Department of Hydraulic and Water Resources Engineering

KOIT, Wollo University

Lecture Notes

Course Code: ***WRIE3154***

Course Title: ***Basics of Hydropower Engineering***

Target Group: ***G3_WRIE***

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Chapter 2: Small Scale Hydropower

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CHAPTER 2: Small Scale Hydropower

2.1. Status of Small Hydropower

2.2. Place of Small Hydro Power in a Power System

2.3. Estimation of small hydropower potential at different locations in Ethiopia.

- 2.3.1. Flow duration curve
- 2.3.2. Firm Power
- 2.3.3. Secondary Power
- 2.3.4. Load Factor
- 2.3.5. Capacity Factor
- 2.3.6. Utilization Factor

Components of Hydropower projects

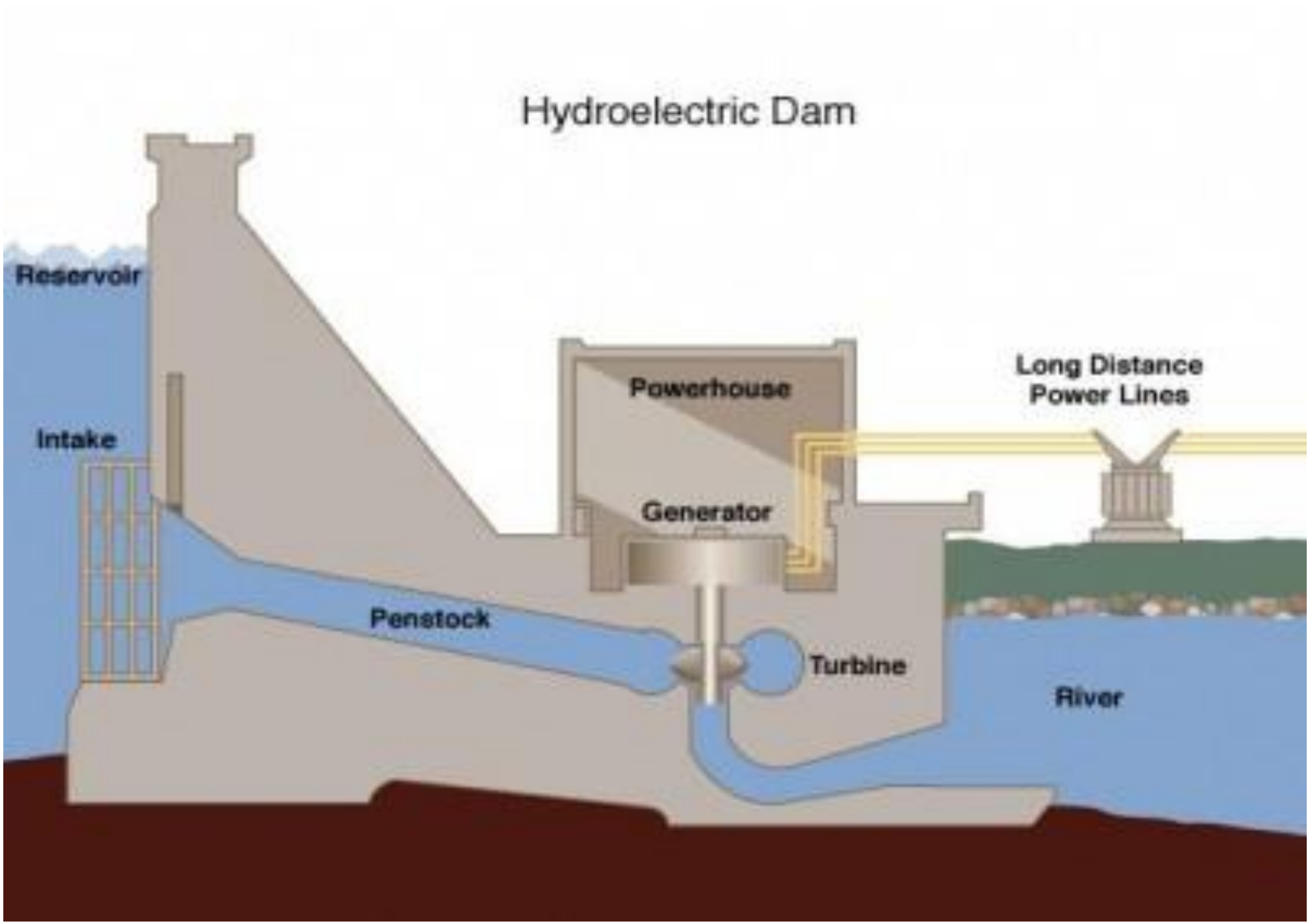
Generally three basic elements are necessary in order to generate power from water:

- a means of **creating head**,
- a conduit to **convey water**, and **a power plant**.

To provide these functions, the following components are used:

- dam,
- reservoir,
- intake conduit or penstock,
- surge tank
- power house,
- draft tube and tail race.

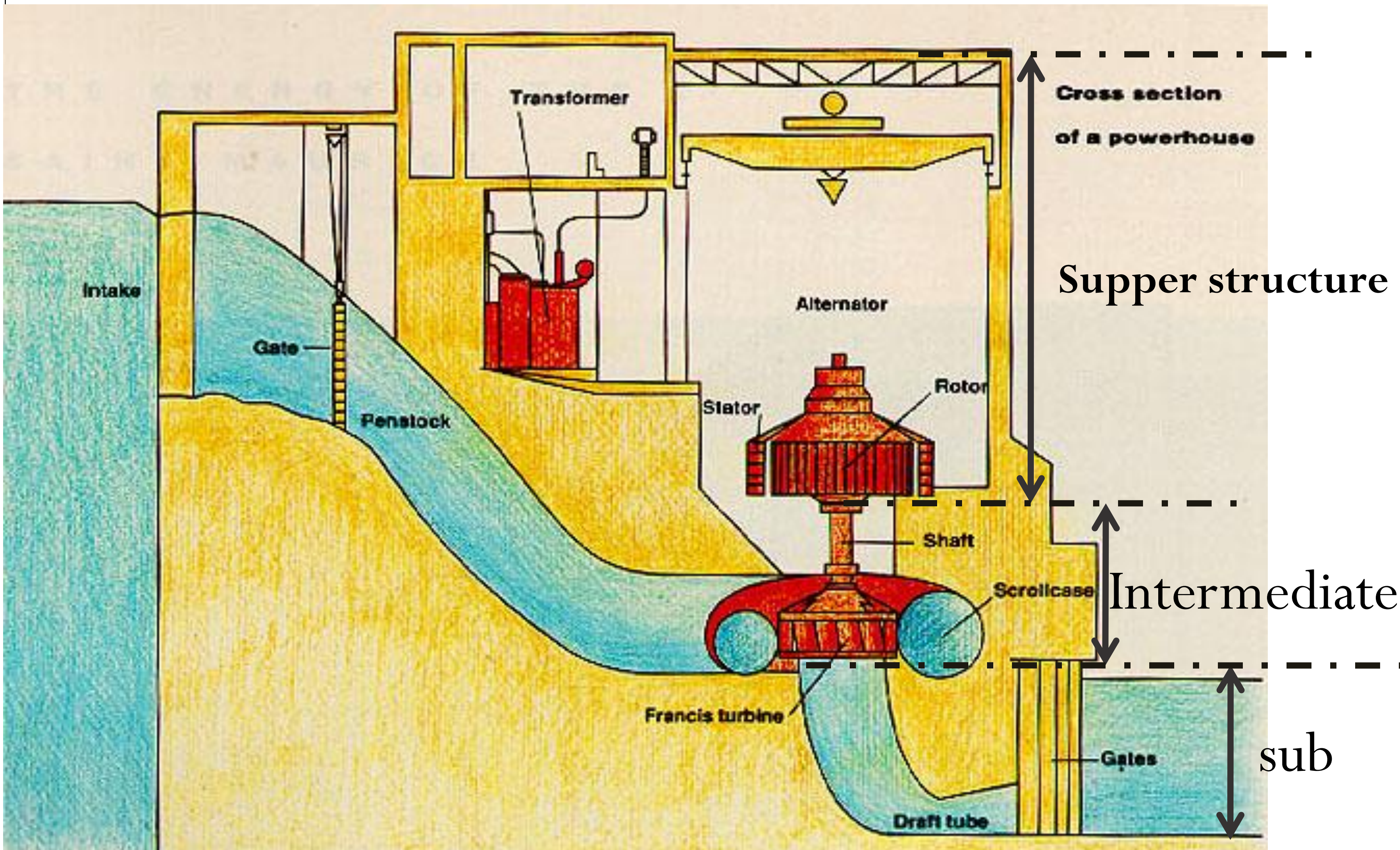
Components of a hydropower project



Power House

- **The essential equipments needed in hydro-electric power generation are housed suitably in a structural complex called Power House.**
- **The major equipments in a power house:**
  - **Turbines, Generators, Transformers, switch boards; shaft, ventilation, cranes, etc**
- **According to the location of the hydropower station, the power houses are classified as surface power house or underground power house.**
- **As the name implies, the underground power house is one which is built underground. A cavity is excavated inside earth surface where sound rock is available to house the power station.**
- **A surface power house is one which is founded on earth's surface and its superstructure rests on the foundation.**
- **The surface power house has been broadly divided into three sections which is separated from the intake :**
  - ***Substructure***
  - ***Intermediate structure***
  - ***Super-structure***

Power House


Transformer
Cross section
of a powerhouse
Intake
Gate
Penstock
Alternator
Supper structure
Stator
Rotor
Shaft
Scrollcase
Intermediate
Francis turbine
Gates
sub
Draft tube

- **The substructure** of a power-house is defined as that part which extends from the bottom of the turbine to the soil or rock. Its purpose is to house the passage for the water coming out of the turbine.
- The **intermediate structure** is part of the power house which extends from the top of the draft tube to top of the generator foundation.
    - This structure contains two important elements of the power house, one **is the scroll case** which feeds water to the turbine. The **generator foundation** rests on the scroll-case which is embedded in the concrete.
- **Superstructure:** The part of the power house above the generator floor right up to the roof is known as superstructure. This part provides walls and roofs to power station and also provides an overhead travelling crane for handling heavy machine parts.

Investigation of Hydropower Projects

- Several planning parameters and comprehensive data and information are needed for investigation of HP resources and planning of hydropower projects.

- The main data are derived from:

1. Forecast of demand for electricity, and from studies of:
    - Hydrology
    - Topography
    - Geology, soils and materials

Investigation of Hydropower Projects

2.Important issues, indirectly part of the planning process, are:

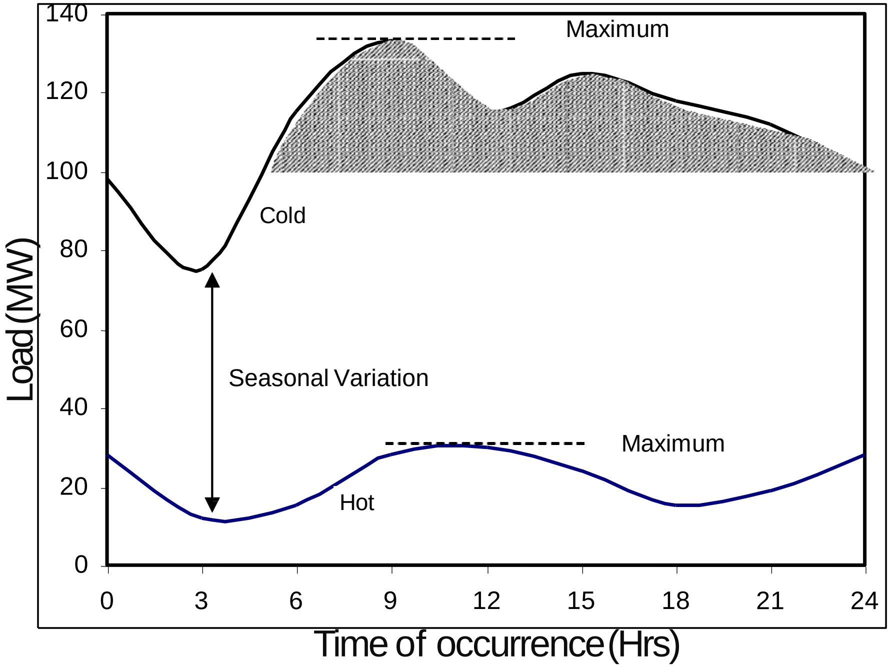
- Environmental constraints
- Socio-economic considerations
- Electricity tariffs, and tariff policy

▪In order to make predictions about the future need for electricity and to establish a demand (or load) forecast, precise and reliable knowledge about the market situation, socio-economic trends and development plans are needed.

Investigation of Hydropower Projects

POWER MARKET

- Demand: Size & Shape



- ✓ **Indicate need for regulation of water course**
- ✓ **Provide data needed to determine the size of generation, installations, unit size and transmission facilities.**
- ✓ **The minimum installation in the development should at least satisfy the energy and power demand required by the load curve often termed as firm power or energy and the maximum size can also be fixed by referring the peak demand.**

Investigation of Hydropower Projects

POWER MARKET

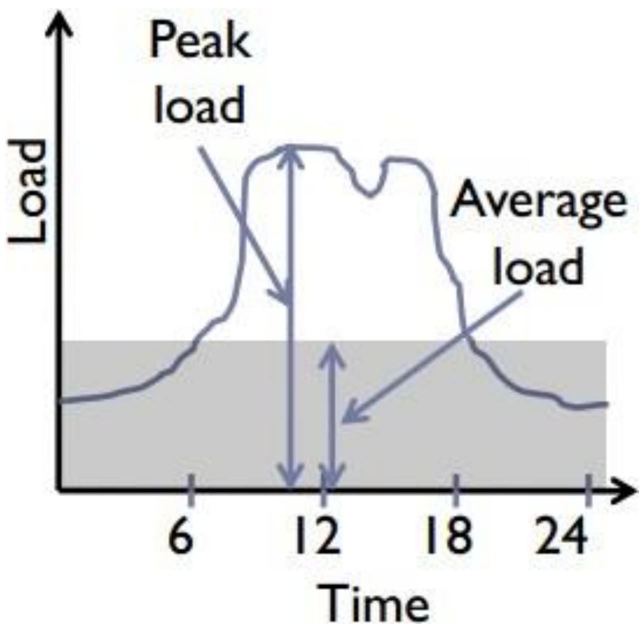
•Power market surveys are means of evaluating the present and potential markets for electric energy in a defined area

•The market survey will consider the effects on the use of electric energy within the survey are of such factors as:

- Geographical location
- Natural resources
- Industrial development
- New power uses, the economic status and prospective growth of the population

Load Terminologies

- **Load** is the amount of power delivered or received at a given point at any instant.
- **Average Load** is the total load produced divided by the number of hours in the time period of interest.
- **Peak Load** is the maximum instantaneous load or a maximum a specified period of time.



- **Base load** is the total load continuously exceeded;

Load Terminologies

- Power demand is defined as the total load, which consumers choose, at any instant of time, to connect to the supplying power system.

- The highest instantaneous value of the demand, strictly speaking, is the peak load or peak demand.

- Generally, peak load is defined as that part of the load carried at intensity greater than 4/3 times the mean load intensity.

Load Factor

- The degree of variation of the load over a period of time is measured by the load factor, which may be defined as the average load divided by the peak load within the given time range.

Load factor = Average load/Peak load

- The load factor measures variation only and does not give any indication of the precise shape of the load-duration curve.

- The area under the load curve represents the energy consumed in kWh; Thus, a daily load factor may also be defined as the ratio of the actual energy consumed during 24 hours to the peak demand assumed to continue for 24 hours.

Capacity Factor

- The capacity factor is the ratio of the energy actually produced by the plant for any given period of time to the energy it would be capable of producing at its full capacity for that period of time.

- The factor is equal to the average load divided by the rated capacity of the plant.

$$Capacity\ factor = \frac{Peak\ load\ x\ Load\ factor}{Rated\ capacity\ of\ the\ plant}$$

Capacity Factor

- For example, if a plant with a capacity of 100MW produces 6,000,000 kWh operating for 100 hours, its capacity factor will be 0.6, i.e.

$$c.f = \frac{6,000,000}{100,000*100} = 0.6$$

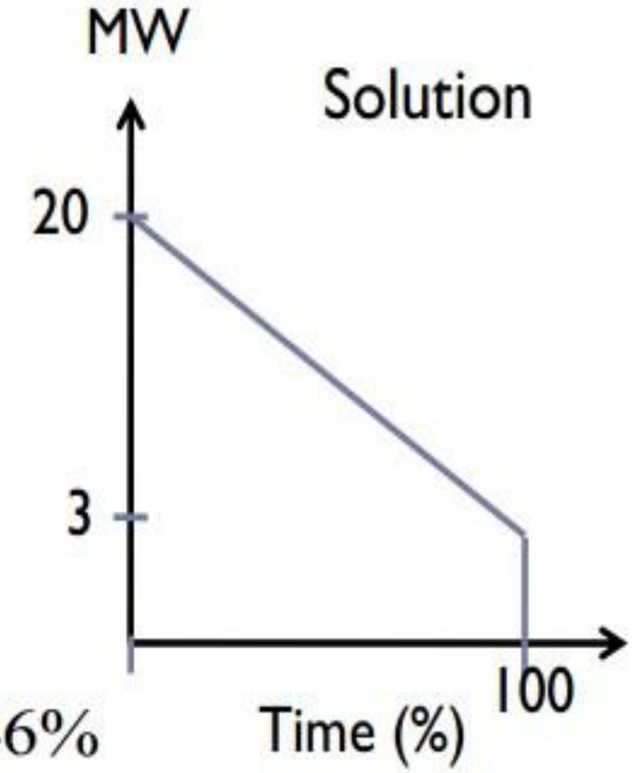
- The capacity factor for hydroelectric plants generally varies between 0.25 and 0.75.

- The capacity factor would be identical with load factor if the peak load were equal to the plant capacity.

Example

- Consider the yearly load duration curve for a certain load center to be a straight line from 20 to 3 MW. To meet this load, three hydropower units, two rated at 10 MW each and one at 5 MW are installed.

  - Load factor (LF)
  - Capacity factor (CF)



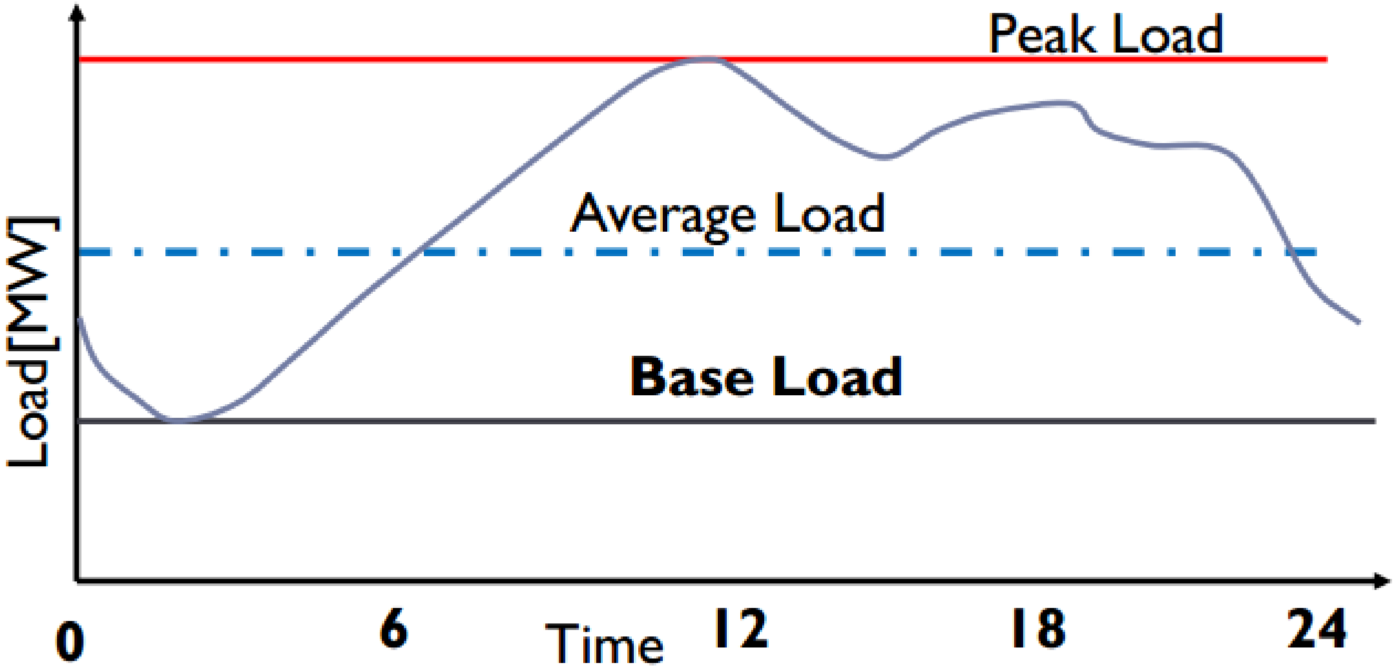
Solution

$$LF = \frac{\frac{3+20}{2} \times 100\% \times t}{20 \times 100\% \times t} \times 100\% = 57.5\%$$

$$CF = \frac{\frac{3+20}{2} \times 100\% \times t}{(10+10+5) \times 100\% \times t} \times 100\% = 46\%$$

Load Duration Curve

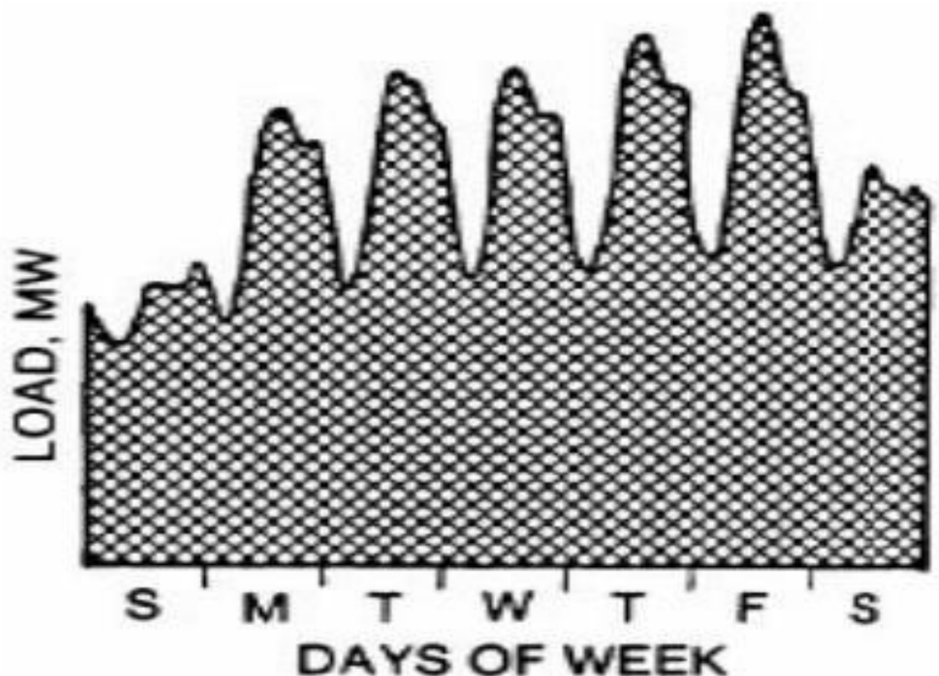
- Load Curve: A load curve is a graph of load consumption with respect to time and directly gives an indication of power used at any time (daily, weekly, monthly, annually, etc.)
- Daily Load Curve: is a curve drawn between load as the ordinate and time in hours as the abscissa for



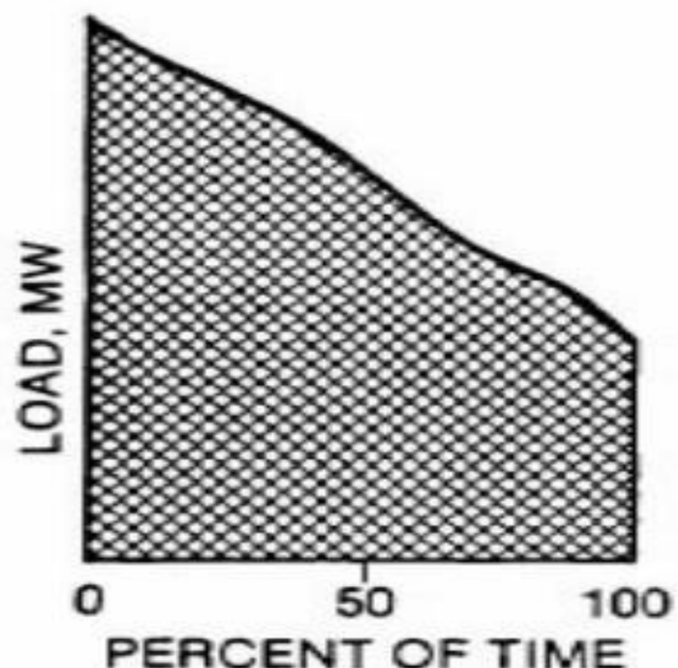
Load Duration Curve

- Firm Power: The firm or primary power is the power which is always ensured to a consumer at any hour of the day and is, thus, completely dependable power.
- Firm power would correspond to the minimum stream flow & is available for all the times;

Weekly Load Curve



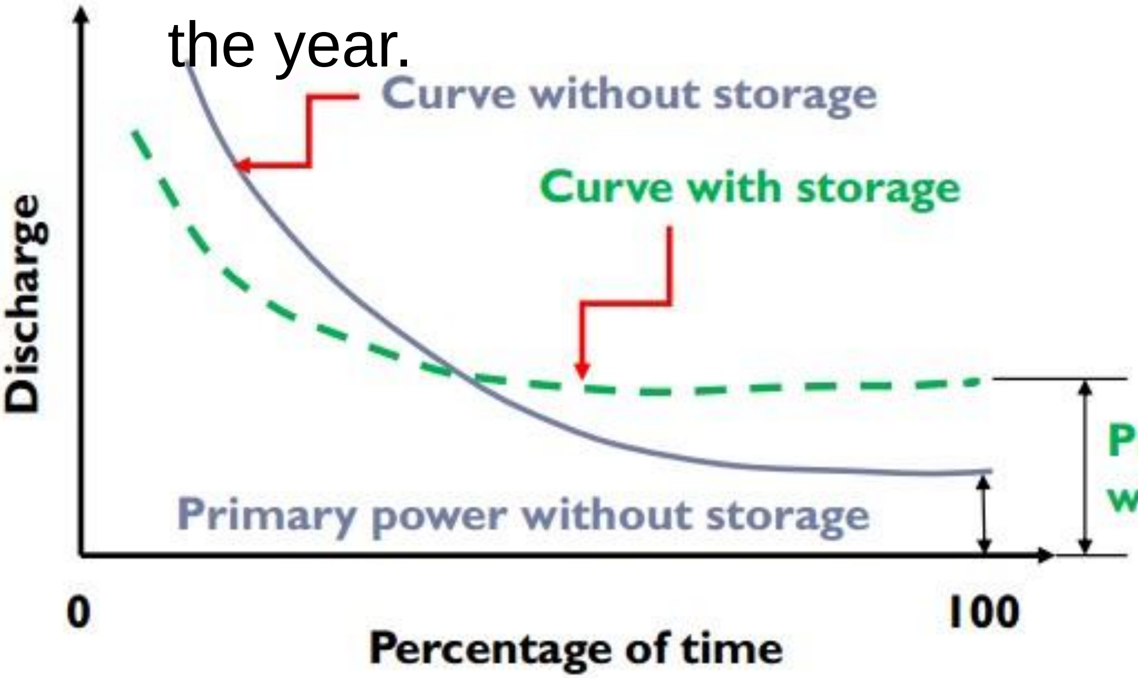
Load Duration Curve



Load Duration Curve

- The area under a load duration curve represents the total energy production for the duration.

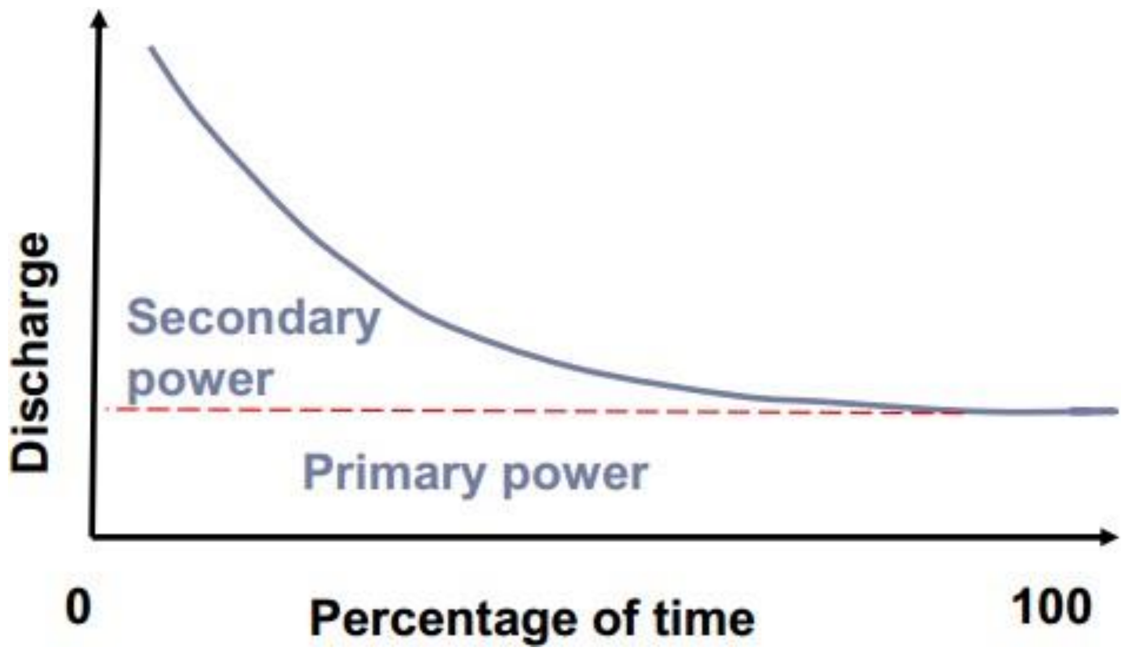
- Thus, annual load factor is given by the ratio of the area under the curve to the area of the rectangle corresponding to the maximum demand occurring during the course of the year.



- The firm power could be increased by the use of pondage (storage).

Load Duration Curve

- Secondary power: Also known as surplus or non-firm power, is the power other than the primary power and is, thus, comparatively less valuable



Power/ Flow Duration Curve (PDC or FDC)

- Before any power plant is contemplated, it is essential to assess the inherent power available from the discharge of the river and the head available at the site.

- The gross head of any proposed scheme can be assessed by simple surveying techniques, whereas

- Hydrological data on rainfall and runoff are essential in order to assess the quantity of water available.

- The hydrological data necessary for potential assessment are:
  - ✓ The daily, weekly, or monthly flow over a period of several

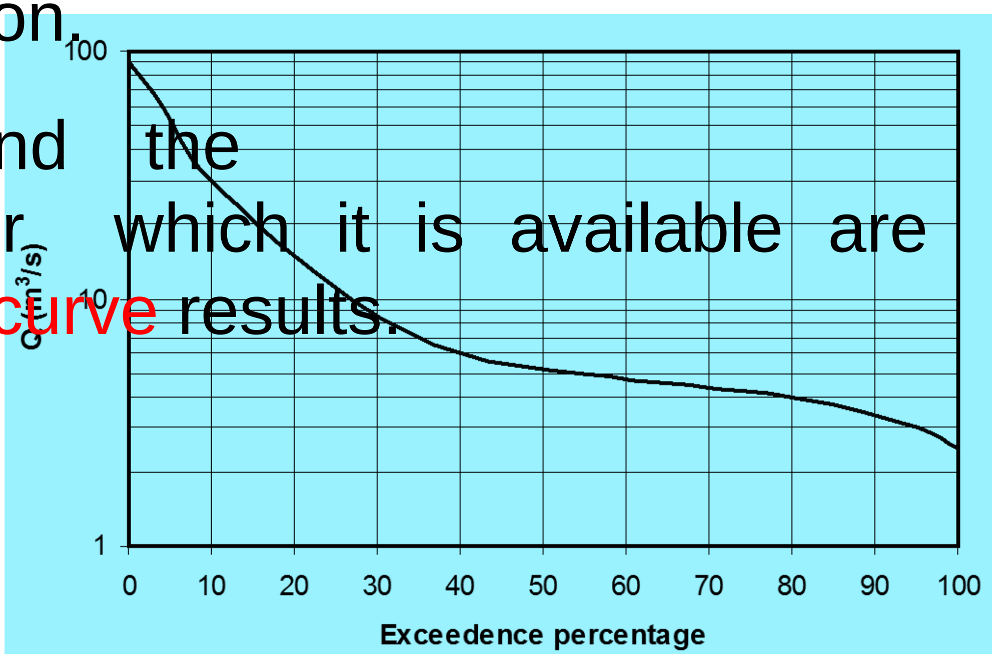
years, to determine the plant capacity and estimate output,

Flow Duration Curve (FDC)

- The actual use of the power equation ($P=\eta\gamma QH$) for estimating the potential is difficult due to the fact that the discharge of any river varies over a wide range.

- High discharges are available only for short durations in a year. Thus the corresponding available power would be of short duration.

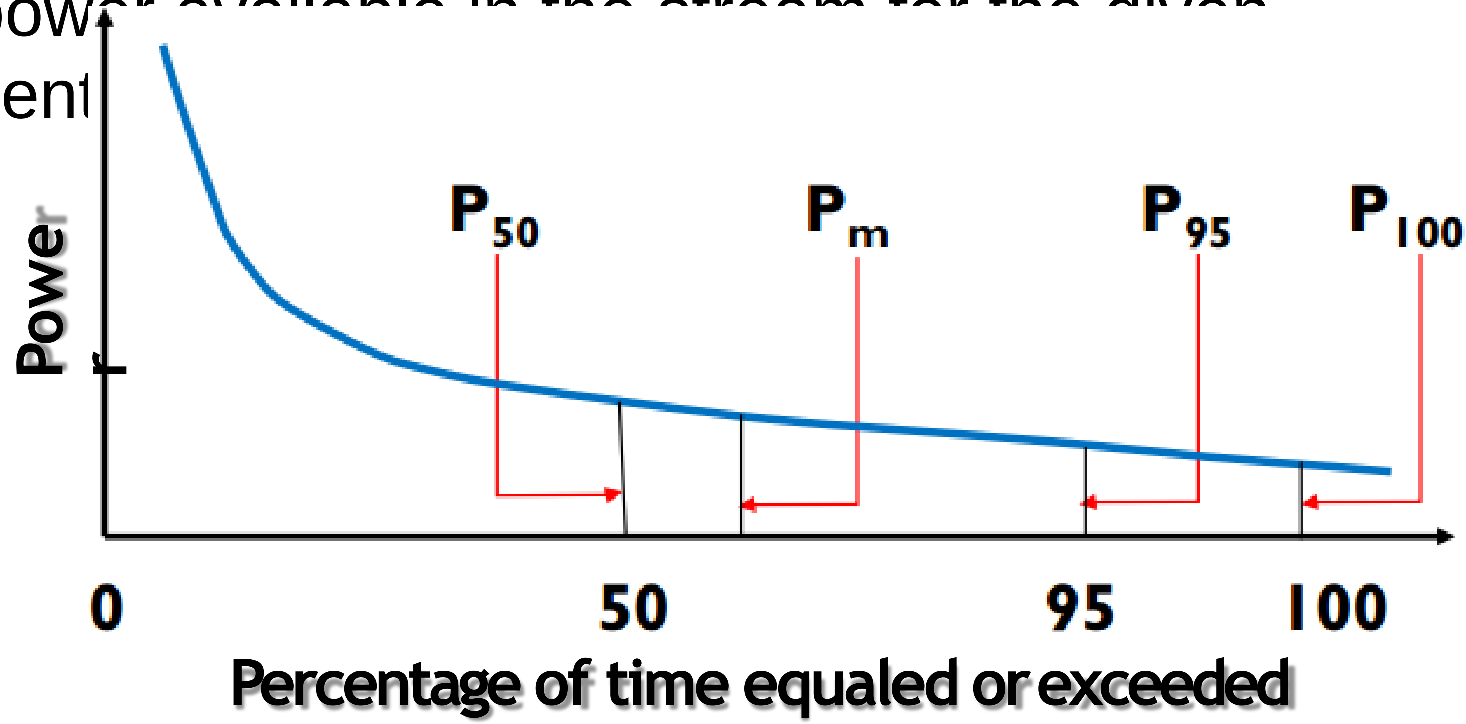
- If the flow rate and the %ge duration of time for which it is available are plotted, a flow-duration curve results.



Power Duration Curve (PDC)

- Power duration curve can also be plotted since power is directly proportional to the discharge and available head.

- Discharge/power duration curve indicates discharge or power available in the stream for the given percent



Power Duration Curve (PDC)

- Minimum potential power computed from the minimum flow available for 100 % of the time (365 days or 8760 hours). This is represented as P_{100};

- Small potential power computed from the flow available for 95 % of time (flow available for 8322 hours). This is represented as P_{95};

- Average potential power computed from the flow available for 50% of the time (flow available for 6 months or 4380 hrs). This is represented as P_{50};

Power Duration Curve (PDC)

- Mean potential power computed from the average of mean yearly flows for a period of 10 to 30 years, which is equal to the area of the flow-duration curve corresponding to this mean year. This is known as 'Gross river power potential' and is represented as P_m.

- Technically available power: With conveyance efficiency of 70% and overall efficiency of the plant as 80%, a combined multiplying factor of 0.56 should be used with the average potential power, P_{50}

$$P_a = 0.56\, P_{50}$$

Power Duration Curve (PDC)

- The value of net water power capable of being developed technically is also computed from the potential water power by:

$$P_{mnet} = (7.4\ to\ 8.0) Q_m h$$

Q_m = the arithmetic mean discharge

- The maximum river energy potential is given as:

$$E_{\max net} = 8760 P_{m\,net} (Kwh)$$

- Note: The longer the record, the more statistically valuable the information that results from the FDC & PDC.

Power Duration Curve (PDC)

Example:- The following is the record of average yearly flow in a river for 15 years. If the available head is 15 m, ***construct*** the **FDC** and power duration curve for the

Year	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970
Flow (m^3/s)	905	865	1050	1105	675	715	850	775	590	625	810	885	1025	1150	925

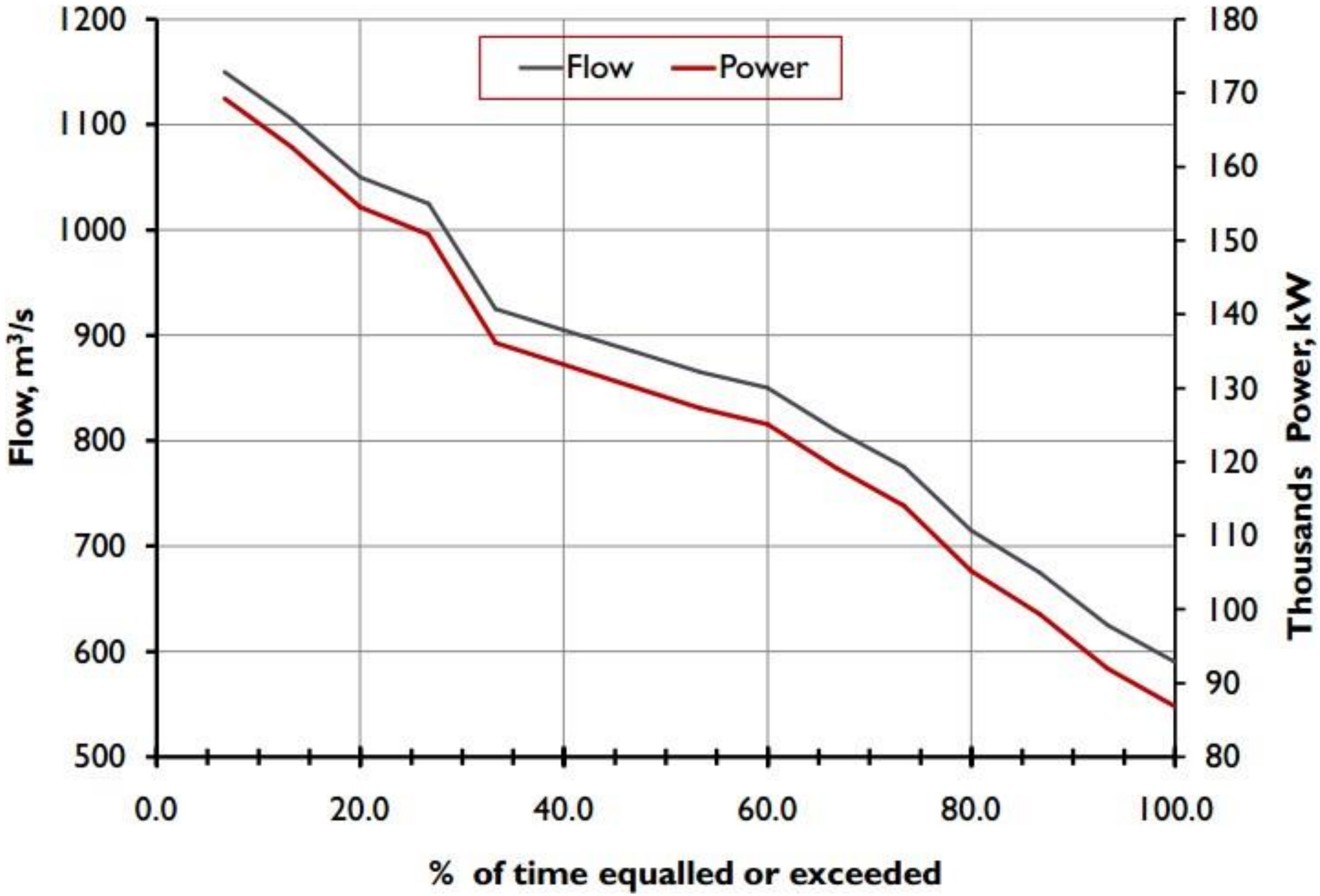
Solution:

- The yearly flow values are arranged in ascending order (see table below).
- The power corresponding to each flow values are calculated assuming the head (=15 m) to be constant.
- Then, FDC and power duration curves are plotted on the same graph.

Power Duration Curve (PDC)

Rank	Flow in ascending order (m^3/s) (1)	Power (= 9.81 QH) [kW] (2)	Percentage of time exceeded =(15 +1-n)*100/15 (3)
1	590	86819	100.0
2	625	91969	93.4
3	675	99326	86.7
4	715	105212	80.0
5	775	114041	73.4
6	810	119192	66.7
7	850	125078	60.0
8	865	127285	53.4
9	885	130228	46.7
10	905	133171	40.0
11	925	136114	33.3
12	1025	150829	26.7
13	1050	154508	20.0
14	1105	162601	13.3
15	1150	169223	6.7

Power Duration Curve (PDC)



Estimation of flow to ungauged sites

- If the project site have no recorded data (ungauged site), the representative data must be estimated from nearby sites having similar geomorphology.

- There are several methods to estimate flows from ungauged catchments :

    - Regional frequency analysis,
    - Sequential flow analysis and
    - Use of Parametric Flow Duration Curve etc.

Regional Frequency Analysis

- A regional frequency analysis involves regression analysis of gauged catchments within the general region.

- Through this technique, sufficiently reliable equations can often be derived for peak flow of varying frequency given quantifiable physical basin characteristics and rainfall intensity for a specific duration.

- Once these equations are developed, they can be then be applied to ungauged basins within the same region and data of similar magnitude used in developing the equations.

Regional Frequency Analysis

- A regional analysis usually consists of the following steps:
  1. Selecting components of interest, such as mean and peak discharge
  2. Selecting definable basin characteristics of gauged watershed: drainage area, slope, shape, length, etc.
  3. Deriving prediction equations with single or multiple linear regression analysis
  4. Mapping and explaining the residuals (differences between computed and observed values) that constitute "unexplained variances" in the statistical analysis on a regional basis.

Regional Frequency Analysis

- Some of the equations may have the form:

$$Q_2 = 0.24 A^{0.88} P^{1.58} H^{0.80}$$

$$Q_5 = 1.20 A^{0.82} P^{1.37} H^{0.64}$$

$$Q_{10} = 2.63 A^{0.80} P^{1.25} H^{0.58}$$

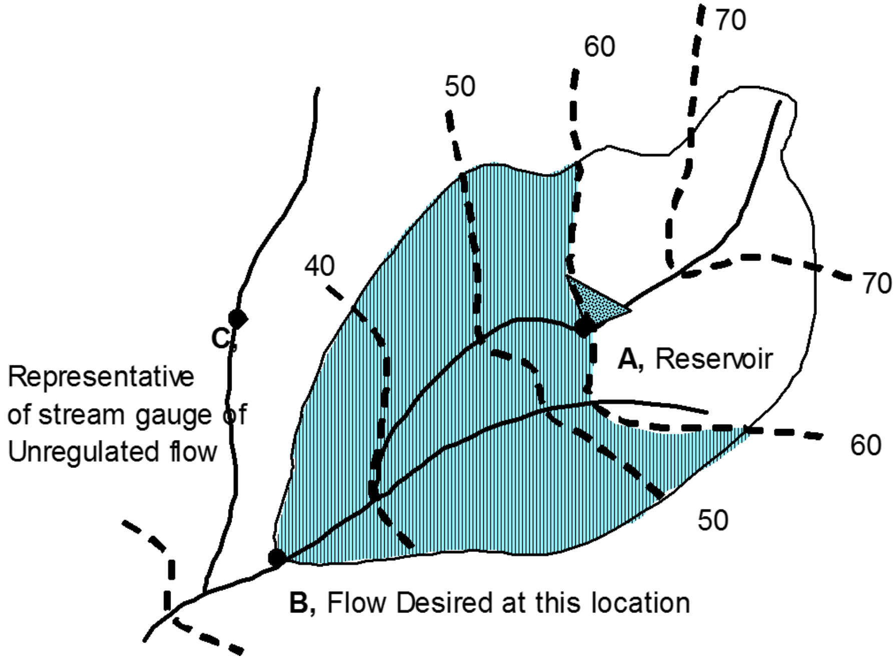
$$Q_{25} = 6.55 A^{0.79} P^{1.12} H^{0.52}$$

$$Q_{50} = 10.4 A^{0.78} P^{1.06} H^{0.48}$$

$$Q_{100} = 15.7 A^{0.77} P^{1.02} H^{0.43}$$

Where:
Q = peak discharge
A = drainage area
P = mean annual precipitation H = altitude index

Sequential Flow Analysis



- **A normal annual ppt. map of the entire drainage area is required**

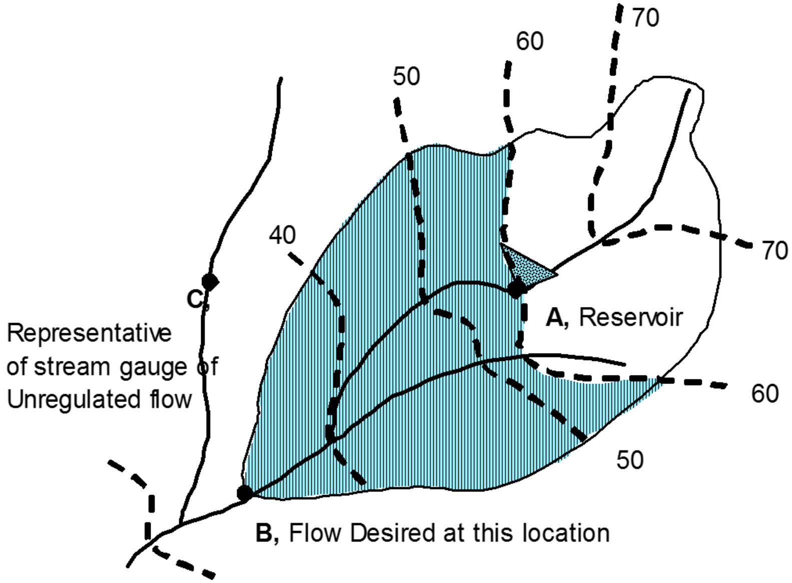
Fig: Method for determining FD of regulated flow combined with ungauged

1. Reservoir Outflow recor → obtain from entity operating reservoir (location at A)
2. Determine average annual runoff from ungauged tributary area. → Planimeter N.A.P. maps and estimate coefficient of runoff. (Location is B considering area M)
3. Compute sequential flow from ungauged tributary area. → See sequential flow analysis flow chart
4. Sum outflows from ungauged tributary area and reservoir outflow → This is simple sequential addition of calculated inflow from ungauged area plus observed reservoir
5. Perform flow duration analysis

or

6. Perform sequential flow analysis → Use standard hydrologic technique

Sequential Flow Analysis



- **A normal annual ppt. map of the entire drainage area is required**

Fig: Flow diagram for computing sequential flow magnitudes from ungauged

Choose representative stream gauge station C

→ Distribution of flow at gauge must be representative of w hatcan be expected from ungauged tributary area M

Compute incremental flow fraction for representative guage at station C

→ a_i = flow volune for period I divided by total volume for entire period I to n

w here ai = incremental flow fraction for particular period *i* *i* w ill be sequentially each number from 1 to n

n = number of time periods in entire record of flow s at station C (months, days)

Compute ungauged tributary area inflow

→ $q_{BMi} = a_i Q_R m/t$

w here q_{BMi} = inflow from ungauged tributary area M for period ***i***

Q_R = average annual runoff in volume units for area M

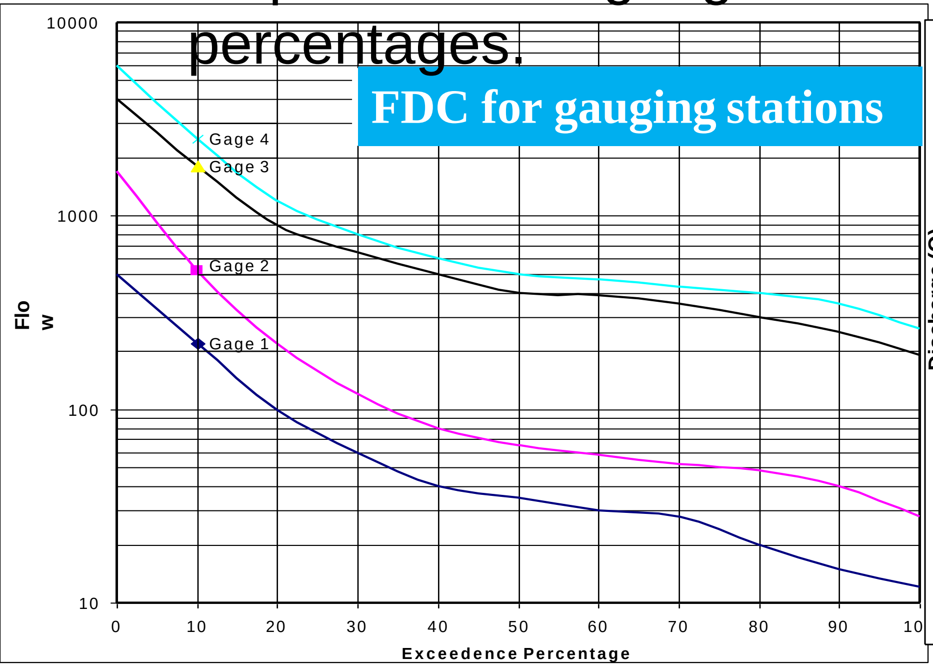
m = number of years in entire period betw een ***i*** = 1 and ***i*** = n

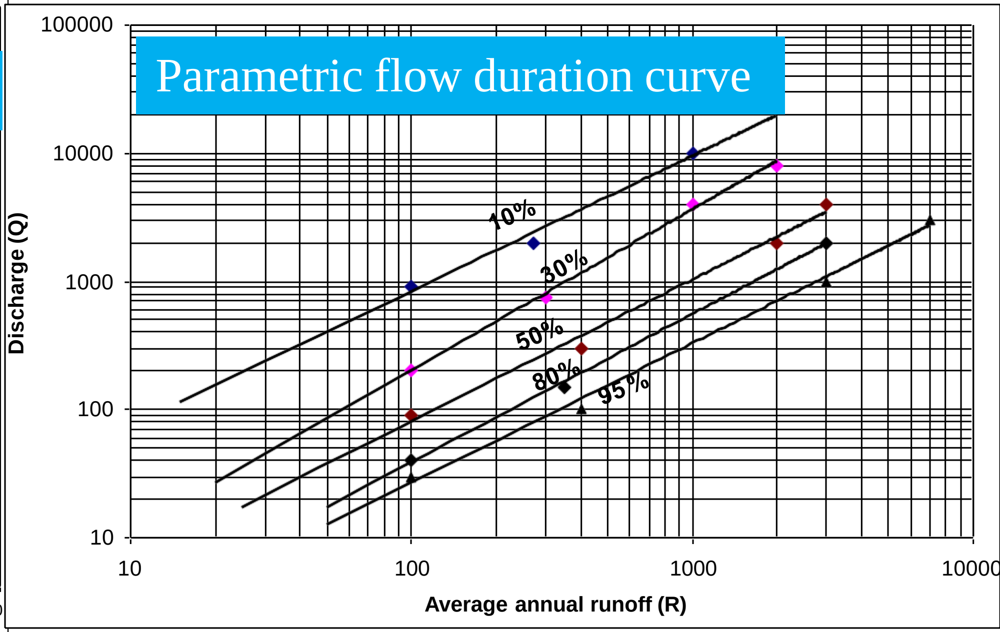
t = time units for each period

Proceed to sum with reulated outflows from reservoir

Use of Parametric Flow Duration Curve

- In regions where stream flow does not vary with respect to the contributing drainage area flow duration curves can be plotted for the gauged sites.
- From these flow duration curves are developed a family of parametric duration curves in which flow is plotted against the average annual runoff (R) or annual discharge(Q), at the respective gauges for several exceedence interval percentages.





Use of Parametric Flow Duration Curve

- 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 to be made.

- Isohytal maps developed for normal annual precipitation in a

river basin are helpful for determining the annual discharge.

- 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.

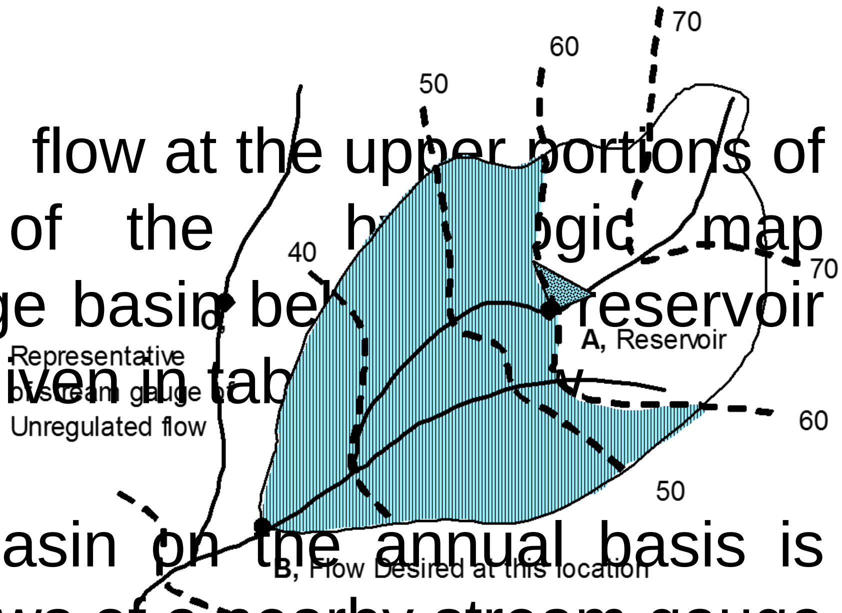
Use of Parametric Flow Duration Curve

$$Q = \frac{k P A}{T}$$

- With the average runoff annual discharge estimate it is possible to enter the parametric flow duration curve and determine values of flow for different exceedence percentages for which the parametric flow duration curve has been developed.

Example

- A drainage basin has a power plant site located at the mouth of the catchment.
- An u/s reservoir regulates the flow at the upper portions of the drainage. The area of the hydrologic map representative of the drainage basin below reservoir has been planimetered and given in table below.



- A runoff coefficient for the basin on the annual basis is 0.65. The historic monthly flows of a nearby stream gauge on the downstream side of the stream are presented in table B.

Example

- The gauge records are considered to be a good representation of seasonal variation of runoff for the ungauged portion of the river drainage basin.

- The outflows from the reservoir are given in table C.

- Using the information provided compute the river flow at its mouth that would be useful for the hydropower study.

- Scale of the isohytal map is 1:400,000.

Example

Table A: Values of planimetered areas downstream of the reservoir

Avg value of pptn b/n Isohytal lines (mm)	Planimetered Area (mm^2)
762	11.94
889	26.13
1016	14.45

Table B: Monthly flows for an average year in a representative gauged stream

Month	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
No. of Days	31	28	31	30	31	30	31	31	30	31	30	31
Discharge (m^3/s)	7.11	7.14	9.88	33.13	80.02	64.31	22.57	11.84	9.40	9.40	9.51	8.44

Table C: Out flow from the upper reservoir

Month	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Discharge (m3/s)	1.42	1.27	2.27	2.83	5.66	7.08	7.08	5.66	1.98	1.84	1.7	1.56

Solution

Step 1: Compute the average annual runoff using NAP

$$\bar{Q} = k\,\bar{P}\,A$$

$$\bar{P} = \frac{\sum PA}{\sum A} = \frac{762*11.94 + 889*26.13 + 1016*14.45}{11.94 + 26.13 + 14.45} = 895.07\,mm$$

$$\bar{Q} = 0.65*895.07/1000*52.52/(1000*1000)*400{,}000^2 = 4888941.2\,m^3/year$$

$$\bar{Q} = \frac{4888941.2}{24*60*60} = 56.58\,m^3/\sec/day$$

Step 2: Compute yearly runoff from the representative gauge

Month	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
No. of Days	31	28	31	30	31	30	31	31	30	31	30	31
Discharge (m3/s)	7.11	7.14	9.88	33.13	80.02	64.31	22.57	11.84	9.40	9.40	9.51	8.44
Run off (m^3/s)/(day)	220.41	199.92	306.28	993.9	2480.62	1929.3	699.67	367.04	282	291.4	285.3	261.64
Yearly Total (m3/s)(days)	8317.48											

Solution

Step 3: Compute monthly fraction of runoff

$$q_i = \frac{Runoff\ \ for\ the\ month}{Total\ runoff\ \ for\ the\ Record\ period},\ q_i\,(Jan) = \frac{220.41}{8317.48} = 0.026$$

Month	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Monthly fraction	0.026	0.024	0.037	0.119	0.298	0.232	0.084	0.044	0.034	0.035	0.034	0.031

Step 4: Compute flow for the downstream portion

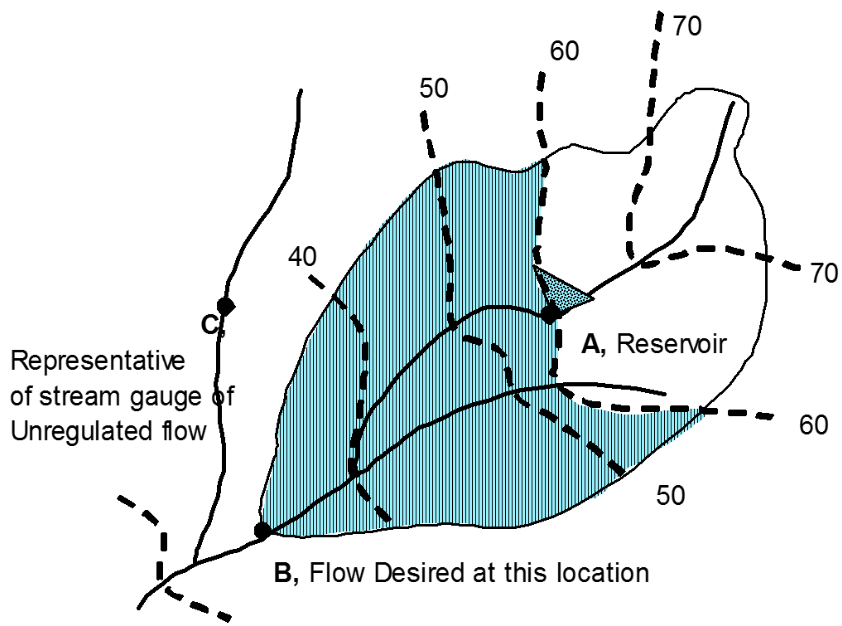
$$Q\,(Jan) = \frac{0.026 * 56.58}{31} = 0.05\,m^3\ /\sec$$

Month	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Monthly flow (m^3/s)	0.05	0.05	0.07	0.23	0.54	0.44	0.15	0.08	0.06	0.06	0.06	0.06

Solution

Step 5: Compute the total flow at the outlet

Month	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Monthly flow (m^3/s)	0.05	0.05	0.07	0.23	0.54	0.44	0.15	0.08	0.06	0.06	0.06	0.06
Flow from upper Res(m^3/s)	1.42	1.27	2.27	2.83	5.66	7.08	7.08	5.66	1.98	1.84	1.70	1.56
Total Flow	1.47	1.32	2.34	3.06	6.20	7.52	7.23	5.74	2.04	1.90	1.76	1.62



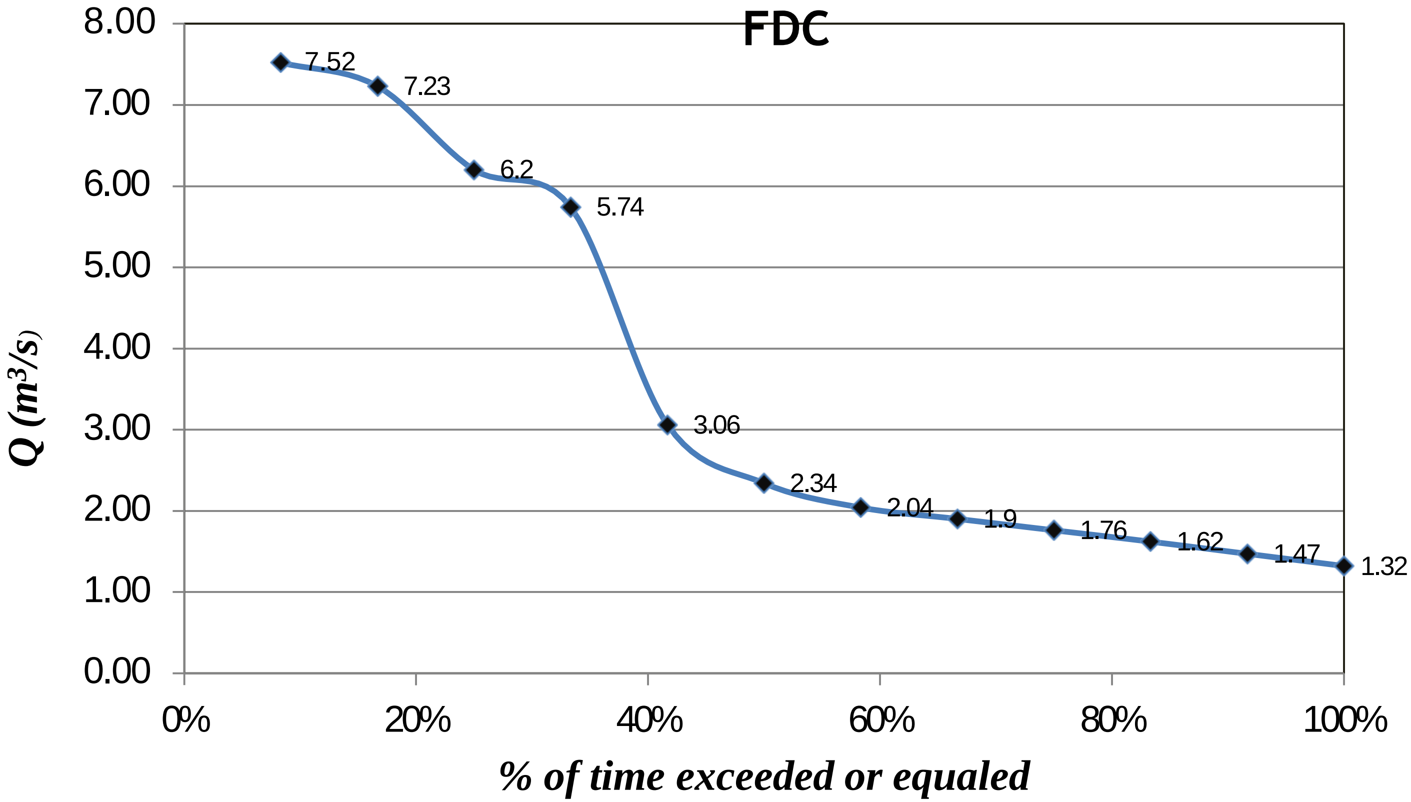
Solution

Step 5: Compute the flow duration curve

Flow	Flow Descending order	Rank	%Exceeded or Equaled
7.52	7.52	1	8.33%
7.23	7.23	2	16.67%
6.20	6.20	3	25.00%
5.74	5.74	4	33.33%
3.06	3.06	5	41.67%
2.34	2.34	6	50.00%
2.04	2.04	7	58.33%
1.90	1.90	8	66.67%
1.76	1.76	9	75.00%
1.62	1.62	10	83.33%
1.47	1.47	11	91.67%
1.32	1.32	12	100.00%

Solution

Step 6: Compute the flow duration curve

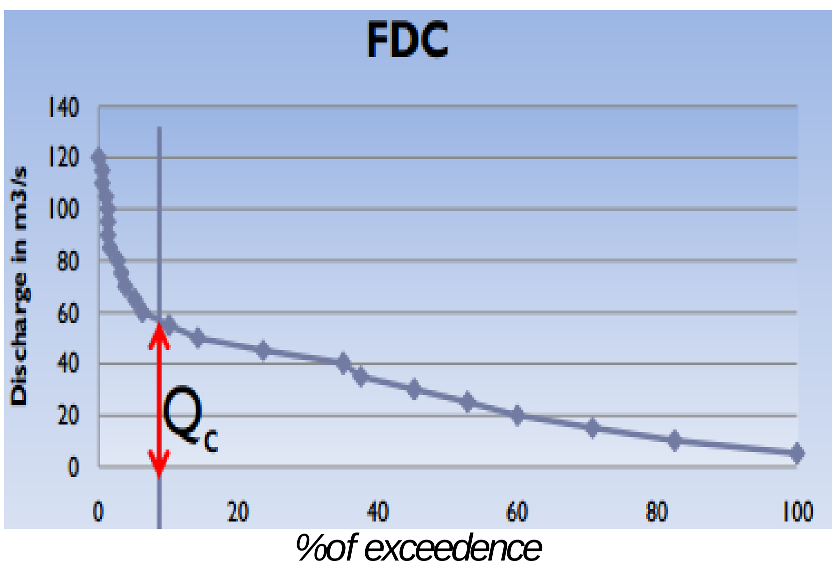


The firm flow = 1.32 m³/sec

Energy & Power Analysis using Flow Duration Approach

- In processing regulated and unregulated flow data, it is important to recognize that in the power equation, flow is the primary limiting factor.

- When a Run-Off-River type of power study is done and a flow duration analysis is used, the capacity or size of the hydropower units determines the maximum amount of water that will go through the unit or units.



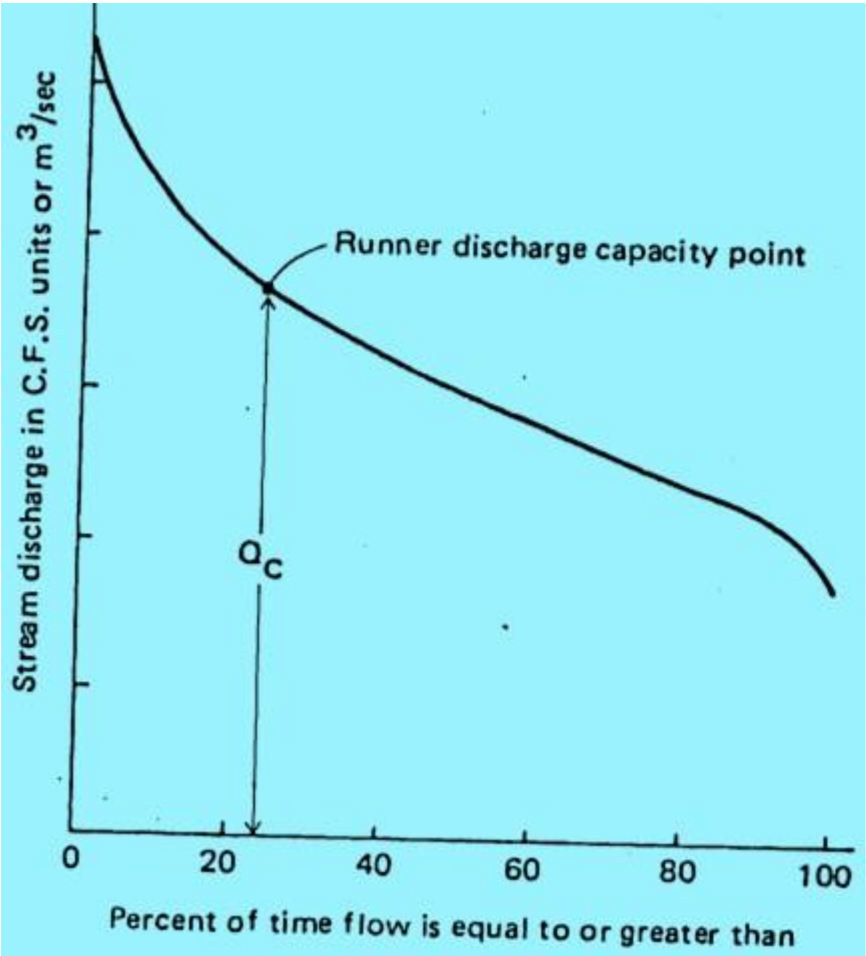
- Q_c is the discharge capacity of the

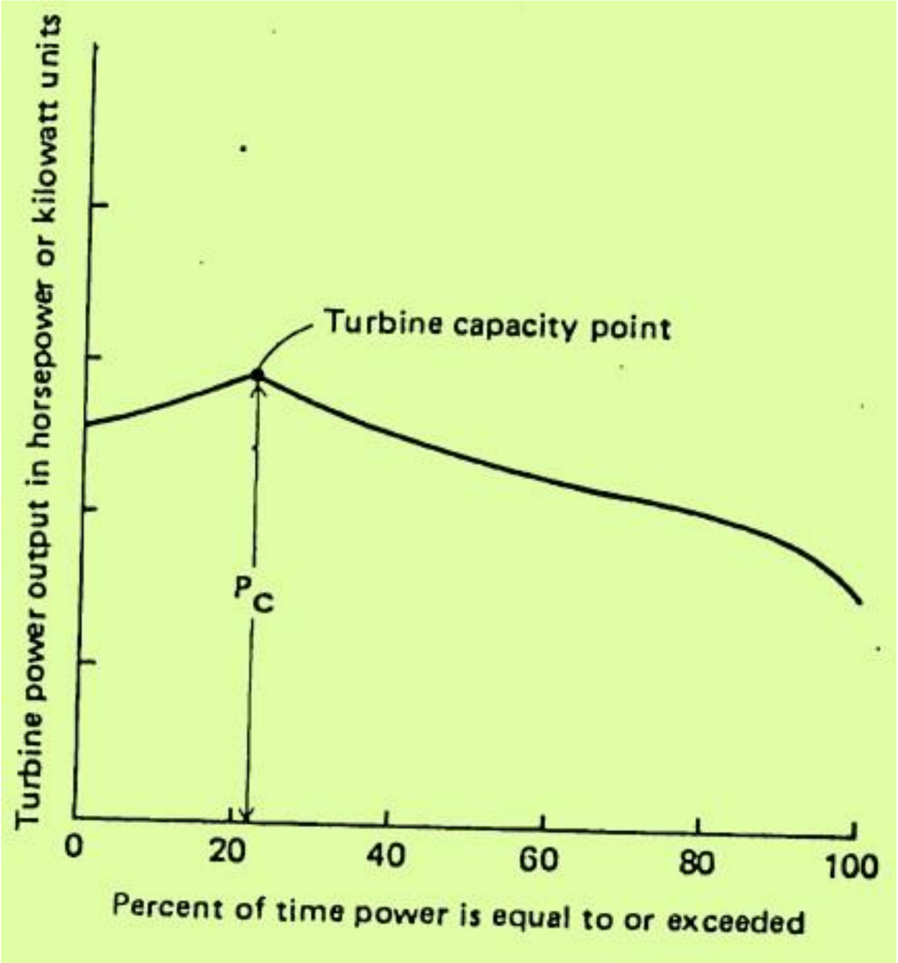
d.

- Q_c is the discharge at full gate opening of the runner under design head

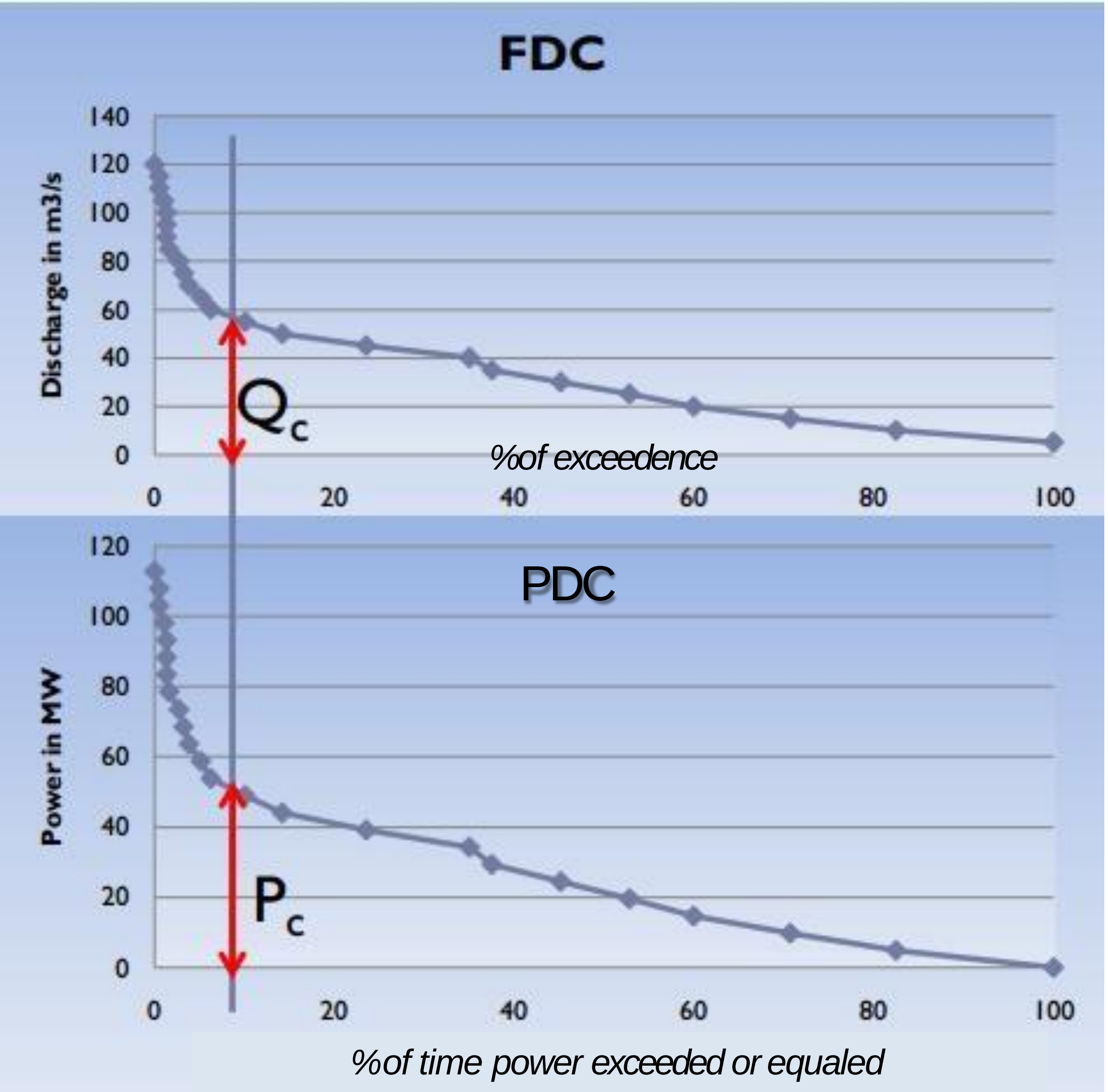
Energy & Power Analysis using Flow Duration Approach

- If hydraulic head & the expected losses in the penstock are known, it is possible to generate a power duration curve from the flow duration curve.





Energy & Power Analysis using Flow Duration Approach



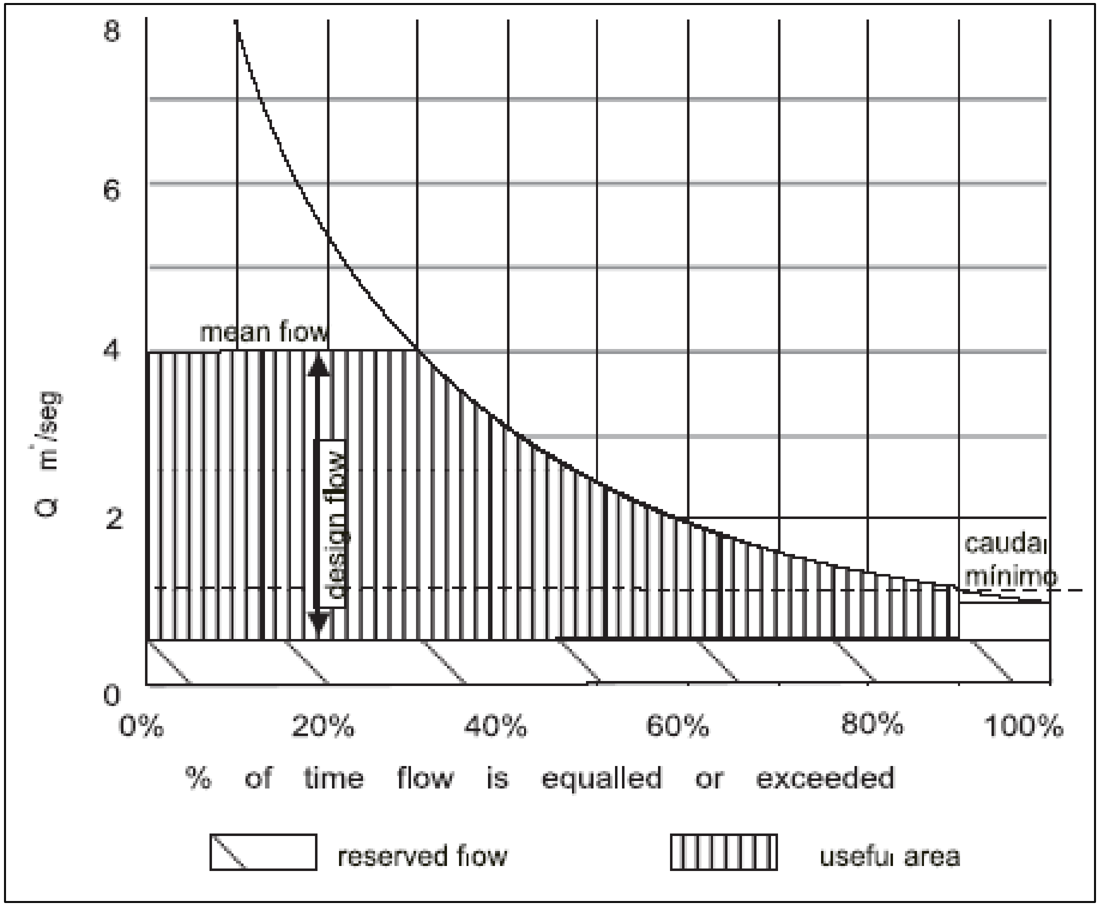
Water pressure or Head

- Measurement of gross head:
  - Digital Theodolites
  - GPS
  - DEM

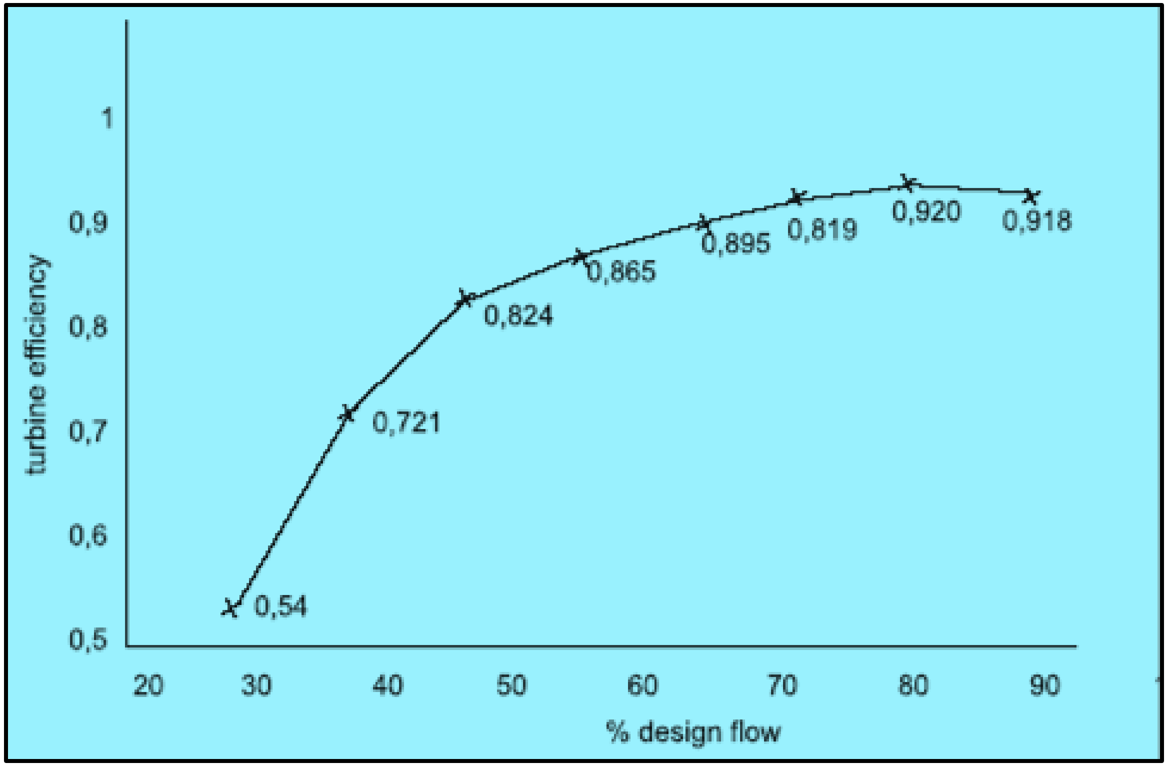
- Estimation of net head:
  - Gross head – losses due to (trash racks, pipe friction, bends, valves, etc)

Estimation of Plant Capacity & Energy Output

- Usually the design flow is assumed to be, in a first approach, the difference between the mean annual flow and the reserved flow ($Q_m - Q_{res}$).



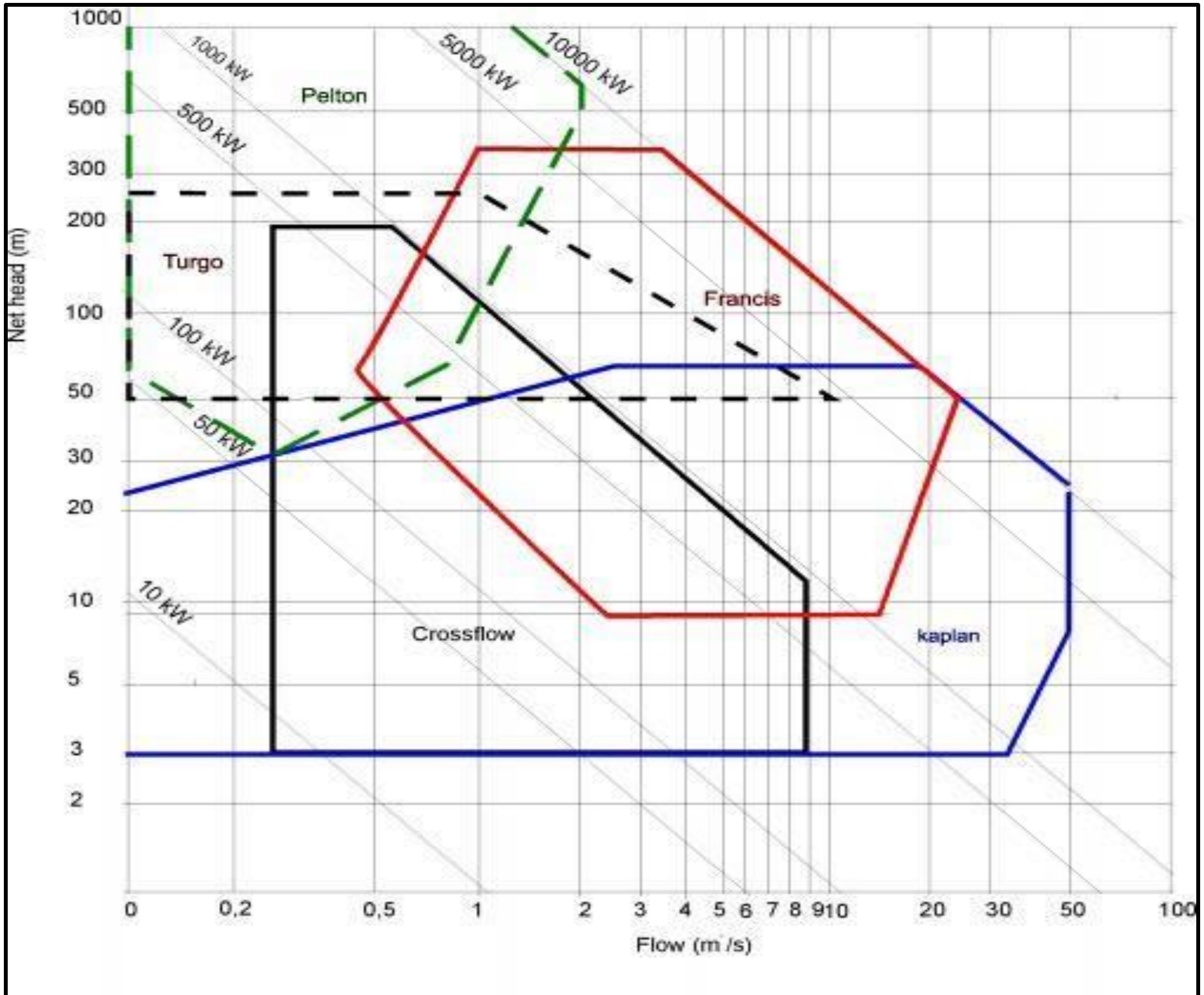
Estimation of Plant Capacity & Energy Output



Turbine Type	Q_{min}	Turbine Type	Q_{min}
Francis spiral	30	Cross flow	15
Francis open flume	30	Pelton Turgo	10
Semi Kaplan Kaplan	15	Propeller	10
	15		65

Estimation of Plant Capacity & Energy Output

- Once the design flow is defined, & the net head is estimated, suitable turbine types must be identified.



Estimation of Plant Capacity & Energy Output

- The gross average annual energy (E in kWh) is a function of:

$$E = fn\,(Q_{median}, H_n, \eta_{turbine}, \eta_{generator}, \eta_{gearbox}, \eta_{transformer}, \gamma, h)$$

  - Where:
    - Q_{median} =flow in m^3/s for incremental steps on the flow duration curve
    - H_n =specified net head
    - $\eta_{turbine}$ =turbine efficiency, a function of Q_{median}
    - $\eta_{generator}$ =generator efficiency
    - $\eta_{gearbox}$ =gearbox efficiency
    - $\eta_{transformer}$ =transformer efficiency
    - h =number of hours for which the specified flow occurs.

Plant Capacity Determination

- Turbine selection and plant capacity determination require detail information on head and possible plant discharge.

- In theoretical sense, the energy output, E, can be expressed mathematically as plant output or annual energy in a functional relation as:

$E = f(h, q, TW, d, n, H_s, P_{max})$

Where: h = net effective head q = plant discharge
TW = tail water elevation d = diameter of runner
n = generator speed
H_s = turbine setting elevation above tail water P_{max} = max. output expected or desired at plant

Limits of Use of Turbine Types

- Impulse turbines normally have most economical application at head above 300 m.

Turbine Type	Range of Flows	Head Range
Francis	50 to 115% of best efficiency discharge	60 to 125% H_d
Fixed blade propler	75 to 100% of best efficiency flow	2 to 70 m (good @<30m)
kaplan	25 to 125% Best Efficiency Discharge	20 to 140% H_d

- Below lower efficiency range there is rough operation that may make extended operation unwise.

- The upper range of flow may be limited by instability or the generator rating and temperature rise.

Determination of Number of Units

- It is cost effective to have minimum number of units at a given installation.
- However, multiple units may be necessary to make the most efficient use of water where flow variation is high.
- Factors affects: space limitations, the difficulty of transporting large runners

Determination of Number of Units

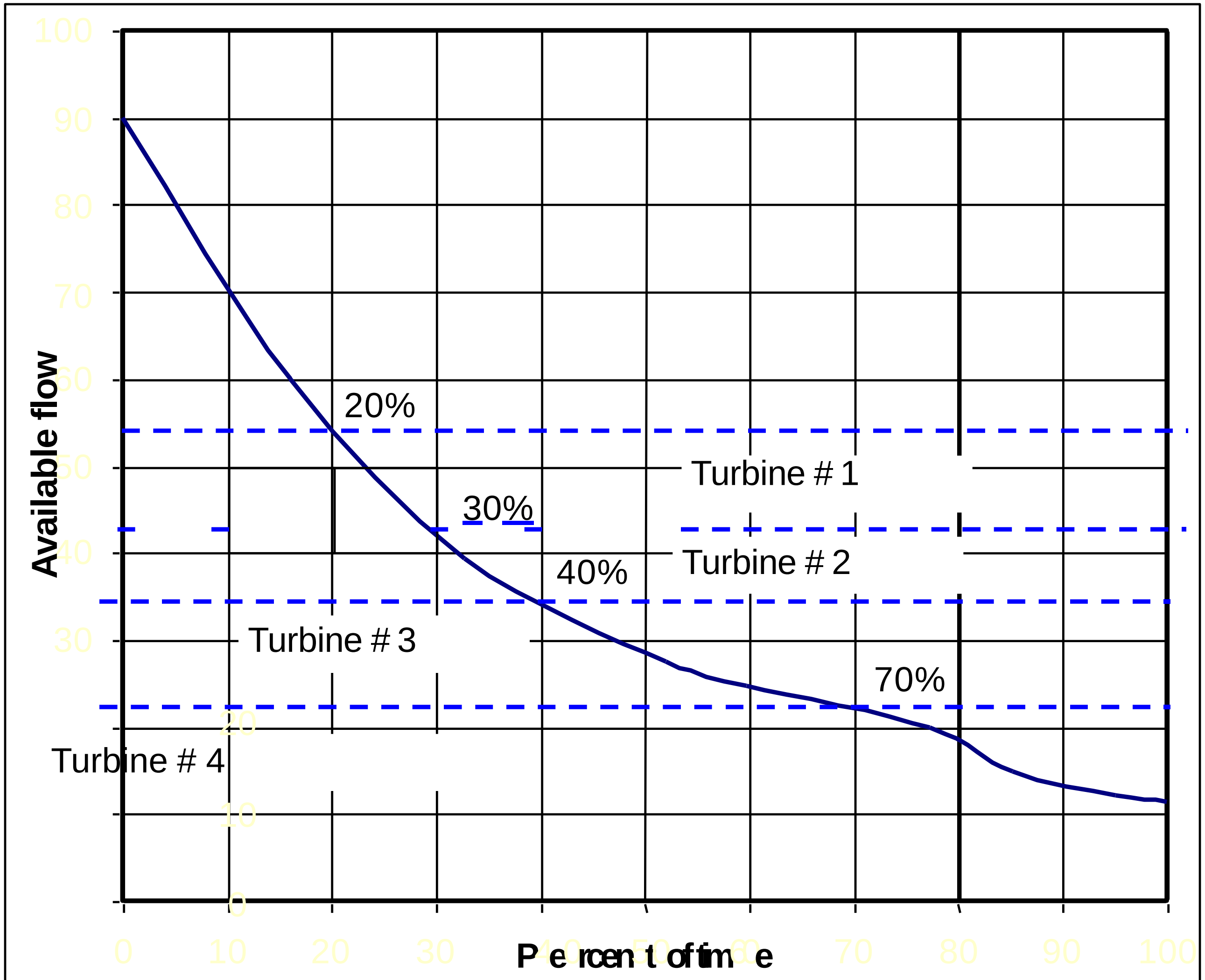
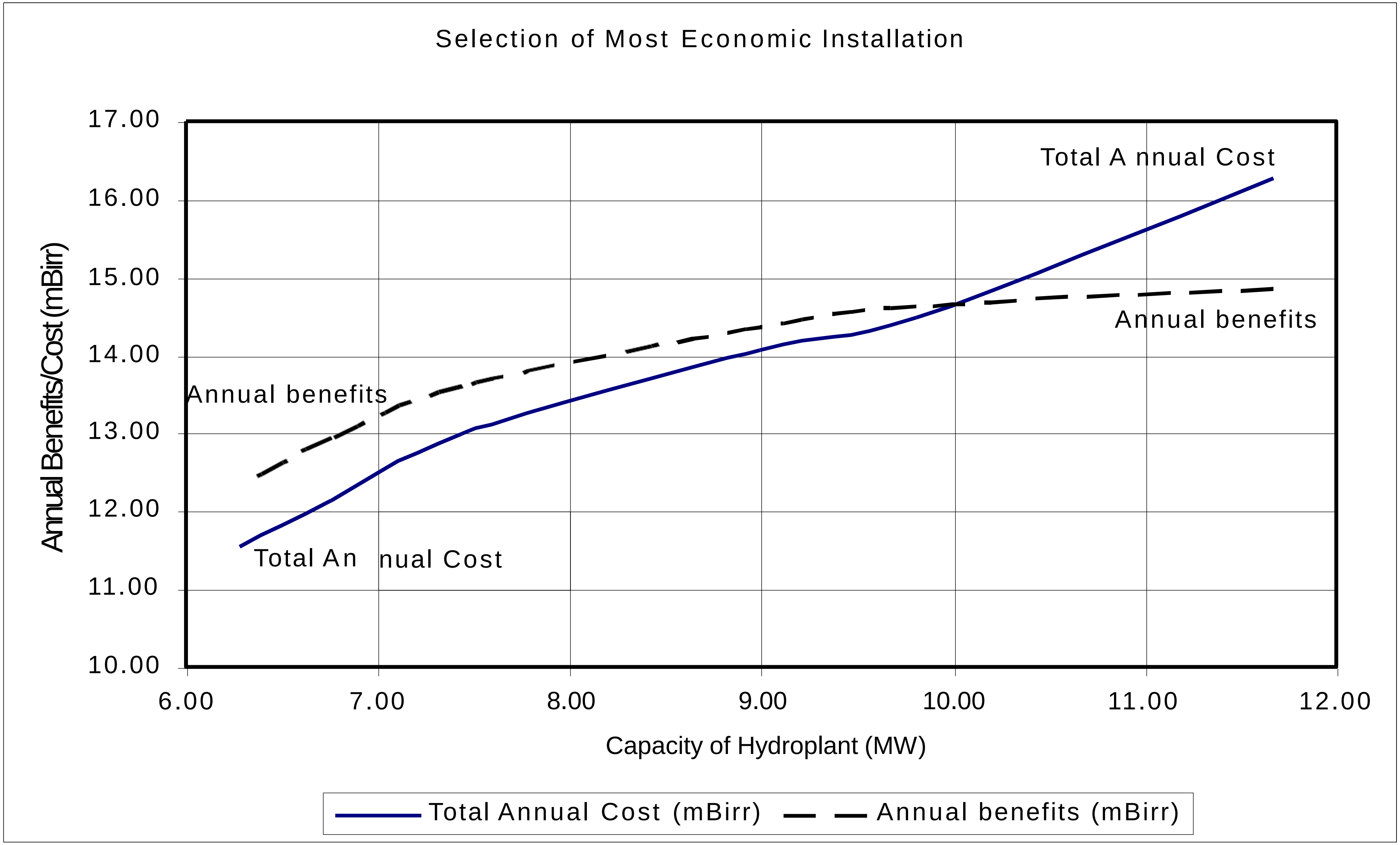


Figure: Effective use of multiple units

Selection of The Most Economical Unit



Turbine Selection Procedure

1. Obtain river flow data
2. Obtain head water elevation at each flow
3. Determine the tail water elevation
4. Estimate head loss
5. Compute the net head
6. Estimate the plant efficiency
7. Choose the wheel
8. Compute the discharge at all flow values for each exceedence percentage
9. Compute the power out put
10. Compute annual energy out put
11. Estimate annual plant cost
12. Calculate benefit
13. Plot a curve or develop the table to show where the maximum net benefit is obtained

Reservoir (Storage) Capacity

- Reservoir capacity is determined by means of mass curve procedure of computing the necessary capacity corresponding to a given inflow and demand pattern.

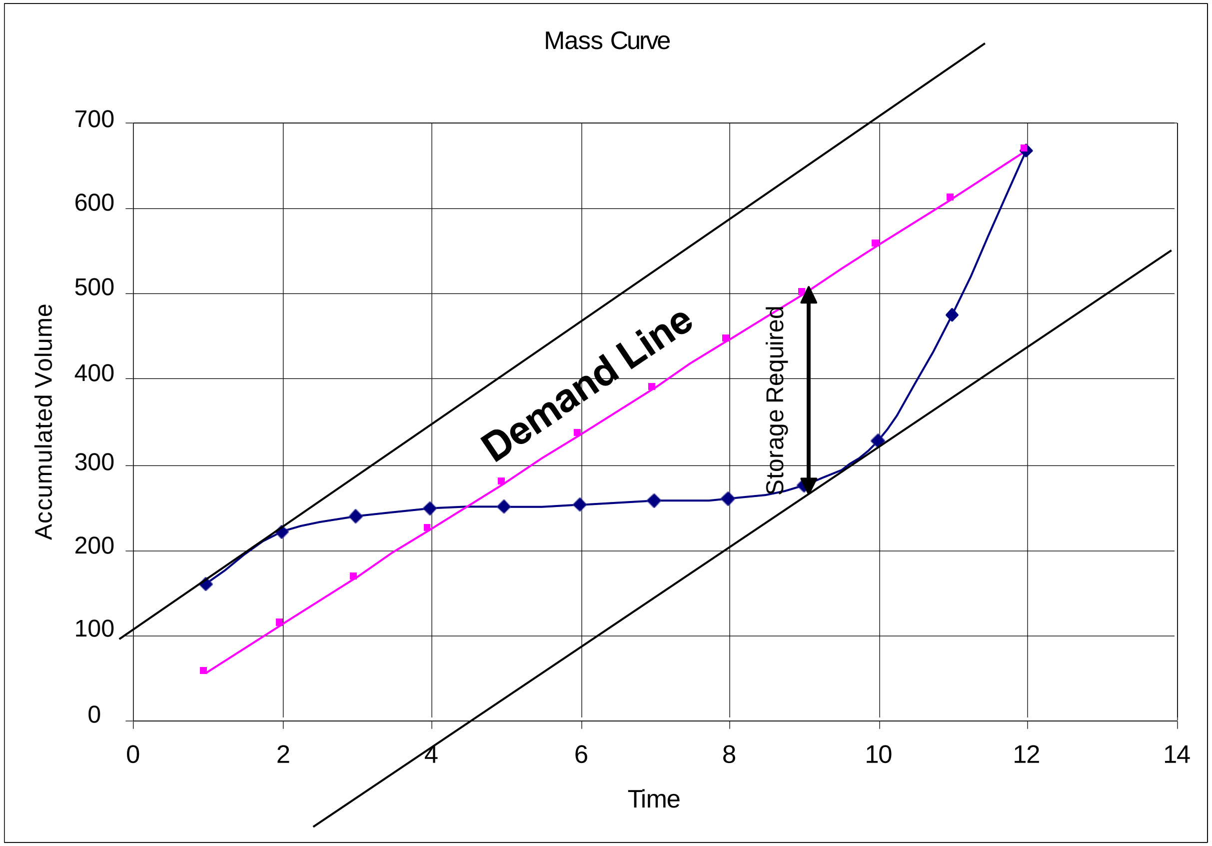
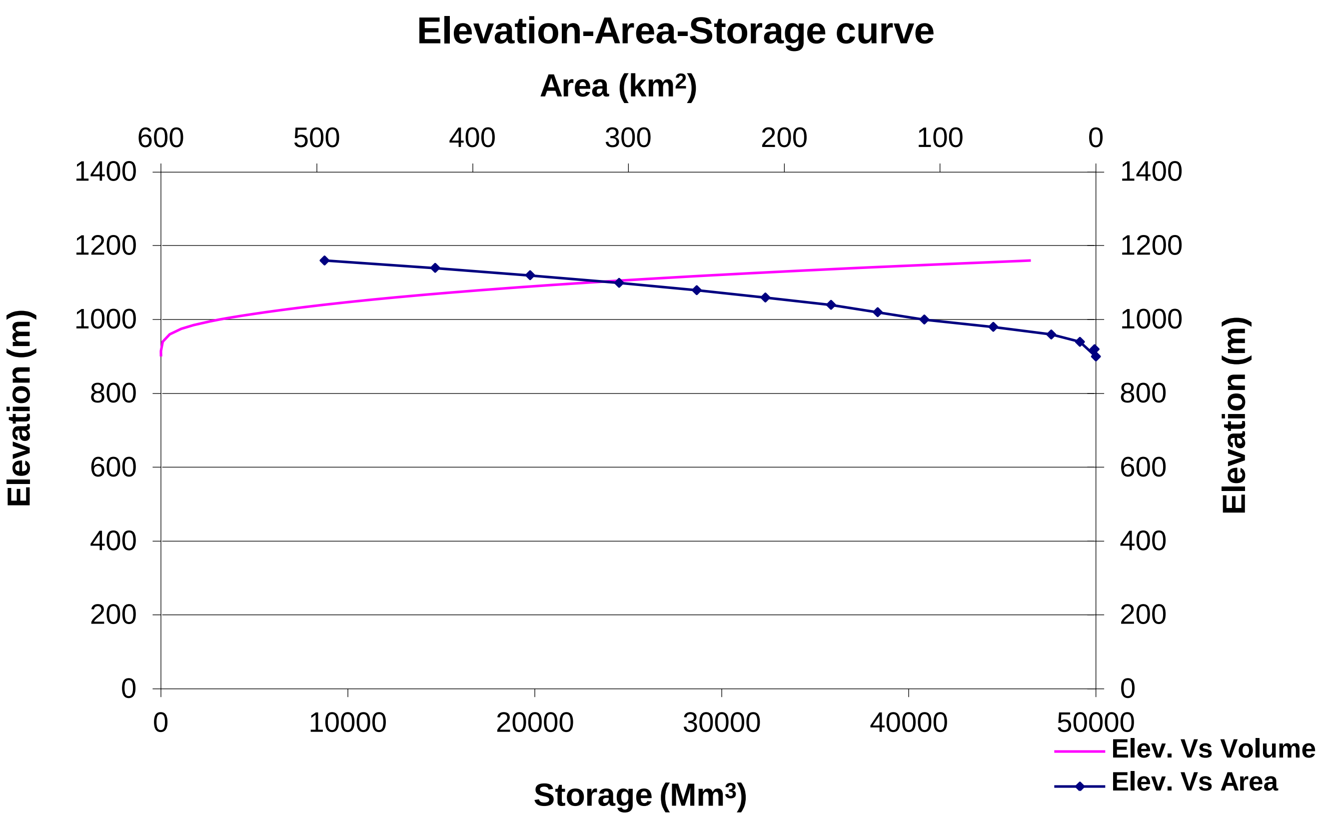


Figure: Reservoir capacity determination: Mass Curve Procedure

Reservoir (Storage) Capacity

- Reservoir capacity has to be adjusted to account for the dead storage, evaporation losses and carry over storage.

Area Capacity Curves



Reservoir (Storage) Capacity

- Reservoir capacity has to be adjusted to account for the dead storage, evaporation losses and carry over storage.
  - Area Capacity Curves
  - Reservoir Rule Curves
  - Evaporation Loss Evaluation from reservoirs
  - Spillway Design Flood Analysis

Reservoir Capacity Determination

Reservoir: During high flows, water flowing in a river has to be stored so that a uniform supply of water can be assured, for water resources utilisation like irrigation, water supply, power generation, etc. during periods of low flows of the river.

Its determination is performed using historical inflow records in the stream at the proposed dam site.

Why store

- Raise head
  - Hydro power
  - Allow greater flow to irrigation
- Smooth flow
  - Reliable Hydro power
  - Off season irrigation
  - Flood control
  - Domestic Water supply
- Other reasons
  - Fishing
  - Leisure

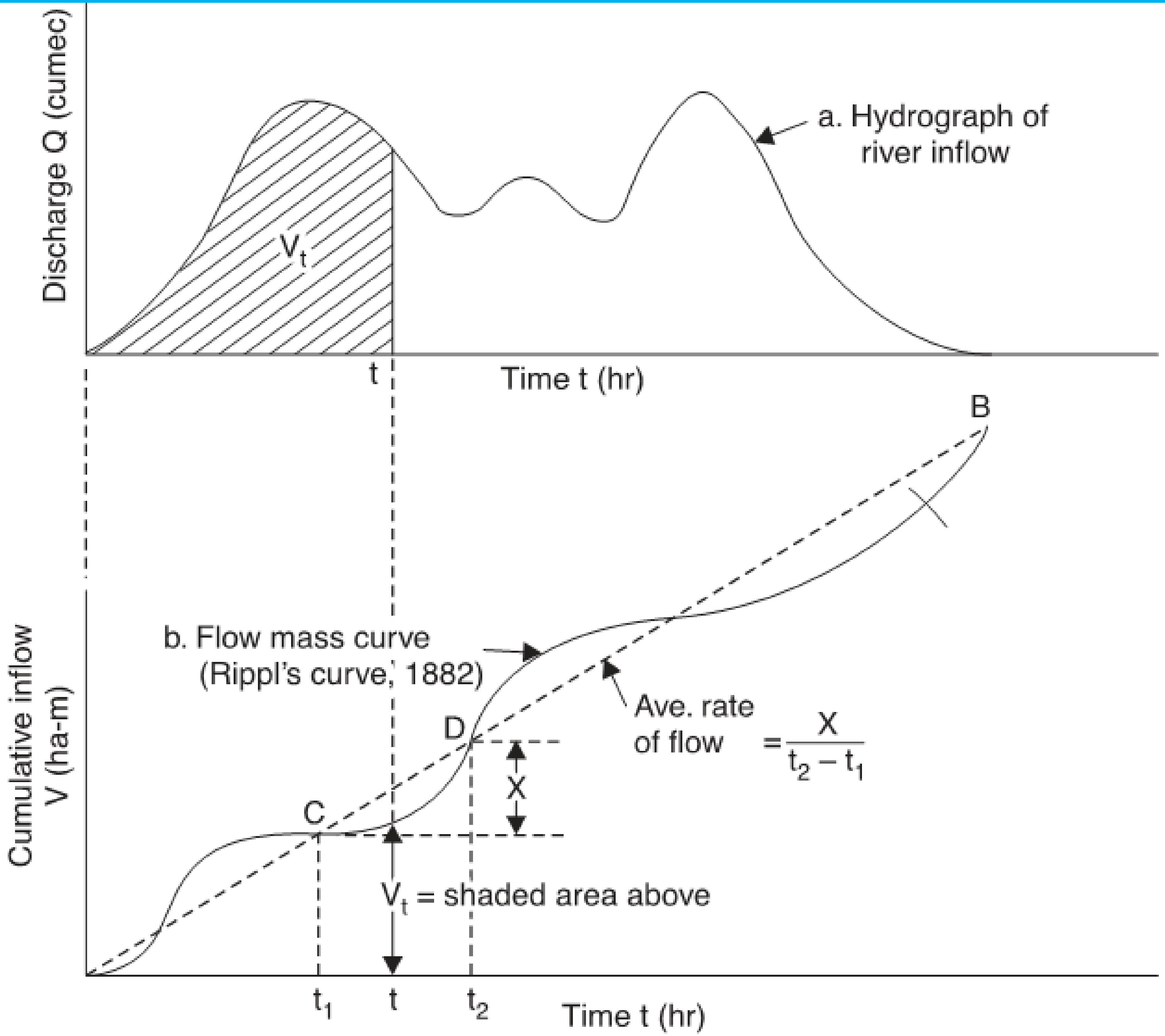
Methods to determine a reservoir storage capacity.

I. **Mass curve (Rippl's)**
II. **Sequent peak algorithm**
III. **Flow duration curve**

I. Mass curve (Rippl's) method:

- A mass curve (or mass inflow curve) is a plot of accumulated flow in a stream against time. It rises continuously as it shows accumulated flows.
- The slope of the curve at any point indicates the **rate of inflow** at that particular time.
- Required rates of draw off from the reservoir are marked by drawing tangents, having slopes equal to the demand rates, at the highest points of the mass curve
- If the demand is at a constant rate then the demand curve is a straight line having its **slope equal to the demand rate**. However, if the demand is not constant then the demand will be curved indicating a **variable rate of demand**.

I. Mass curve method



I. Mass curve method

- The maximum departure between the **demand line** and the **mass curve** represents the **storage capacity** of the reservoir required to meet the demand.

- A demand line must intersect the mass curve when extended forward, otherwise the reservoir is not going to refill.

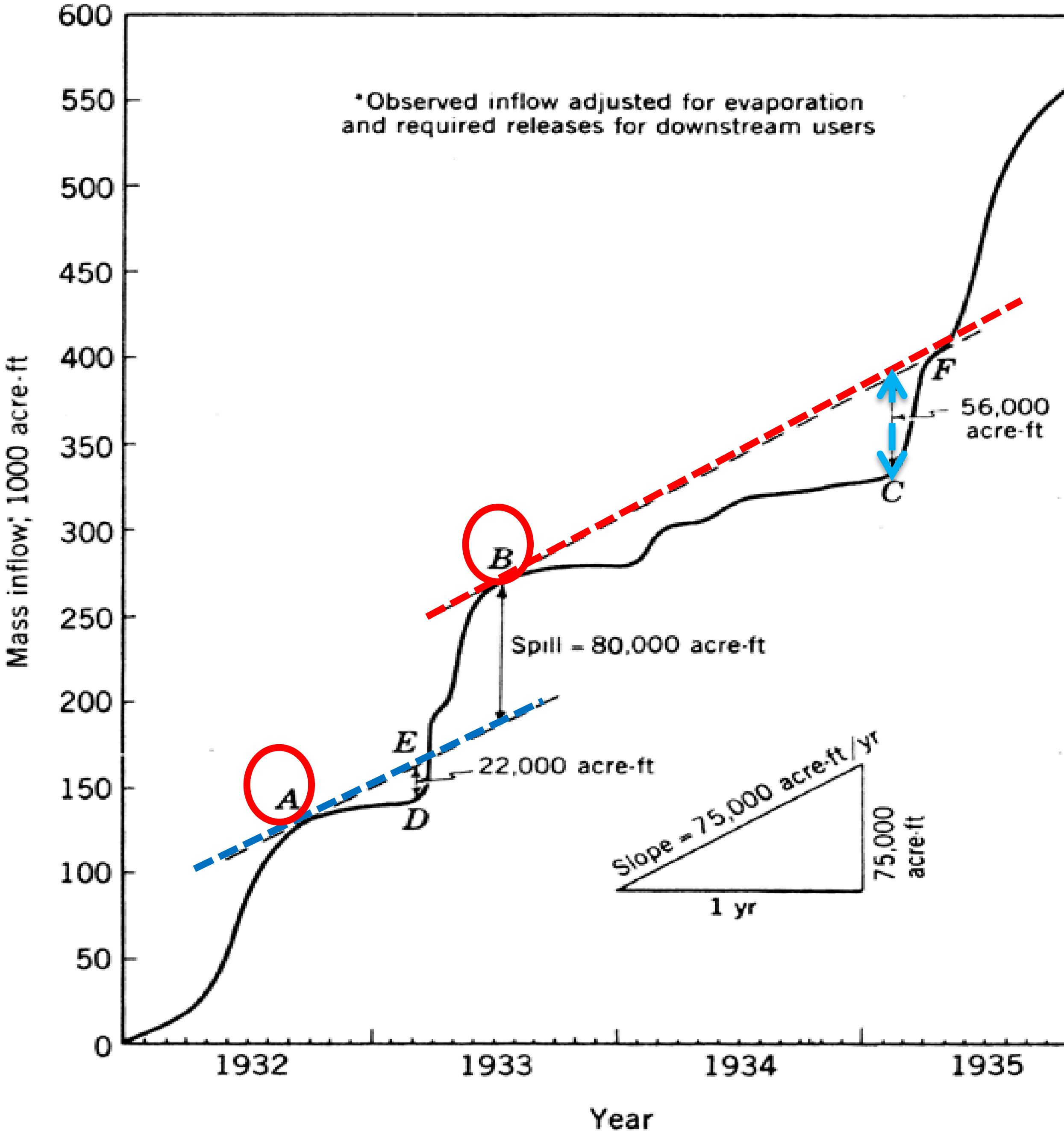
Assumptions

- The reservoir is full at time zero.
- In using historical flow data it is implicitly assumed that future flow sequence will not contain a more severe drought than the historical flow sequence.

Attributes

- The procedure is simple and it is widely understood
- It takes into account seasonality

I. Mass curve method



I. Mass curve method

Variable demand

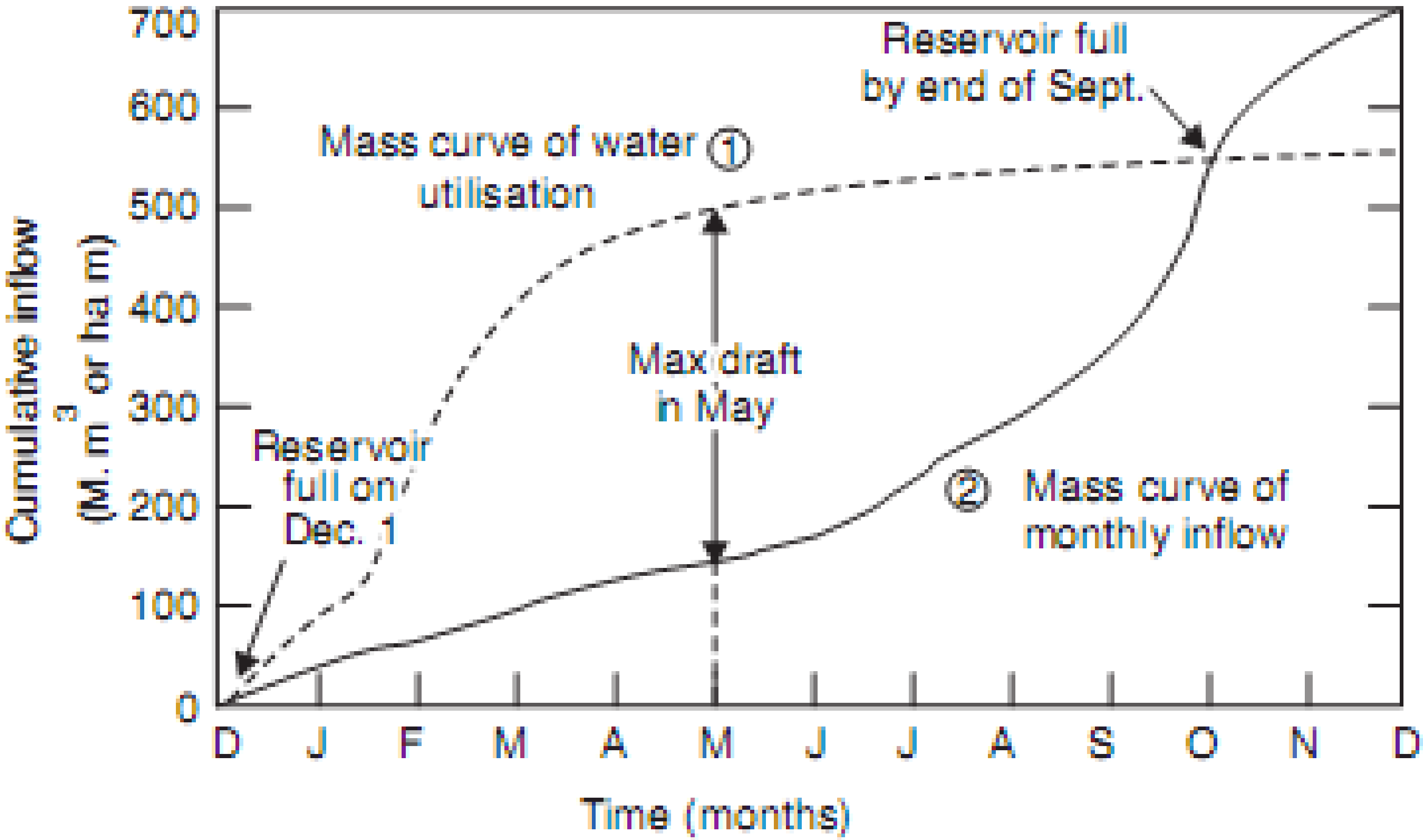


Fig. 10.2 Mass curves of water utilisation and monthly inflow

II. Sequent peak algorithm

Given an **N** year record of streamflow at site of proposed dam and demand, it is required to find a reservoir of minimum capacity such that the design demand can always be satisfied if the flows and demands are repeated in acyclic progression of cycles of **N** periods each.

Steps

I. Calculate (Flow-Demand) for all **i = 1, 2, …… , 2N** and hence the net cumulative flow $\sum_{i=1}^{t}(\boldsymbol{Flow} - \boldsymbol{Demand})$ *for* all **i = 1, 2, …… , 2N**

II. Locate the first peak, $\mathbf{H_1}$ in the column of cumulative net inflows

III. Locate the sequent peak, $\mathbf{H_2}$, which is the next peak of greater magnitude than the first.

IV. B/n this pair of peaks find the lowest trough $\mathbf{T_1}$ and calculate $\mathbf{H_1 - T_1}$.

V. Starting with $\mathbf{H_2}$, find the next sequent peak, $\mathbf{H_3}$, that has a magnitude greater than $\mathbf{H_2}$.

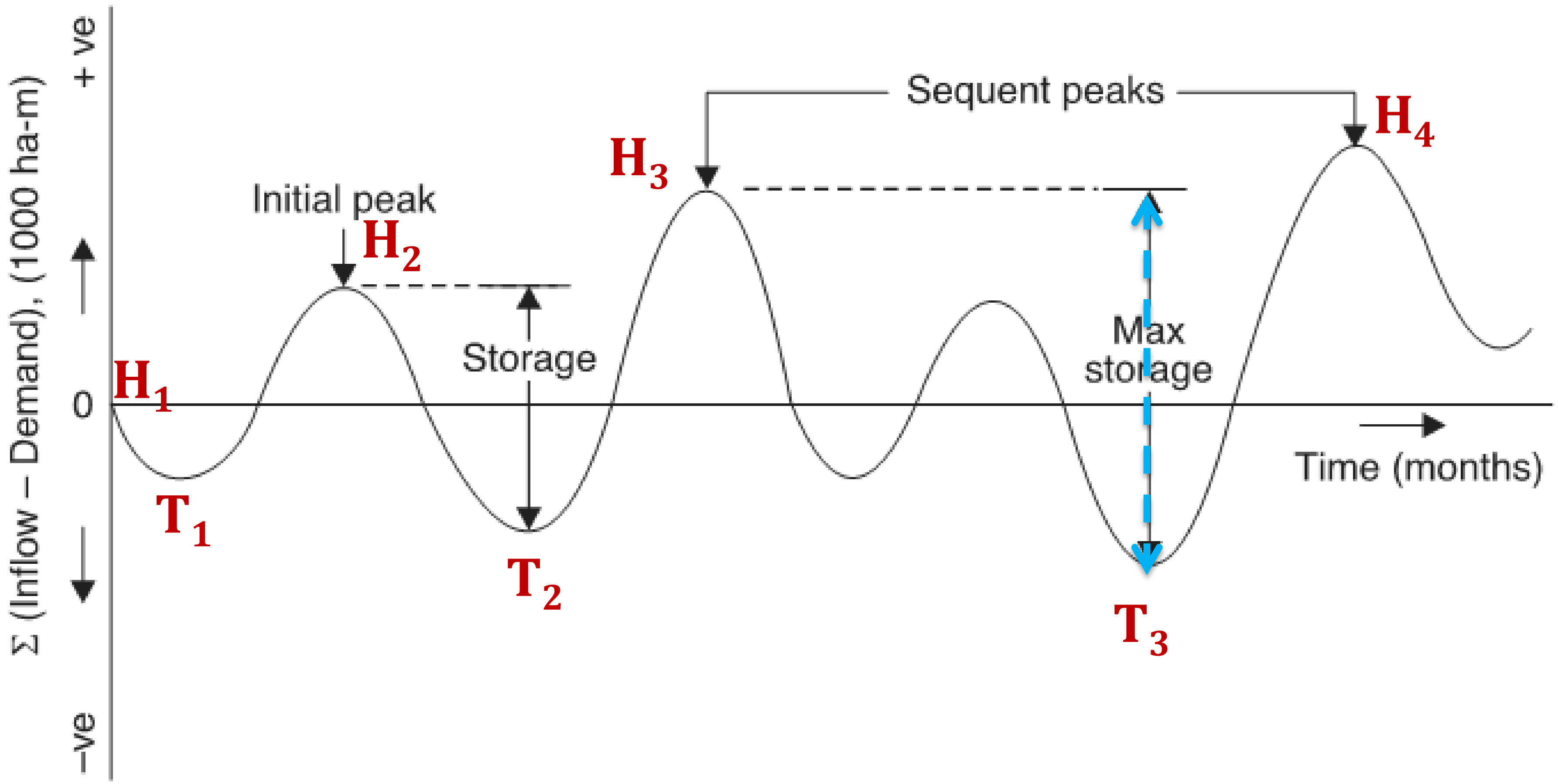
VI. Find the lowest trough, $\mathbf{T_2}$, b/n $\mathbf{H_2}$ and $\mathbf{H_3}$ and calculate $\mathbf{H_2 - T_2}$.

VII. Starting with $\mathbf{H_3}$, find $\mathbf{H_4}$ and $\mathbf{T_3}$ as above; calculate $\mathbf{H_3 - T_3}$.

VIII. Continue until all **k** sequent peaks in the series of the **2N** periods have been found.

IX. The required capacity is $\mathbf{C = max\ (H_k - T_k)}$

II. Sequent peak algorithm



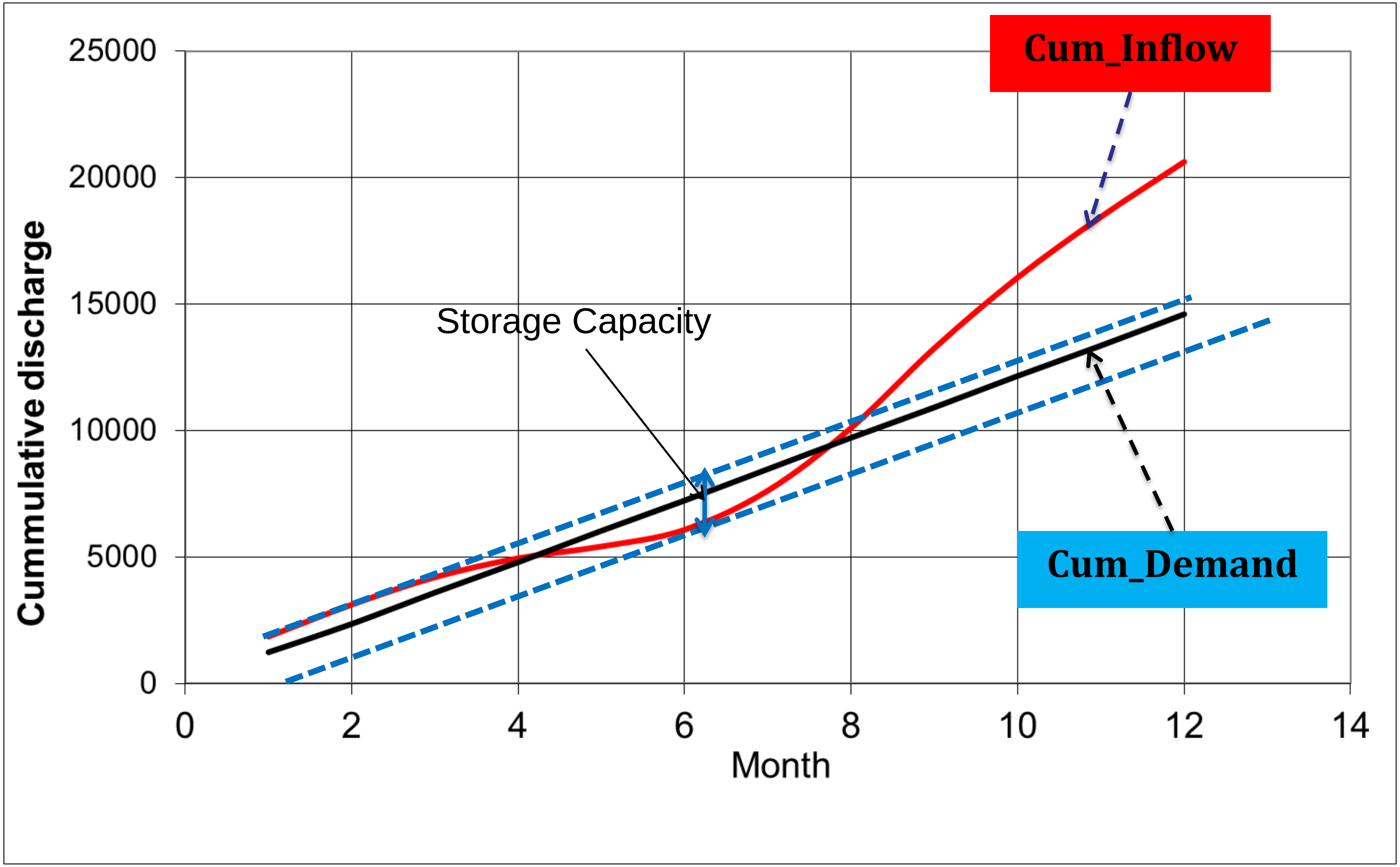
Example 1 Reservoir Capacity

The following table gives the mean monthly flows in a river during certain year. Calculate the minimum storage required for maintaining a demand rate of 40m3/s: (a) using graphical solution (b) using tabular solution.

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Mean flow M3/s	60	45	35	25	15	22	50	80	105	90	80	70

Month	Mean flow m3/s	Monthly flow (m3/s).day	Accum flow (m3/s). Day	Demand m3/s	Demand (m3/s). Day	Accum demand (m3/s). Day
Jan (31)	60	1860	1860	40	1240	1240
Feb (28)	45	1260	3120	40	1120	2360
Mar(31)	35	1085	4205	40	1240	3600
Apr(30)	25	750	4955	40	1200	4800
May(31)	15	465	5420	40	1240	6040
Jun(30)	22	660	6080	40	1200	7240
July(31)	50	1550	7630	40	1240	8480
Aug(31)	80	2480	10110	40	1240	9720
Sep(30)	105	3150	13260	40	1200	10920
Oct(31)	90	2790	16050	40	1240	12160
Nov(30)	80	2400	18450	40	1200	13360
Dec(31)	70	2170	20620	40	1240	14600

Example 1: Mass curve



Example 1: Sequent peak algorithm

1	2	3	4 = (2 - 3)	5
Month	Monthly flow (m3/s).day	Demand (m3/s). Day	Departure (m3/s).day	Cum departure (m3/s) .day
Jan	1860	1240	620	620
Feb	1260	1120	140	**760**
Mar	1085	1240	-155	605
Apr	750	1200	-450	155
May	465	1240	-775	-620
Jun	660	1200	-540	-1160
July	1550	1240	310	-850
Aug	2480	1240	1240	390
Sep	3150	1200	1950	2340
Oct	2790	1240	1550	3890
Nov	2400	1200	1200	5090
Dec	2170	1240	930	6020
Jan	1860	1240	620	6640
Feb	1260	1120	140	6780

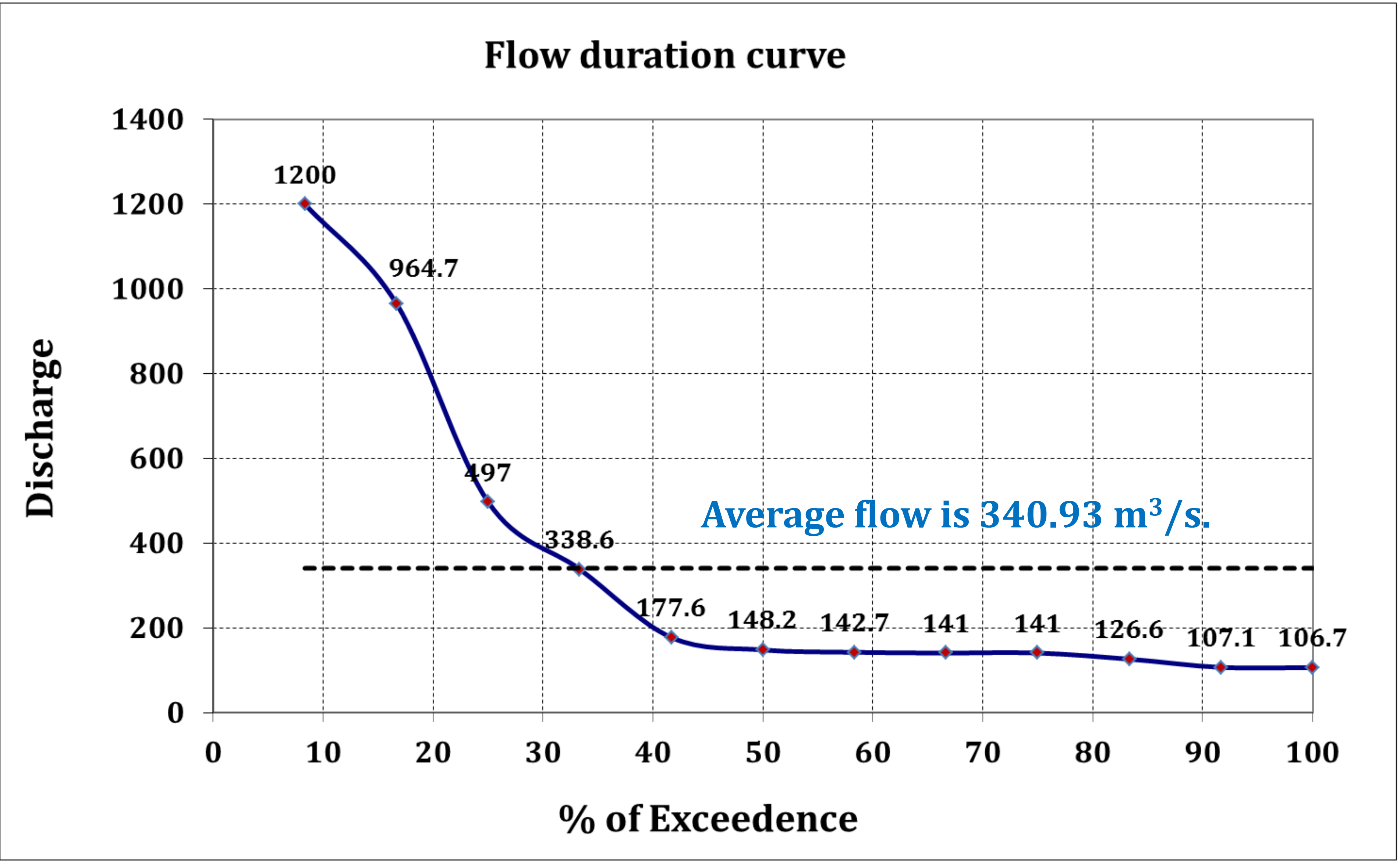
(H-T)=
760-(-1160)=
1920 Cumec-day

III. Flow duration curve method

Example 2: Reservoir Capacity determination by using **flow duration curve**. Determine the reservoir capacity required if a hydropower plant is designed to operate at an average flow. (p=m/n)

Month	Discharge (m3/s)	Rank	Discharge	% exceeded	Constant flow
Jan	106.7	1	1200	8.33	340.93
Feb	107.1	2	964.7	16.67	340.93
Mar	148.2	3	497	25.00	340.93
Apr	497	4	338.6	33.33	340.93
May	1200	5	177.6	41.67	340.93
Jun	964.7	6	148.2	50.00	340.93
Jul	338.6	7	142.7	58.33	340.93
Aug	177.6	8	141	66.67	340.93
Sep	141	9	141	75.00	340.93
Oct	141	10	126.6	83.33	340.93
Nov	142.7	11	107.1	91.67	340.93
Dec	126.6	12	106.7	100	340.93
Average flow			**340.93**		

III. Flow duration curve method



III. Flow duration curve method

1	2	3	(3-1)	Area	No. days
Discharge	% exceeded	Constant flow			
1200	8.33	340.93	0	0	31
964.7	16.67	340.93	0	0	28
497	25.00	340.93	0	0	31
338.6	33.33	340.93	2.33	6.90	30
177.6	41.67	340.93	163.33	14.84	31
148.2	50.00	340.93	192.73	16.29	30
142.7	58.33	340.93	198.23	16.59	31
141	66.67	340.93	199.93	16.66	31
141	75.00	340.93	199.93	17.26	30
126.6	83.33	340.93	214.33	18.67	31
107.1	91.67	340.93	233.83	19.50	30
106.7	100.00	340.93	234.23		31
340.93			Sum	126.72	30.417

Storage (Mm^3)	332.83

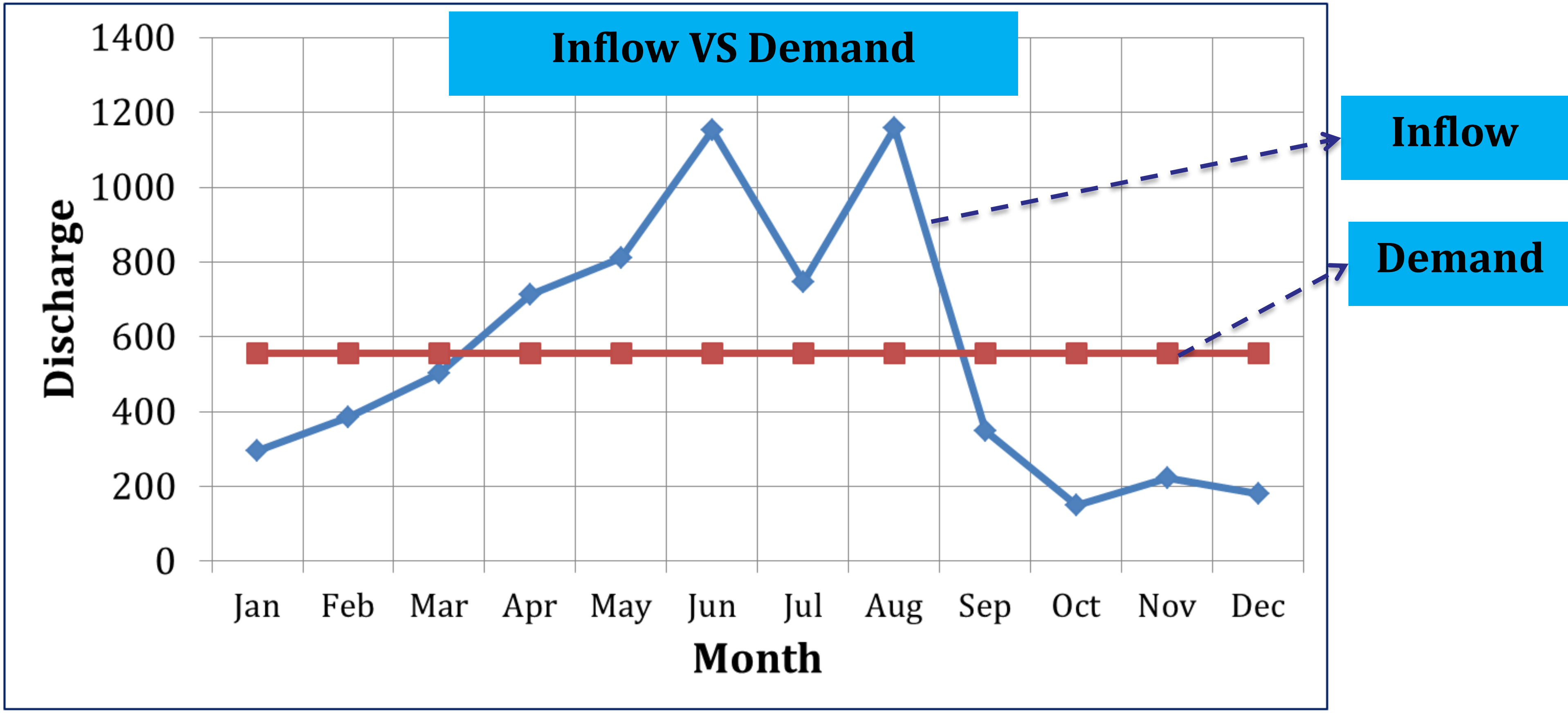
Area =((2.33+163.3)/2)*(41.67-33.33)*(1/100)

Storage = (126.72*30.4*24*60*60) / (1000000)

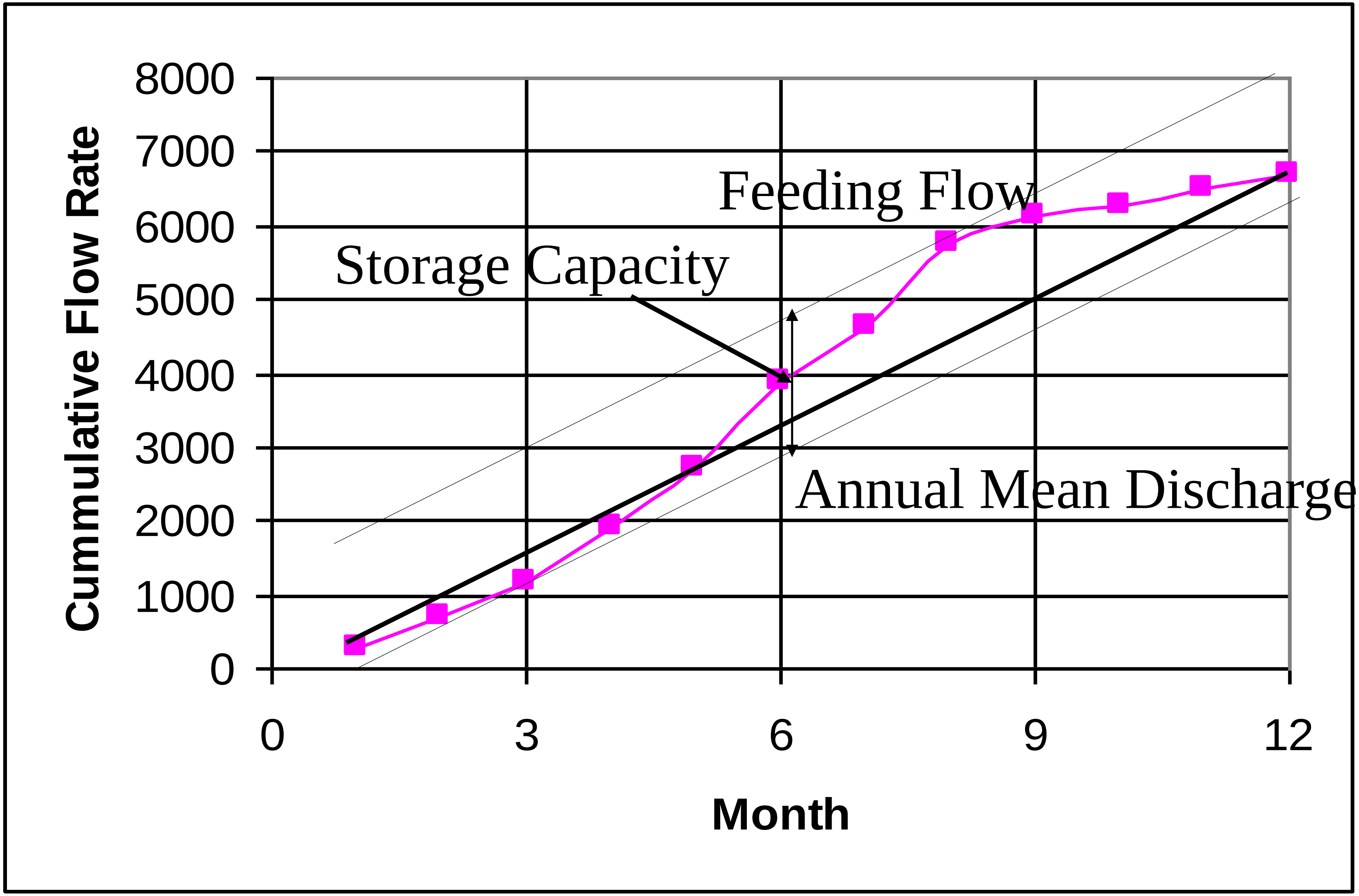
Example 3 Reservoir Capacity

The following table gives the mean monthly flows in a river during certain year. Calculate the minimum storage required for maintaining a demand rate of Mean flow (Average flow): **Mean flow = 555.9167**

Month	1	2	3	4	5	6	7	8	9	10	11	12
Discharge (MCM)	296	386	504	714	810	1154	746	1158	348	150	223	182



Example 3: Mass curve

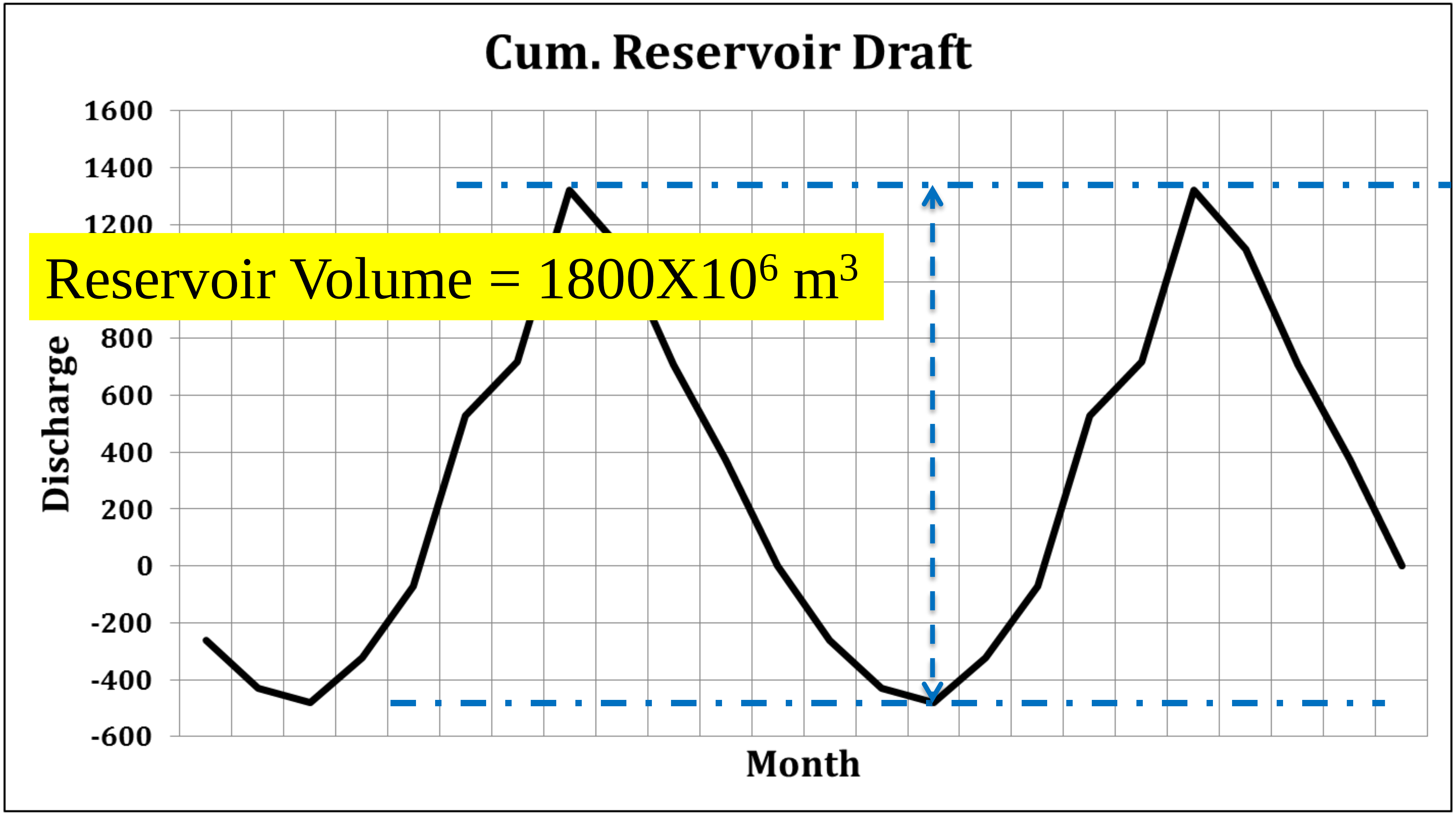


Example 3: Sequent peak algorithm

Month	Inflow Discharge	Inflow-Draft	Cum. Reservoir Draft
			0
1	296	-259.92	-259.9167
2	386	-169.92	-429.83
3	504	-51.92	**-481.75**
4	714	158.08	-323.67
5	810	254.08	-69.58
6	1154	598.08	528.50
7	746	190.08	718.58
8	1158	602.08	**1320.67**
9	348	-207.92	1112.75
10	150	-405.92	706.83
11	223	-332.92	373.92
12	182	-373.92	0.00
1	296	-259.92	-259.92
2	386	-169.92	-429.83
3	504	-51.92	**-481.75**
4	714	158.08	-323.67
5	810	254.08	-69.58
6	1154	598.08	528.50
7	746	190.08	718.58
8	1158	602.08	**1320.67**
9	348	-207.92	1112.75
10	150	-405.92	706.83
11	223	-332.92	373.92
12	182	-373.92	0.00

(H-T)= 1320.67-(-481.75)
=1802 Mm³

Example 3: Sequent peak algorithm



Reservoir Volume = $1800X10^6$ m^3

Thank you!!