge for every 100 square mile area is generally preferred.

In the design of hydro-electric projects, the rainfall record of nearly 35 years is required. This period is accepted as giving a reasonably accurate assessment of mean annual rainfall. Many times, it is not possible to wait many years for rainfall data and in such cases, shorter periods are accepted by design engineers with reserve and allowance made for possible error.

Location of Rain Gauge. The following points are taken into consideration while selecting the site for the rain gauge station.

(1) The rain gauge station should be easily accessible to the observer. (2) The gauge should be erected on a level ground. (3) A wind shelter should be provided to reduce the effect of wind. (4) The rain gauging station should not be close to the trees and buildings. The distance of the gauge from every object should not be less than twice the height of the object above the gauge. (5) The location of rain gauge should be true representative of the area whose average rainfall is to be measured.

Average or Mean Depth of Rainfall. The primary purpose of rain gauging in hydro-electric work is to determine the mean monthly and annual rainfalls over the catchment area. When the rain-gauging stations are more than one for a particular basin, the question arises which value of rainfall should be taken. We are always interested to find out only one value of rainfall which will represent the whole catchment area. The following three methods are used for calculating the average of rainfall depending upon the area of the basin.

1. Arithmetic Mean Method. In this method, the values of rainfalls of all the stations are added and the sum is divided by the number of gauging stations. This can be represented mathematically as

$$h_a = \frac{h_1 + h ...... + h_n}{n} = \frac{\Sigma h}{n}.$$

If the gauges are uniformly distributed and the variation of individual gauge reading from the mean is not large, this method gives the reading as accurate as any other method. This method is conveniently used when the area of the basin is less than 500 km.

2. Thiesson Method. This method is very accurate and generally used when the catchment area lies between 500 to 5000 km square. The use of this method is explained with the following example. Assume that there are stations in the given basin named as 1, 2, 3, 4, 5, 6, 7 and 8. It is very essential to divide the total basin area in such a way that each located station in the basin represents that area in the true sense.

In this method, the gauging stations are marked on the basin area as shown in Fig. 2.7. All the stations are joined to each of the adjacent stations as shown by dotted lines so as to form a system of triangles. Each rain gauging station forms a vertex of a triangle. After forming the triangles, draw the perpendicular bisectors of each of the sides of all triangles as shown in the figure by full lines. This construction divides the whole basin area into 8 number of polygons. Each polygon encloses only one gauging station and it is the domain of that rain gauging station. After forming the polygons, the area of each polygon is calculated by the use of planimeter.

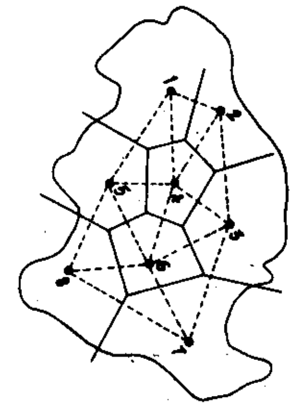


Fig. 2.7. Construction of Thiesson Method.

The measured gauge readings and areas of the polygons enclosing the gauges are tabulated in the following table :

Station (a)	**Rainfall in cm* (b)	*Area of polygon fall in polygon* (c)	*Total volume in rainfall in polygon* (d) = b × c
1	h_1	A_1	$h_1 \times A_1$
2	h_2	A_2	$h_2 \times A_2$
3	h_3	A_3	$h_3 \times A_3$
4	h_4	A_4	$h_4 \times A_4$
5	h_5	A_5	$h_5 \times A_5$
6	h_6	A_6	$h_6 \times A_6$
7	h_7	A_7	$h_7 \times A_7$
8	h_8	A_8	$h_8 \times A_8$

The column (*a*) represents the number of station, column (*b*) represents the average rainfall at each gauging station and column (*c*) represents the area of each corresponding polygon.

The mean rainfall of the basin is given by

$$h_a = \frac{\Sigma(d)}{\Sigma(c)} = \frac{h_1A_1 + h_2A_2 + h_3A_3 + h_4A_4 + h_5A_5 + h_6A_6 + h_7A_7 + h_8A_8}{A_1 + A_2 + A_3 + A_4 + A_5 + A_6 + A_7 + A_8}$$

This method gives better result than arithmetic mean method because each point on a perpendicular bisector of the line joining the two gauging stations will be equidistant from both the stations. If we move slightly this or that side of the bisector, our position will distinctly fall in the domain of that station of which our position is now nearer.

(3) **Iso-hyetol method.** Iso-hyete is a contour joining the points of equal rainfall in the given catchment area. Iso-hyetes have the following properties :

(1) Two different iso-hyetes do not cross each other. (2) Each iso-hyete closes on itself. (3) Iso-hyete of higher value indicates the higher rainfall.

In this method, iso-hyetes are drawn in given basin by joining the points of equal rainfall as shown in Fig. 2.8. The points of equal rainfall can be computed from the rainfall values of rain gauging stations.

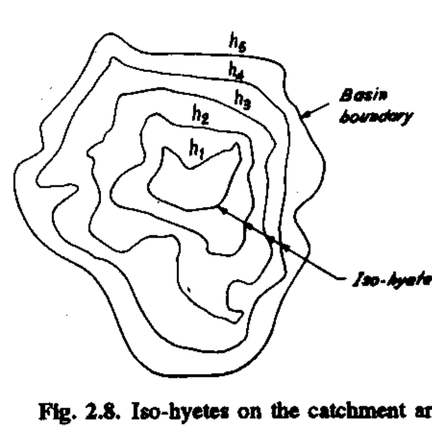


Fig. 2.8. Iso-hyetes on the catchment area.

Generally interval of the iso-hyete is one cm. After drawing the iso-hyetes, the areas between each two successive iso-hyetes are measured with the help of planimeter. The rest of the procedure of finding out the mean rainfall is similar to the described in method two. The highest spot rainfall value in area is h_1. The results of the method are tabulated as given in Table 2.1.

Table 2.1.

Iso-hyetol interval (*a*)	*Mean* (*b*)	*Area between two successive iso-hyetes* (*c*)	*Mean × Area* (*d*) = *b* × *c*
$h_1 - h_2$	$(h_1 + h_2)/2$	A_1	$(h_1 + h_2)A_1/2$
$h_2 - h_3$	$(h_2 + h_3)/2$	A_2	$(h_2 + h_3)A_2/2$
$h_3 - h_4$	$(h_3 + h_4)/2$	A_3	$(h_3 + h_4)A_3/2$
$h_4 - h_5$	$(h_4 + h_5)/2$	A_4	$(h_4 + h_5)A_4/2$
h_5 – *boundary*	$(2h_5 - 1)/2$	A_5	$(2h_5 - 1)A_5/2$

In this analysis, the difference between h_1 and h_2, $(h_1 - h_2)$ may not exactly be one as h_1 represents the highest rainfall. The difference between the iso-hyete h_5 and boundary is considered one which is the common interval. The interval between the iso-hyetes h_2 and h_3, h_3 and h_4, h_4 and h_5 is 1 cm.

The column (*a*) represents the iso-hyete interval, column (*b*) represents the average of iso-hyete interval and column (*c*) represents the area enclosed between the two successive iso-hyetes.

The mean rainfall of the basin is given by

$$h = \frac{\Sigma(d)}{\Sigma(c)}$$

$$= \frac{(h_1 + h_2)A_1 + (h_2 + h_3)A_2 + (h_3 + h_4)A_3 + (h_4 + h_5)A_4 + (2h_5 - 1)A_5}{2[A_1 + A_2 + A_3 + A_4 + A_5]}$$

This method is commonly used for the basin area above 500 sq. km.

The analysis of rainfall for power purposes is usually more concerned with dry years than with wet years and for the assessment of storage requirements, it is often necessary to determine the driest period for which provision must be made.

2.3. RUNOFF AND ITS MEASUREMENT

As the rain falls upon the drainage basin, a portion of it is evaporated directly by the sun, another large portion is taken up by vegetation and growing crops particularly in growing season and some percolates into the ground. The percolating water may be partly absorbed by the roots of vegetation or it may reappear in course of time as spring water either inside or outside the catchment area. The remaining portion of rainfall flows through the catchment area on the surface of the earth and is known as runoff. The suitability of runoff for power generation depends on the magnitude and time distribution of flow and head made available by the surrounding topography. In general, the runoff is given by

$R = P - L$ where R (Runoff) $= R_s + R_c$

and P = Precipitation by rainfall L = All losses

R_s = Runoff over the surface

R_c = Runoff reaching the catchment area through the pervious earth.

To find out the runoff rate through the catchment area is the first phase in the design of hydro-electric power project. The unit of runoff is cum/sec or* day-second-metre or it is also expressed in cm of water depth over the entire catchment area or** $(\text{km})^2$-cm/hr.

Factors affecting the runoff. The knowledge of the factors affecting the runoff characteristics of drainage areas is particularly essential when, in the absence of stream flow records, the recorded runoff of the

* Day-second-metre is the flow collected at the rate of 1 cum/sec for one day = 1 × 24 × 60 × 60 = 86400 m^3/day.

** $(\text{km})^2\text{-cm/hr} = 1000 \times 1000 \times \frac{1}{100} \times \frac{1}{3600} = 2.78\ m^3/\text{sec}$.

neighbouring stream is used to estimate the probable amount and distribution of runoff of a stream by a comparison of the relative runoff characteristics of the two watersheds.

The factors affecting the runoff are listed and described below.

(1) **Rainfall pattern.** The runoff is more if the rainfall is heavy. The runoff increases more rapidly with increase in rainfall because the time allowed for evaporation and percolation losses is small when the intensity of rainfall is high. If the duration of the rainfall is more, the runoff will also be prolonged because the soil tends to become saturated and lowers the rate of seepage and humid atmosphere slows evaporation.

(2) **Character of catchment area.** The topography, shape, its vegetal cover and nature of the surface and sub-surface geology have a great influence upon the runoff characteristics of the catchment area. The steep and rocky surface gives more runoff.

(3) **Shape and size of the catchment area.** Large catchment area gives more runoff. The runoff at the point A as shown in Fig. 2.9 (a) is more than the runoff at the point A as shown in Fig. 2.9 (b), even the catchment area of both is same. The reason for this is obvious from the figures itself.

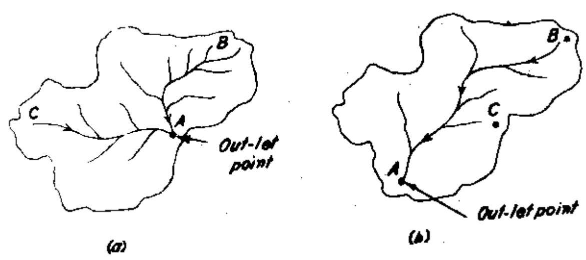


Fig. 2.9. Distribution of runoff over the catchment area.

(4) **Vegetation.** The nature and extent of vegetation including crops determine the transpiration and interception losses. Vegetation, particularly of forest, has considderable effect upon the runoff. It consumes a proportion of the rainfall, causes interception losses and provides physical obstruction for runoff.

(5) **Geology of the area.** The geology of the catchment area is of fundamental importance in the consideration of runoff. Rocky area gives higher runoff than softy or sandy area.

(6) **Weather conditions.** Low temperature, high relative humidity and low winds give high runoffs because the evaporation losses increase with the increase in temperature, decrease in relative humidity and increase in wind velocity. Water absorbed by the hot earth is also more which reduces the runoff.

Measurement of Runoff. To find out the available energy in a given river, we must know the quantity of water flowing and its variation with time over a long period of years. For measuring the runoff, the following methods are used :

1. **Use of Rainfall Records.** The lack of availability of direct runoff data often makes it necessary to derive the runoff characteristics from rainfall observations and estimated losses.

The runoff is calculated from the rainfall data available for sufficiently long period by multiplying with a coefficient known as "Runoff coefficient." The value of runoff coefficient is decided considering all the factors which affect runoff. Such coefficients are noted for different types of catchment areas as given below :

Values of Runoff Coefficients (K) for various Surfaces.

Garden apartment	... 0.50
Commercial and industrial	... 0.90
Forest areas depending on soil	... 0.05 – 0.10
Parks, farmland, pasture	... 0.05 – 0.30
Asphalt of concrete pavement	... 0.85

$\therefore$ Runoff = Rainfall × Runoff Coefficient.

This method is generally used for small catchment area.

This is an uncertain method of estimating run-off because of the wide range of conditions encountered in a large catchment area, the difficulty of measuring the losses accurately, and the manner in which they sometimes vary throughout the season. Therefore, this method is used for small catchment area and due to non-availability of run-off data.

2. **Runoff Formulae.** In this method, the runoff is given directly in terms of rainfall for specified region :

(*a*) Khosla's Formula

$$R = P - 4.811\ T.$$

(*b*) Inglis Formulae, for area in Maharashtra,

$$R = 0.85\ P - 304.8 \text{ for Ghat area,}$$

and

$$R = \frac{(P - 177.8)P}{2540} \text{ other than Ghat area}$$

R = Run-off in mm P = Rainfall in mm

and T = Mean temperature in °C.

These formulae are mostly based on observations made by a person and extensive experiments conducted by him. These formulae are useful only for specific regions.

3. **Actual Gauging.** Direct measurement by stream gauging at a given site for a long enough time is the only precise method of evaluation.

The water flow volume through a selected channel of fixed cross-section is measured by measuring the velocity of water at enough points for different water levels.

The depths at different points are measured with the help of rope at regular intervals. The mean velocity in each section is measured with the float method or current meter directly.

Fig. 2.10 shows a typical stream-gauging station.

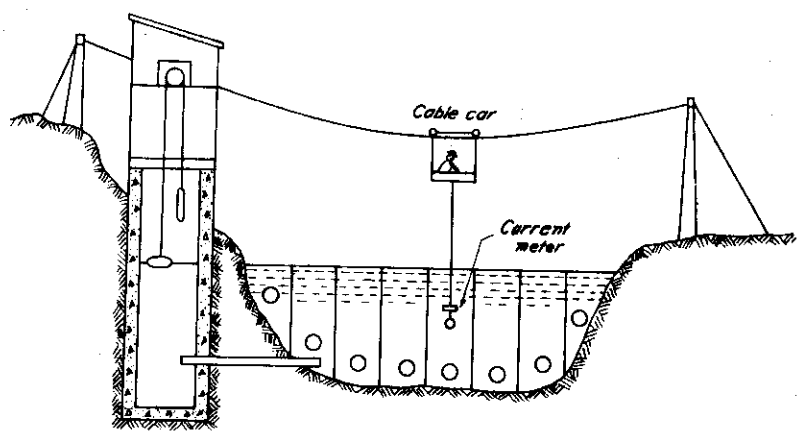


Fig. 2.10. Actual stream gauging station.

The runoff through the cross-section of the river shown is given by

$$Q = A_1V_1 + A_2V_2 + A_3V_3 + A_4V_4 + A_5V_5 + A_6V_6 + A_7V_7 + A_8V_8$$

where $A_1, A_2 \ldots\ldots A_8$ are the areas of the sections considered as shown in figure and $V_1, V_2 \ldots\ldots V_8$ are the mean velocities of water flowing through the cross-sectional areas $A_1, A_2 \ldots\ldots A_8$ respectively.

U.S. Geological Survey and cooperating authorities established gauging stations to measure the runoff on most important rivers about 1906 upto 1960 and have increased the number of sites since then.

Besides the annual total and average rates of flow, the maximum and minimum rates must also be known. Maximum flood flow governs the size of the headworks and the dam to be built. If the failure of the dam would cause loss of life below the site, the dam would be designed for a flood occurring once in 1000 years or even 10,000 years. A dam on a remote river might be designed to hold floods occurring once in 10 to 20 years, the recurring costs of repairing damages caused is greater than the design flood being cheaper in the long run than installing a larger, costlier dam initially. If a dam is built to resist the maximum possible flood of all time, the high cost would make the construction economically unattractive.

The minimum flow and that part which can be stored fix the amount of primary power that will be available. That part of the capacity of a hydraulic plant available at all times when energy is needed is classed as primary power. Average flow must be known to figure the maximum marketable energy and revenue the projected plant may be expected to yield.

The maximum rate of flow through the river is either calculated by using empirical formulae or energy curves. Flood marks also help to give the maximum rate of flow.

Few empirical formulae are listed below for finding maximum discharge.

1. Dicken's Formula.

$$Q = CA^{0.75}$$

where C = 11.37 for the Northern India, 13.77 to 19.28 for the Central India and 22.04 for the Western India.

2. Ryve's Formula. This formula is used only in Southern India

$$Q = C \cdot (A)^{2/3}$$

C = 6.74 for areas within 24 km from sea coast
= 8.45 for areas within 24 to 161 km from sea coast
= 10.1 for hilly areas.

3. Inglis Formula.

$$Q = \frac{123.2\,A}{\sqrt{A + 10.36}}$$

This is used for all types of catchment areas.

2.4. HYDROGRAPHS

Hydrograph is defined as a graph showing discharge (run off) of flowing water with respect to time for a specified time. The time period for discharge hydrograph may be hour, day, week or month. The discharge may be m^3/sec, km^2-cm/hr or day-second-metre. Discharge hydrographs are known as flood or run-off hydrographs. Each hydrograph has a reference to a particular river site.

The common nature of hydrograph is shown in Fig. 2.11.

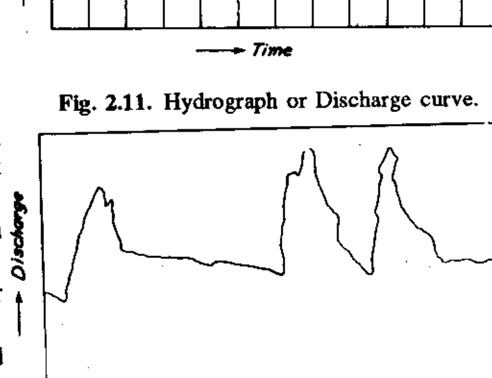


Fig. 2.11. Hydrograph or Discharge curve.

We can read the followings from the hydrograph.

1. Rate of flow at any instant during the duration period.
2. Total volume of flow upto that instant as the area under hydrograph denotes the volume of water in that duration.
3. The mean annual run-off or mean run-off for each month of the year.
4. The maximum and minimum run-off for the year and for each month.
5. The maximum rate of run-off during the floods and duration and frequency of the flood. The hydrograph shown in Fig. 2.12 taking time period as month indicates that the flood reached thrice in a month.

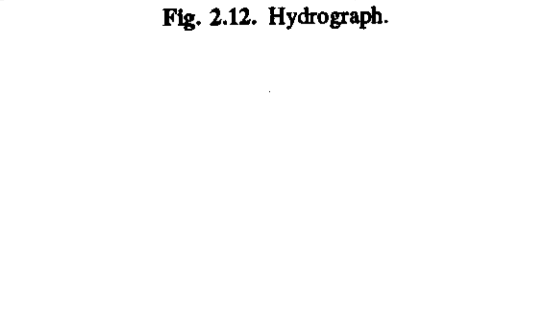


Fig. 2.12. Hydrograph.

The hydroelectric engineer is always interested in the above-mentioned characteristics of the catchment area before going to the design of the project.

The hydrograph can be drawn taking day, month or year as time axis as shown in Fig. (2.13). The hydrograph on the basis of day gives an idea about the flood period during this month. The hydrograph on the basis of month gives an idea about the dry period of the year. This also decides the period during which the water should be collected and to be used during the dry period of the year. The year-wise data provides information concerning the lean or draught year. Such information is very essential for deciding the location and size of the hydel power plant.

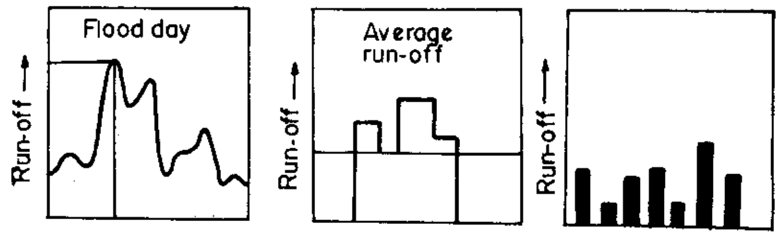


Fig. 2.13.

Hydrograph and Determination of Storage Capacity. A hydrograph of the typical river is shown in Fig. 2.14 taking day as time period on X-axis and discharge in m^3/sec on Y-axis.

A constant demand line of 3000 m^3/sec is also indicated on the same diagram. If all flows above the flow demand line of 3000 m^3/sec are discarded, then the total area below the demand line of the hydrograph indicates the total natural flow of *29200 $m^3/sec \times$ month available for power generation. Similarly, the total shaded areas or 6800 $m^3/sec \times$ month is required from storage of auxiliary plant. This much quantity (6800) can be collected from the run-off when the run-off rate is higher than the demand line as shown in figure.

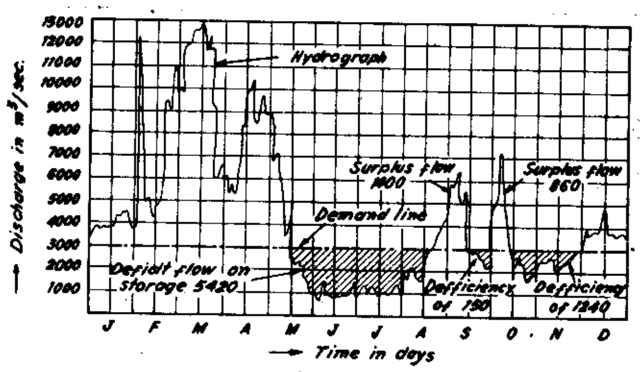


Fig. 2.14. Daily hydrograph of a river for one year.

The deficit flow starts from 15th of May and continues upto 22nd August and it would require total storage of 5420 $m^3/sec \times$ month to provide the flow demand of 3000 m^3/sec. From August 22 to September 15, the excess flow of 1400 $m^3/sec \times$ month due to run-off will reduce the reservoir depletion from 5420 to $(5420 - 1400) = 4020$ $m^3/sec \times$ month. On Ist October, the depletion of the reservoir would increase by 150 $m^3/sec \times$ month and total depletion would be $4020 + 150 = 4170$ $m^3/sec \times$ month. On October 15, the depletion would be reduced from 4170 to $(4170 - 860) = 3310$ $m^3/sec \times$ month due to the surplus addition of 860 $m^3/sec \times$ month during the period of 1st October to 15th October and finally on December 1, the depletion would be $3310 + 1240 = 4550$ $m^3/sec \times$ month due to the deficit flow of 1240 $m^3/sec \times$ month during the period of October 15 to December 1.

*$m^3/sec \times \text{month} = 1 \times 30 \times 24 \times 3600 = 2592000 = 2592 \times 10^3 m^3$.

It is obvious from the above calculations, reservoir would have been drawn to its fullest extent of 5420 m^3/sec × month of August 22 and this represents the capacity of the reservoir required to regulate the constant flow demand of 300 m^3/sec throughout the year.

The Unit Hydrograph. The runoff hydrographs from two storms (rainfall) would be same if two identical rainstorms could occur over a drainage besin with identical conditions prior to the rain. This principle was expressed by Sherman in 1932 introducing his theory of the "*Unit Hydrograph*". He pointed out that all hydrographs have the same time base resulting from rainfalls of a given duration. If the rainfall distribution in the storms is similar with respect to time and area, the ordinate of each hydrograph will be proportional to the volume of runoff. The unit hydrograph is a hydrograph with a volume of 1 cm of runoff resulting from a rainfall of specified duration and a real pattern. If the above-mentioned theory is sound, the hydrograph for any other similar rainfall of the same duration can be constructed by just multiplying the ordinates of the unit hydrograph by the storm runoff.

Hydrographs of various rainfalls will be similar in shape with ordinates proportional to the runoff volumes within the limitations of a fixed duration and similar rate and a real distribution of rainfall. Actually the occurrence of identical rainfalls is very rare. The rainfalls may vary in duration, amount, and area distribution. The effect of storage basin also varies. Therefore, unit hydrographs of very large floods differ somewhat from those of small rainfalls.

Construction of Unit Hydrograph. A unit hydrograph can be constructed from a hydrograph of the actual runoff when there is uniform rainfall intensity and uniform areal distribution.

The following steps are used for the construction of unit hydrograph :

1. The total volume of runoff (area under *ABC*) is measured first from the actual hydrograph.

2. The ordinates of the unit hydrograph are found by dividing the ordinates of actual runoff by the total volume of runoff in cms over the drainage area. The resulting hydrograph is the unit hydrograph for the basin.

3. Find out the effective duration of runoff-producing-rain for which the unit hydrograph is applicable by a study of the rainfall records.

The construction of unit hydrograph from the actual hydrograph of runoff is shown in Fig. 2.15.

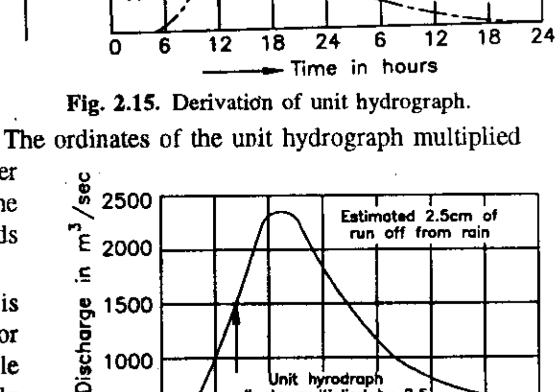


Fig. 2.15. Derivation of unit hydrograph.

The use of unit hydrograph is shown in Fig. 2.16. The ordinates of the unit hydrograph multiplied by the estimated volume of direct runoff in cm of water over the basin gives the ordinates of the actual hydrograph. The estimation of direct runoff is made by any of the methods described earlier in the article 2.3.

The number of unit hydrographs for a given basin is theoretically infinite as there may be one unit hydrograph for every possible duration of rainfall and every possible distribution pattern of rainfall in the basin. In practice, only a limited number of unit hydrographs are used for a given basin. It is also common practice to neglect the variations in rainfall distribution within the basin area. This assumption is reasonably applied for small basins but the variations over large areas cannot be neglected as variations are large. Therefore, it is not adviseable to use unit hydrograph method for basins over 5000 sq. kilometres in area.

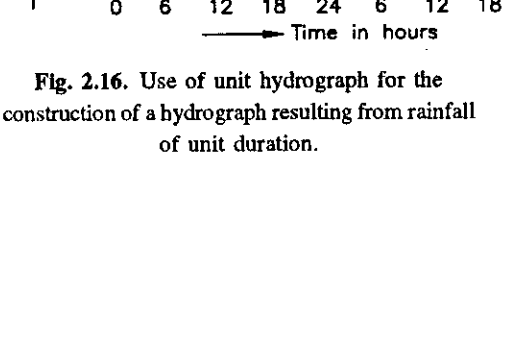


Fig. 2.16. Use of unit hydrograph for the construction of a hydrograph resulting from rainfall of unit duration.

The unit hydrographs can be applied successfully to basin areas as large as 25000 sq. kilometres if distribution patterns are classified into different types and unit hydrographs are developed for each type. It is always preferable to divide the large basin into sub-areas, utilise hydrographs for each sub-area independentally and combine the resulting hydrographs together.

Limitations to the use of unit hydrographs

1. Similar rainfall distribution over a large area from storm to storm is rarely possible. Therefore, its use is limited to areas under about 5000 sq. kilometres.

2. Odd-shaped basins, particularly long and narrow, have very uneven rainfall distribution, therefore, unit-hydrograph method is not adopted to such basins.

3. In mountain areas, the areal distribution is very uneven, even then unit hydrograph method is used because the distribution pattern remains same from storm to storm.

2.5. FLOW DURATION CURVE

Flow duration curve is another useful form to represent the runoff data for the given time. The magnitudes of runoff as ordinates against the corresponding percentage of time as abscissae results in a so called "*flow duration curve*". If the magnitude on the ordinate is the potential power contained in the stream flow, then the curve is known as "power duration curve". This curve is a very useful tool in the analysis for the development of water power.

The flow duration curve is drawn with the help of hydrograph from the available runoff data. The method used for drawing the flow duration curve is illustrated with the help of following example.

Runoff Data

Month	*Discharge in m^3/sec*	*Month*	*Discharge in m^3/sec*
1.	599	7.	2000
2.	400	8.	3000
3.	200	9.	1600
4.	100	10.	600
5.	200	11.	400
6.	800	12.	300

The hydrograph can be drawn as shown in Fig. 2.17 for the given runoff data.

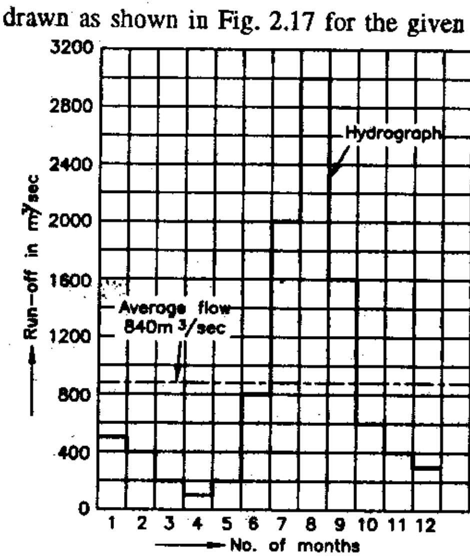


Fig. 2.17. Hydrograph.

To obtain the flow duration curve from the hydrograph, it is necessary to find out the length of time during which certain flows are available. This information either from runoff data or from hydrograph (this is more easy) is tabulated as given below.

Discharge m^3/sec (a)	*Total No. of months available* (b)	*Percentage time available* $c = \frac{b}{12} \times 100$
100 (and more)	12	100
200 (and more)	11	91.6
300 (and more)	9	76
400 (and more)	8	66.6
500 (and more)	6	50
600 (and more)	5	41.5
800 (and more)	4	33.3
1600 (and more)	3	25
2000 (and more)	2	16.6
3000 (and more)	1	8.3

Now the flow duration curve taking 100% time on the X-axis and runoff on Y-axis can be drawn as shown in Fig. 2.18.

If the head of discharge is known, the possible power developed from the water in kW can be determined by using the following equation.

$$\text{Power in kW} = \frac{mgH}{1000} \times \eta$$

where m = Discharge in kg/sec.
H = Head available in metres, η = Combined efficiency of hydraulic prime mover and electric generator.

The area under the flow duration curve gives the total quantity of runoff during that period as flow duration curve is representation of hydrograph with its flows arranged in order of descending magnitude.

Thus the flow duration curve can be converted to a power duration curve with some other scale on the same graph.

The selection of time unit depends solely on the purpose of the curve. If a project for diversion without storage is to be designed, the time unit should be the day so that the absolute minimum flows will be indicated on the curve. The time unit, month or year may be safely taken for reservoir design depending upon the reservoir size in relation to the inflow.

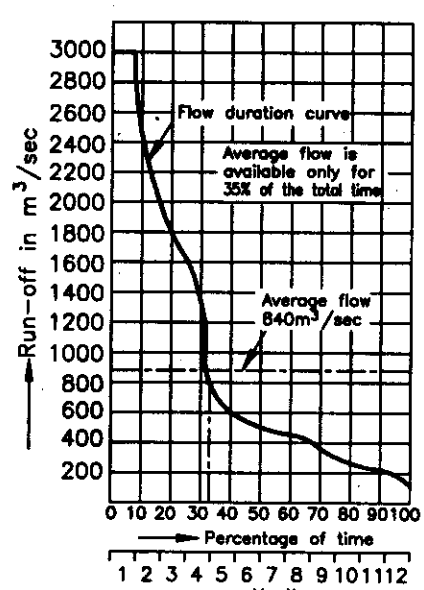


Fig. 2.18. Flow Duration Curve.

Flow duration curves are most useful for preliminary studies and for comparisons between streams. Fig. 2.19 compares the flow duration curve of River *X* with flow duration curve of River *Y*. The flow duration curve of river *X* offers no chance of successful development without provision for storage to provide water during periods of low natural flow. The river *Y* provides minimum 100 m^3/sec, throughout the year for direct use. Storage would be required on both streams to meet the constant demand of 140 m^3/sec but the storage volume required for river Y (*abc*) is much less than for river X (*ebd*). The river Y produces considerably more runoff than river X and it (river Y) can provide a much higher yield than river X if adequate yield facilities are provided. The exact storage requirements are dependent on the actual sequence of flow and cannot be estimated accurately from flow duration curve.

The main defect of the flow duration curve as design tool for water power development is that it does not present the flows in natural sequence of occurrence. It is also not possible to tell from flow duration curve whether the lowest flows occurred in consecutive periods or were scattered throughout the considered period.

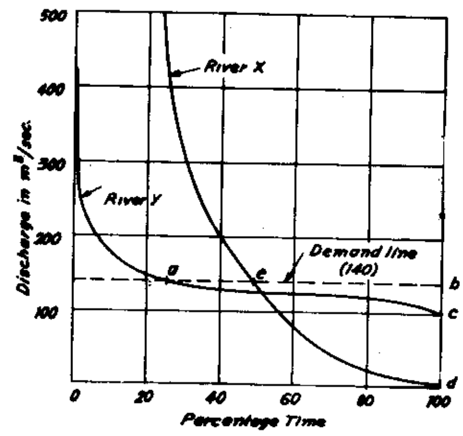


Fig. 2.19. Comparison of flow duration curves for two streams.

A storage must be provided at the power site when a large part of the natural flow is not to be wasted. The water can be stored during off peak periods and can be made available during peak periods. Storage collects the natural flow of the stream during low load condition (lower than the inflow) and supplies with a uniform rate if the load is constant. Storage also reduces the average flow due to increased evaporation losses from water surface area. Therefore, the effective storage is the accumulated water after adjusting the evaporation and other losses. The effect of storage on the flow duration curve is to lower the upper portion of the curve and raise the lower portion as shown in Fig. 2.20.

If there were no evaporation and leakage losses, the area below the unregulated curve and above the regulated curve should be equal to the area below the regulated curve and above the unregulated curve.

In case of runoff river power plants without storage facilities, the unregulated flow duration curve should be used and firm power is customarily assumed on the basis of the flow available 90 to 97% of the total time. The flow duration curve always should be developed from as long a stream flow record as possible to avoid undue influence by abnormally wet or dry periods and should be modified to correct for upstream reservoir storage.

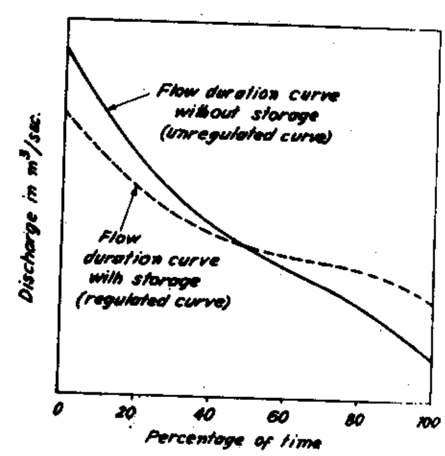


Fig. 2.20. Effect of storage on flow duration curve.

2.6. MASS-CURVE AND STORAGE

The graph of the cumulative values of a water quantity (runoff) against time is known as "*Mass Curve*". A mass curve is an integral curve of the hydrograph which expresses the area under the hydrograph from one time to another.

Mathematically the flow mass curve is expressed as

$$V = \int_{t_1}^{t_2} Q_t \cdot d_t.$$

where V is the volume of runoff and Q_t is the discharge in m^3/sec as a function of time.

The mass curve of the river whose monthly average runoff is given in the following table is drawn as shown in Fig. 2.21.

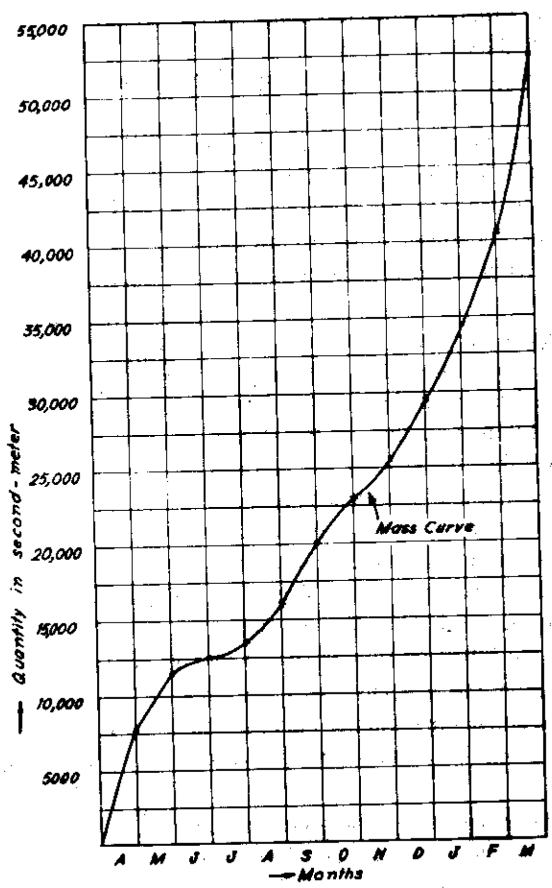


Fig. 2.21. Mass-curve.

Month	*Second-metre mean-monthly run-off*	*Second-metre months-accumulative*
April	7000	7000
May	4000	11000
June	1500	12500
July	1000	13500
August	2500	16000
September	4000	20000
October	3000	23000
November	2500	25500
December	4000	29500
January	5000	34500
February	6000	40500
March	12000	52500

The mass-curve plotted from mean monthly flows is correct only at the beginning and end of each month, as the variation in flow during the month is not taken into account. A summation of daily flows, instead of monthly flow, results in more accurate mass-curve ; but this involves an excessive amount of work. The mass curve on daily flow basis is seldom used in practice except for critical periods.

The abscissa of each point on mass curve represents the total time from the beginning of the period and ordinate of each point represents the total quantity of water available during this time.

If the rainfall is uniform throughout the year, the mass curve for a river in such area will be a straight line as the mean monthly flow throughout the year remains constant. The mass curve for such flow is shown in Fig. 2.22.

If V is total volume of the water collected during the time period t, then the slope of the curve, tan θ gives the rate of flow.

$$\therefore \quad Q = \text{(rate of flow)} = \frac{V}{t} = \tan\theta.$$

It is obvious that the slope at any point on the mass-curve represents the inflow rate at that instant.

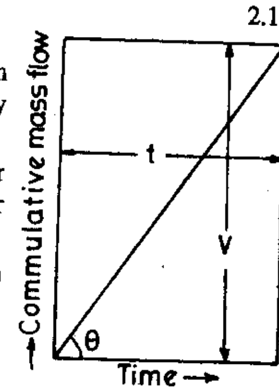


Fig. 2.22. Mass curve for uniform flow.

The determination of required capacity for a reservoir is generally more complex. Many problems involving storage capacity determination can be solved conveniently with the help of mass curve. The use of the mass-curve for deciding the storage capacity of the dam and spillway capacity required for the selected dam capacity is explained with the help of following example.

A mass flow on the basis of accumulated monthly mass flow for a river in New York for four years is shown in Fig. 2.23.

The slope of the straight line '*ab*' as mentioned earlier, joining the end points of the mass curve represents the average flow of 8.90 m^3/sec over the period considered. The straight line '*cd*' parallel to '*ab*' and tangent to the mass curve at its lowest point '*g*' is called a "Use Line". The storage volume required to supply 890 m^3/sec of water continuously is given by the greatest ordinate between the use line and mass curve, in this case (*ef*) or 210 × 10^3 day-second-metre. A reservoir with this capacity and with supplying 890 m^3/sec would be full at point '*f*' (assuming it contained a volume equal to '*cl*' at point *c*) and would be empty at point '*g*'.

If it is desired to determine the required storage for some other required uniform flow rate, straight lines such as '*fj*' and '*hi*' are drawn tangents to the high points of the mass curve, with a slope equal to the desired flow (600 m^3/sec in this case). The required storage for continuous supply of 600 m^3/sec is given by the maximum ordinate between such lines and mass curve or in this case '*jk*' which is equal to 100 × 10^3 day-second-metre.

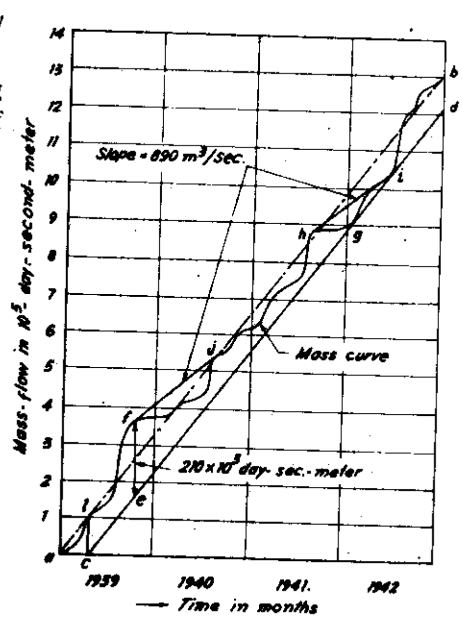


Fig. 2.23. Mass curve and determination of storage capacity.

A mass curve for another river on monthly flow basis is shown in Fig. 2.24. The tangents to the mass-curve at the points *a* and *b* represent the demand line of 75 × 10^3 km^2-m/year. The maximum departure of the demand line from the mass curve occurs at point '*d*' which is 56000 km^2-m. This is the required reservoir capacity for the continuous supply of 75 × 10^3 km^2-m/year. The reservoir would be full at '*a*' depleted to (5600 – 22000) = 34000* km^2-m of storage at *c* and full again at '*e*'. The vertical distance between the successive tangents (80 × 10^3 km^2-m) represents water wasted over the spillway during the time period '*t*'. The reservoir would remain full between *e* and *b* and all inflow excess of the demand would

*One (km)^2-m = 1000 × 1000 × 1 = 10^6 m^3.

be wasted downward through the spillway. The reservoir would be empty at the point d and it would be full again at the point 'f'.

Many other problems can also be solved with the help of mass curves. The maximum uniform flow possible with a given storage capacity can be determined from the mass curve by locating the line with the smallest slope which will be tangents to the mass curve and has a maximum departure from it equal to the assumed storage capacity. The lines ab and cd are drawn as tangents to the given mass curve as shown in Fig. 2.25 such that their maximum departure from the mass curve in each case is 30×10^3 km^2-m, which is the known capacity of the storage. The line 'cd' has the minimum slope, therefore, the maximum uniform flow possible with an available storage capacity of 30×10^3 km^2-m is the slope of line ab or 60×10^3 km^3-m/year. The tangent at point 'a' indicates a possible supply of 95×10^3 km^2-m/year but this demand could not be satisfied between the points c and d without storage in excess of 30×10^3 km^2-m. The demand line must intersect the mass-curve when extended forward, otherwise the reservoir will not refill. If the tangent from any point parallel to any demand lines fails to intersect the mass-curve, it means that during this period the supply is inadequate for the demand or in other words, to ensure a full reservoir a parallel tangent drawn backward from the low points on the curve must intersect the curve at some previous point. In practice, the observed flow should be adjusted for evaporation and seepage losses before the analysis is made. Many reservoirs have failed to supply the expected flow because of these losses only.

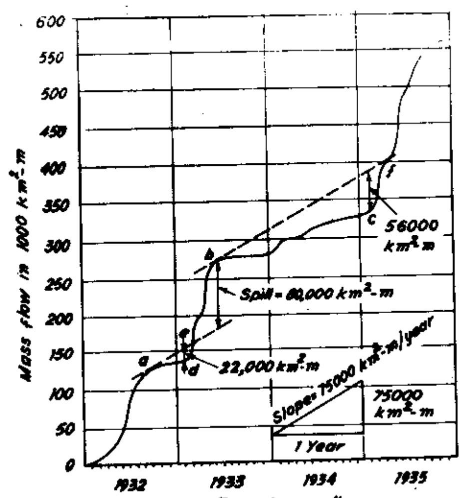


Fig. 2.24. Mass-curve and determination of available yield for given capacity of the reservoir.

The mass curve will always have a positive slope but of a greater or less degree depending upon the variations in the quantity of inflow water available. The negative inclination of mass curve would show that the amount of water flowing in the reservoir was less than the loss due to evaporation and seepage.

The flow demand line may be curved if the seasonal power demand is not constant. In this case, the flow demand line represents a flow mass-curve. The procedure to find out the reservoir capacity, required when the inflow varies with respect to time and demand also varies with respect to time is outlined with the help of the following example.

The discharge curves or hydrographs for inflow and demand for irrigation purposes are shown in Fig. 2.26 at a site chosen for the construction of dam on a river. In Fig. 2.26, the full line represents the natural discharge of river or runoff and the dotted line shows the requirements of water for irrigation purposes.

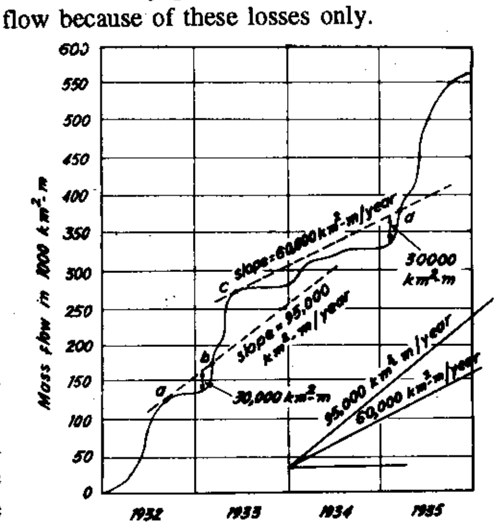


Fig. 2.25. Mass-curve and determination of storage capacity and spillway.

It is evident that the area A_1 gives the excess of the natural discharge over the requirements whereas the area A_2 represents the deficiency of the discharge. Therefore, it is obvious that the reservoir must be filled during the period from May to August (both inclusive) when there is surplus of water in the river and must be emptied from October to April to compensate for the insufficiency of the natural discharge in these months.

Now from the given hydrographs, we can find out the cumulative inflow as well as cumulative demand for the time considered (that is 12 months).

The cumulative values of the inflow and demand for 12 months are listed in the table. From the cumulative values of inflow and demand, we can draw the mass-curves for the inflow and demand as shown in Fig. 2.27.

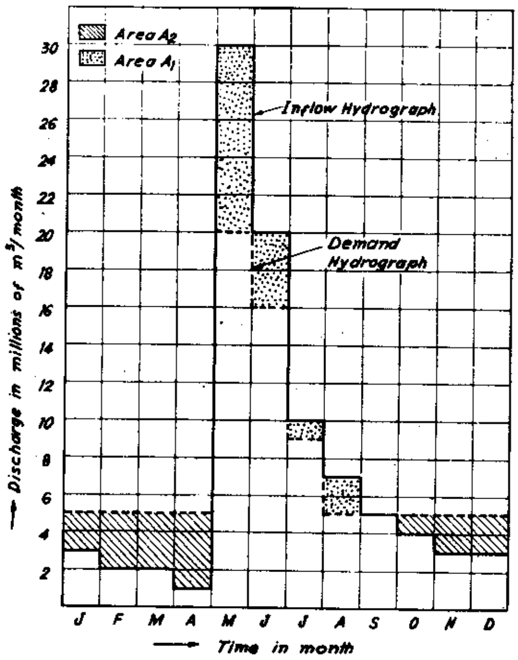


Fig. 2.26. Hydrographs for demand and inflow.

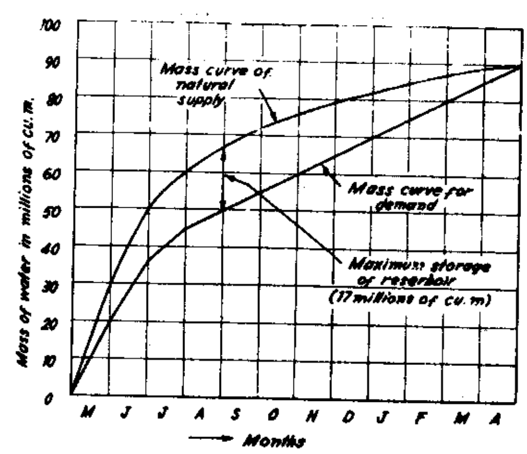


Fig. 2.27. Mass curves for inflow and demand.

Month	Monthly discharge in millions of m^2/per month	Total mass water discharged in millions of cu. m	Monthly demand in millions of m^3 per month	Total mass of water required in millions of cu. m
May	30	30	20	20
June	20	50	16	36
July	10	60	9	45
Aug.	7	67	5	50
Sept.	5	72	5	55
Oct.	4	76	5	60
Nov.	3	79	5	65
Dec.	3	82	5	70
Jan.	3	85	5	75
Feb.	2	87	5	80
March	2	89	5	85
April	1	90	5	90

From the two mass-curves, it is obvious that the difference between the amount which entered the reservoir and that which left the reservoir must represent the amount kept back in the reservoir. The maximum difference between the ordinates of two mass-curves represents the maximum contents of the reservoir.

SOLVED PROBLEMS

Problem 2.1. *What is the volume of rainfall in day sec-metres if 6.2 cm rainfall occurs over an area of 2346 square kilometres ? Also find out in terms of km²-m.*

Solution. Total rainfall

$$= 2346 \times 10^6 \times \frac{6.2}{100} \text{ cu. m} = \mathbf{2346 \times 6.2 \times 10^4 \ m^3}$$

$\therefore$ Rainfall in day-sec-metres

$$= \frac{2346 \times 6.2 \times 10^4}{86400} = \mathbf{1690 \ day\text{-}sec\text{-}metre}$$

$$\text{Rainfall in km}^2\text{-m} = \frac{2346 \times 6.2 \times 10^4}{10^6} = \mathbf{146 \ km^2\text{-}m.}$$

Problem 2.2. *A lake behind Hoover Dam has a capacity of 30,000 km²-m approximately. For how many days would this water supply be sufficient to a city of 10^6 population if daily requirement per person is 400 litres.*

Solution. Per day requirement $= 400 \times 10^6$ litres $= \mathbf{400 \times 10^3 \ m^3}$

Available water in the dam $= 30{,}000 \times 10^6 \ m^3$.

$\therefore$ No. of days water supplied $= \dfrac{30{,}000 \times 10^6}{400 \times 10^3} = \mathbf{75{,}000 \ days.}$

Problem 2.3. *The average daily stream flows for 7 days resulting from a heavy storm on a basin of 3350 square kilometres is tabulated as given below. Find the total flow volume in day-sec-metre km²-m, cm and millions of cu-m.*

Days	*Ist*	*2nd*	*3rd*	*4th*	*5th*	*6th*	*7th*
Mean daily flow in m³/sec	*100*	*320*	*210*	*120*	*50*	*30*	*25*

Solution. Total flow volume for 7 days

$$= 24 \times 3600\ (100 + 320 + 210 + 120 + 50 + 30 + 25)\ m^3$$
$$= 24 \times 3600 \times 855\ m^3$$
$$= \frac{24 \times 3600 \times 855}{10^6} \text{ million cu-m} = 73.8 \text{ million-m}^3$$
$$= \frac{24 \times 3600 \times 855}{86400} \text{ day-sec metre} = 85.5 \text{ day-sec-metre}$$
$$= \frac{24 \times 3600 \times 855}{3350 \times 10^4} \text{ cm} = 2.2 \text{ cm}$$
$$= 73.8 \text{ km}^2\text{-m as } 1 \text{ km}^2\text{-m} = 1 \text{ million of cu-m.}$$

Problem 2.4. *It is proposed to utilise the energy of the monsoon stream by constructing a dam across it. The stream discharge during the monsoon season of four months is 20 m³/sec and for the remaining year, it should be taken as 2.5 m³/sec. Find :*

(*a*) *The minimum capacity required of the reservoir on the upstream side of the dam.*

(*b*) *If the head loss in the pipe is 3% of the actual head and overall efficiency of the generation is 90%, find the output of the generating station.*

Take the mean level of the water in the reservoir above the tail race level 80 metres.

Take monsoon period from Ist June to 30th September and take the year of 365 days.

Solution. The number of days during which the discharge of 20 m³/sec is available

$= 30 + 31 + 31 + 30 = 122$ days

and the number of days during which the discharge of 2.5 m^3/sec is available

$= 365 - 122 = 243$ days.

Total flow during the year

$= 20 \times 3600 \times 24 \times 122 + 2.5 \times 3600 \times 24 \times 243 = 3600 \times 24 \times 3047.5 \text{ m}^3.$

Average discharge

$$= \frac{3600 \times 24 \times 3047.5}{3600 \times 24 \times 365} = 8.35 \text{ m}^3/\text{sec}.$$

The difference between the maximum and average discharge

$= 20 - 8.35 = 11.65$ m^3/sec.

Reservoir capacity to store the excess water

$= 11.65 \times 3600 \times 24 \times 122 \text{ m}^3$

$$= \frac{11.65 \times 3600 \times 24 \times 122}{86400} = 141 \text{ day-second-metre.}$$

Average kW generated

$$= \frac{mgH_{net}\eta}{1000}$$

$$= \frac{8.35 \times 1000 \times 9.81 \times (80 \times 0.97)}{1000} \times 0.90 = 572 \text{ kW} = 5.72 \text{ MW}.$$

Problem 2.5. *The catchment area of a hydro-electric power plant is 2260 sq. km and the annual average rainfall is 154 cm. The head drop available at a power house site is 120 metre. Assuming turbine efficiency 85% and a generation efficiency of 90%, find the kW that can be developed from the hydro-electric plant. Take percolation and evaporation losses as 20% and load factor as unity.*

If the speed of the runner is to be maintained below 240 rpm, also suggest the type of prime-mover to be used.

Solution. The quantity of water available for power generation per year

$= 2260 \times 10^6 \times (154/100)\ (1 - 0.2)$ m^3 as 1 sq. km $= 10^6$ m^2

$= 2.78 \times 10^8$ cu. m.

Q (quantity of water available per second)

$$= \frac{2.78 \times 10^8}{365 \times 24 \times 3600} = \mathbf{8.83\ m^3/sec.}$$

Power developed in kW

$$= \frac{mgH}{1000} \times \eta_m \times \eta_g$$

where η_m and η_g are mechanical and generator efficiencies.

$\therefore$ Power developed in kW

$$= \frac{1000 \times 8.83 \times 9.81 \times 120}{1000} \times 0.85 \times 0.9 = 7952 \text{ kW} = \mathbf{7.95\ MW}$$

$$N_a = \frac{N\sqrt{P}}{(H)^{5/4}} = \frac{240 \times \sqrt{7952}}{(120)^{1.25}} = \mathbf{53.88.}$$

Single Pelton wheel with 4-jets can be used. This is also suggested from the small flow rate and high head available.

Problem 2.6. *A storage type hydro-electric power plant having a catchment area of 200 sq. km and annual average rainfall of 100 cm is used to generate power. 80% of the total run-off is available for power generation. The mean head available is 80 m. Assuming an overall efficiency of generation of 75%, find the capacity of the plant. If the average period of working the power plant is 16 hours per day, find the energy generated in kWh per year.*

Solution. Total water available for power generation per year

$$= 200 \times 10^6 \times 0.8 \times 1 \text{ m}^3\text{/year}$$

$$= \frac{160 \times 10^6}{365 \times 24 \times 3600} = \mathbf{5.07\ m^3/sec}$$

Capacity of the plant in kW

$$= \frac{mgH}{1000} \times \eta_g$$

$$= \frac{1000 \times 5.07 \times 9.81 \times 80}{1000} \times 0.75 = \mathbf{2984\ kW.}$$

Energy generated per year

$$= 2984 \times 16 \times 365 \text{ kWh}$$

$$= 2.984 \times 1.6 \times 3.65 \times 10^6 = \mathbf{17.43 \times 10^6\ kWh.}$$

Problem 2.7. *A medium capacity storage type hydro-electric power plant covers 1200 sq. km area. The annual rainfall in catchment area is 160 cm. The head available at the power plant site is 360 metres. Assuming 25% of the rainfall is lost in evaporation and percolation, find the average power developed by the power plant and maximum demand. Take overall efficiency of the plant as 75% and load factor 0.5.*

Solution. Water available per year for power generation

$$= 1200 \times 10^6 \times \frac{160}{100} \times (1 - 0.25) = \mathbf{9 \times 10^6 \times 160\ m^3/year.}$$

Average flow per second

$$= \frac{9 \times 10^6 \times 160}{365 \times 24 \times 3600} = \mathbf{45.7\ m^3/sec.}$$

Average power developed in kW

$$= \frac{mgH}{1000} \times \eta$$

$$= \frac{1000 \times 45.7 \times 9.81 \times 360}{1000} \times 0.75 = 121046 \text{ kW} = \mathbf{121.05\ MW.}$$

$$\text{Load factor} = \frac{\text{Average load}}{\text{Max. demand}}$$

$$\therefore \quad \text{Max. demand} = \frac{121.05}{0.5} = \mathbf{242.1\ MW.}$$

Problem 2.8. *A hydro-electric power plant having 50 sq. km reservoir area and 100 m head is used to generate power. The energy utilised by the consumers whose load is connected to power plant during a five hour period is 13.5 × 10⁶ kWh. The overall generation efficiency is 75%. Find the fall in the height of water in the reservoir after 5-hours period.*

Solution. Assume the fall in the height in the reservoir level is H metres.

$\therefore$ Water used during 5-hours $= 50 \times 10^6 \times H$ m^3

$$Q \text{ (discharge/sec)} = \frac{50 \times 10^6 \times H}{5 \times 3600}$$

$$\text{kW} = \frac{mgH}{1000} \times \eta$$

$$= 1000 \times \frac{50 \times 10^6 \times H}{5 \times 3600} \times 9.81 \times \frac{100}{1000} \times 0.75 = \mathbf{0.208 \times 10^6\ H}$$

The energy produced during 5-hours period

$$= 5 \times 0.208 \times 10^6\ H = 1.04 \times 10^6\ H \text{ kWh}$$

$$1.04 \times 10^6\ H = 13.5 \times 10^6$$

$$\therefore \quad H = \frac{13.5}{1.04} = \mathbf{12.98 \text{ metres.}}$$

Problem 2.9. *The catchment area of the dam used for hydroelectric station is 250 km². The annual rainfall is 125 cm. If 70% of the water in the dam is used for power generation at a head of 60 m, find the capacity of the power plant in MW. Assume turbine efficiency of 90% and generator efficiency of 95%. Neglect all other losses.*

Solution. Total water used for power generation

$$= (250 \times 10^6) \times 1.25 \times 0.7 \text{ m}^3 = \mathbf{218 \times 10^6 \text{ m}^3}$$

Water flow rate

$$q = \frac{218 \times 10^6}{365 \times 24 \times 3600} = \mathbf{6.95 \text{ m}^3\text{/sec.}}$$

$$\text{Power } (P) = \frac{mgH}{1000} \times \eta_t \times \eta_g \times \frac{1}{1000} \text{ MW.}$$

where η_t are η_g are turbine and generator efficieincies.

$$\therefore \quad P = \frac{6.95 \times 1000 \times 9.81 \times 60}{1000} \times 0.9 \times 0.95 \times \frac{1}{1000} = \mathbf{3.5 \text{ MW.}}$$

Problem 2.10. *A hydro-electric power station is supplied from a reservoir at a head of 40 m. If the area of the reservoir is 1.8 km² and generating 24 MW power, determine the rate at which the water level will fall in the reservoir. Take overall efficiency as 80%.*

Solution. The power generating capacity is given by

$$P = \frac{mgH}{1000} \times \eta_{overall} \times \frac{1}{1000} \text{ MW}$$

$$\therefore \quad 24 = \frac{q \times 1000 \times 9.81 \times 40}{1000} \times 0.8 \times \frac{1}{1000}$$

$$\therefore \quad q = \frac{24 \times 1000}{9.81 \times 40 \times 0.8} = \mathbf{76.45 \text{ m}^3\text{/sec.}}$$

If x m is the rate of fall of height of reservoir in m/sec, then

$$1.8 \times 10^6 \times x = 76.45 \times 3600$$

$$x = \frac{76.45 \times 3600}{10^6 \times 1.8} = \mathbf{0.153 \text{ m/hr.}}$$

Problem 2.11. *A hydel plant is supplied from a reservoir of 6×10^6 m³ capacity at a head of 75 m. Determine the number of electrical units produced (kWh) during the year if the load factor is 0.6 and overall efficiency of generation is 72%.*

Solution. The power capacity of the plant in kW is given as

$$P = \frac{mgH}{1000} \times \eta_{overall}$$

$$= \frac{6 \times 10^6}{365 \times 24 \times 3600} \times \frac{1000 \times 9.81 \times 75}{1000} \times 0.72 = \mathbf{14.27 \text{ kW}}$$

Energy produced in kWh

$= P \times \text{Load factor} \times (365 \times 24)$

$= 14.27 \times 0.6 \times 365 \times 24 =$ **750003 kW.**

Problem 2.12. *A hydro-electric power station has to operate with a mean head of 30 m and supplied from a reservoir whose catchment area is 250 square km and average rainfall is 125 m per year. If 70% of the total rainfall can be used at a expected load factor of 50%, calculate the power in kW for which, the station can be designed. Assume head loss in the system is 8%, mechanical η of the turbine is 90% and generator efficiency is 95%.*

Solution. Water available during the year

$= 250 \times 10^6 \times 1.25 \times (0.7) = \mathbf{218 \times 10^6\ m^3}$

Water flow per second

$$Q = \frac{218 \times 10^6}{8760 \times 3600} = \mathbf{6.9\ m^3/sec = 6.9 \times 1000\ kg/sec.}$$

Available head $H = 30$ m

The power P in kW is given by

$$P = \frac{Q\rho \cdot gH}{1000} \times \eta_0 \text{ (kW)}$$

where η_0 (overall efficiency) $= \eta_h . \eta_m . \eta_g$

where suffix h, m and g indicate, hydraulic, mechanical and generating efficiencies.

$\therefore \qquad \eta_0 = 0.92 \times 0.9 \times 0.95 = 0.7865$

$$\therefore \qquad P = \frac{6.9 \times 1000 \times 9.81 \times 30 \times 0.7865}{1000} = \mathbf{1597\ kW}$$

With 80% load factor,

$$\text{Generator capacity} = \frac{1597}{0.8} = \mathbf{1996.4\ kW.}$$

Problem 2.13. *The mean monthly discharge for 12 months at a particular site of a river is tabulated below :*

Month	*Discharge in millions of m^3 per month*	*Month*	*Discharge in millions of m^3 per month*
A (April)	*500*	*O*	*2000*
M	*200*	*N*	*1500*
J	*1500*	*D*	*1500*
J	*2500*	*J*	*1000*
A	*3000*	*F*	*800*
S	*2400*	*M*	*600*

Draw :

(*a*) *Hydrograph for the given discharges and find the average monthly flow.*

(*b*) *The power available at mean flow of water if the available head it 80 metres at the site and overall efficiency of the generation is 80%.*

Take 30 days in a month.

Solution. The hydrograph is shown in Fig. Prob. [2.13 (*a*)].

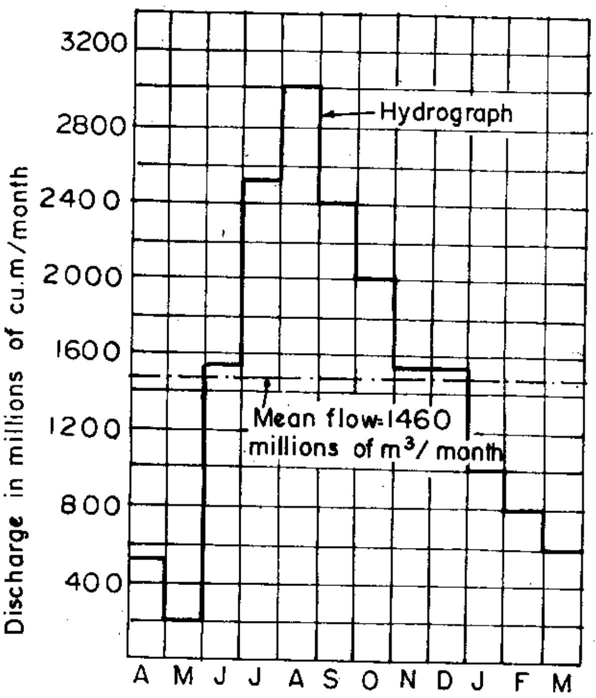


Fig. Prob. 2.13. (*a*)

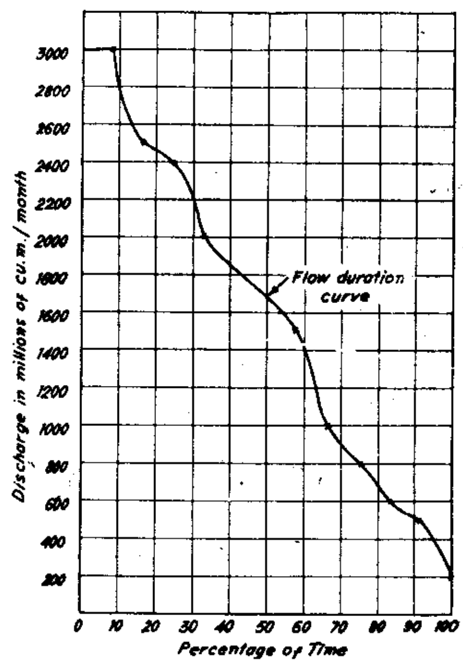


Fig. Prob. 2.13. (*b*)

The average monthly flow is given by (from the figure)

$$= \frac{(500 + 200 + 1500 + 2500 + 3000 + 2400 + 2000 + 1500 + 1500 + 1000 + 800 + 600)}{12}$$

$$= \frac{100}{12} \times 175 = 1460 \text{ millions of m}^3\text{/month.}$$

It is necessary to find the lengths of time during which certain flows are available to obtain the flow duration curve. This information is tabulated using the hydrograph in the following table :

Discharge in millions of m^3/month	*Total number of months during which flow is available*	*Percentage time during which flow is available*
200	12	100
500	11	91.8
600	10	83.40
800	9	76.00
1000	8	66.60
1500	7	58.40
2000	4	33.30
2400	3	25.00
2500	2	16.65
3000	1	8.325

By using the above tabulated data, we can draw the flow duration curve as shown in Fig. Prob. [2.13 (*b*)].

The average flow available per second

$$= \frac{1460 \times 10^6}{30 \times 24 \times 3600} = \mathbf{564\ m^3/sec.}$$

Average kW available at the side

$$= \frac{mgH}{1000} \times \eta_g$$

$$= \frac{564 \times 1000 \times 9.81 \times 80}{1000} \times 0.8 = 36096 \text{ kW} = \mathbf{36.096\ MW.}$$

Problem 2.14. *The runoff data of a river at a particular site is tabulated below :*

Month	*Mean discharge in millions of cu m per month*	*Month*	*Mean discharge in millions of cu m per month*
J	*80*	*J*	*150*
F	*50*	*A*	*200*
M	*40*	*S*	*250*
A	*20*	*O*	*120*
M	*0*	*N*	*100*
J	*100*	*D*	*80*

(*a*) *Draw a hydrograph and find the mean flow.*

(*b*) *Also draw the flow duration curve.*

(*c*) *Find the power in MW available at mean flow if the head available is 100 m and overall efficiency of generation is 80%.*

Take each month of 30 days.

Solution. (*a*) The hydrograph for the given data is drawn as shown in Fig. Prob. (2.14).

The mean discharge for the given data

$$= \frac{80 + 50 + 40 + 20 + 0 + 100 + 150 + 200 + 220 + 120 + 100 + 80}{12}$$

$$= \frac{1160}{12} = 96.67 \text{ millions of m}^3\text{/month.}$$

(*b*) It is necessary to find the lengths of time during which certain flows are available to obtain the flow during curve. This information is tabulated using the hydrograph in the following table.

Discharge in millions of cu m per month	*Total number of months during which flow is available*	*Percentage time*
0	12	100%
20	11	91.8%
40	10	83.4%
50	9	75%
80	8	66.6%
100	6	50%
120	4	33.3%
150	3	25%
200	2	16.65%
220	1	8.325%

The flow-duration curve can be drawn using the data tabulated as shown in Fig. Prob. 2.14 (*b*).

(*a*) Average MW energy available

$$= \frac{mgH}{1000} \times \eta_a \times \frac{1}{1000}$$

$$= \frac{96.67 \times 10^6 \times 9.81}{30 \times 24 \times 3600} \times \frac{1000 \times 100}{1000} \times 0.8 \times \frac{1}{1000}$$

= **298.4 MW**

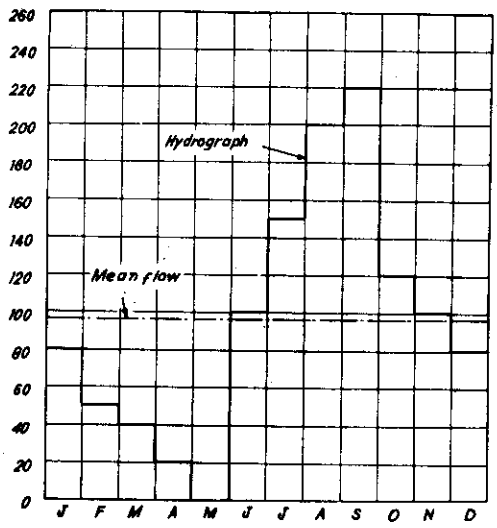


Fig. Prob. 2.14. (*a*)

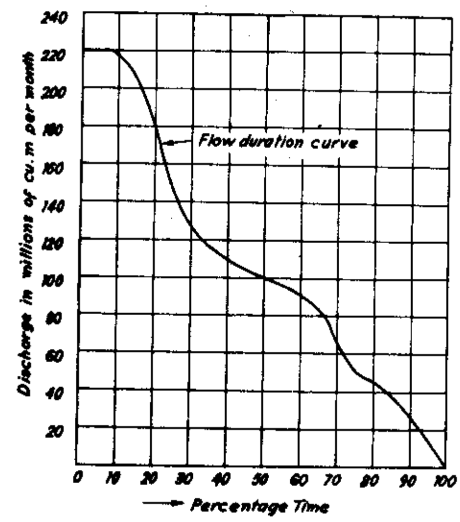


Fig. Prob. 2.14. (*b*)

Problem 2.15. *The data for a weekly flow at a particular site is given below for 12 weeks.*

Week	*Weekly flow in m^3/sec*	*Week*	*Weekly flow in m^3/sec*
1	*6000*	*7*	*1200*
2	*4000*	*8*	*4500*
3	*5400*	*9*	*8000*
4	*2000*	*10*	*4000*
5	*1500*	*11*	*3000*
6	*1000*	*12*	*2000*

Find the size of the reservoir and the possible rate of available flow after the reservoir had built in with the help of mass curve.

Solution. For drawing the mass curve, we have to find the cumulative volume of water that can be stored week after week. This is done as tabulated in the following table.

Week (a)	*Weekly flow in m^3/sec (b)*	*Weekly flow in day-sec-metre $c = b \times 7$*	*Cumulative volume in day-sec-metres (d)*
1	6000	42000	42,000
2	4000	28000	70,000
3	5400	37800	1,07,800
4	2000	14000	1,21,800
5	1500	10500	1,32,300
6	1000	7000	1,39,300
7	1200	8400	1,47,700
8	4500	31500	1,79,200
9	8000	56000	2,35,200
10	4000	28000	2,63,200
11	3000	21000	2,84,200
12	2000	14000	2,98,200

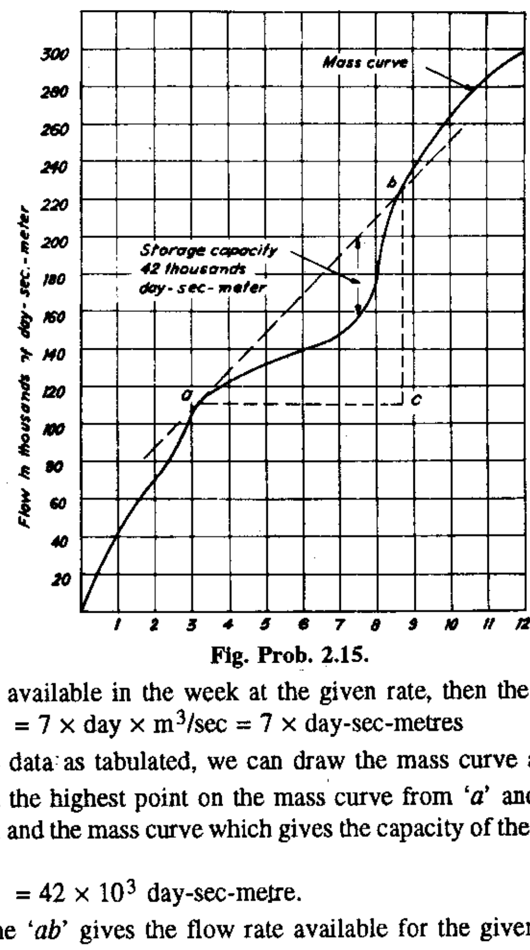


Fig. Prob. 2.15.

If the mean flow is available in the week at the given rate, then the total flow in the week

$= 7 \times \text{day} \times \text{m}^3/\text{sec} = 7 \times \text{day-sec-metres}$

By using the above data as tabulated, we can draw the mass curve as shown in Fig. Prob. 2.15.

Draw the tangent at the highest point on the mass curve from '*a*' and measure the highest distance between the tangent drawn and the mass curve which gives the capacity of the reservoir. In this case, capacity of the reservoir

$= 42 \times 10^3$ day-sec-metre.

The slope of the line '*ab*' gives the flow rate available for the given capacity reservoir.

$$\text{Flow rate available} = \frac{bc}{ac}$$

$$= \frac{5.7 \times 20 \times 10^3 \text{ day-sec-metre}}{5.5 \times 7 \text{ day}} = \mathbf{2960\ m^3/sec.}$$

Problem 2.16. *The data for twelve months flow at a particular site is given below :*

Month	*Flow in millions of cu-m-per month*	*Month*	*Flow in millions of cu-m-per month*
1	*100*	*7*	*190*
2	*50*	*8*	*40*
3	*20*	*9*	*30*
4	*80*	*10*	*200*
5	*10*	*11*	*170*
6	*10*	*12*	*80*

Find :

(a) The required reservoir capacity for the uniform flow of 50 millions cu-m per month throughout the year.

(b) Spill-way capacity.

(c) Average flow capacity if whole water is used and required capacity of the reservoir for this condition

Solution. For drawing the mass curve, we have to find the cumulative volume of water that can be stored month after month. This is done as shown in the following table.

Month	*Flow in millions of m^3 per month*	*Cumulative volume in millions of cu-m*
1	100	100
2	50	150
3	20	170
4	80	250
5	10	260
6	10	270
7	190	460
8	40	500
9	30	530
10	200	730
11	170	900
12	80	980

By using the values given in the table, we can draw the mass curve.

For finding the capacity of the reservoir for uniform flow of 50 millions cu-m per month, construct the triangle Δ-*xyz* as shown in Fig. Prob. (2.16). *xy* represents one month and *yz* represents 50 millions cu-m.

Now draw the parallel lines to the line *xz* through the points *e* and *g* which are the apex of mass curve. The greatest departure of the mass curve from these lines drawn parallel to *xy* represents the storage capacity.

∴ Storage capacity = $\mathbf{80 \times 10^6\ m^3}$

Spillway capacity required (from the Fig.)

$= 85 \times 10^6\ m^3$

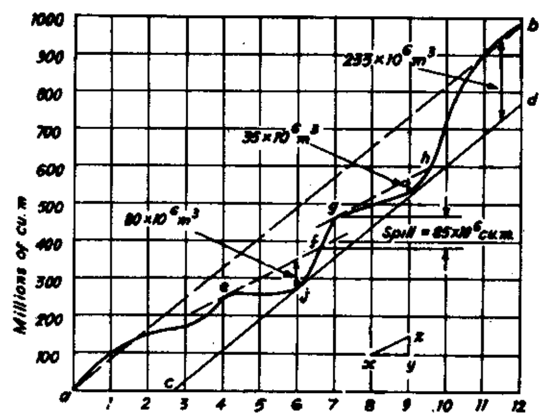


Fig. Prob. 2.16.

Join the points *a* and *b*, then the slope of the line *ab* represents the uniform discharge throughout the year.

$$= \frac{980}{12} \times 10^6 = \mathbf{81.7 \times 10^6\ m^3/month.}$$

Draw the line '*cd*' parallel to *ab* which touches the mass curve to its lowest point '*j*'. The maximum departure of the line *cd* from the mass curve represents the required storage capacity for the uniform supply of $81.7 \times 10^6/m^3$ month. In this case, storage capacity required

$= \mathbf{233 \times 10^6}$ **cu-m.**

Problem 2.17. *The following runoff data is collected for ten months at a particular site of the river.*

Month	*Discharge in millions of cu-m-per month*	*Month*	*Discharge in millions of cu-m-per month*
1	200	6	180
2	100	7	40
3	20	8	280
4	20	9	60
5	260	10	120

Find the maximum flow available throught the year if the storage capacity at the site is 100 million cu-m.

Solution. First we have to draw the mass curve from the given data and we have to find out the cumulative volume of water that can be stored month after month. This is done as tabulated in the following table.

Month	*Cumulative volume in millions of cu-m*	*Month*	*Cumulative volume in millions of cu-m*
1	200	6	780
2	300	7	820
3	320	8	1100
4	340	9	1160
5	600	10	1280

We can draw the mass curve with the above tabulated data. Now draw the tangents from the points a, b and c in such a way that the distance x, y and z, each will be equal to 100 millions cu-m (or 1 cm as per the scale).

Now measure the slopes at the points a, b and c which will directly give flow rates.

Flow rate at point a

= 72.6 millions of cu-m/month

Flow rate at point b

= 166.4 millions of cu-m/month

Flow rate at point c

= 137.6 millions of cu-m/month

The lowest rate (72.6) among the three is the minimum available flow rate throughout the period considered.

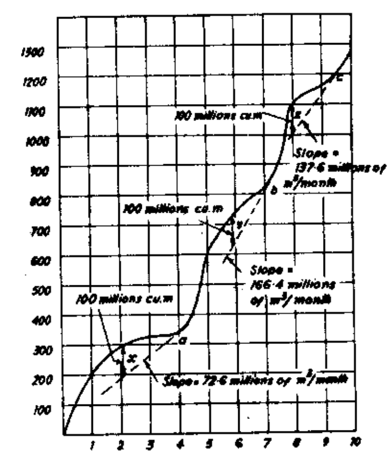


Fig. Prob. 2.17.

EXERCISES

2.1. What is the importance of rainfall and run-off data in the design of hydro-electric power plant ?

2.2. What different methods are used to measure the rainfall ? Discuss the relative merits.

2.3. What different methods are used to find the average rainfall ? Discuss the relative merits.

2.4. How the run-off is measured in practice ?

2.5. What factors affect the run-off data at a particular site ?

2.6. Define hydrograph and explain its importance in the design of storage type hydro-electric power project. Explain the effect of time unit on the storage capacity of the catchment area required.

2.7. What do you understand with the term "Unit hydrograph". Explain its uses in practice.

2.8. Explain the construction of flow duration curve and discuss its importance in comparing the power potentiality of different storages used for power generation.

2.9. Define the mass-curve and explain its use in the design of dam capacity and spill-way capacity.

2.10. How the minimum supply is calculated using mass-curve when the storage capacity is known beforehand. Explain with example.

2.11. A dam has a capacity of 20 million of km^2-m. Find the number of years of water supply to a city of 50,00,000 population using 400 litres per person per day.

2.12. What is the volume of rainfall in day-sec-metre if 10 cm rainfall occurs over an area of 4000 km^2 ? Also find the rainfall in km^2-m.

2.13. The discharge through a monsoon stream may be taken as follows :

Month	*Discharge in m^3/sec*	*Month*	*Discharge in m^3/sec*
Jan.	2.0	July	8
Feb.	1.5	Aug.	10
Mar.	1.0	Sept.	12
April	0.6	Oct.	6
May	0	Nov.	4
June	0	Dec.	3

Draw a hydrograph and find :

(*a*) Average discharge. (*b*) The storage reservoir capacity if the dam is constructed across the stream. (*c*) If the mean level of water on the upstream side is 100 metres above the tail race level, find the kW supplied. Assume overall efficiency of generation 80%.

2.14. Mean weekly discharge at a particular site for 12 weeks is given below :

Week	*Discharge in m^3/sec*	*Week*	*Discharge in m^3/sec*
1	100	7	800
2	200	8	600
3	300	9	1000
4	1200	10	600
5	600	11	400
6	900	12	200

Draw the hydrograph and (*a*) Find the mean flow available throughout the period considered (*b*) Draw the flow duration curve using the above given data. (*c*) Also draw the power duration curve if the available head at the site is 100 m and overall efficiency of generation is 90%.

2.15. The average weekly discharge at a particular side for 26 weeks is given as follows :

Week	*Discharge in m^3/sec*	*Week*	*Discharge in m^3/sec*	*Week*	*Discharge in m^3/sec*
1	1000	10	800	19	400
2	900	11	1000	20	400
3	900	12	1100	21	300
4	800	13	1100	22	300
5	800	14	1200	23	400
6	600	15	1060	24	400
7	500	16	900	25	500
8	500	17	800	26	500
9	800	18	500		

Draw the hydrograph and flow duration curve for a period of 26 weeks as 100% time. Also find the minimum, maximum and average power and energy produced during 26 weeks in kW-hr if the head available is 50 m and overall generation efficiency is 85%.

2.16. In a typical 4-hour storm producing 5 cm of run-off from the big basin, the flows in the stream are as follows :

Time in hour	*Flow in m^3/sec*	*Time in hour*	*Flow in m^3/sec*
0	0	8	14
2	3	12	8
4	10	16	3.5
6	20	20	0

Find the peak flow and the time of its occurrence in a flood created by an 8-hour storm which produces 2.5 cm of run-off during first 4-hour and 3.75 cm of run-off during the next 4-hour.

2.17. The run-off data at a particular site for 12 weeks is collected as tabulated below. Draw the mass-curve and find the size of the reservoir and possible rate of flow which would be available after the reservoir had been built.

Week	*Weekly flow in m^3/sec*	*Week*	*Weekly flow in m^3/sec*	*Week*	*Weekly flow in m^3/sec*
1	6000	5	1000	9	8000
2	5000	6	500	10	5000
3	4000	7	1000	11	2000
4	2000	8	4000	12	1000

2.18. Construct the mass curve from the following data collected at a particular site and find (*a*) the size of the reservoir and (*b*) maximum possible rate of flow that could be available :

Week	*Weekly flow in m^3/sec*	*Weeks*	*Weekly flow in m^3/sec*
1 to 6	600	25 to 30	1700
7 to 12	700	31 to 36	900
13 to 18	300	37 to 42	600
19 to 24	400	43 to 48	300

2.19. What reservoir capacity is required to produce uniform yield of 60 km^2-m per year for a site where the monthly flows during a critical flow period are as tabulated below for three years.

Month	*Discharge in km^2-m/sec*	*Month*	*Discharge in km^2-m/sec*	*Month*	*Discharge in km^2-m/mnth*
Oct.	18	Oct.	5	Oct.	15
Nov.	22	Nov.	6	Nov.	16
Dec.	87	Dec.	6	Dec.	25
Jan.	26	Jan.	5	Jan.	47
Feb.	15	Feb.	3	Feb.	16
March	32	March	2	March	18
April	8	April	1	April	7
May	3	May	0	May	4
June	0	June	0	June	0
July	0	July	0	July	1
Aug.	0	Aug.	0	Aug.	3
Sep.	0	Sep.	7	Sep.	3

□□□

3

Different Hydro-electric Power Plants

3.1. Introduction. 3.2. Site Selection for hydro-electric power plants. 3.3. Classification of hydro-electric power plants 3.4. Run-off River plants without pondage. 3.5. Run-off River plants with pondage. 3.6. Storage Reservoir plants. 3.7. Pump storage plants. 3.8. General Arrangement of an hydroelectric project and its operation. 3.9. Advantages of hydro-electric power plants.

3.1. INTRODUCTION

The purpose of this chapter is to introduce the readers with different types of hydro-electric power plants and make them conversant with various parts of the plant and their functions.

India's total economic hydro power potential has been assessed as 84000 MW at 60% load factor which corresponds to 1,60,000 MW installed capacity. The potential developed so far is only 14% and another 7% is under development. Thus, about 79% potential is still to be harnessed.

3.2. SITE SELECTION FOR HYDRO-ELECTRIC POWER PLANTS

In the choice of location for hydro-power-plant, several structures may be involved like dam, conduits, intakes, surge tank, power house and many others. There is no easy answer to the question raised, which is suitable site for hydel power plant ? The only solution is to study several alternative layouts and adopt one which appears to be most economical. Sometimes the most desirable location is apparent to an experienced engineer. Sometimes there is no choice for site except considerable investigation and study are required to determine the most economical location.

The scope for the site investigations depends partly on the availability of existing published data, partly on the nature and size of the proposed plants, and partly on the difficulties presented by the existing topographical and geological features which in turn affects the number of alternatives which have to be tried out.

It is a common practice for both office studies and site investigations to be carried out in two main stages.

1. Preliminary Investigations. The purposes of preliminary investigations are to provide sufficient information to find out the practicability of the proposed scheme and to choose between alternative schemes. The preliminary designs and estimations can be prepared and recommendations are made with reasonable confidence.

2. Final investigations. The final investigations include the detailed exploration of the recommended site so as to establish the complete suitability and to enable the final designs.

The preliminary and final investigations include mainly :

(*a*) hydrological (*b*) topographical and (*c*) geological.

Once the location of power plant is chosen, the exact position of different components will be fixed after careful consideration of the following factors.

(*a*) Requirement of head, flow availability and storage capacity.

(*b*) The character of the foundation, particularly for dams.

(*c*) The topography of the surface at proposed location.

(*d*) Arrangement and type of dam, intakes, conduits, surge tank, power-house and many others.

(*e*) Availability of materials for construction.

(*f*) Transportation facilities.

(*g*) The cost of the project and period required for completion.

(*a*) **Hydrological Investigations.** The hydrological investigations include the investigations of water availability, storage capacity, head of water available, load centre from the plant and approach to the site by rail and road.

1. Water Availability. To find out the availability of water, the runoff data at the proposed site must be available beforehand. This is most important as all other designs are based on the availability of water.

It is not always possible to have the run-off data at proposed site but data concerning the rainfall over the large catchment area is always available. Therefore, office calculations concerning water availability are based on the analysis of rainfall data available and characteristics of catchment area. The average water quantity available, minimum quantity available, the duration and intensity of flood will be known from hydrograph if the runoff data for sufficient long period is available.

2. Water Storage. It is always necessary to store the water for continuous generation of power as there is wide variation in rainfall during the year. The storage capacity can be calculated with the help of mass curve or the minimum quantity of available water for the available storage capacity can also be calculated with the help of mass curve as described in earlier chapter. There is mathematical approach to find out the relation between the dam height and storage capacity which will give the least cost of construction.

Maximum storage should justify the expenditure on the project. There are two types of storages in use :

(*a*) The storage is constructed to provide just sufficient storage (including all losses) for one year only. In this case, there is no carry over water for the next season. Storage becomes empty at the end of each year and becomes full at the beginning of next year.

(*b*) The storage is constructed to provide enough storage so it will be sufficient even during the worst dry periods.

3. Water Head. The available waterhead depends upon the topography of the area. An every increase in head for the given output reduces the quantity of water to be stored and, therefore, the capital cost. In order to find out the most effective and economical head, it is necessary to consider all possible factors which many affect it.

4. Ground water data. The underground movement of water has important effects on the stability of ground slopes and also on the amount and type of grounding required to prevent leakage.

This data is of primary importance in the design of cutoffs which have to be sunk through permeable overburden in order to reach a sound foundation.

It is always desirable that the selected site should be as near as possible to the load centre and it should be accessible by rail and road. But these factors do not control the site of the plant to be selected as other factors are more important as the life of the plant and its potentiality are concerned.

(*b*) **Topographical Investigations.** It is generally desirable that the topographical features of the whole catchment area should be mapped sufficiently for alternative schemes to be planned and compared.

The mapping for the catchment area is done with a level contour at 3 to 6 metres intervals whereas the mapping of the area where dam, conduit and power-station are proposed is done with level conductors at 70 cm to 150 cm intervals.

The mapping can be done either by ground surveying or aerial surveying methods. The aerial surveying or photography is most popular for larger areas and difficult terrain. Aerial photographs can be produced into large topographic maps showing features and conditions which can be advantageously compared for alternative sites.

(*c*) **Geological Investigations.** The object of geological investigations is to provide the most accurate picture of the ground character on which the proposed hydroelectric works may be constructed.

The selection of suitable site depends upon the following factors :

1. The tight basin of ample size.
2. A narrow outlet requiring a dam of less volume.

3. A strong foundation able to support the dam structure.
4. An opportunity for building a safe and ample spillway for the disposal of surplus water.
5. Impounded water should not submerge valuable minerals and agricultural lands.
6. Availability of materials for constructing a dam.

A co-operation between engineers, geologists, hydrologists and soil specialists is necessary to select the most desirable and healthy site for the power plant. The advice of the geologists is essential for factors, 1, 3, 5 and 6 as it decides the suitability and strength of the foundation. He should also help in determining the suitability of spill site, as far as the foundation conditions are concerned.

Geological Investigation of Reservoir Area. The geological investigation of reservoir area includes investigations concerning possible leakage from basin and submergence of mineral deposits. Certain structural features like faults, shear zones and bedding planes may allow a free passage to water, and, therefore, their nature and distribution deserve careful study.

It is also evident that if any mineral deposits in the reservoir area be submerged, it has to be carefully assessed. Since all engineering projects are based on economical gains and, therefore, it may become sometimes necessary to reject a particular project, if the assessed value of the minerals to be submerged exceeds that of the benefits to earn from the proect.

Geological Investigation of Dam Site and Appurtenant Structures. The dam is very costly structure in the hydro-power plants. Its safety is most important as its failure causes heavy economical loss as well as loss of life and property caused by the sudden release of the impounded water. Therefore, the geological investigation of a dam site involves close study of soil and rock present in the foundation area. All possible three-dimensional information of the rock directly below the dam foundation as well as a little upstream and downstream is necessary. The necessary requirements of the foundation rocks for a masonry dam are listed below :

1. The rock should be strong enough to withstand the stresses transmitted from the dam structure as well as the thrust of the water when the reservoir in full.

2. The rock in the foundation of the dam should be reasonably impervious.

3. The rock should neither change in volume, soften nor dissolve in water. It should be stable under all conditions.

4. One of the prerequisites in the investigation of dam site is to find out the susceptibility of the area to earthquakes.

Sub-surface geological investigations are carried out by collecting the the specimens of rocks with the help of drilling boreholes. Other methods of investigations use electrical, seismic or magnetic properties of the soil. The electrical and seismic methods are found more suitable for civil engineering investigation.

The type of dam that will be suitable depends on the nature of the foundation as well as on the availability of construction materials. It will be more economical to build an earthen dam in a river with a thick cover of sand gravel. A masonry dam would be preferable where hard rock is available close to the river surface. It requires careful removal of overburden as well as weathered rocks. The type and design of the masonry dam depend on the nature of the foundation. An arch dam will be preferable with gravity section if the abutments are stronger.

(*d*) **Consideration of Water Pollution Effects.** The effects of polluted water on the power plant is one of the major considerations in selecting the site of hydraulic power plant.

In some hydro-electric installations, certain peculiar effects as presence of foul smelling gases in the station and vicinity, corrosion of metallic structures and electrical equipments, and overheating of machine parts have been noticed immediately after commissioning of the stations. The above-mentioned effects affect the economy and reliability of the power-plant. These troubles originate very often from the poor quality of water.

The causes for the deterioration of the water and its effects on the power plant are listed below.

Causes of water pollution. The water gets polluted if the area submerged under the water contains mineral deposits of harmful nature. The presence of sulphates forms H_2S under the action of micro-organisms and presence of alkaline and acidic deposits largely increase the corrosive properties of water. Submerged vegetation is one of the main causes of water pollution. The considerable amount of twigs, leaves, logs etc. under water are allowed to decay and badly smelling gases are generated.

In large reservoirs, wind velocity may not be high enough to mix up warm water at the top with the cold dense water at the bottom. There is also a depletion of dissolved oxygen in lower strata due to chemical decomposition of organic matter. This depletion of oxygen and thermal stratification in lower strata generates the harmful gases such as CO_2, H_2S and CH_4 which pollute the water. The presence of algae is another cause of water pollution. Some of the dense planktonic cover the surface of the reservoir water and thus prevents the sunlight from entering the deeper layers of water. This prevents photosynthesis in the submerged vegetation and thereby accelerates the process of decay.

Adverse effects of water pollution. The adverse effects of polluted water involve damage to the dam structure and fitting, damage to electrical machinery and health hazards to operating personnel.

The water containing H_2S, CO_2, CH_4 etc. is highly corrosive to dams and concrete structures. The H_2SO_4 formed by the oxidation of H_2S attack the cement constituents and disintegrate the concrete. The presence of the above-mentioned gases leads to an increase in the solubility of insoluble soil and rock constituents. Serious damage to the dam has been reported in Norway where water from mountain streams is highly polluted. Structures, metallic piping and penstock are also affected by the corrosive gases like H_2S and CH_4. The actions are rapid in humid atmosphere which is common in hydro-electric plants.

Damage of electrical machinery is mainly due to the presence of corrosive gases like H_2S. SO_2 and others. These gases which are generated, as water are churned by the turbine, attack equipment in the vicinity. Presence of SO_2 and H_2S affect voltage drop at brush contacts in generators and leads to the poor commutation. Silver contacts of relays get blackened under the presence of H_2S and lead to high contact resistance and failure of relay occurs. The copper busbars are corroded at a faster rate in the presence of H_2S. The water from the trailrace is generally used for cooling purpose in all hydro-electric plants. If this water is not chemically pure, it can cause considerable damage to tubes and equipments.

The presence of H_2S and SO_2 can cause health hazards also. Headache, dizziness, dryness and nose, throat and chest pains are the effects of H_2S. The high concentration (>300 ppm) of H_2S even causes paralysis. It is not advisable to select the site for power plant where the action of polluted water on machine parts is severe and there are more chances of health hazards.

(*e*) **Sedimentation Effects.** The sedimentation of the reservoir is important from two points of view. The sedimentation robs the capacity of the reservoir and it further causes the rapid erosion of the turbine blades. The impact caused by the natural phenomenon of sedimentation must be carefully considered in the selection of a hydro-electric generation site.

It is always necessary to estimate the life of the plant on the basis of sedimentation collected in the reservoir and capacity of the plant reduced by sedimentation per year. If the sedimentation collection is sufficiently large and plant life is comparatively small on this basis, it is not worthwhile to select such site for hydro-electric plant.

The benefits from the hydro-projects are at their maximum at the beginning, but keep on falling and get completely wiped out as reservoirs get silted up gradually. Therefore, the total extent of benefits derived is determined by the life of the dams which in turn depends upon the condition of catchment area from which rivers bring silt, eroded by rainfall. Originally many of the larger dams in India were presumed to possess life span of 500 to 800 years but actually silt measurements have shown that the reservoirs are most likely to be filled up in 25% of the expected time or even less. This vast reduction in the ages of dams has given quite a different complexion to development of river valley projects, from being semi-permanent features they have suddenly become temporary measures and thereby profoundly affect our power planning strategy.

The life of Bhakra reservoir was estimated to be 350 to 400 years on the basis of estimated rate of siltation. The current rate of siltation is 28000 acre-ft/year against 19600 acre-ft/year in the project report and has reduced the estimated life of the plant considerably.

(*f*) **Environment Aspects of Site Selection.** In addition to being efficient and economical for its intended purpose, the project should be designed on the basis of best available information so as to :

(1) minimise the impact of the project,

(2) to enhance the local environment, and

(3) be in the best public interest.

Environment and engineering disciplines must work together in the site selection process. If the mutual interrelations between engineering and environment considerations are recognised at the beginning of the planning stage, a final design can be developed that is both compatible with the local environment and efficient for its intended function.

The site selection should fulfil all the following requirements.

(1) To assure safe, healthful, productive and culturally pleasing surroundings.

(2) To avoid the health hazards or other undesirable and unintended consequences.

(3) To preserve important historic, cultural and natural aspects of the site.

All three aspects mentioned above can be affected to a greater or lesser degree by electric-power plant. The evaluation of the potential impact of the proposed plant on these resources should be on the line of geological and hydrological evaluations.

The potential impact of power plant on existing land resources is dependent upon specific site considerations. In addition to surface and subsurface geological investigations, the site feasibility study should also include determinations of important characteristics of the area including the topography, history, geography, ecology and land use. The unquantifiable values such as unique natural environments, scenic values, historic and archeological sites should also be identified. The present and probable future land use should be determined in sufficient details so as to identify changes which may be induced as a result of plant construction.

Environmental conditions in artificial impoundment water are entirely different from those in free flowing water. The impoundment of water presents barriers to the free movement of fishes and requires design and installation of fish passage facilities. All these potential effects should be considered carefully prior to development of a new hydro-electric project.

3.3. CLASSIFICATION OF HYDRO-ELECTRIC POWER PLANTS

The hydroelectric power plants are generally classified according to (*a*) availability of head, (*b*) according to the nature of load and (*c*) according to the quantity of water available for generation.

(A) Classification according to the availability of head.

(1) Low head plants. When the head of water available is below 30 metres, the plant is known as low head plant. In this case, a dam is built across the river to create the necessary head of water. The excess water is allowed to flow over the dam itself. In this case, no surge tank is required as the power house is located near the dam itself and the dam is designed to take pressure created due to the back flow under part load conditions. Francis, Propeller or Kaplan type turbines are generally used in such power plants because these are mostly suitable for low head plants.

(2) Medium head power plants. When the operating head of water lies between 30 to 100 metres, the power plant is known as medium head power plant. The forebay provided at the beginning of penstock serves as water reservoir. In these plants, the water is generally carried in open canals from main reservoir to the forebay and then to the power house through the penstock. The forebay itself works as surge tank in this plant. Sometimes, the water is directly carried through the dam to the power house. Such arrangement is shown in Fig. 3.1 (*a*). The common types of prime movers used in these plants are Francis, Propeller and Kaplan.

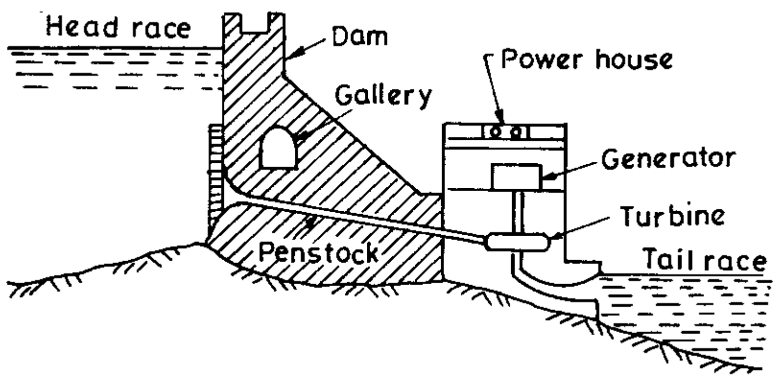


Fig. 3.1 (*a*). Medium head storage type plant.

Many times, it becomes necessary to divert the water through a separate canal to the power house which is located sufficiently away from the diversion point as shown in Fig. 3.1 (*b*). The water from the power house is discharged back into the original river at a downstream point. The high head diversion plant is shown in Fig. 3.1 (*c*). The distinguished feature is a complicated water conveyance system.

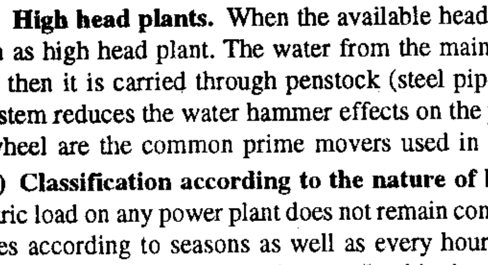


Fig. 3.1. (*b*) Medium head diversion plant.

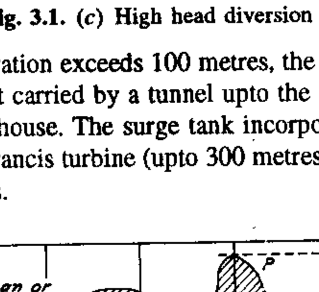


Fig. 3.1. (*c*) High head diversion plant.

(3) High head plants. When the available head for power generation exceeds 100 metres, the plant is known as high head plant. The water from the main reservoir is first carried by a tunnel upto the surge tank and then it is carried through penstock (steel pipe) to the power house. The surge tank incorporated in the system reduces the water hammer effects on the penstock. The Francis turbine (upto 300 metres) and Pelton wheel are the common prime movers used in high head plants.

(B) Classification according to the nature of load. The electric load on any power plant does not remain constant and varies according to seasons as well as every hour in a day of twenty-four hours. The load curve (load hydrograph or demand hydrograph) for a highly industrial town is shown in Fig. 3.1 (*d*). The capacity of the power plant required to fulfil the demand as shown in Fig. 3.1 (*d*) is the peak load *P*. If the power plant is designed for capacity of *P* MW, then most of the time, the plant is working under low load conditions and it is not utilised properly and economically

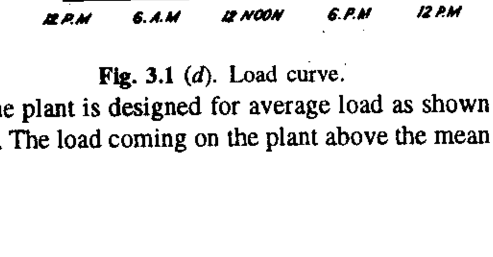


Fig. 3.1 (*d*). Load curve.

as the load factor of the plant is far below one. Therefore, the plant is designed for average load as shown in Fig. 3.1 (*d*). This type of plant is known as base load plant. The load coming on the plant above the mean load as shown in Fig. 3.1 (*d*) by shaded area is taken by another smaller plant which is known as peak load plant.

(1) Base load plants. This type of plant takes the load on the base portion of the load curve. The load on the plant remains more or less constant throughout the operation period. Base load plants are generally large in capacity. The run-off-river and storage type power plants are used as base load plants. The load factor of such plants is considerably high.

(2) Peak load plants. The peak load plants are designed primarily for taking care of peak loads of the demand curve as shown in Fig. 3.1 (*d*). Runoff river plants with pondage and pumped storage plants are generally used as peak load plants. In case of runoff river hydroplants with pondage, a large pond is essential and extensive seasonal storage is usually provided. These types of plants have large seasonal storage and relatively high-heads and are likely to be located on small watersheds. They store the water during offpeak period and supply during peak periods on the top of the load curve. The load factor of peak plants is considerably low compared with base load plants.

(C) Classification according to the quantity of water available

1. Run-off River Plant without Pondage. This type of plant does not store the water and uses the water as it comes. This plant has no control over the river flow. Therefore, water is wasted during low load and high flood conditions. During dry seasons, the capacity of the plant goes down due to the low flow rates of the water. The utility of these plants is very less compared with other plants due to non-uniformity of supply and lack of assurance for continuous constant supply.

2. Run-off River Plant with Pondage. The usefulness of the run-off river plant is increased by incorporating a pond in the plant. The pond permits to store water during off peak hours and uses during peak hours of the same day. The pondage capacity is decided to take the fluctuating load based on 24-hours basis. Pondage increases the stream capacity for a short period, a hour or week depending on the capacity of the pond. The tail race conditions should be such that the tail-race water level should not increase during floods because it reduces the effective head of the plant. This plant can be used as base load or peak load plant.

Such plants are many in number in Europe and all major rivers have series of such plants along their course of flow. The reason for not having such plant in India is typical monsoon which brings rain or flow only for 4 months. Against this, European rivers have more or less uniform distributed flow throughout the year which is the prime requirement of run-off river plant.

The flow duration curve shown in Fig. (3.2 *a*) is most unsuitable for run-off river plant whereas the flow duration curve shown in Fig. (3.2 *b*) is most suitable as minimum required quantity of flow is available for maximum period of the year (70%).

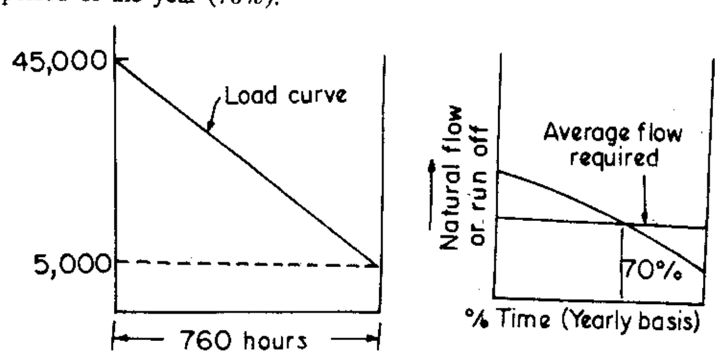


Fig. 3.2. Flow duration curve.

3. Storage Type Plants. If the rainfall occurs during a short period of the year and remaining period of the year is dry, it becomes essential to store water during rainy season and supply the same during dry-season. A storage type plant is one with a reservoir of sufficiently large size to permit carry-over storage from the wet season to the dry season and thus to supply firm flow substantially more than the minimum natural flow. This plant can be used as base load plant as well as peak load plant as water is available with control as required. The majority of hydro-electric plants in the world and all plants in India are of this type. The flow duration curve shown in Fig. 3.2 (*a*) is suitable only for such plants.

4. Pump storage plants. Pump storage plants are generally used for peak loads. If there is shortage of water at a particular location of the plant for power generation, then the water after passing through the turbine is pumped back from the tail race to head race during off peak periods of thermal or nuclear plant, provided the ponds are constructed at head and tail water locations. This type of plant generates power for peak load but during off-peak period, water is pumped from tail water pond to the head water pond for future use. The pumps are powered with secondary power from some other plant as steam plant or run-off-river plant where water would otherwise be wasted over the spillway.

Pumped storage plant is a special type of hydro-electric plant. It works generally in combination with thermal plants to improve overall efficiency of the combined system.

The effect of the load on efficiency of hydro and thermal power plants is shown in Fig. 3.3. The efficiency of the thermal plant decreases rapidly with decrease in load, whereas the decrease in efficiency is not very much marked (upto 25% load) with respect to load in case of hydro-plant. Therefore, it is not at all desirable to operate the thermal plant at part load.

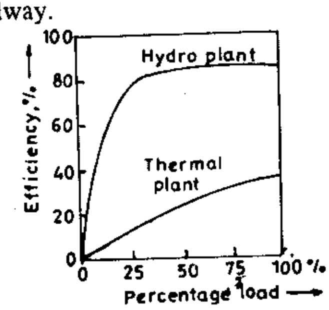


Fig. 3.3. Load versus efficiency for hydro and thermal plants.

If the capacity of the thermal plant is 100 MW and if the load on the plant is only 80 MW then instead of operating the plant at 80 MW, it is operated at 100 MW and extra 20 MW power generated is used to pump water from a lower level reservoir into the upper level reservoir and this energy is stored in form of potential energy of water. Now if the load on the plant increases say 110 MW, then the 100 MW is supplied by thermal plant and the remaining 10 MW by hydel (pumped storage) plant as some stored energy (in form of stored water during off-peak period) is available in the hydel plant. Such type of the system to pump the water from lower storage to upper storage when the load on the thermal plant decreases below its rated load and to use the pumped water again for power generation when the load on the thermal plant increases above its rated load, is known as Pumped Storage Plant. Such combined operation increases the overall system efficiency and also solves the problem of peak load.

Usually reversible pump turbine-motor generators are used in such plant. That is the same unit can be run a turbine or a pump. Also the generator can be used as a motor for running the pump, by the supply of electrical power.

The arrangement of the components of the pump storage plant is shown in Fig. 3.4 (*a*) and Fig. 3.4 (*b*).

Water leaving the turbine of main hydro-electric plant is stored in tail race pond as shown in Fig. 3.4 (*a*). This water is again lifted to head race reservoir by means of a separate pump as shown in Fig. 3.4 (*b*) and used for power generation at the peak load time.

A unique feature of pumped storage plant is that, very little water is required for its operation. Once the head water and tail water ponds are filled, the only water needed is to take care of evaporation and seepage. The pump storage plant decreases the operating cost of steam plant when working in combination with it because it serves to increase the load factor of the steam plant and provides added capacity to meet peak loads. Pump storage plants are widely used in Germany and now-a-days these types of plants gained high popularity throughout the world.

A small capacity of this type of plant is in operation at Jarkwadi (Maharashtra) from last many years and another plant is also in operation in Tamilnadu.

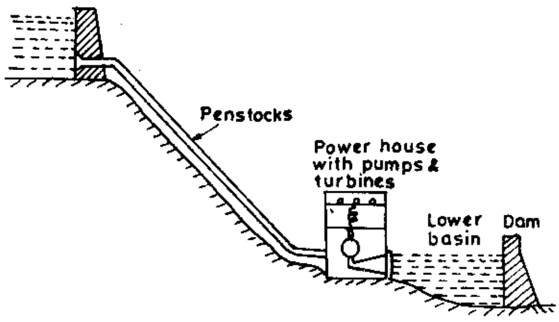


Fig. 3.4. (*a*) Arrangement of different components of pumped storage hydro-electric power plant.

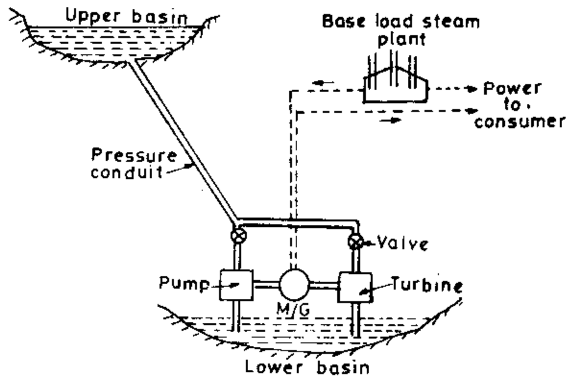


Fig. 3.4. (*b*) Pumped storage power plant for peak load in conjunction with steam plant as base load plant.

5. Mini and Micro-Hydel Plants. The present energy crisis which is engulfing the world today is not showing any sign of abating. India is also gripped in this crisis as mentioned earlier. To develop mini (5 m to 20 m head) and micro (< 5 m) hydel potential in our country is partly a solution to face the present power crisis. The low head hydro-potential is scattered in this country and estimated potential from such sites could be as much as 20,000 MW.

In India, the high head and medium head sites have been explored but low head, low output sites are neglected. There is tendency to utilize high head sites because higher the head, lesser is the capital cost per kW. As high head plant provides higher velocity which reduces the size of turbine-generator considerably.

These sites are available at sluices admitting water to the canals for irrigation purposes and on the canal falls. At sluice inlets and canal falls, lot of energy is wasted because it cannot be utilised and costly civil engineering works have to be undertaken to dissipate this energy which would otherwise do great harm. To overcome this difficulty with an advantage of getting more power is to set up a small hydropower house which forms a small fraction of total cost.

If properly planned and implemented, it is possible to commission a small hydro-generating set-up of 5 MW with a period of one and half year against the period of a decade or two for large capacity power plants. Several such sets upto 1000 kW each have been already installed in Himachal Pradesh, U.P., Arunachal Pradesh, W.B. and Bhutan.

A suitable type of turbine known as *bulb turbine* is developed for such small hydro plants. In this turbine, the scroll case has been modified in the form of nearly horizontal tapering duct with the flow passage forming a sort of throat where the turbine rummer is located. A straight diverging tube acts as a draft tube. Thus the whole path of the water is straight resulting in minimum hydraulic losses.

Such schemes have been successfully adopted in U.K., USA, France, Germany and China. China has developed lot of power through mini and micro plants as small head power capacity in the country is estimated as 150×10^3 MW against 580×10^3 MW total. Chinese scientists are developing tubler turbine sets which are especially suitable for very low heads with large flow rates. When compared with conventional vertical shaft Kaplan turbines, tubler turbines have better performance characteristics at large flow rates. In fact, the conditions in India are more favourable than in other countries for such installations.

3.4. RUN-OFF-RIVER PLANTS WITHOUT PONDAGE

Hydroelectric power plants can be located at suitable places along a stream of river. The water for power generation in these stations is used just as it comes to them without storing. The run-off river plants can be built with low expenditure on civil work compared with other plants but the head that would be available and the amount of power that could be generated may not be appreciable. In these plants, the regulation of water flow according to the load on the plant is not possible, therefore, these plants do not carry much importance, if considered individually. The heads are sometimes quite low, and often, at times of flood, tail water rises to such an extent that the plants become inoperative. No doubt these plants have the capacity of generation but their capacity is seldom as useful as that of other types of plants.

It may be possible for run-of-river plants to regulate the water flow to suit the fluctuations in load demand but this limitation could be offset operating the run-off-river plant in conjunction with thermal plant. During the period when there is heavy discharge from the dam, either for irrigation or during floods, the run-off-river plant could take the bulk of the load where the thermal power plants provide energy when the discharge is insufficient to cope up with the load.

The generation capacity to be installed requires a careful investigation on economic ground. The investment cost per kW capacity could be brought down by increasing the installed capacity but on the other hand, the cost per kW-hr energy generated would tend to go up on accound of reduction in load factor of the plant imposed by the restricted water availability. Therefore, it is necessary to work out a number of alternative sizes to arrive at the optimum size of power plant that would generate the energy with minimum cost. The installation as well as generation cost varies widely from project to project depending on the head and discharge of water available and civil and hydraulic works required.

The power duration curve for such type of plant can be drawn from the knowledge of water flow and average head that would be available for power generation as shown in Fig. 3.5.

The main function of the run-off-river plant in conjunction with thermal plant is to save the coal that would otherwise be necessary to burn in steam plant. The hydro-plant of 72 MW capacity on the Ohio river and Winfield and Marmet plants on the Kanawha River are the examples of run-of-river power plants.

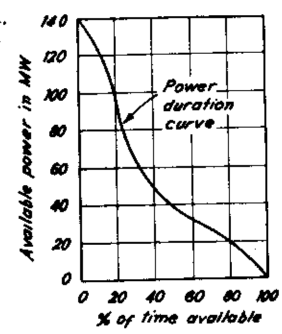


Fig. 3.5. Power duration curve of a typical run-off-river plant.

The run-off-river hydro-plant can also be used as base load plants (very rarely) on the rivers which exhibit a substantial and steady minimum discharge. Such rivers could be utilised to generate electric power without much expenditure on civil and hydraulic works for storage facilities at suitable locations. Generally, the installed capacity of base load hydroplant of run-off-river type is so sized that the discharge at full load seldom exceeds the minimum flow of the river. Base load run-off-river hydro-plant with high load factor (0.8 to 1) plays a useful and important role in integrated system as they can substantially reduce the size of the thermal power plant or even eliminate the thermal power plant from the system.

3.5. RUN-OFF-RIVER PLANT WITH PONDAGE

The usefulness of run-off-river plant can be increased considerably by introducing a pondage provided the tail water conditions are such that the floods will not "drawn out the plant". The pondage capacity should be able to take care of hour to hour fluctuations in load on the plant throughout the period of week.

During those weeks when plenty of water is available in the river, these plants could operate on the base of load curve considerably relieving the burden on the thermal power station when connected to loads which are served by both steam and hydro power stations.

The Fig. 3.6 (*a*) shows the distribution of load between hydro and thermal during the weeks when adequate water is available. It can be further observed that the curve representing the power output of hydro plant follows more or less the same shape as that of the load curve. This situation of hydro-power output would allow the thermal station to generate uniform and steady power output. This reduces the specific fuel consumption of thermal power plant although operating at a reduced output.

When there is insufficient flow of water and pondage capacity is inadequate to meet the weekly requirements, the steam plant gradually changes over the base of the load curve allowing the hydroplant to function as peak load station as shown in Fig. 3.6 (*b*).

In conventional run-off-river plants with pondage, installation is on a high margin in relation to minimum stream flow. The full discharge of the plant may be of the order of 10 to 20 times minimum stream flow. The full plant discharge often lies between 1.5 to 3 ft^3/sec. per square mile of water shed area. The load factor for this plant lies between 0.4 to 0.65.

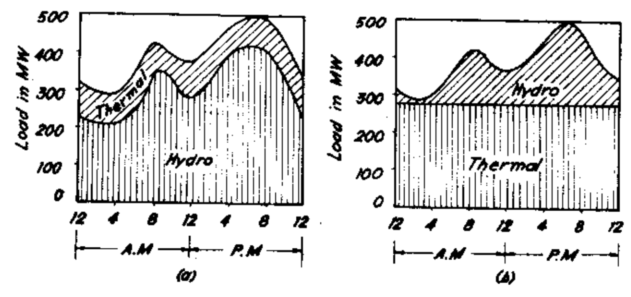


Fig. 3.6. Diagrams illustrate utilization of run-off-river hydro plant with pondage.

The operation of hydro plant of this type in conjunction with steam plant offers many advantages. This reduces the fuel consumption as well as renders possible exploitation of water sources otherwise wasted. It (combined power plant) reduces overall generation cost of the electrical energy by minimising the reserve capacity needed if neither of the two power plants were operated independentally.

The Conowingo hydroplant on Susquehanna River of 252 MW capacity with average flow 1000 m^3/sec and Safe Harbar hydro-plant are the examples of run-off-river power plant with pondage.

3.6. STORAGE RESERVOIR PLANTS

Majority of the hydro-electric power plants come under this category. It is more economical to store a substantial portion of the annual water flow for power generation where a fairly high natural head is available along a river course. The heavy capital cost of such large storage plants could be paid off by the comparatively high energy content available from every cu-metre of water stored. The cost of power plant per kW of installed capacity is considerably reduced in high head plants because one could expect a comparatively low cost increment for plants with reservoir. Notable examples of such plants are Hoover Dam on Colorado river and Grand Coulee on the Columbia river.

3.7. PUMP STORAGE POWER PLANTS

The large generating units of modern steam power stations and nuclear power stations operate most economically when they run day and night (load factor approaches to 1) at constant load. The major problem with these power plants is the peak load as mentioned earlier. Covering of short peak load demands with steam power station is economically undesirable and is not adaptable due to slow peak up.

Pump storage plants for peak load operations in interconnected system are more suitable where the quantity of water available for power generation is insufficient but natural site for high dam construction is most suitable.

The pump storage power plant essentially consists of a head water pond and a tailwater pond. During the off-peak period of an interconnected power plants system (steam + pump-storage), the water from the tail water pond is pumped with the help of a pump using the extra energy available from thermal power plant during off-peak hours as shown in Fig. 3.7. With surplus available energy (E_a) during off-peak period, is stored in the form of hydraulic potential energy by lifting the water from lower level to higher level. The same stored hydraulic energy is used during peak load period by supplying the water from the upper basin to the water turbine through the penstocks. The quantity of water pumped back may be equal to all the water passing through the water turbine during peak load period or part of that depending on the requirements.

The requirement of ideal pump storage plant is

$$E_a \eta = E_s$$

where η is known as the efficiency of the pumped storage plant. If $E_a . \eta > E_s$ then the quantity of water pumped back during off-peak period is less than the quantity of water supplied during peak load conditions. If $E_a < E_s$ then the thermal plant capacity is designd in such a way that $E_a \eta$ becomes equal to E_s. Every care has been taken in the design of interconnected system to equalise E_s with $E_a \eta$.

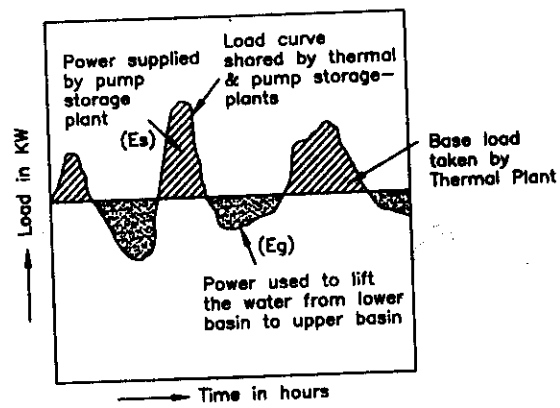


Fig. 3.7. Load Curve.

The concept of pump storage for meeting peak loads and decreasing thermal station operating cost is not new and number of inter-connected pump storage hydro-plants with capacities ranging up to 1000 MW are in successful operation. The present trend to establish large capacity thermal or nuclear plants at high capital outlay has emphasized more and more importance and growing popularity of interconnected pump storage plants in countries where the water power resources are limited or have been almost fully utilized.

3.8. GENERAL ARRANGEMENT OF STORAGE TYPE HYDRO-ELECTRIC PROJECT AND ITS OPERATION

The storage type hydro-projects have large contents of water and the water collected during heavy-rain period is supplied during dry-period of the year. The collection of water is done on seasonal basis (yearly), therefore, the capacity of the reservoir required is extremely large compared with the other types of hydraulic power plants.

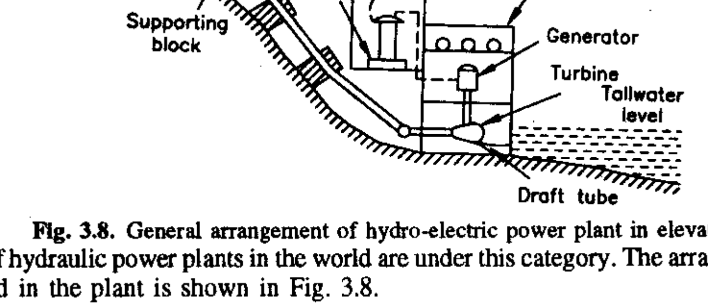


Fig. 3.8. General arrangement of hydro-electric power plant in elevation.

Majority of hydraulic power plants in the world are under this category. The arrangement of the different components used in the plant is shown in Fig. 3.8.

The arrangement of different components for hydro electric power generation is shown in Fig. 3.9 when the water supply tunnel is directly carried through the dam. The power plant shown in Fig. 3.9 is Grand Coulee power plant on Columbia River at Washington. The Bhakra power house in India is of the same type.

The basic requirement of a hydro-electric power station is a reservoir where large quantity of water is stored during flood season and used during dry season. The reservoir is generally built by constructing a dam across a river. The water from the reservoir is drawn by the forebay through an open canal or tunnel. The water from the forebay is supplied to the water prime mover through the penstock which is located at much lower level than the height of water in the reservoir. The water entering into the turbine rotates the turbine shaft and ultimately the generator shaft which is coupled to turbine shaft. The current flows from the generator to the transformer where the voltage is stepped up to be transmitted by huge pylons.

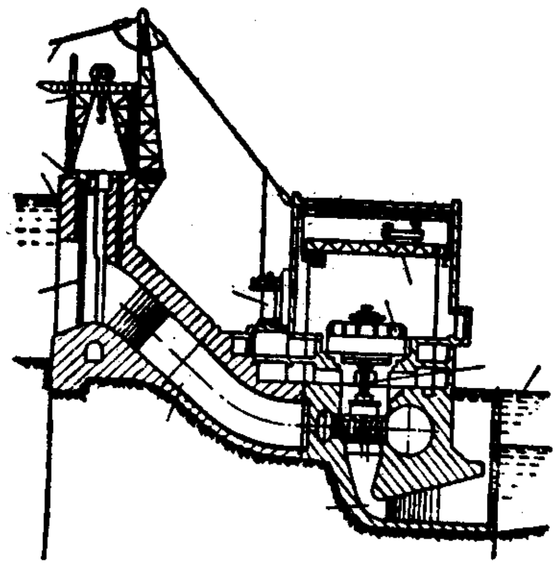


Fig. 3.9. Hydro-electric power plant.

The functions of different components used in storage type hydraulic power plant are described below :

1. Reservoir. The main purpose of the reservoir is to store the water during rainy season and supply the same during dry season.

2. Dam. The function of the dam is to increase the height of water level behind it which ultimately increases the reservoir capacity. The dam also helps to increase the working head of the power plant. Many times high dams are built only to provide the necessary head to the power plant.

3. Trash rack. The water intakes from the dam or from the forebay are provided with trash rack to prevent the entry of debris which might damage the wicket gates and turbine runners or choke-up the nozzles of the impulse turbine. If the winters are severe, special provision is made to prevent the trouble from ice. To prevent ice from clinging to the trash racks, they are often heated electrically. Sometimes an air bubbling system is provided in the vicinity of the trashracks which brings warmer water to the surface of trashracks.

4. Forebay. The forebay serves as a regulating reservoir temporarily storing water when the load on the plant is reduced and provides water for initial increment of an increasing load while water in the canal is being accelerated. In many cases, the canal itself may be large enough to absorb the flow variations. If the canal is long, its end is sometimes enlarged to provide necessary temporary storage. In short, forebay is a naturally provided storage which is able to absorb the flow variations. This can be considered as naturally provided surge tank as it does the work of surge tank. The forebay is always provided with some type of outlet structure to direct water to the penstock depending upon local conditions.

5. Surge tank. There is sudden increase of pressure in the penstock due to the sudden decrease in the rate of water flow to the turbine when the gates admitting water to the turbines are suddenly closed owing to the action of governor. This happens when the load on the generator decreases. This sudden rise of pressure in the penstock above normal due to reduced load on generator is known as "*water hammer*".

When the turbine gates suddenly open because the turbine needs more water to supply an increased load demand, water has to rush through the penstock and there is a tendency to cause a vacuum in the water system. The penstock must withstand the positive hammer caused by sudden closing of turbine gates and no vacuum should be produced in the system when the gates suddenly open under increased load conditions.

A surge tank is introduced in the system between the dam and power-house nearest to the power house, and preferably on the high ground to reduce the height of the tower to provide better regulation of water pressure in the system during variable load conditions. When the turbine gates are partly closed and water flow into the turbine is reduced suddenly, water rises in the surge tank. This produces a retarding head and decreases the velocity of water in the penstock. When the velocity of the water in the penstock is reduced to the value demanded by the turbine, the level of the water in the surge tank starts falling and fluctuates up and down till its motion is damped out by friction. When there is sudden rise in the load on the turbine, additional water is supplied from surge tank. This lowers the water surface in the surge tank thus producing an accelerating head which increases the flow of water in the penstock. When the discharge of water corresponds to the turbine demand, the water surface in the tank ceases to fall. The surge tank thus helps in stabilising the velocity and pressure in penstock and reduces the water hammer effect.

6. Penstock. A pipe between the surge tank and prime-mover is known as penstock. The structural design of the penstock is same as for any other pipe except it has to bear very high pressure on inside surface during decreased load conditions on generator and on onside surface during increased load conditions on generator. Penstocks are most commonly made of steel through reinforced concrete. If the distance from the forebay to the power house is short, separate penstocks are used for each turbine. Penstocks are usually equipped with head gates at the inlet which can be closed during the repair of the penstocks. An air inlet valve downstream from the gate is provided to prevent collapse of pipe immediately after the head gate is closed. A sufficient water depth should be provided above the penstock entrance in the forebay or surge tank to avoid the formation of vortices which may carry air into the penstock and results in lower turbine efficiency.

In very cold weather conditions, it is sometimes advised to bury the penstock to prevent the ice formation in the pipe and to reduce the number of expansion joints required. Uncovered (running on the ground) penstocks are usually more expensive because of the expansion joints, anchors and other apparatus required but they have the advantage of being accessible for inspection and repairs.

7. Spillway. Spillway is considered a safety valve for a dam. It must have the capacity to discharge major floods without damage to the dam and at the same time keeps the reservoir level below some predetermined maximum level.

8. Power House. A power house consists of two main parts, a sub-structure to support the hydraulic and electric equipment and superstructure to house and protect this equipment. The elevation of the turbine with respect to the tailwater level is determined by the necessity of avoiding cavitation.

The superstructure of most power houses is a building housing all operating equipments. The generating units and exciters are usually located on the ground floor. The turbines which rotate on vertical axis are placed just below the floor level while those rotating on a horizontal axis are placed on the ground floor along-side the generator.

It is always advantageous to locate the power house underground under certain topographic conditions where there is no convenient site for a conventional type. There are many underground power houses in Europe. The Koyna power house in India is the example of underground power house. One of the largest underground power houses in the world is Kemano power house in Canada having a generating capacity of 1670 MW under a head of 785 metres.

9. Prime Movers. The main purpose of the prime mover is to convert the kinetic energy of water into mechanical energy to produce electric energy. The prime movers which are in common use are Pelton turbine, Francis turbine, Kaplan turbine and propeller turbines. The details concerning the design, construction and choice of the prime mover will be discussed in the next chapter.

10. Draft tube. The draft tube is essential part of reaction turbine installation. It supplements the action of the runner by utilising most of the remaining kinetic energy of the water at the discharge end of the runner.

The draft tube is a diverging discharge passage connecting the running with tailrace. It is shaped to decelerate the flow with a minimum loss so that the remaining kinetic energy of water coming out of runner is efficiently regained by converting into suction head, thereby increasing the total pressure difference on the runner. This regain of kinetic energy of water coming out from reaction turbine is the primary function of the draft tube.

The regain of static suction head in case where the runner is located above tail water level is the secondary purpose of draft tube. When the vertical distance of the runner above tail race water level is well within an atmospheric head and when the outlet of the draft tube is sufficiently submerged in water to assure a water seal, the negative static draft head on the runner is added to the positive head from the head water level to make up the total static head on the turbine. Although the atmospheric head is 10.3 metres (34 ft.) of water at sea level, the static draft head should not exceed 4.55 metres (15 ft.) and even this should not be reached except during low water conditions of short duration with prime movers of low specific speed and relatively high heads.

Operation of Hydro-Electric Project. In hydro-electric plants, the potential energy of water is converted into kinetic energy first passing through the tunnel to the power house. The kinetic energy of the water is converted into mechanical energy in the water turbines. The mechanical energy of the water turbine is further utilised to run the electric generator. This is the common principle of hydro-electric generation.

The load on the generator fluctuates according to the demand, therefore, the mechanical power developed by the turbine must also change and that is controlled by the governor by changing the quantity of water supplied to the turbine.

3.9. ADVANTAGES OF HYDRO-ELECTRIC POWER PLANTS

Advantages. The hydrostations are the best from many points of view. These include simplicity of design, easy maintenance, absence of pollution and zero fuelling cost, as the source is perpetual one and goes to waste if not exploited. Therefore, it is clear that every possible source of hydel energy must be fully exploited. Hydro generation has a unique and significant role to play particularly in the operation of interconnected power system. In fact, thermal or nuclear power can seldom produce electrical energy economically without an adequate proportion of hydro power generation.

1. The operating cost of the hydro-electric plant including auxiliaries is considerably low compared with thermal plants. As per recent calculations, the operating cost of hydro-plant is Rs. 120 per kW installed capacity at 100% load factor against the operating cost of thermal plant of Rs. 305 kW at 100% load factor.

2. The cost of each unit of electrical energy delivered from a thermal power plant is very adversely affected by the reduction of load factor at which the plant is operated. The cost per kW generated by a thermal plant designed for 80% load factor would go up by 20% if operated at 60% load factor and by 65% if operated at 40% load factor.

The cost of generation by hydro-electric plant is more or less unaffected by the load factor. The generator cost is 0.5 to 1 Re./kWh against 1.75 Rs./kWh of thermal plant.

3. The useful life of a thermal plant is 20-25 years, as against 100-125 years for hydro plant and the annual operating and maintenance cost of a thermal plant is approximately five to six times that of hydro plant of equal capacity.

4. The fuel needed for the thermal plants has to be purchased whereas in hydro plant the fuel cost is totally absent. The security of thermal power plant is mostly dependant on transport facilities and its security is less when the fuel is imported from outside countries.

5. There is no problem of handling the fuel and ash and no nuisance of smoke exhaust gases and soots and no health hazards due to air pollution.

6. The machines used in hydel plants are more robust and generally run at low speeds at 300 to 400 RPM whereas the machines used in thermal plants run at a speed 3000 to 4000 RPM. Therefore, there are no specialised mechanical problems or special alloys required for construction. There are no complications due to high temperature and pressures. Therefore, the outages of the machines are very few.

7. Usually the hydrostations are situated away from the developed areas, so the cost of land is not a major problem.

8. The outstanding features of hydro-electric plants is a quick response to the change of load compared with thermal or nuclear plant. Full output can be reached in about 10 to 15 seconds. Therefore they are ideally suited for peaking purposes. The rapid fluctuating loads are served most economically by hydro-plants.

9. Hydel power plays a major role not only providing an economic source of energy but also in improving the operation of the combined power system by meeting the system load at various times and providing regulating functions. Thus full measure of flexibility and economy in production is obtained.

10. The efficiency of hydro-plant does not change with age but there is considerable reduction in efficiency of thermal as well as nuclear power plant with age.

11. There are no stand-by losses whereas these are unavoidable for thermal plants.

12. The number of operations required is considerably small compared with thermal power plants.

13. In many hydro-electric developments, it is also possible to create ancillary benefits, such as domestic water supply, field and wild life enhancement, flood control and recreation. Moreover, hydro-projects can frequently be planned to provide cooling water for steam-electric plants.

14. It does not contribute to air and water pollution to *Green House Effect*.

Disadvantages. 1. The capital cost (cost per kW capacity installed) of the hydro-plant is considerably more than thermal plant.

2. Power generation by the hydro-plant is only dependent on the quantity of water available which in turn depends on the natural phenomenon of rain. The dry year is more serious for the hydroelectric project.

3. The site of hydro-electric station is selected on the criterion of water availability at economical head. Such sites are usually away from load centres. The transmission of power from power station to the load centre requires long transmission lines. Therefore, investment required for long transmission lines and loss of power during transmission are unfavourable factors for the economical selection of hydro-plants.

4. It takes considerable long time for its erection compared with thermal plants.

In practice, hydro-electric generation should be considered as an essential complement to thermal plant and not as a competitor. In power system planning, consideration should be given to the development of both hydro and thermal power so as to enable effective utilization of national resources for production of electrical energy at minimum cost.

A realistic assessment of national water resources for power production is essential to form national grids when integrated operation is required.

SOLVED PROBLEMS

Problem 3.1. *The average monthly run-off data of two rivers A and B for twelve months is tabulated as given below. The water source of river B is from a snow-fall region. The run-off is given in millions of cu-m per month.*

Month	*J*	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*
River A	*40*	*30*	*30*	*20*	*20*	*160*	*180*	*180*	*100*	*80*	*50*	*50*
River B	*50*	*50*	*60*	*80*	*100*	*100*	*90*	*90*	*70*	*60*	*60*	*60*

The head available for river A is 80 metres and for river B is 82 metres.

Using the above data, find :

(a) Which river is more suitable for storage type hydro-electric power plant ? Assume the overall efficiency of generation is same for both sites.

(b) If a run-off-river power plant is to be established then select the proper river for the same. The minimum quantity of water must be available for 85% of the total year for run-off-river plant. Also find the ratio of power generation if both plants are used as run-off-river plants for 80% period of the year at constant run-off.

(c) The ratio of run-off of river A and river B as well as ratio of power if the constant run-off from both rivers is required for 60% of the year.

(d) At what percentage of time, the run-off rate of both sites is same ?

Sol. First we have to draw the hydrographs and then the flow duration curves for both rivers. The hydrographs are drawn as shown in Fig. Prob. 3.1 (*a*) and the required data to draw the flow duration curve is tabulated as given in the following table.

River A			*River B*		
Discharge in millions of cu-m. per month	*Total No. of months during which flow is available*	*Percentage time during which flow is available*	*Discharge in millions of cu-m per month*	*Total No. of months during which flow is available*	*Percentage time during which flow is available*
20	12	100	50	12	100
30	10	83.30	60	10	83.3
40	8	66.60	70	6	50
50	7	58.3	80	5	41.55
80	5	41.65	90	4	33.30
100	4	33.3	100	2	16.66
160	3	25			
180	2	16.66			

(*a*) The average flow per month for river *A*

$$= \frac{40 + 30 + 30 + 20 + 20 + 150 + 180 + 180 + 100 + 80 + 50 + 50}{12}$$

= 78.33 millions of cubic metres per month.

The average flow per month for river *B*

$$= \frac{50 + 50 + 60 + 80 + 100 + 100 + 90 + 90 + 70 + 60 + 60 + 60}{12}$$

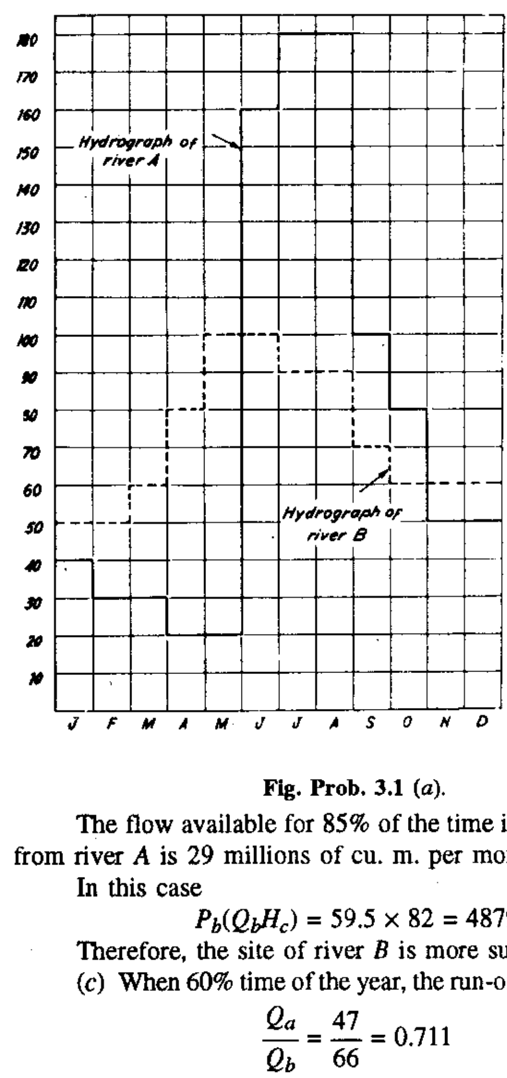
= 72.5 millions of cu. m. per month.

The power developed $\propto HQ$.

$$\therefore \qquad \frac{P_a}{P_b} = \frac{Q_a H_a}{Q_b H_b} = \frac{78.33 \times 80}{72.5 \times 82} = 1.05$$

As $P_a > P_b$, the river *A* is more suitable for storage type power plant.

(*b*) From Fig. Prob. 3.1 (*a*).



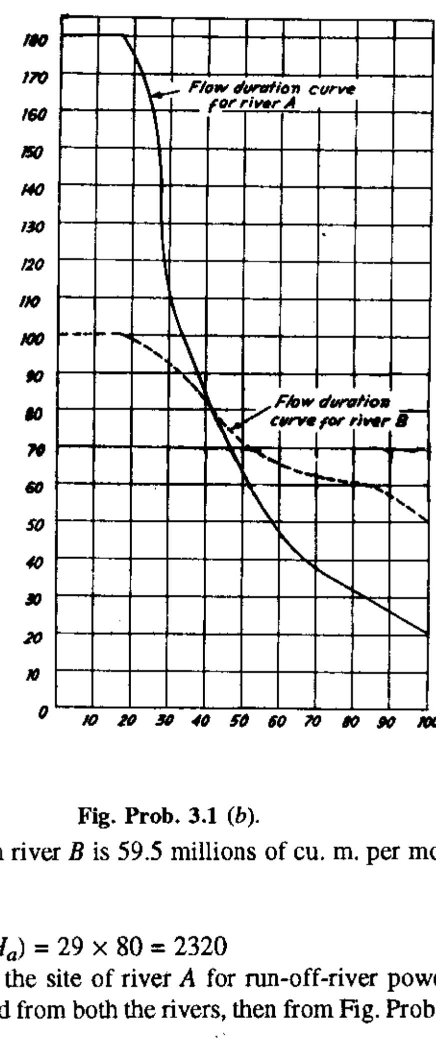


Fig. Prob. 3.1 (*a*). **Fig. Prob. 3.1** (*b*).

The flow available for 85% of the time in year from river *B* is 59.5 millions of cu. m. per month and from river *A* is 29 millions of cu. m. per month.

In this case

$$P_b(Q_bH_c) = 59.5 \times 82 = 4879 > P_a(Q_aH_a) = 29 \times 80 = 2320$$

Therefore, the site of river *B* is more suitable than the site of river *A* for run-off-river power plant.

(*c*) When 60% time of the year, the run-off is required from both the rivers, then from Fig. Prob. 3.1 (*b*).

$$\frac{Q_a}{Q_b} = \frac{47}{66} = 0.711$$

and
$$\frac{Q_aH_a}{Q_bH_b} = \frac{47 \times 80}{66 \times 82} = 0.694$$

(*d*) From Fig. Prob. 3.1 (*b*), the percentage of time at which the run-off for both rivers is same is the intersection point of two flow duration curves and that is 80 millions of cu. m. per month and percentage time available is 43%.

Problem 3.2. *The run-off data of two rivers for twelve months is tabulated as given below. The run-off is given in millions of cu. m. per month.*

Month	*J*	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*
River A	*40*	*30*	*20*	*15*	*10*	*80*	*140*	*120*	*100*	*60*	*50*	*40*
River B	*50*	*50*	*40*	*40*	*40*	*90*	*100*	*100*	*80*	*70*	*60*	*70*

Using the above data, find (a) the ratio of run-off of river A and river B if the constant run off is required for 40% time of the year. If the constant run-off for 80% time of the total year is required which river site is more preferable for run-off plant and why ? (c) Which site of the river is more preferable for storage type plant and why ? (d) At what percentage of time, the run-off rate of both rivers is same.

Sol. First we have to draw the hydrographs and then the flow duration curves for river A and B and the required data is tabulated as given in the following table.

(*a*) From Fig. Prob. 3.2 (*a*).

At 40% of the time, the flow of river B = 72 millions of cu. m. per month.

At 40% of the time, the flow of river A = 61 million of cu. m. per month.

$$\therefore \qquad \text{Ratio} = \frac{72}{61} = 1.18$$

Therefore, 18% flow is more from river B for 40% time of the year.

River A			*River B*		
Discharge in millions of m³/month	*Total No. of months during which flow is available*	*Percentage time during which flow is available*	*Discharge in millions of m³-month*	*Total No. of months during which flow is available*	*Percentage time during which flow is available*
10	12	100	40	12	100
15	11	91.6	50	9	75
20	10	83.30	60	6	50
30	9	75	70	5	41.65
40	8	66.6	80	4	33.3
50	6	50	90	3	25
60	5	41.65	100	2	11.66
70	4	33.3			
80	4	33.3			
90	2	25			
100	3	25			
110	2	16.66			
120	2	16.66			
140	1	8.30			

From Fig. Prob. 3.2 (*b*).

(*b*) The flow from river A for 80% of the year = 23 million of cu-cm per month.

The flow from river B for 80% of the year = 48 millions of cu-cm. per month.

The more quantity of water is available from river B for 80% of the year (48 > 23), therefore, river B is preferable for run-off type power plant.

(*c*) Total flow from the river A in the whole year

$$= 40 + 30 + 20 + 15 + 10 + 180 + 100 + 120 + 100 + 60 + 50 + 40$$
$$= 705 \text{ millions of cu-cm. per year.}$$

Total flow from river B in the whole year

$$= 50 + 50 + 40 + 40 + 40 + 90 + 100 + 100 + 80 + 70 + 60 + 50$$
$$= 770 \text{ millions of cu-cm. per year.}$$

$$\text{Average flow for river } A = \frac{705}{12} = 58.75 \text{ cu-cm./month.}$$

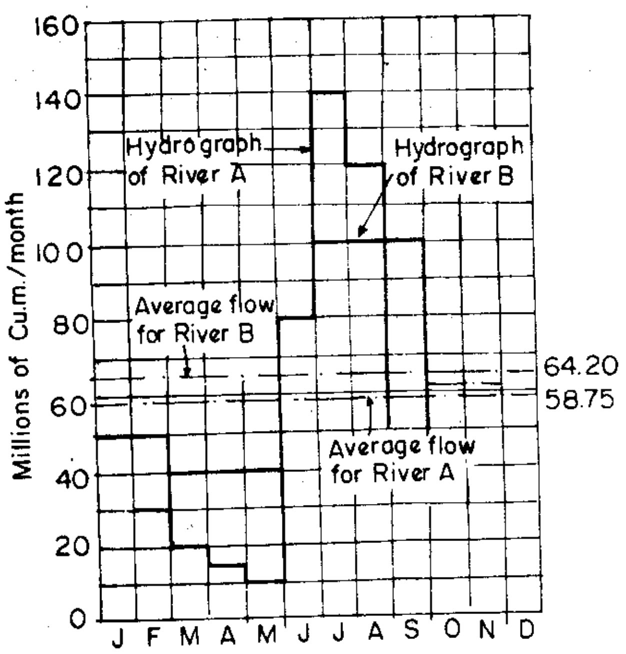


Fig. Prob. 3.2 (*a*).

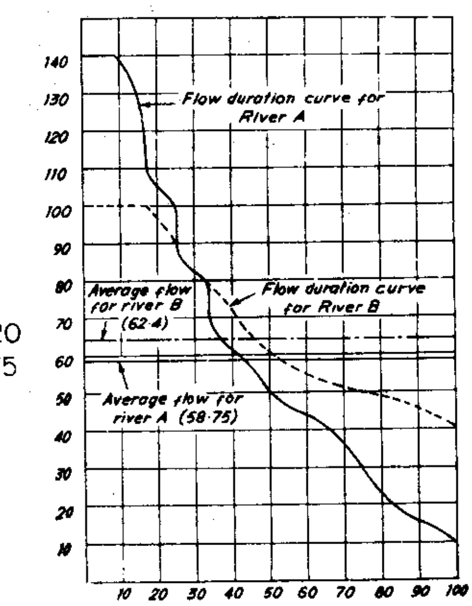


Fig. Prob. 3.2 (*b*).

Average flow for river $B = \dfrac{770}{12} = 64.17$ cu-cm./month.

As the average flow from river B is greater than average flow from river A, therefore river B is more preferable for storage type plant also.

(*d*) From Fig. Prob. 3.2 (*b*).

The run-off rate of both rivers is same at 25% (90 cu-cm/month) and 33.3% (80 cu-cm./month) of the year.

Problem 3.3. *The nature of load required for 24 hours is tabulated as given below.*

Time Period	*10 A.M. to 6 P.M.*	*6 P.M. to 8 P.M.*	*8 P.M. to 12 A.M.*	*12 A.M. to 6 A.M.*	*6 A.M. to 10 A.M.*
Load in MW	*160*	*80*	*40*	*20*	*100*

(*a*) *Find the total input to the thermal plant if the load is supplied by the single thermal plant only. Take the thermal efficiencies of the plant at 160, 80, 40, 20, 100 MW as 35%, 25%, 15%, 10% and 30% respectively.*

(*b*) *If the above load is taken by combined thermal and pump storage plant, then find the percentage saving in the input to the plant. Thermal plant efficiency at full load = 35%.*

(*c*) *Also find the overall efficiencies in both cases.*

In pump storage plant, the pump and turbine are separate. The efficiency of pump is 80% and water turbine is 90%.

Sol. (*a*) The load curve is shown in Fig. Prob. 3.3.

$$\text{Total output per day} = 100 \times 4 + 160 \times 8 + 80 \times 2 + 40 \times 4 + 20 \times 6$$
$$= 400 + 1280 + 160 + 160 + 120 = 2120 \text{ MW-hrs.}$$

The input to the thermal plant

$$= \frac{100 \times 4}{0.3} + \frac{160 \times 8}{0.35} + \frac{80 \times 2}{0.25} + \frac{40 \times 4}{0.15} + \frac{20 \times 6}{0.1}$$

$$= 1333.3 + 3660 + 640 + 1067 + 1200 = \mathbf{7900 \text{ MW-hrs.}}$$

$\therefore$ Overall efficiency $= \dfrac{2120}{7900} = 0.268 = \mathbf{26.8\%}$.

(*b*) The overall efficiency of the pump-storage plant

$$= 0.8 \times 0.9 = 0.72 = 72\%.$$

Assume the capacity of the thermal plant is x MW when it is working combinely with pump storage plant.

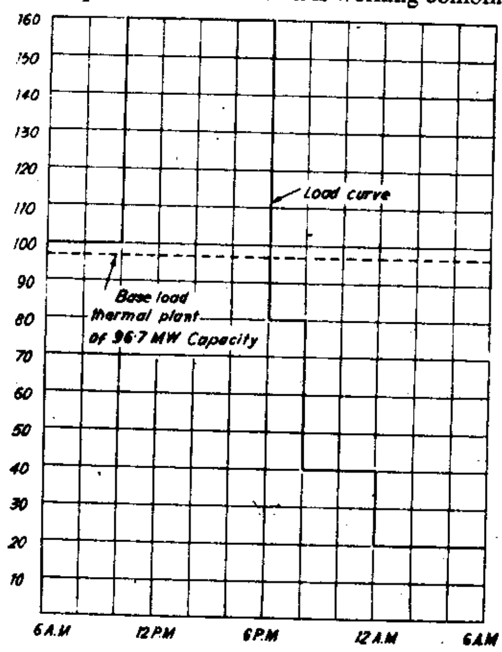


Fig. Prob. 3.3.

The energy used from the thermal plant to pump the water of pump storage plant during off-peak period must be equal to the energy supplied by the pump-storage plant during peak period.

From the Fig. Prob. 3.3.

$$[(x - 80) \times 2 + (x - 40) \times 4 + (x - 20) \times 6] \times 0.72 = (100 - x) \times 4 + (160 - x) \times 8$$

$\therefore$ $8.64x - 316.8 = 1680 - 12x$

$$x = \mathbf{96.7 \text{ MW}}$$

The energy supplied in the second case

$$= \frac{96.7 \times 24}{0.35} = \mathbf{6640 \text{ MW-hrs.}}$$

The overall efficiency of the combined plant

$$= \frac{2120}{6640} = 0.32 = \mathbf{32\%}$$

The percentage saving in input is the load taken by combined plant instead of single thermal plant

$$= \frac{7900 - 6640}{7900} \times 100 = \mathbf{15.95\%}.$$

Problem 3.4. *A load required by the consumers from the power plant for 24 hours in tabulated as given below :*

Time Period	*6 A.M. to 10 A.M.*	*10 A.M. to 6 P.M.*	*6 P.M. to 12 P.M.*	*12 P.M. to 6 A.M.*
Load in MW	*60*	*120*	*40*	*10*

(*a*) *Find the net revenue earned if the load is taken by a single thermal power plant. The energy rate is Rs. 1.5 per kw-hr. and cost of input is Rs. 2.2 per 20000 kJ. The thermal efficiency of plant may be taken as 40% at 120 MW load, 35% at 60 MW load, 30% at 40 MW load and 20% at 10 MW load.*

(*b*) *It is proposed to take the above load by a combined thermal and pump-storage plant. If the thermal plant always runs at constant load with 40% thermal efficiency and overall efficiency of pump storage plant is 80%, find the capacity of the thermal plant required and percentage increase in the revenue earned. The cost of power-sell and cost of energy input is same as given above.*

Sol. Referring to Fig. Prob. 3.4.

(*a*) Total energy generated by the thermal plant during 24 hours

$$= 60 \times 4 + 120 \times 8 + 40 \times 6 + 10 \times 6 = 240 + 960 + 240 + 60$$

$$= 1500 \text{ MW-hrs.} = \mathbf{1500 \times 10^3 \text{ kW-hrs.}}$$

Total cost of selling the power for 24 hours

$$= 1.5 \times 1500 \times 10^3 = \mathbf{2250 \times 10^3 \text{ rupees.}}$$

Total input to the thermal plant during 24 hours

$$= \frac{120 \times 8}{0.4} + \frac{60 \times 4}{0.35} + \frac{40 \times 6}{0.3} + \frac{10 \times 6}{0.2} = 2400 + 686 + 800 + 300$$

$$= 4186 \text{ MW-hrs.} = 4186 \times 10^3 \text{ kW-hrs.} = \mathbf{4186 \times 10^3 \text{ kWh}}$$

$\therefore$ Total cost of input energy during 24 hours

$$= 2.2 \times \frac{1}{20000} \times \frac{4186 \times 10^3 \times 3600}{1} = \mathbf{Rs.\ 1657.7 \times 10^3}$$

$\therefore$ Net revenue earned from the thermal plant

$$= 2250 \times 10^3 - 1657.7 \times 10^3 = \mathbf{592.3 \times 10^3 \text{ rupees per day.}}$$

(*b*) Assume the capacity of the thermal plant is x MW when it is working in combination with pump-storage plant.

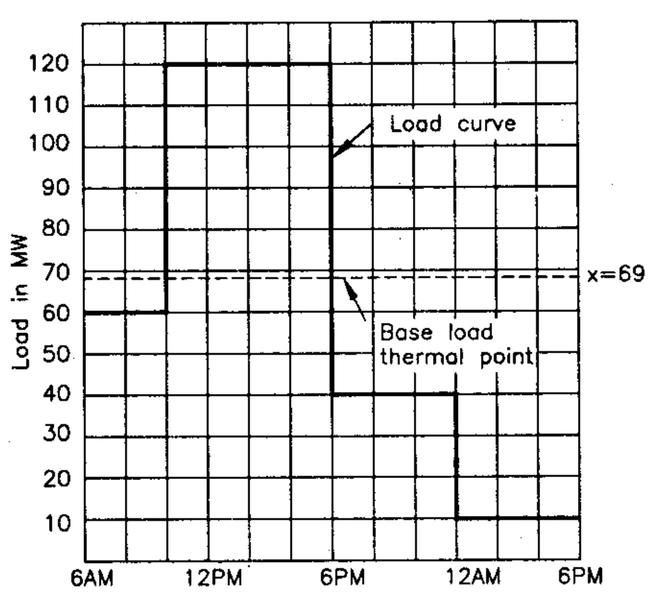


Fig. Prob. 3.4.

From Fig. Prob. 3.4, the energy used from thermal plant to pump the water of pump-storage plant during off-peak period must be equal to the energy supplied by the pump-storage plant during peak-period.

$$\therefore \quad [(x-60)4 + (x-40)6 + (x-10)6] \times 0.8 = (120-x)8$$

$$12.8x - 432 = 960 - 8x$$

$$\therefore \quad 20.8x = 1392$$

$$x = \frac{1392}{20.8} = \mathbf{67\ MW.}$$

Therefore, the base load of 67 MW must be taken by thermal plant.

As the total energy generated remains same, therefore, total revenue earned also remains same.

Now total input to the thermal plant in 24 hours

$$= \frac{67 \times 24}{0.4} = 4020 \text{ MW-hrs.} = \mathbf{4020 \times 10^3 \times 3600\ MJ.}$$

$\therefore$ Total cost of input energy during 24 hours

$$= 1.5 \times \frac{1}{20000} \times \frac{4020 \times 10^3 \times 3600}{1} = \mathbf{1085.4 \times 10^3\ rupees.}$$

$\because$ Net revenue earned from the combined plant per day

$$= 2250 \times 10^3 - 1085.4 \times 10^3 = \mathbf{1164.6 \times 10^3\ rupees.}$$

Percentage increase in the profit

$$= \frac{1164.6 - 592.3}{592.3} \times 100 = \mathbf{96.6\%}.$$

EXERCISES

3.1. What are the different factors to be considered while selecting the site for hydro-electric power plant ?

3.2. How the hydro-electric power plants are classified ?

3.3. What do you understand by base load and peak load power plants ? What type of power plants are used as base load and peak load plants and why ? What factors are considered in selecting a plant as base load plant or peak load plant ?

3.4. What do you understand by run-off river power plant ? How its performance is increased by introducing a pondage in the plant ?

3.5. What are the specific advantages of storage reservoir type power plant ? How they differ from other types of hydro power plant ?

3.6. What do you understand by "pump storage plant" ? What are the advantages and limitations of this power plant ? Where can such schemes be best applied ?

3.7. Draw a neat diagram of storage type hydro-electric power plant and describe the function of each component used in the plant.

3.8. Mention the advantages and disadvantages of hydro-electric power plants compared with thermal power plants.

3.9. Why the combined operation of hydro and thermal plants is more economical than individual operation of the plant ?

3.10. How the most economical capacity of hydro-electric plant is decided ?

What is the purpose in carrying out the economic analysis of hydro-electric power project and how it is done ?

3.11. At a potential hydraulic-plant site, average elevations of head water and tail water levels are 605 and 525 metres respectively. The average annual water flow was determined to be equal to that volume flowing through a rectangular channel 10 metre wide with a depth of 120 cm and an average velocity of 5 m/sec. Find the annual electric energy in kW-hrs when turbine efficiency is 85% and generator efficiency is 95%. Take the loss in headworks equal to 35 meters of the available head.

3.12. A factory is situated at a fall of 60 metres drop in a river. The factory requires a source of energy with a capacity of 300 kW. All during the year, the river flow on an average in any one year is 8 m^3/sec for 2 months, 3 m^3/sec for 2 months, 2 m^3/sec for 1 month, 1.2 m^3/sec for 8 months,

(*a*) If the site is developed as a run-off river power plant without storage, what capacity must be provided in a stand-by plant ? Take the hydraulic plant efficiency as 80%.

(*b*) If the reservoir is built upstream, would a stand-by plant be necessary ?

3.13. A 10 MW run-off-river hydro-electric plant operates on an available head of 60 metres and has overall efficiency of 90% at all loads. For a day during low water season, the customers receiving primary power have the following loads.

8 MW for 2 hours, 6 MW for 2 hours, 4 MW for 10 hours, 2 MW for 10 hours.

For a river flow remaining constant at 15 m^3/sec, how much secondary power (energy) could this plant deliver during entire day ?

3.14. The average monthly run-off data of two rivers *A* and *B* for twelve months is tabulated as given below. The run-off is given in millions of cu. m. per month.

Month	*J*	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*
Run-off (river *A*)	8	5	10	3	2	20	30	40	35	20	10	10
Run-off (river *B*)	10	5	5	10	5	50	80	100	20	20	15	15

The head available for river *A* is 20 metres and for river *B* is 18.5 metres.

Using the above data, find :

(*a*) Which river is more suitable for storage type hydro-electric power plant ? Assume the overall efficiency in both cases is same.

(*b*) If the quantity of water available must be assured for 90% of the time of the year, which river is more suitable for run-off-river plant ?

(*c*) Which plant gives more power if both the rivers are used as run-off-plants for 70% period of the year.

(*d*) At what percentage of the time, the run-off rate of both rivers is same ?

3.15. The run-off data of two rivers is tabulated below for 12 months. The run-off is given in millions of cu. m. per month.

Month	*J*	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*
River (*A*)	15	15	30	40	70	60	80	100	80	30	20	20
River (*B*)	10	10	5	5	2	100	120	120	100	50	40	20

Using the above data, find :

(*a*) The ratio of run-off of river *A* and *B* if the constant run-off is required for 50% time of the year.

(*b*) Which river is more suitable for run-off river plant if the constant run-off is required for 70% of the time of the year and why ?

(*c*) Which river is more perferable for storage type plant and why ?

(*d*) What is the percentage time when the run-off rate of both rivers is same ?

3.16. The nature of the load required for 24 hours for an industrial town tabulated below.

Time	6 A.M. 8 A.M.	8 A.M. 10 A.M.	10 A.M. 12 P.M.	12 P.M. 5 P.M.	5 P.M. 8 P.M.	8 P.M. 11 P.M.	11 P.M. 6 A.M.
Load in MW	120	160	200	120	240	140	100

Find out (*a*) the total input to the thermal plant if the load is supplied by single thermal plant only. Use the following data :

Load in Percentage	100	80	60	40	20
Thermal Efficiency	35	30	26	20	16

(*b*) If the above load is taken by combined thermal and pump storage plant, then find the saving in input to the thermal plant.

The energy of thermal plant during off-peak period is used for pump storage plant and the energy during peak period is supplied by pump-storage plant.

Take the overall efficiency of pump storage plant as 80%.

(*c*) Also find the number of hours available for pumping.

□□□