Department of Hydraulic and Water Resources Engineering

KOIT, Wollo University

Lecture Notes

Chapter 2: Reading and Summarizing Assignment

Course Code: ***WRIE3154***
Course Title: ***Basics of Hydropower Engineering***
Target Group: ***G3_WRIE***
2020

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Reading and Summary Assignment

Write a summery note about this lecture Note. Your assignment should be approximately 1-2 pages.

- The first page should summarize the lecture note.
- The second page should write what you understand of the lecture note (including chapter 1 and this reading lecture note) .

Successful assignments will be typed and double-spaced, with one-inch margins and 12 point font. The assignment will count toward your final “Section Assignments Grade”.

Definition:

- Hydropower engineering refers to the technology involved in converting the pressure energy and kinetic energy of water into more easily used electrical energy.
- The prime mover in the case of hydropower is a water wheel or hydraulic turbine which transforms the energy of the water into mechanical energy.
- Sources of water power?

History of Water Power

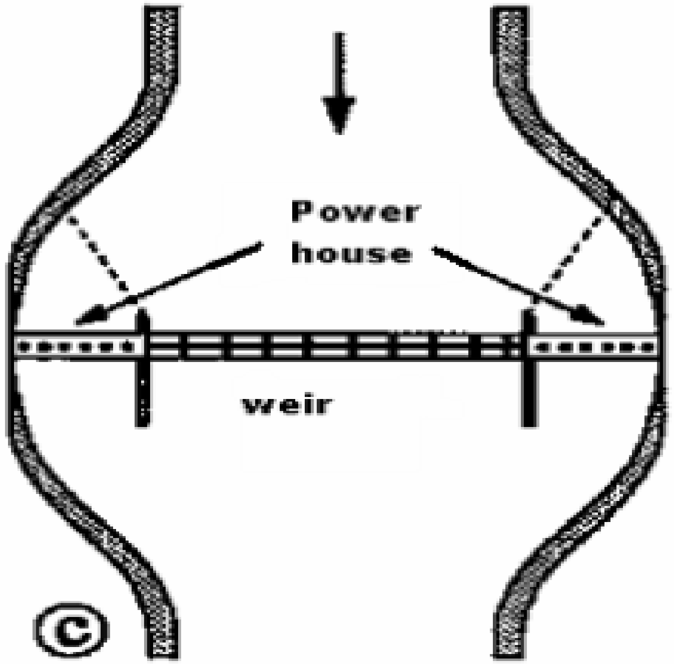
- Greek poet Antipater (400 B.C.) refers to energy of falling water
- ~200 B.C., Egyptians were grinding grain with horizontal water mills
- Technology from the Persians (Iran/Iraq), who may have gotten it from China
- By the First Century, the wheels were turned to operate vertically (horizontal axis) at much better efficiency
- About 1800, water mills were common in Europe
- In 1820s, Benoit Furneyron invented the turbine
- First electric power of 12 kW on Fox River, Appleton Wisconsin, 1882

1.1 Types of developments

- **In studying the subject of hydropower engineering, it is important to understand the different types of development. The following classification system are commonly used:**
  - **Operational feature**
  - **Basis of operation**
  - **Purpose of development**
  - **Uses to meet the demand for electrical power**
  - **Hydraulic feature**
  - **Plant capacity**
  - **Operational head**

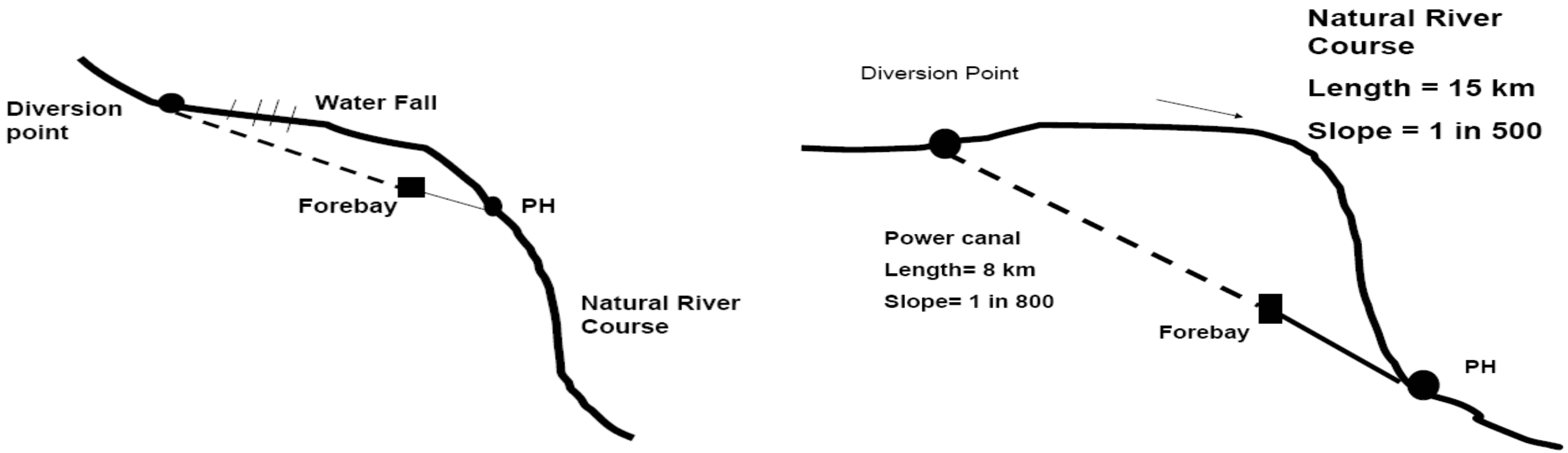
Operational feature

- **Run-of-river developments:**
  - The normal flow of the river is not disturbed
  - There is no significant storage
  - A weir or barrage is built across a river and the low head created is used to generate power
  - Power house is in the main course of river
  - Preferred in perennial rivers with moderate to high discharge, flat slope, little sediment and stable reach of a river.



Operational feature

- **Diversion and canal developments:**
  - **Power canal or tunnel diverts** water from main stream channel
  - **Powerhouse** is provided **at suitable location along the stretch** of canal or tunnel
  - Water from power house is **returned to main stream by tailrace channel**
  - **Short term pondage/storaged** requirement is met through **a pool called fore bay** in the case of diversion canals and by means of a surge tank in case of diversion tunnel

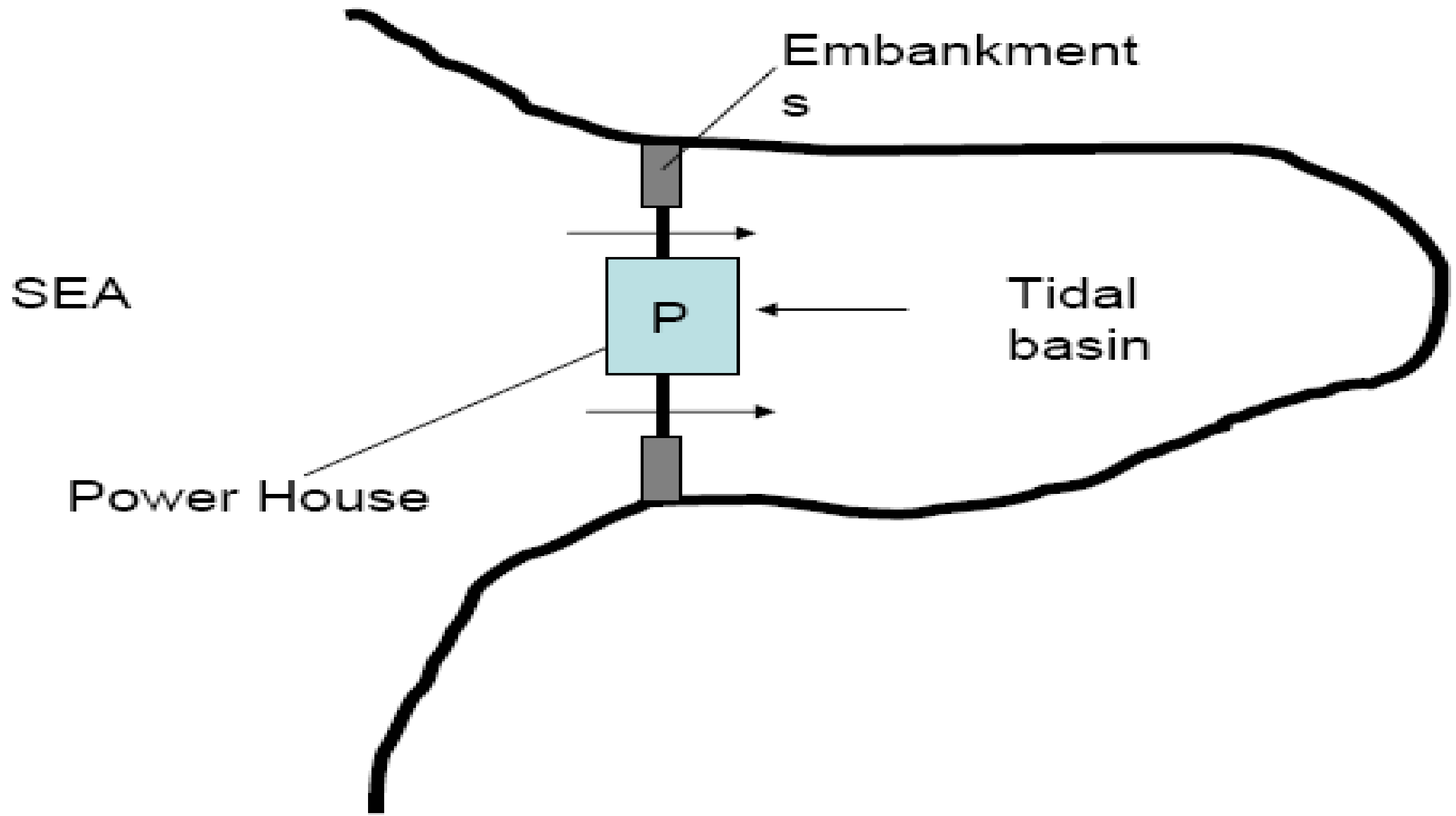


Operational feature

- **Storage regulation developments:** An extensive impoundment at the power plant or at reservoirs upstream of the power plant permits changing the flow of the river by storing water during high-flow periods to augment the water available during the low-flow periods, thus supplying the demand for energy in a more efficient manner.
- **Valley Dam Types of Hydropower Plants are storage** regulation development type that have their powerhouse **immediately at the toe of the dam.** The head difference between the reservoir water surface and the tail water level is characterized by its variability depending on the reservoir's storage conditions.

Operational feature

- **Tidal power developments:** In some estuaries, tidal power can be economically harnessed to develop electric energy.



Basis of operation/Purpose

- **Basis of Operation:**
  - **Off-grid** (isolated) plant operating independently
  - **In a grid system:** Plant operating as part of the interconnected grid system. In this system, a particular power plant may serve as a base load plant or as a peak load plant. Hydropower plants are best suited as peak load plants, because hydropower plants can start relatively quickly and can thus accept load quickly.
- **Purpose**
  - **Single-purpose developments:** The water is used only for the purpose of producing electricity.
  - **Multipurpose developments:** Hydropower production is just one of many purposes for which the water resources are used. Other uses might include, for example, irrigation, flood control, navigation, municipal, and industrial water supply.

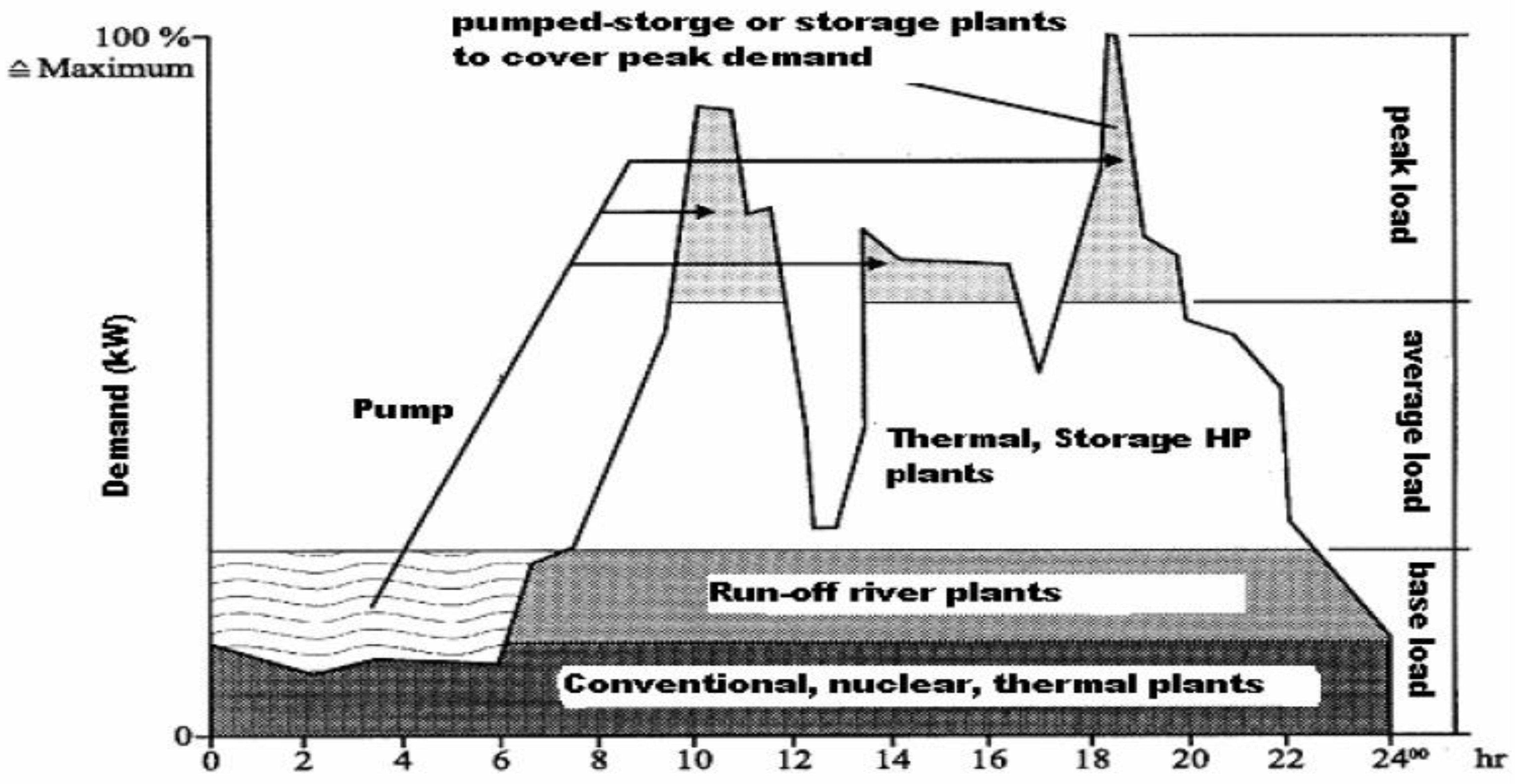
Hydraulic feature

- Conventional Hydro-plants
  - Use normally available hydraulic energy of the flow of river
  - Run-off-river plant, diversion plant, storage plant
- Pumped-storage plants
  - Use the concept of recycling the same water
  - Normally used in areas with shortage of water
  - It has a function of indirect energy storage
- Unconventional Hydro-plants
  - Tidal power plant (Use the tidal energy of seawater)
- Depression power plants
  - Energy generated by diverting water into a low lying depression
  - Tailwater to be absorbed by evaporation

Basis of uses

Uses to meet the demand for electrical power:

- **Base-load developments:** When the energy from a hydropower plant is used to meet all or part of the sustained and essentially constant portion of the electrical load or firm power requirements, it is called a base-load plant. Energy available essentially at all times is referred to as firm power.
- **Peak-load development:** Peak demands for electric power occur daily, weekly, and seasonally. Plants in which the electrical production capacity is relatively high and the volume of water discharged through the units can be changed readily are used to meet peak demands. Storage of the water supply is necessary.



pumped-storge or storage plants
to cover peak demand
100 %
≙ Maximum
Demand (kW)
peak load
average load
base load
Pump
Thermal, Storage HP
plants
Run-off river plants
Conventional, nuclear, thermal plants
0
0
2
4
6
8
10
12
14
16
18
20
22
24⁰⁰
hr

Plant capacity and head

- **Plant capacity: Usually this type of classification is arbitrary: for example:**
  - Micro hydro < 100 kW
  - Mini hydro < 1000 kW
  - Small to Medium < 60 MW
  - Large Hydro > 60 MW
- **Classification based on head too arbitrary:**
  - Low head plants < 15 m
  - Medium head plants 15 – 50 m
  - High head plants 50-250 m
  - Very high head plants > 250 m

Contents

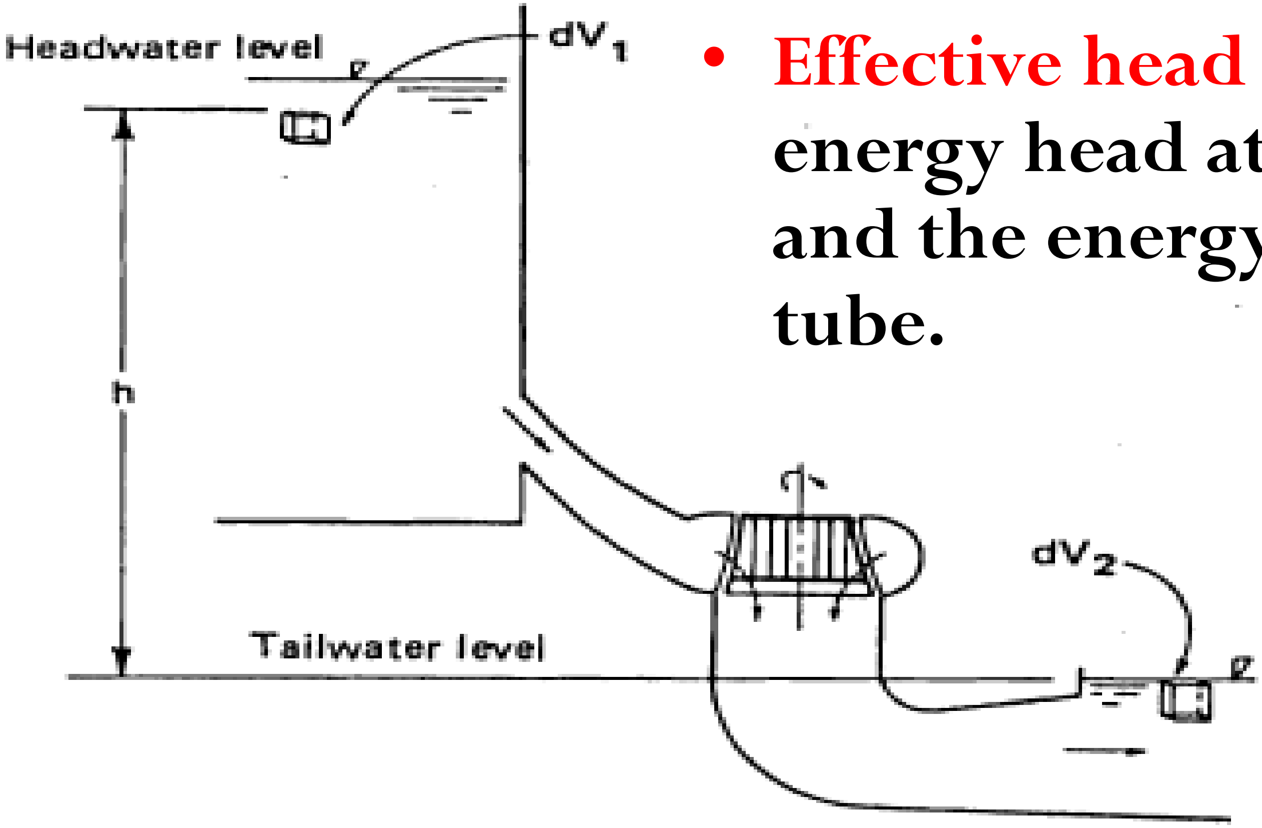
1. **Hydraulic Theory**
2. **Hydrologic analysis for hydropower**
3. **Flow Duration Analysis**
4. **Other Hydrologic Considerations**

2.1 Hydraulic theory

- **Energy-work approach:**
  - Work (W) = Force x Distance in the direction of force
  - Work = weight of water x the distance it falls

$$W = \rho_w V_w g h$$

- Where: ρ_w is density of water; g- acceleration due to gravity; V_w- volume of water falling; *h*- the vertical distance the water falls.
- It is conventional in hydropower computations to treat *h* as the effective head that is utilized in producing power.



- **Effective head (h)** is the difference between energy head at the entrance to the turbine and the energy head at the exit of the draft tube.

- The *h* has been purposely designated as slightly below the headwater or fore-bay level. Hence, in the Figure, the losses of head in the water moving through the penstock to the entrance of the turbine have been accounted for in positioning the elemental cube.

- **Power (P) = Work / time**

$$P = \frac{W}{t} = \frac{\rho_w V_w g h}{t} = \rho_w Q g h$$

$$Note\ Q = \frac{V_w}{t}$$

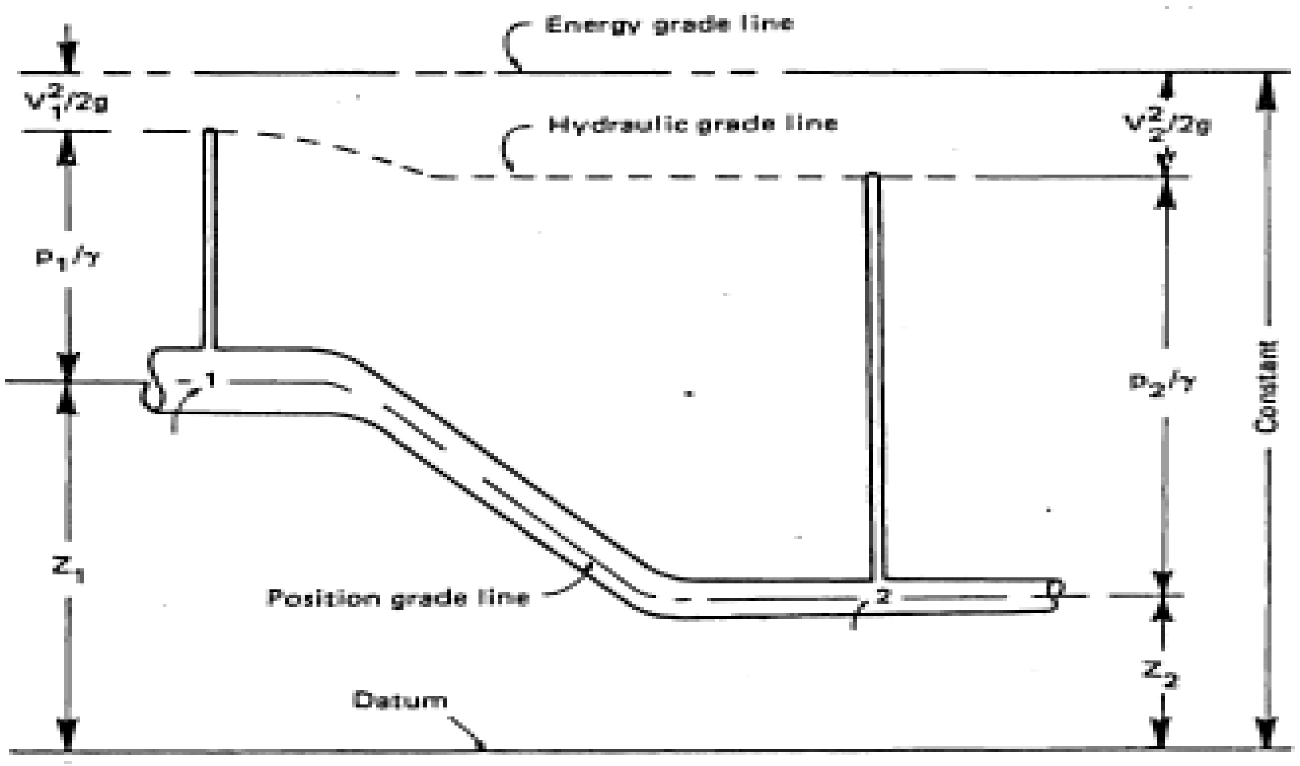
- Where **Q is discharge**.
- **P is in watt.** To compare kilowatts and horsepower remember that:

$$P_{kw} = 0.746 P_{hp}$$

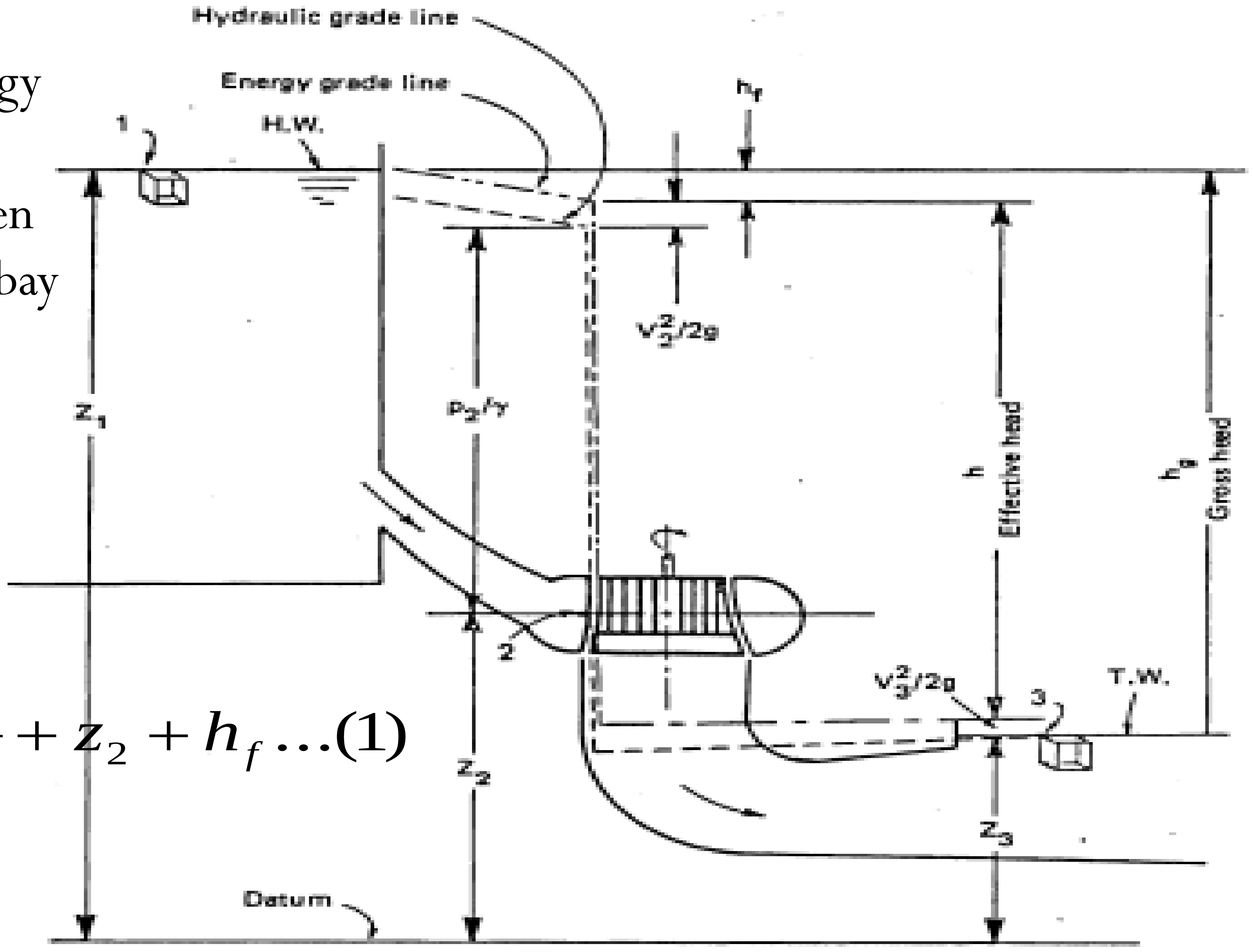
- **Energy Equation Approach**
- Mathematical development in terms of energy grade lines and hydraulic grade lines, using the Energy Equation.

$$\frac{v_1^2}{2g} + \frac{p_1}{\gamma} + z_1 = \frac{v_2^2}{2g} + \frac{p_2}{\gamma} + z_2 + h_f = Cons.$$

- where V_1 = *water velocity at point 1*
- p_1 = pressure at point 1
- $\gamma = \rho g$ = *specific weight of water*
- Z_1 = *potential head at point 1 referenced to the datum*
- V_2 =*water velocity at point 2*
- p_2 =*pressure at point 2*
- Z_2 =*potential head at point 2*
- h_f = *head loss in flow passage between points 1 and 2*



- Referring to the Figure, the Energy equation for a hydropower installation is first written between point 1 at the surface of the fore-bay and point 2 at the entrance to the turbine as



$$\frac{v_1^2}{2g}+\frac{p_1}{\gamma}+z_1=\frac{v_2^2}{2g}+\frac{p_2}{\gamma}+z_2+h_f \ldots(1)$$

- Then the **Energy equation** is written between points 2 and 3, the surface of the water at the exit to the draft tube:

$$\frac{v_2^2}{2g}+\frac{p_2}{\gamma}+z_2=\frac{v_3^2}{2g}+\frac{p_3}{\gamma}+z_3+h\ldots(2)$$

  - Where h is effective head on the turbine

- Recognizing that for practical purposes V_1, p_1, *and* p_3 *are equal to zero, then solving* for p_2/γ *in Eq. 1, the result is:*

$$\frac{p_2}{\gamma}=z_1-\frac{v_2^2}{2g}-z_2-h_f\ldots(3)$$

$$h=\frac{v_2^2}{2g}+\frac{p_2}{\gamma}+z_2-\frac{v_3^2}{2g}-z_3=\frac{v_2^2}{2g}+\left(z_1-\frac{v_2^2}{2g}-z_2-h_f\right)+z_2-\frac{v_3^2}{2g}-z_3$$

$$h=z_1-z_3-h_f-\frac{v_3^2}{2g}\ldots(4)$$

- Because the Energy equation defines terms in units of Kilogram –meter per Kilogram of water flowing through the system, it should be recognized that the **Weight of water** flowing through the turbine per unit of time by definition is $\rho g Q$.
- Now recognizing that energy per unit of time is power, it is simple to calculate by multiplying Eq. (4) and $\rho g Q$ *or* γQ *to obtain the theoretical power delivered by the water to* the turbine as $\gamma Q h$ which is the theoretical power

2.2 Hydrology of hydropower

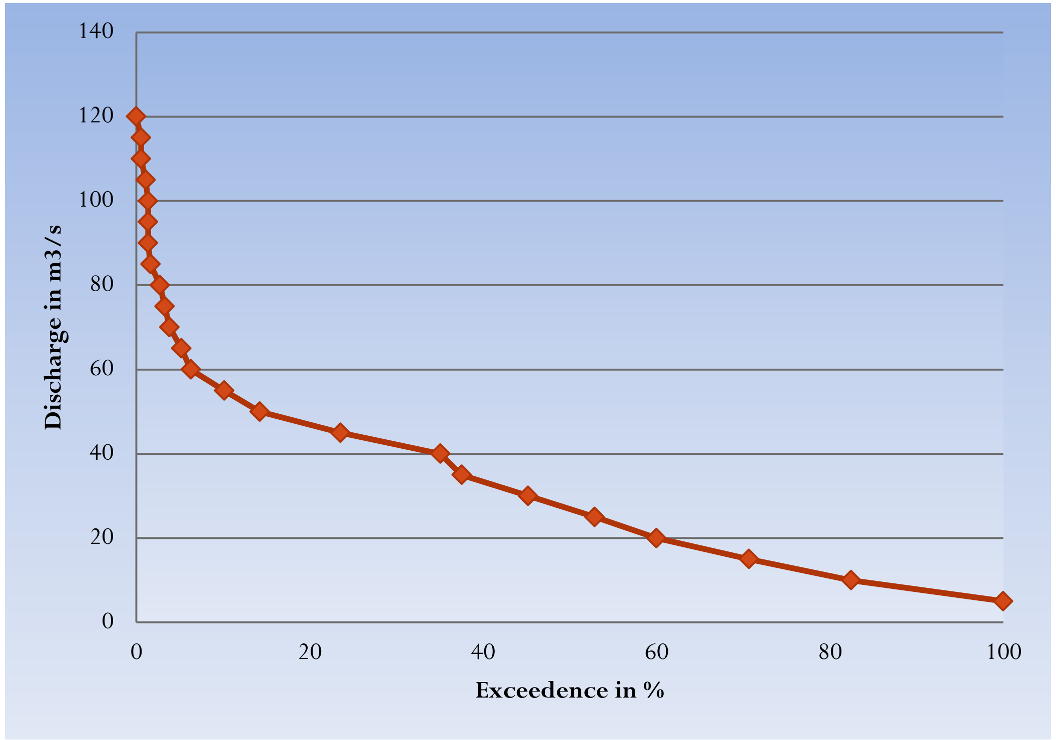
- **Hydrology** is the study of the occurrence, movement and distribution of water on, above, and within the earth's surface.
- **Parameters necessary in making hydropower** studies are **water discharge (Q)** and hydraulic **head (h)**. The measurement and analyses of these parameters are primarily hydrologic problems.
- Determination of the **head for a proposed** hydropower plant is a **surveying problem** that identifies **elevations of water** surfaces as they are expected to exist during operation of the hydropower plant.

2.2 ctd.

- In some reconnaissance studies, **good contour maps** may be sufficient to determine the value for the hydraulic head.
- Because the **headwater elevation and tail-water elevations** of the impoundment can vary **with stream flow,** it is frequently necessary to develop headwater and tail-water curves that show variation with time, river discharge, or operational features of the hydropower project.

2.3 Flow duration analysis

- **Flow Duration Curves:** is a plot of flow versus the percent of time a particular flow can be expected to be equaled or exceeded.
- A flow duration curve merely reorders the flows in order of magnitude instead of the true time ordering of flows in a flow versus time plot.



Flow…

- **Flow duration curve, very often, plotted using the average monthly values of the flow.**
- **The capacity estimate for firm power is then made by using the entire recorded flow data and plotting in a single flow duration curve.**
- **In such a case two different methods are in use.**

  (i) the *total period /rank ordered method*, and

  (ii) the *calendar year/ Class - interval* method.
- **Both methods utilize the flow data available for the entire period for which records are available.**

Flow…

- *Total period method/Rank ordered Method:*
- **Considers a total time series of flows that represent equal increments of time for each measurement value, such as mean daily, weekly, or monthly flows, and ranks the flows according to magnitude.**
- **The entire available record is used for drawing the FDC. Thus, ten years' record would produce 120 values of monthly average flows.**
- **These are first tabulated in the ascending order starting from the driest month in the entire period and ending with the wettest month of the ten-year duration.**

Flow…

- The rank-ordered values are assigned individual order numbers, the smallest beginning with order 1. The order numbers are then divided by the total number in the record and multiplied by 100 to obtain the percent of time that the mean flow has been equaled or exceeded during the period of record being considered.
- The flow value is then plotted versus the respective computed equaled or exceeded percentage.
- For the 10 year example the FDC would then be drawn with the help of 120 values.

Flow…

- *Calendar year method/Class Interval Method*: each year's/interval average monthly/interval values are first arranged in ascending order.
  - Then the average flow values corresponding to the driest year, second driest year, and so on up to the wettest month are found out by taking arithmetic mean of all values of the same rank. These average values are then used for plotting flow duration curve.
  - Such a curve for example would have only ten points for the ten year example.
  - The class-interval technique: is slightly different in that the time series of flow values are categorized into class intervals. The classes range from the highest flow value to the lowest value in the time series.

Flow…

   - **A tally is made of the number of flows in each, and by summation the number of values greater than a given upper limit of the class can be determined.**
   - **The number of flows greater than the upper limit of a class interval can be divided by the total number of flow values in the data series to obtain the equaled or exceeded percentage.**
   - **The value of the flow for the particular upper limit of the class interval is then plotted versus the computed equaled or exceeded percent.**
- ***The total period/rank ordered method gives more correct results than the calendar year method which averages out extreme events.***
- **Naturally, the longer the record, the more statistically valuable the information that results.**

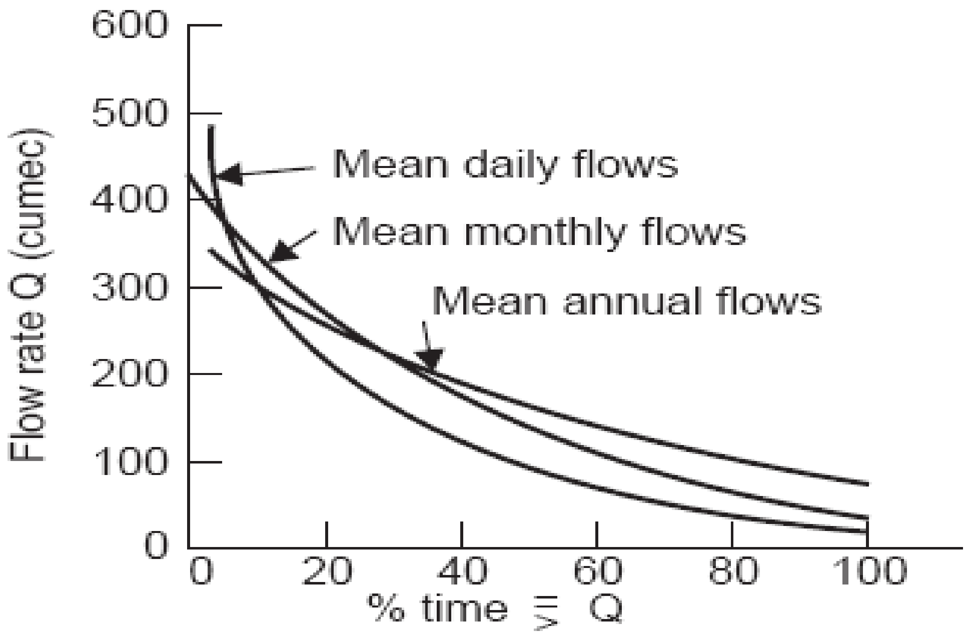
Characteristics of Flow Duration Curves

- **The flow duration curve (FDC) shows how flow is distributed over a period (usually a year).**
- **A steep flow duration curve implies a *flashy catchment* – one which is *subject to extreme floods and droughts*.**
- **Factors which cause a catchment to be flashy are:**
  - **Rocky, shallow soil,**
  - **Lack of vegetation cover,**
  - **Steep, short streams,**
  - **Uneven rainfall (frequent storms, long dry periods).**

Flow…

- **Such type of FDC (i.e. steep) is not suitable for hydropower development (especially run-of-river type).**
- **A flat flow duration curve is good because it means that the total annual flow will be spread more evenly over the year, giving a useful flow for longer periods, and less severe floods.**

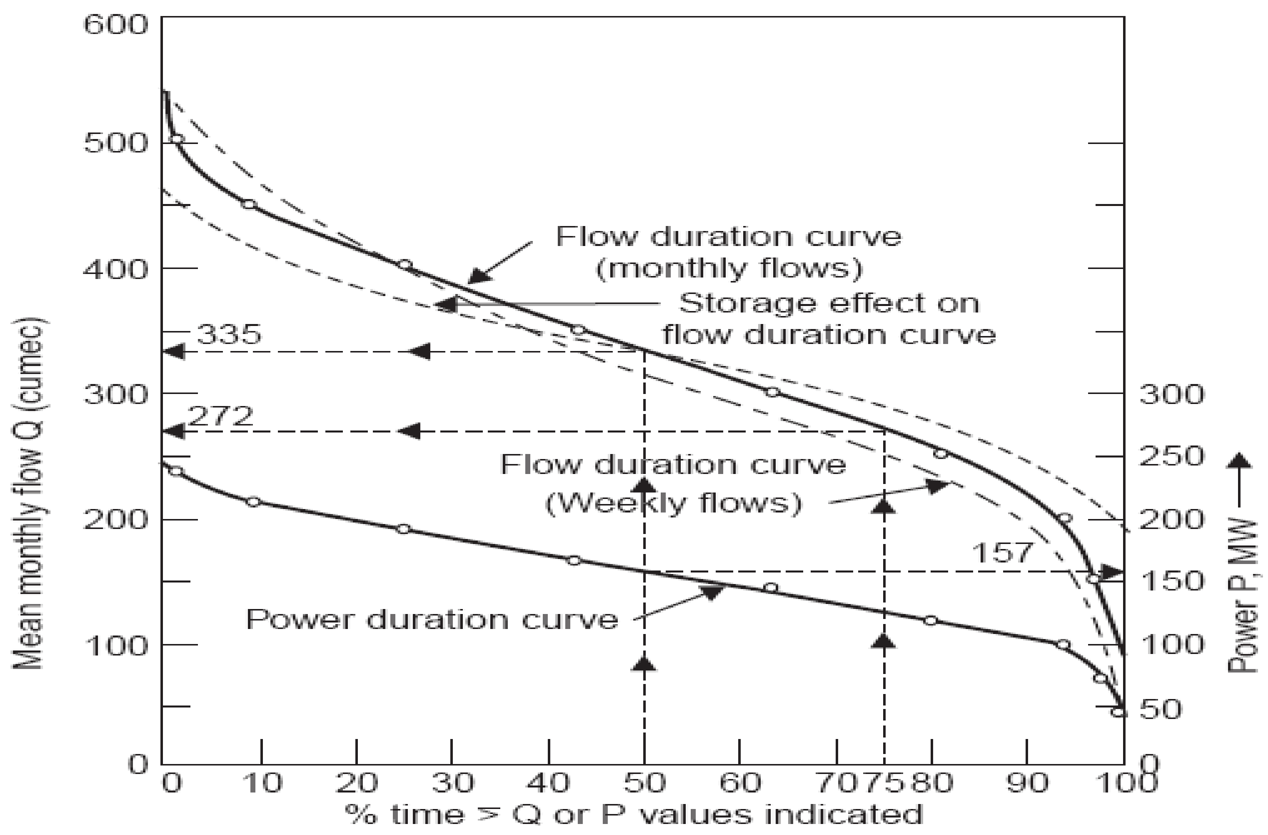
- The selection of the time interval for FDC depends on the purpose of the study.
- As the time interval increases the range of the curve decreases.
- While daily flow rates of small storms are useful for the pondage studies in a run-off river power development plant, monthly flow rates for a number of years are useful in power development plants from a large storage reservoir



•The flow duration curve is actually a river discharge frequency curve and the longer the period of record, the more accurate is the indication of the long term yield of a stream

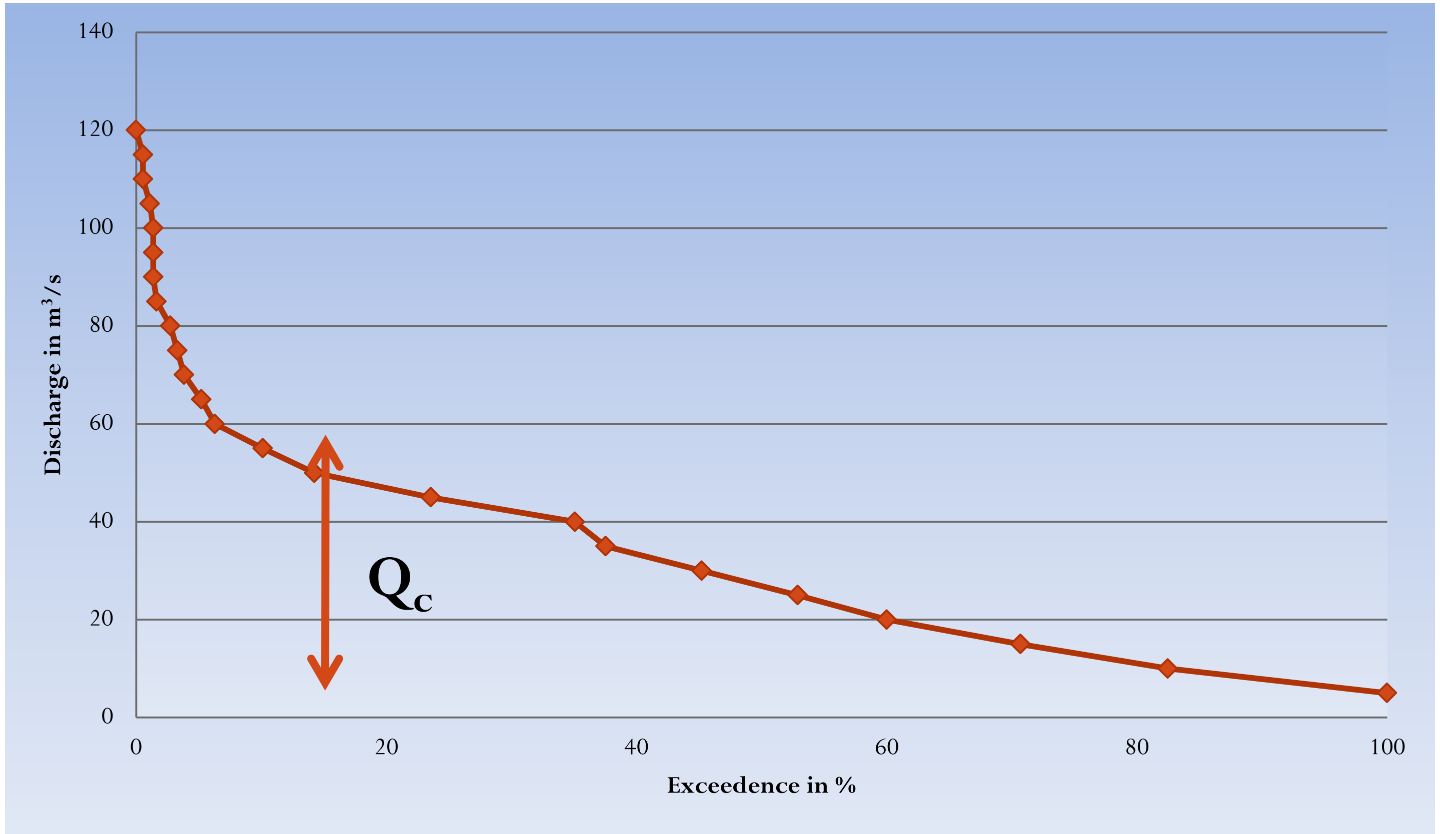
- Since the area under the curve represents the volume of flow, the storage will affect the flow duration curve as shown

by the dashed line in the Fig.; *i.e.*, reducing the extreme flows and increasing the very low flows.



Discharge capacity of a plant

- **Discharge capacity (Q_c) of a plant is the discharge the plant can pass at its full gate opening of the runner(s) of the turbine(s) under design head.**



- A flow duration curve is used to explain discharge capacity (Q_c) as labeled in the Figure. Even though to the left of that point on the duration curve the stream discharge is greater, it is not possible to pass the higher discharges through the plant.

Extrapolation of Flow Duration Data to Un-gauged Sites

- **Method 1 (Gladwell, et al. 1978): Useful in regions where stream flow does not vary directly with the area of the contributing drainage.**
- **The procedure is to make plots of flow duration curves for all gauged streams within a drainage basin, as shown in the Fig.A.**

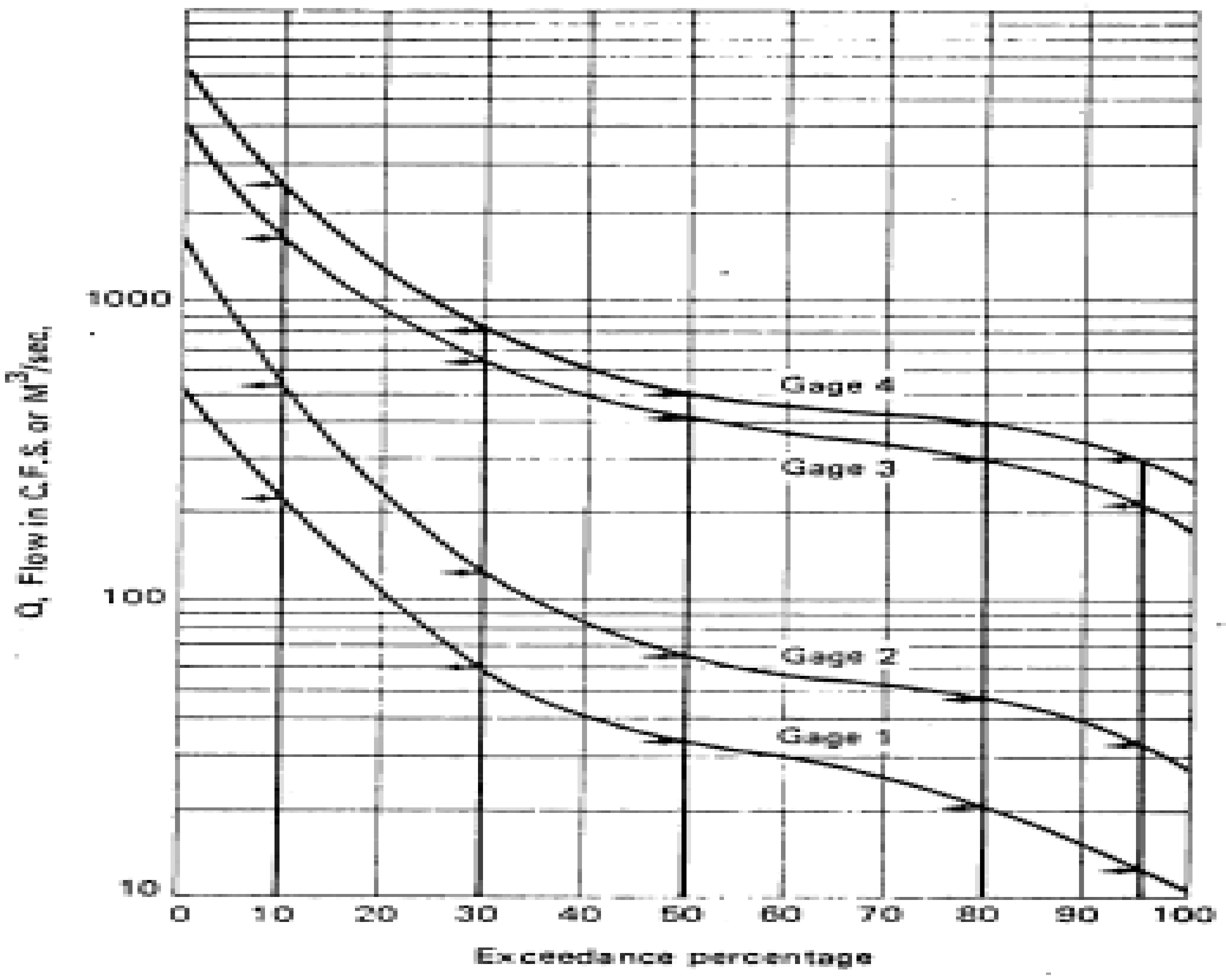


Figure A

- Develop a family of parametric duration curves in which flow (Q) is plotted against the average annual runoff (R), *at the respective gauges for several exceedance percentages. A* separate curve is developed for each exceedance interval used.
- A correlation analysis is then performed to obtain the best-fitting curve for the data taken from the measured records of stream flow. The result is a parametric flow duration curve such as the one shown in the Figure.

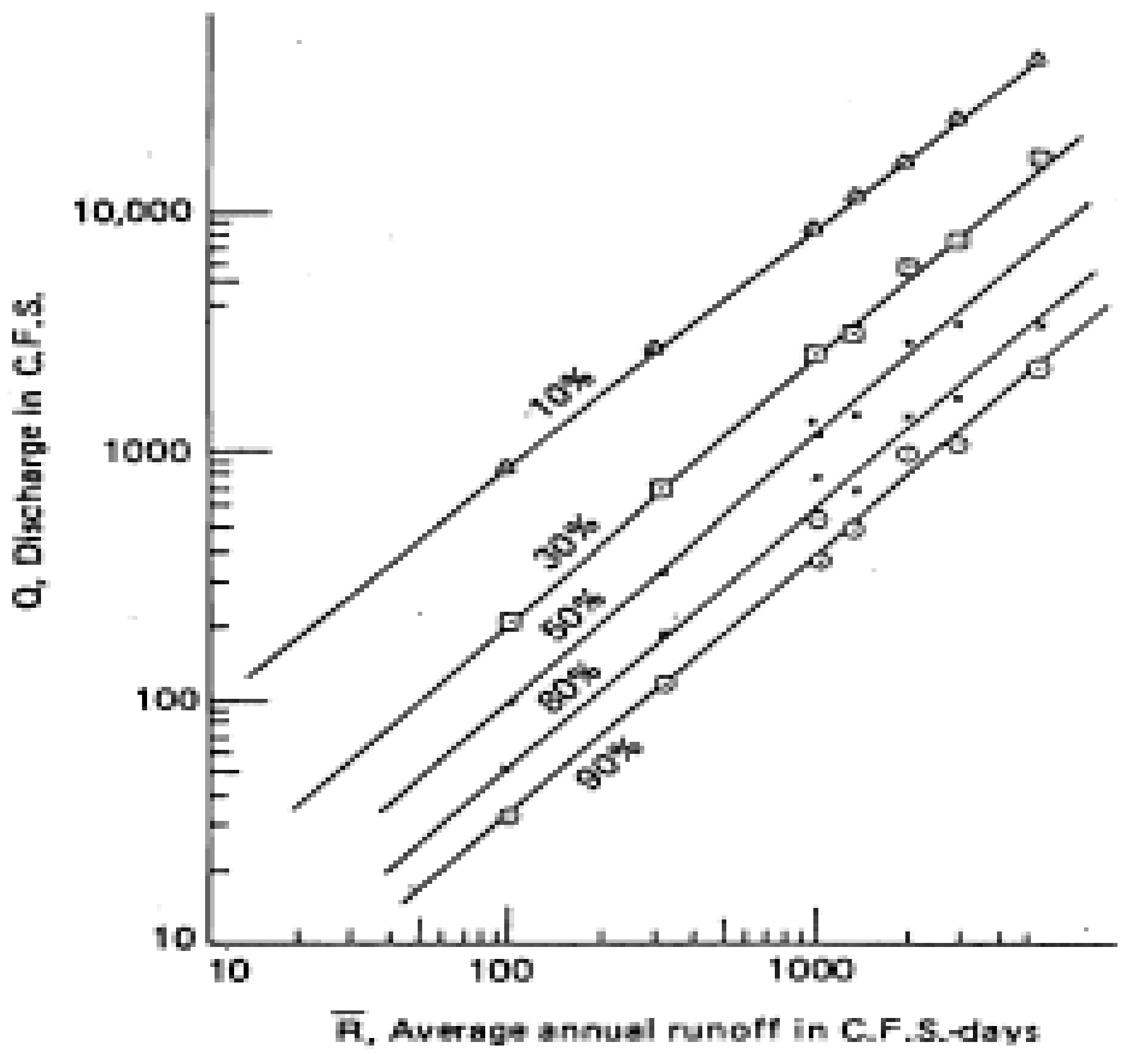
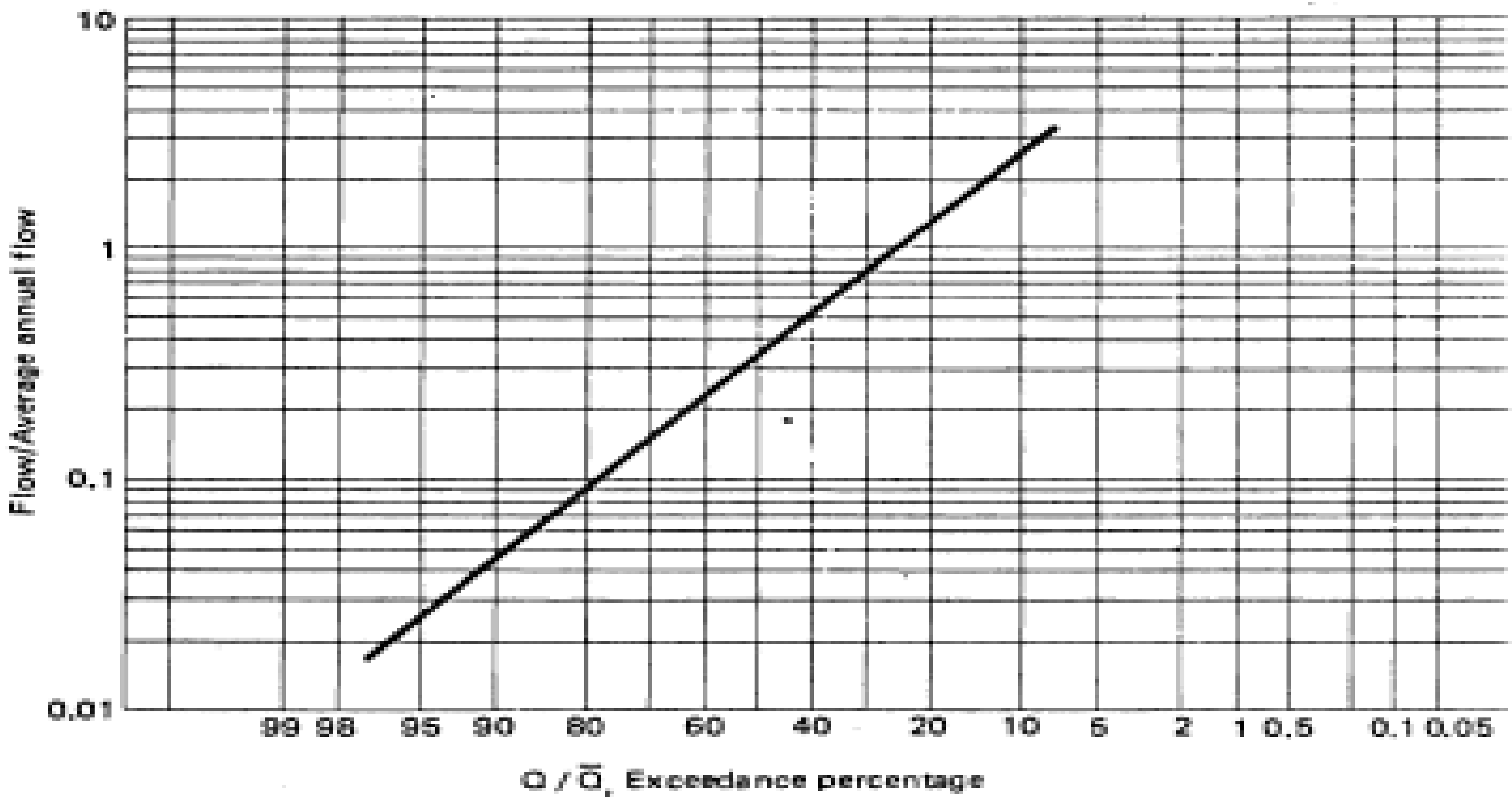


Figure B

- Method 2, (Heitz, 1978): The values of flow for each flow duration for a given exceedance point are divided by the average annual discharge, *Q*, to give a dimensionless flow term. These are then plotted against the particular exceedance interval on logarithmic probability paper as shown in the Figure (next slide) to give a dimensionless flow duration curve.
- Then a best-fitting curve is developed for a particular area having homogeneous hydrology so that a single curve results that relates a characteristic dimensionless flow term to the exceedance percentage.
- It is easy to recognize that at the limits of the curve the reliability of the curve is questionable because the number of values are minimal and these outlier values are the unusual occurrences of flash floods or extremely low flows.



10
1
0.1
0.01
Flow/Average annual flow
99 98 95 90 80 60 40 20 10 5 2 1 0.5 0.1 0.05
Q / Q̄, Exceedance percentage

Figure C

Determination of Average Annual Discharge

- To use the parametric flow duration curves effectively, it is necessary to determine the average annual discharge, *Q*, at the point or location on the stream for which a hydropower analysis is to be made.
- A procedure for making that determination follows.
  - First an accurate isohyetal map of normal annual precipitation (NAP) of the river basin involved must be obtained or developed. Isohyetal maps contain lines representing equal precipitation for a geographic region.
  - Care should be taken that the map represents the same period of record as the stream flow data for which flow duration data are available and needed.

- Then, utilizing the records of average annual precipitation input to the basins at measured streams nearby or having similar hydrologic characteristics, a runoff coefficient is estimated for the drainage basin being studied. This value can be rather subjective in determination and thus represents a place for making a considerable error.
- Much care should be exercised in estimating the annual runoff coefficient. The product of this coefficient and the computed normal annual precipitation input to the basin and the basin area can be used to calculate the average annual discharge using the formula:
  - **$Q = kPA$,**
  - Where Q is average annual discharge
  - k is annual runoff coefficient as a decimal value
  - P is weighted average annual precipitation
  - A is drainage area

- Given: A stream location on the Clearwater River in Idaho has been identified for making a hydropower analysis. The location is at a point where no stream flow record is available. A parametric flow duration curve has been developed for the streams in the river basin being studied and is shown in Fig. B. A normal-annual precipitation map showing the isohyetal lines is presented in Fig. D. The planimetering of the respective areas between isohyetal lines for the map areas of Fig. B is indicated in Table Below and an annual runoff coefficient based on the work of Emmert (1979) has been estimated to be 0.73.

Designation	P b/n Isohytal lines (in)	Planimeterd area on map (in^2)	% of total area
A	60	0.46	1.24
B	60	8.16	22.01
C	55	27.41	73.92
D	50	1.05	2.83
Total		37.08	100

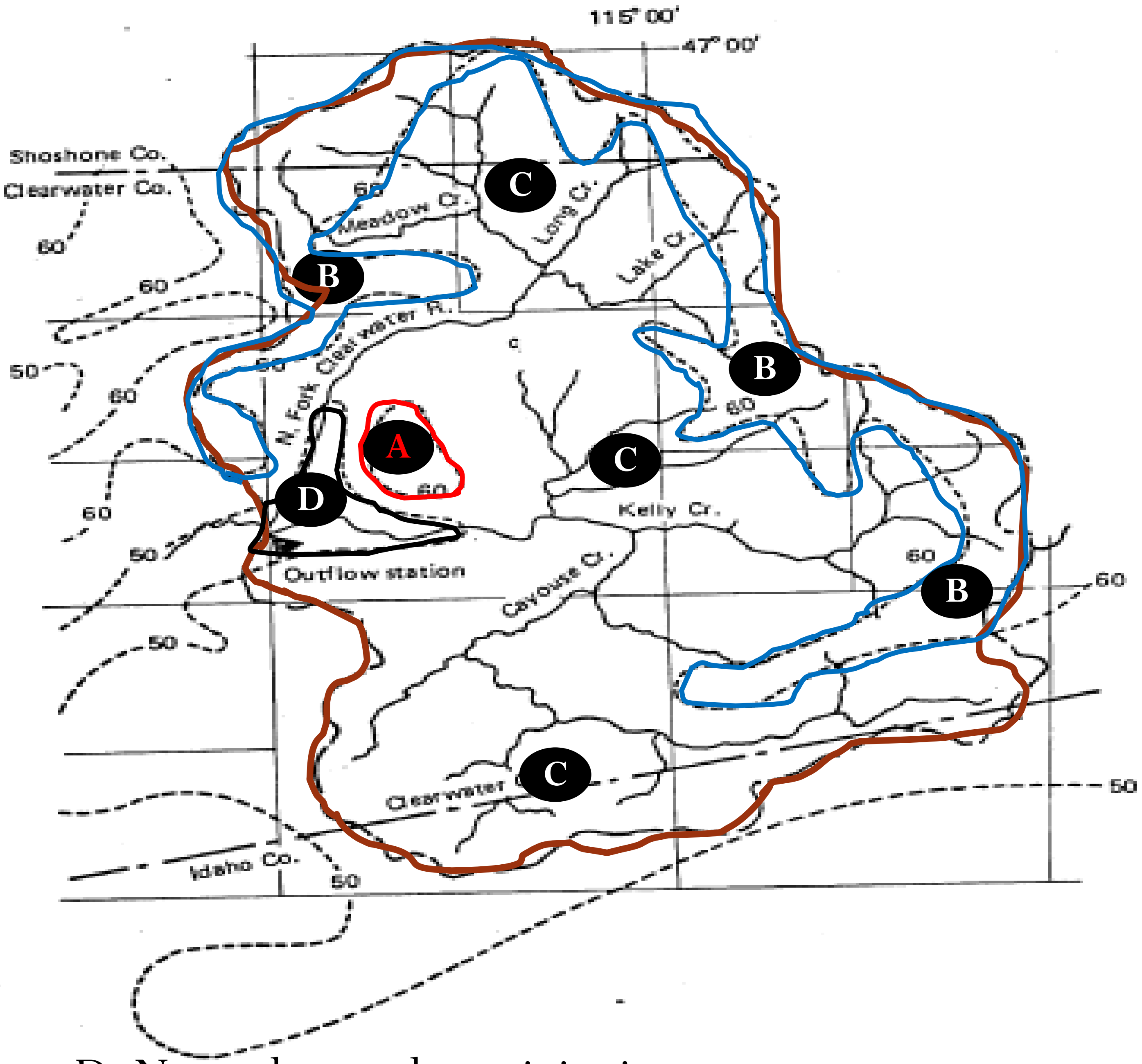


Figure D: Normal-annual-precipitation map

Required: Determine the average annual discharge at the marked location and develop ordinate values for a flow duration curve at the site designated.

- Analysis and solution: First, determine average annual precipitation input to basin using data from the above table.

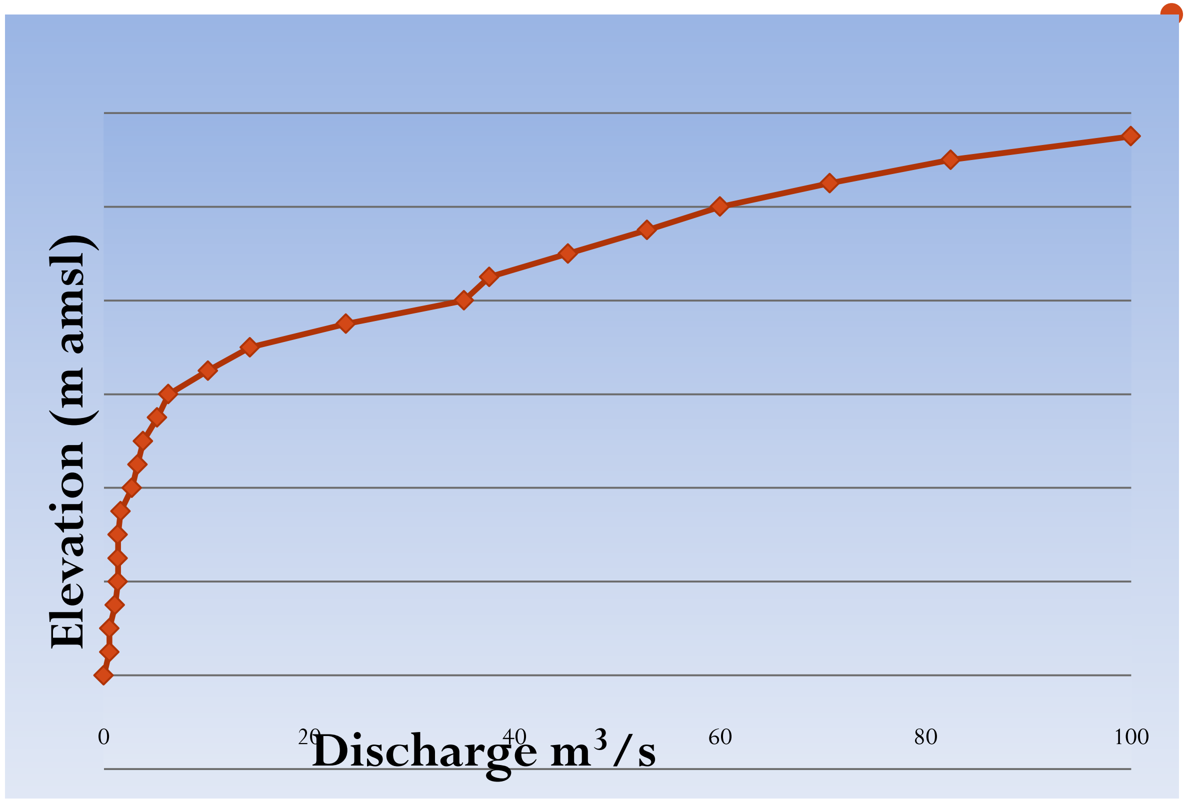
$$\overline{P} = \frac{P_A A_A + P_B A_B + P_C A_C + P_D A_D}{A_A + A_B + A_C + A_D} = 56.02in$$

- Convert this to volume units of runoff per year R. The map used had a scale of 1: 250,000, so

$$R = \frac{56.02 \times 37.08 \times 250000^2}{144 \times 12} \times 0.73 = 5.485 \times 10^{10} \frac{ft^3}{yr} = 1739 \frac{ft^3}{s}$$

- Because the parametric flow duration curve was developed on the basis of average annual runoff expressed in (ft^3/sec)(day) units, it is necessary to convert to R(ft^3/sec)(day) which is done by multiplying by 365 (the number of days in year), so: 1739 x 365 = 643.7
- Entering the parametric flow duration curve of Fig. C or using the regression equation for each specified exceedance percentage, it is possible to arrive at the following values for the ordinates of a specific flow duration curve for flow at the outflow station designated on Fig. D:
  - **Q_{95} = 240; Q_{80} = 360, Q_{50}= 690,** *Q_{30} = 1468,* **Q_{10}= 5214 ft^3/sec**

2.4 Other hydrologic considerations



- **Tail water Relationships:** As releases of water over spillways and any other releases into the stream immediately below a hydropower plant are made, the tail water elevation below the outlet to the turbines will fluctuate. Therefore, it is important to develop a tail water elevation versus river discharge curve over the complete range of flow that is to be expected.

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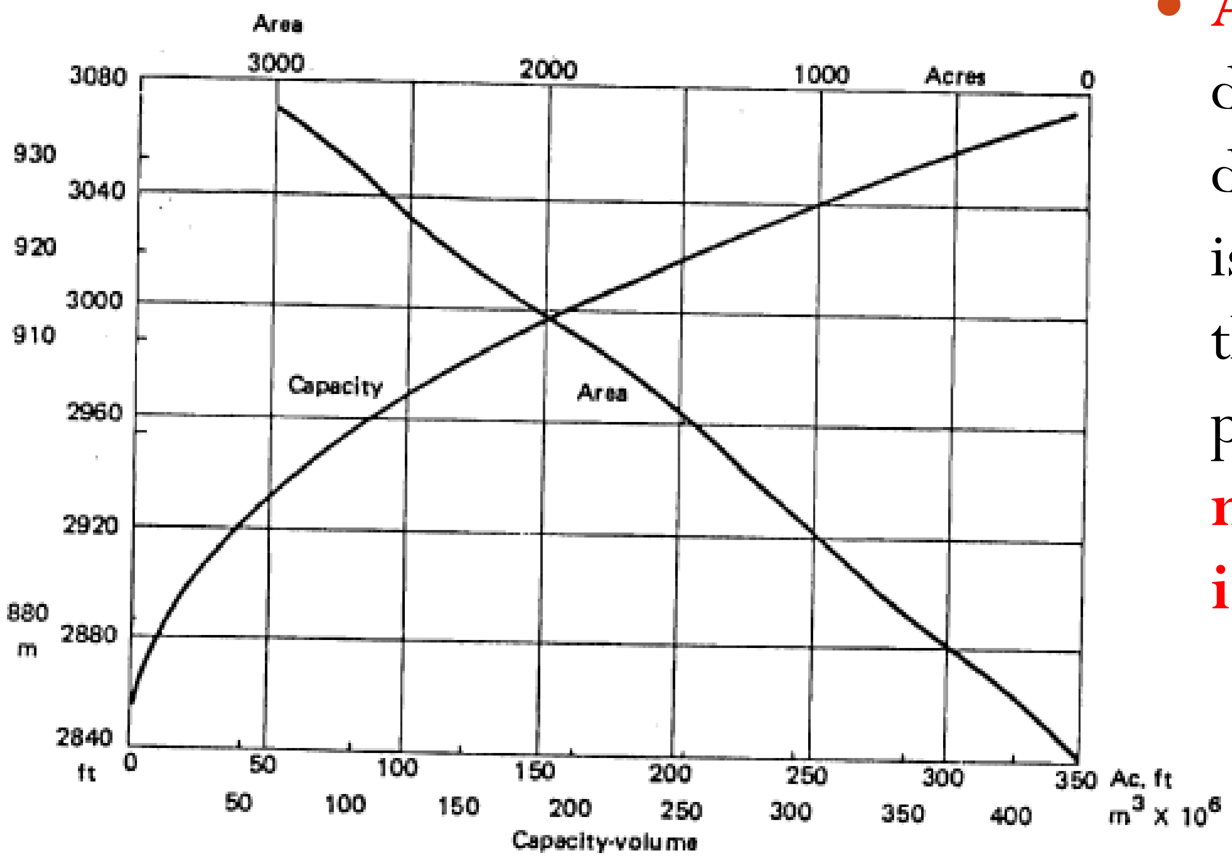
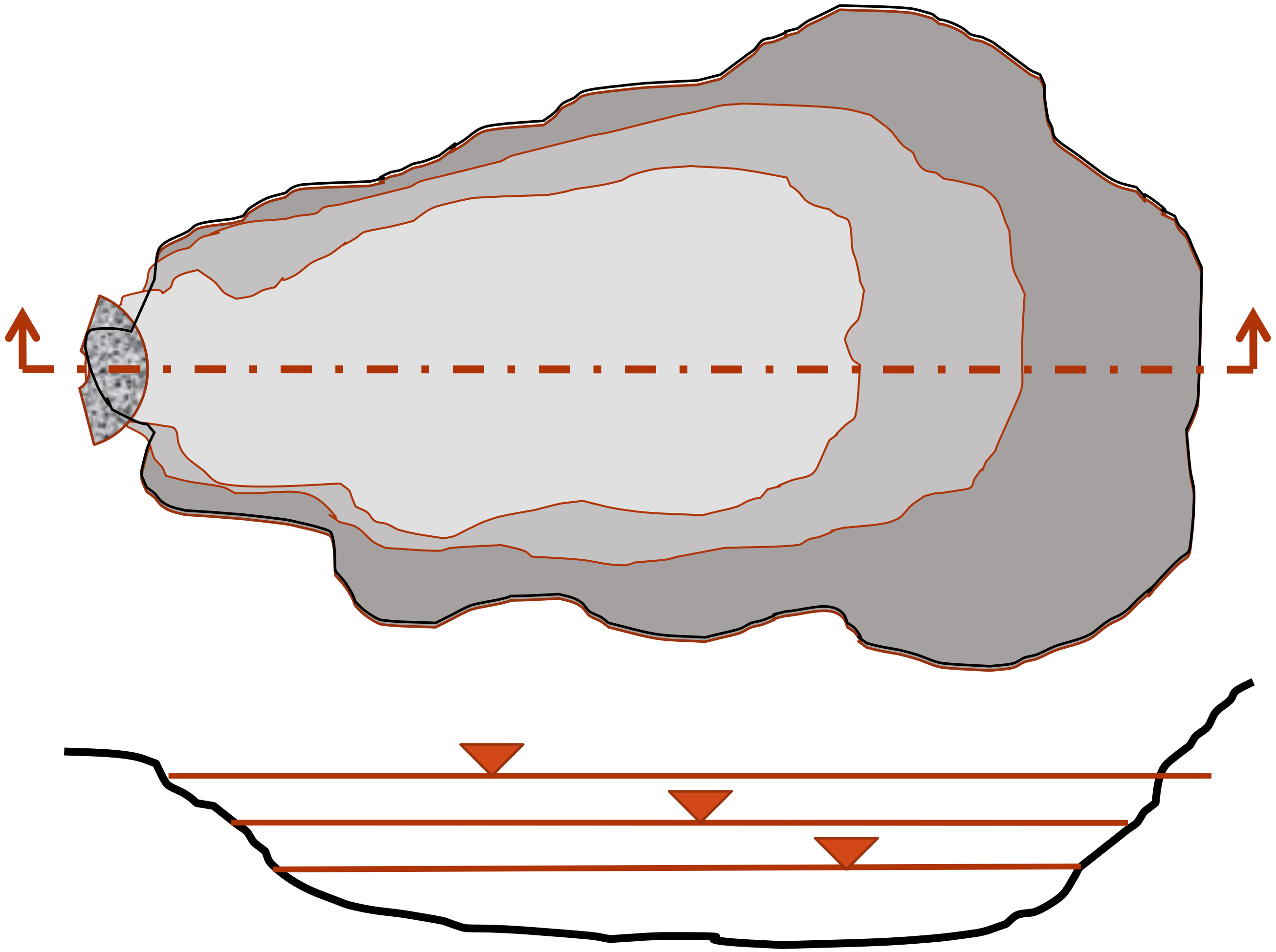


- **Area capacity curves:** Most hydropower developments involve an impoundment behind a dam. As the water in storage in the impoundment is released the headwater elevation changes and this will influence the design of the plant and the pattern of operation. **Therefore, it is necessary to have a storage volume versus impoundment surface elevation curve.**

Area-Capacity curve



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- **Reservoir Rule Curves:** When releases from reservoirs are made, the schedule of releases is often dictated by considerations other than just meeting the flow demands for power production. The needs for municipal water supply, for flood control, and for downstream use dictate certain restraints. The restraints are conventionally taken care of by developing reservoir operation rule curves that can guide operating personnel in making necessary changes in reservoir water releases.

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- **Evaporation Loss Evaluation:** Where there is an impoundment involved in a hydropower development there is need to assess the **effect of evaporation loss from the reservoir surface.**
- **Spillway Design Flood Analysis:** Many hydropower developments require a dam or a diversion that blocks the normal river flow. This then requires that provisions be made for passing flood flows. Spillway design flood analysis treats a unique type of hydrology that concerns the occurrence of rare events of extreme flooding. It is customary on larger dams and dams where failure might cause a major disaster to design the spillway to pass the probable maximum flood. For small dams, spillways are designed to pass a standard project flood.