Surface Water Hydrology
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Lecture – 25
Flow Characteristics Curves and Estimation of Reservoir Storage

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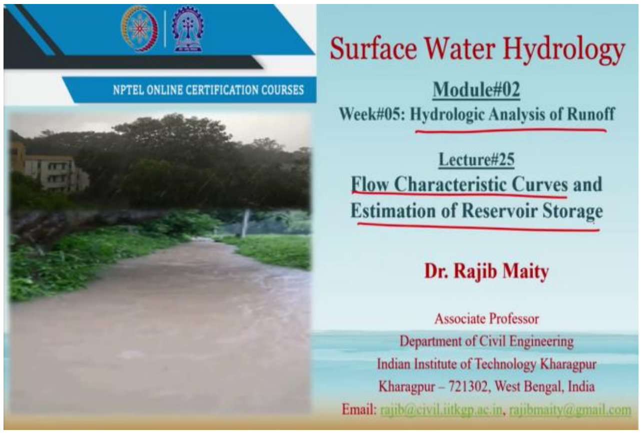

Lecture number-25 will discuss two things. One is the flow characteristics curve and secondly, the estimation of reservoir storage, how much water needs to be stored while we are designing one reservoir.

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The two major concepts, one is the flow characteristics curve, and the estimation of reservoir storage will be covered in this lecture.

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The outline of this lecture goes like this. So, first, we will give the introduction, and under these two curves that flow duration curve and flow mass curve; And then, using these characteristic curves and how these can be utilized for the estimation of the reservoir storage; and also some maintainable demands for a particular reservoir. The calculation based on the variable storage and variable demand will also be discussed. One algorithm, the sequent peak algorithm will be discussed and after that summary will be presented.

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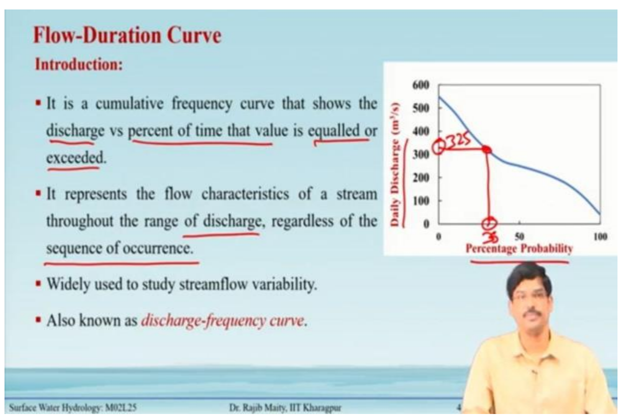

Flow-Duration Curve

Introduction:

It is a cumulative frequency curve that shows the discharge versus the percent of the time; that particular value is equaled or exceeded. In fig.1 y-axis shows the daily discharge; it can be daily or any other temporal scale of course. And in the x-axis shows the percentage probability.

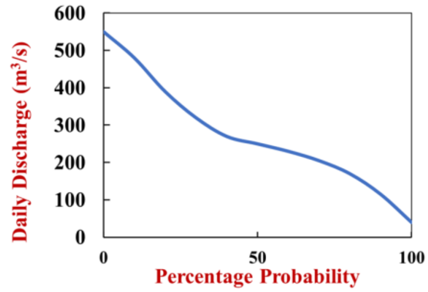

Fig.1 shows the flow-duration curve

If take any point on the y-axix in the fig.1, then this amount of discharge value that will be equaled or exceeded for this much percentage of the time. So, it represents the flow characteristics in a stream throughout the range of the discharge, regardless of its sequence of occurrence. It is utilized widely to study the streamflow variability, how it varies, particularly on an annual scale. And then, we also this kind of diagram is known as the discharge frequency curve.

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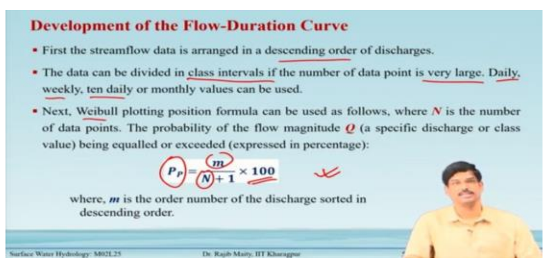

Development of the Flow-Duration Curve

- First, the streamflow data are arranged in descending order of discharges.
- The data can be divided into class intervals if the number of the data point is very large. Daily, weekly, ten daily or monthly values can be used.
- Next, the Weibull plotting position formula can be used as follows, where $\boldsymbol{N}$ is the number of data points. The probability of the flow magnitude $\boldsymbol{Q}$ (a specific discharge or class value) being equaled or exceeded (expressed in percentage):

$$\boldsymbol{P_P = \frac{m}{N+1} \times 100}$$

where m is the order number of the discharge sorted in descending order.

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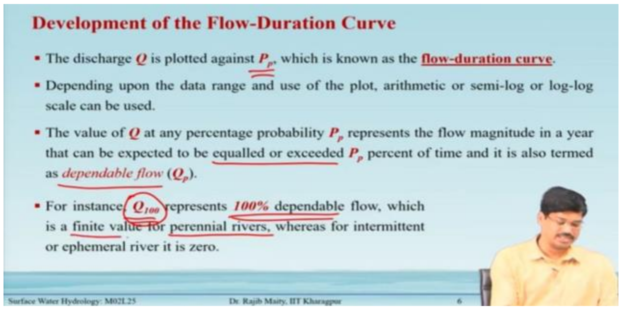

- The discharge Q is plotted against P_p, which is known as the flow duration curve.
- Depending upon the data range and use of the plot, arithmetic or semi-log or log-log scale can be used.
- The value of Q at any percentage probability P_p represents the flow magnitude in a year that can be expected to be equaled or exceeded P_p percent of the time and it is also termed as dependable flow (Q_p).
- For instance, Q_{100} represents 100% dependable flow, which is a finite value for perennial rivers, whereas for the intermittent or ephemeral river it is zero.

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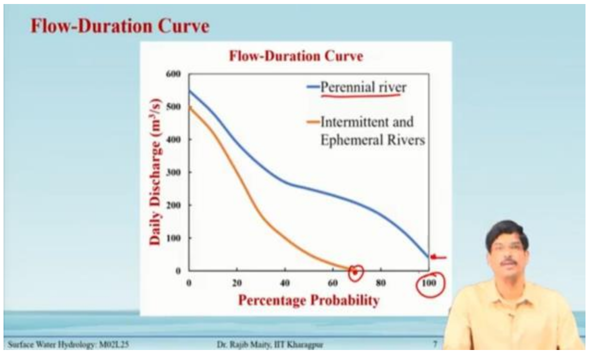

In fig.2 blue line is for the perennial river, and the red line is intermittent or ephemeral rivers are shown. Here it is not 0 at the 100 percent, so far as the perineal viewer is concerned. But, whereas for the other type it is touching 0, maybe around some percentage here, so that Q_{100} is 0.

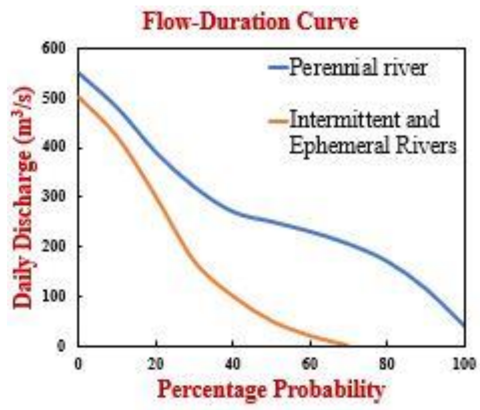

Fig. 2shows the flow duration curve for a different types of rivers

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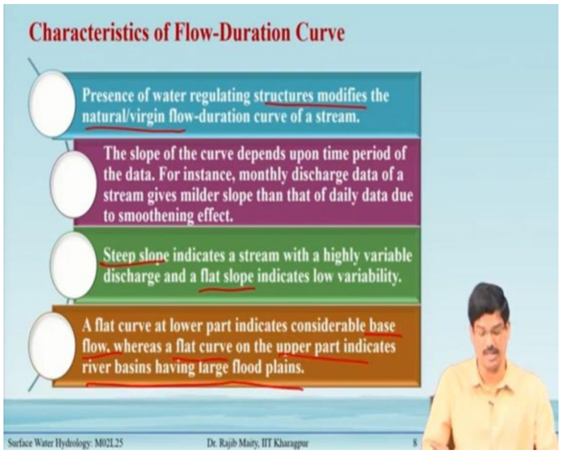

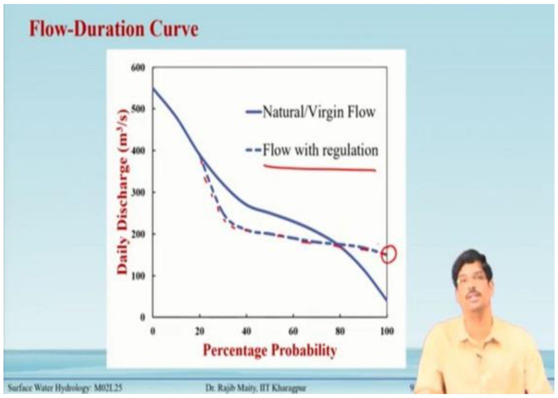

Characteristics of Flow-Duration Curve

- The presence of water regulating structures modifies the natural/virgin flow-duration curve of a stream.

- The slope of the curve depends upon the time period of the data. For instance, monthly discharge data of a stream gives a milder slope than that of daily data due to smoothening effect.
- The steep slope indicates a stream with a highly variable discharge and a flat slope indicates low variability.
- A flat curve at the lower part indicates considerable base flow, whereas a flat curve on the upper part indicates river basins having large flood plains.

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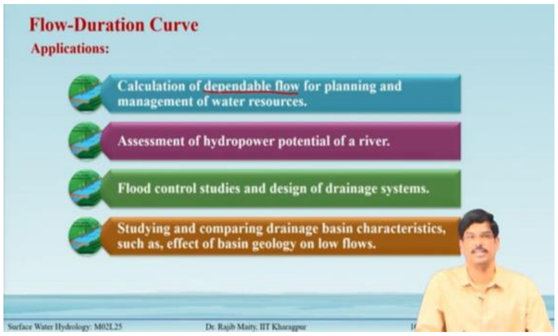

Applications of the flow-duration curve:

- Calculation of dependable flow for planning and management of water resources.
- Assessment of hydropower potential of a river.
- Flood control studies and design of drainage systems
- Studying and comparing drainage basin characteristics, such as the effect of basin geology on low flows.

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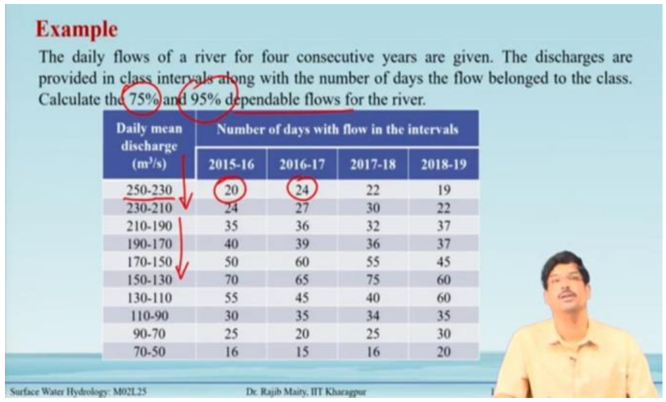

Example

The daily flows of a river for four consecutive years are given. The discharges are provided in class intervals along with the number of days the flow belonged to the class. Calculate the 75% and 95% dependable flows for the river.

Daily mean discharge (m^3/s)	Number of days with flow in the intervals			
	2015-16	2016-17	2017-18	2018-19
250-230	20	24	22	19
230-210	24	27	30	22
210-190	35	36	32	37
190-170	40	39	36	37
170-150	50	60	55	45
150-130	70	65	75	60
130-110	55	45	40	60
110-90	30	35	34	35
90-70	25	20	25	30
70-50	16	15	16	20

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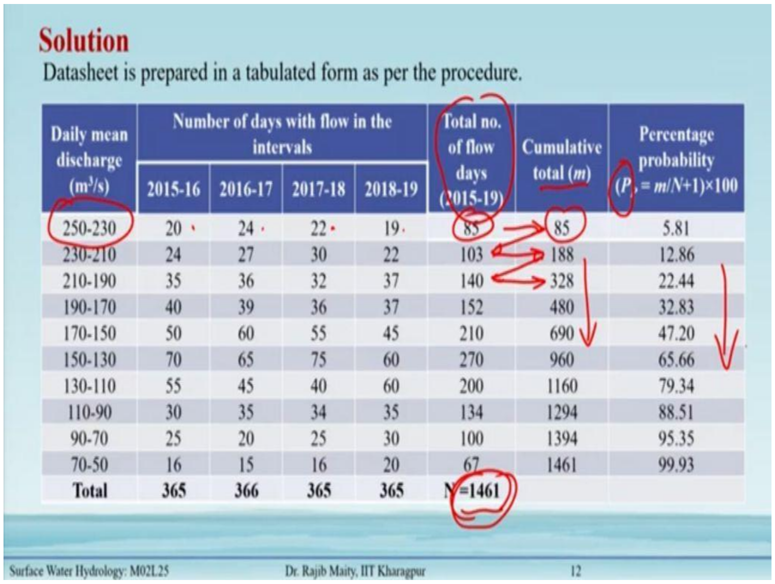

Solution

A datasheet is prepared in a tabulated form as per the procedure.

Daily mean discharge (m^3/s)	Number of days with flow in the intervals				Total no. of flow days (2015-19)	Cumulative total (m)	Percentage probability ($P_P = m/N+1)\times100$
	2015-16	2016-17	2017-18	2018-19			
250-230	20	24	22	19	85	85	5.81
230-210	24	27	30	22	103	188	12.86
210-190	35	36	32	37	140	328	22.44
190-170	40	39	36	37	152	480	32.83
170-150	50	60	55	45	210	690	47.20
150-130	70	65	75	60	270	960	65.66
130-110	55	45	40	60	200	1160	79.34
110-90	30	35	34	35	134	1294	88.51
90-70	25	20	25	30	100	1394	95.35
70-50	16	15	16	20	85	1461	99.93
Total	**365**	**366**	**365**	**365**	**N =1461**		

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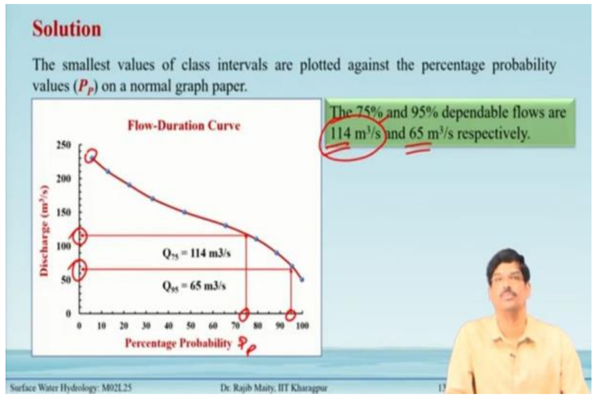

The smallest values of class intervals are plotted against the percentage probability values (P_P) on a normal graph paper.

The 75% and 95% dependable flows are 114 m^3/s and 65 m^3/s respectively.

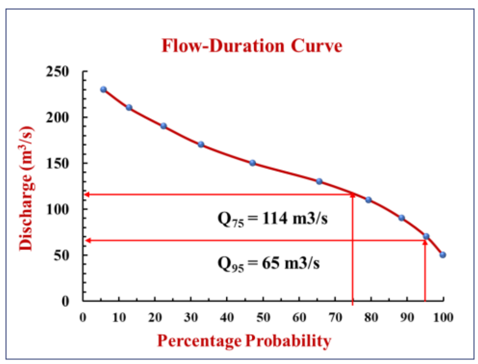

Fig.3 shows the flow duration curve- example

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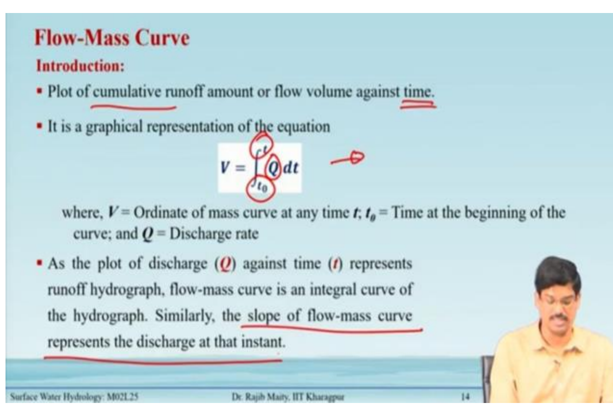

Introduction:

- A plot of cumulative runoff amount or flow volume against time.
- It is a graphical representation of the equation

$$V = \int_{t_0}^{t} Q\, dt$$

where, V = Ordinate of the mass curve at any time t; t_0 = Time at the beginning of the curve; and Q = Discharge rate

- As the plot of discharge (Q) against time (t) represents runoff hydrograph, a flow-mass curve is an integral curve of the hydrograph. Similarly, the slope of the flow-mass curve represents the discharge at that instant.

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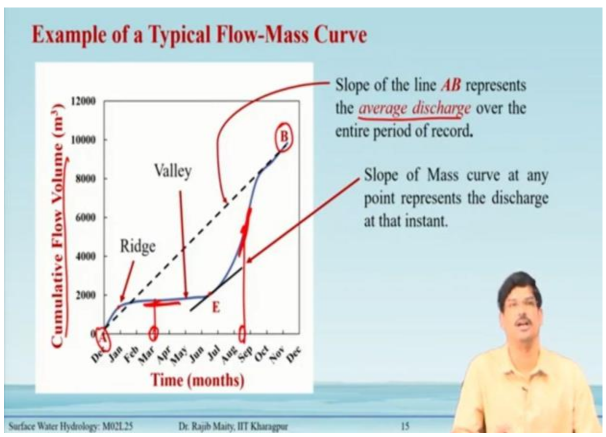

One typical flow-mass curve is shown in fig.4. The blue line is shown for e different months and the cumulative flow volume is shown in meter cube per thing. A is the starting point of the curve and B is the one, and there are some reach points.

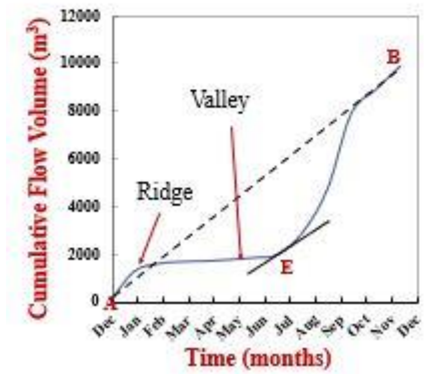

Fig.4 shows the flow mass curve

The slope of the Mass curve at any point (E point) represents the discharge at that instant. When the slope is flat that time the discharge is less; when the slope is high, the discharge is high. In fig.4 the month of March, the discharge rate is less and in the month of say, August, September, the discharge is very high. And if we just add up the starting and the ending point, the dotted line that is shown here; the slope of this average line AB that is the average discharge, that is occurring place over the entire time that has been shown in the x-axis.

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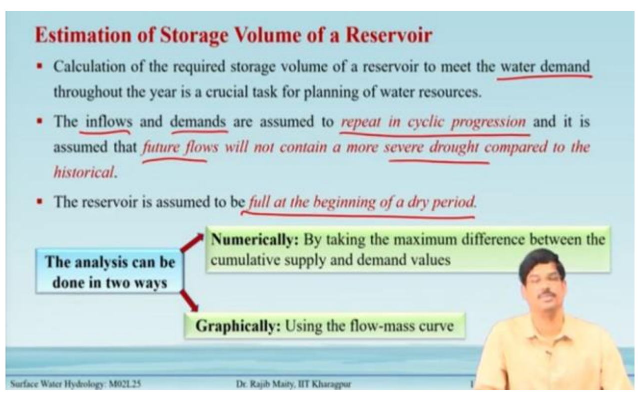

Estimation of Storage Volume of a Reservoir

Calculation of the required storage volume of a reservoir to meet the water demand throughout the year is a crucial task for the planning of water resources.

The inflows and demands are assumed to repeat in cyclic progression and it is assumed that future flows will not contain a more severe drought compared to the historical. The reservoir is assumed to be full at the beginning of a dry period.

The analysis can be done in two ways

Numerically: By taking the maximum difference between the cumulative supply and demand values

Graphically: Using the flow-mass curve

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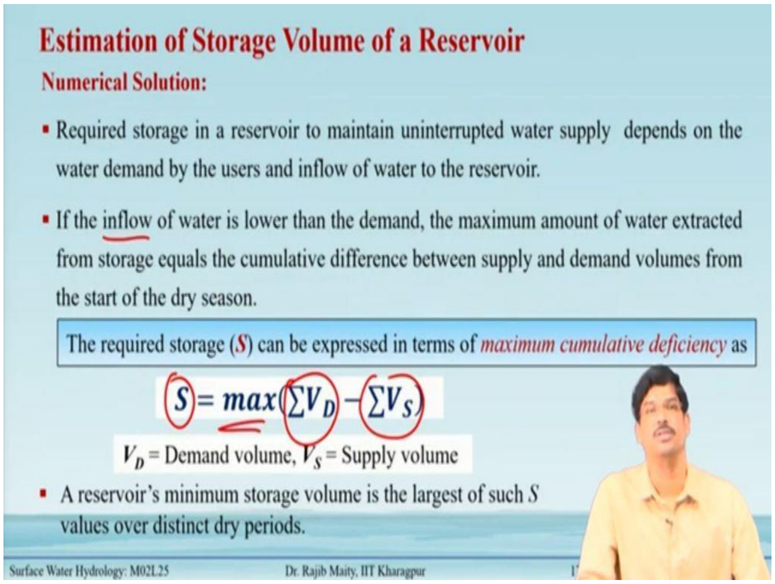

Numerical Solution:

Required storage in a reservoir to maintain an uninterrupted water supply depends on the water demand by the users and the inflow of water to the reservoir. If the inflow of water is lower than the demand, the maximum amount of water extracted from storage equals the cumulative difference between supply and demand volumes from the start of the dry season.

The required storage (S) can be expressed in terms of maximum cumulative deficiency as

$$S = max\left(\sum V_D - \sum V_S\right)$$

$\boldsymbol{V_D}$ = Demand volume, $\boldsymbol{V_S}$ = Supply volume

A reservoir's minimum storage volume is the largest of such S values over distinct dry periods.

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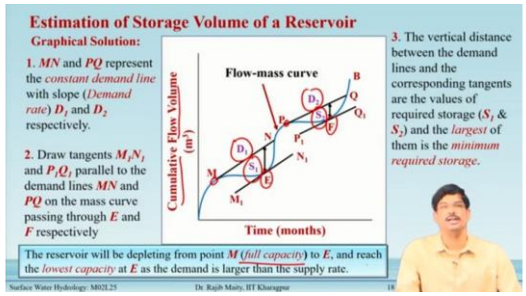

Graphical Solution:

The cumulative flow-volume curve is shown in fig. 5. Now, there are two almost two cycles are there; the M is the first reach point, then P is another reach point.

> **1**. MN and PQ represent the constant demand line with slope (Demand rate) D_1 and D_2 respectively.
>
> 2. Draw tangents M_1N_1 and P_1Q_1 parallel to the demand lines MN and PQ on the mass curve passing through E and F respectively
>
> 3. The vertical distance between the demand lines and the corresponding tangents are the values of required storage (S_1 & S_2) and the largest of them is the minimum required storage. The reservoir will be depleted from point M (full capacity) to E, and reach the lowest capacity at E as the demand is larger than the supply rate.

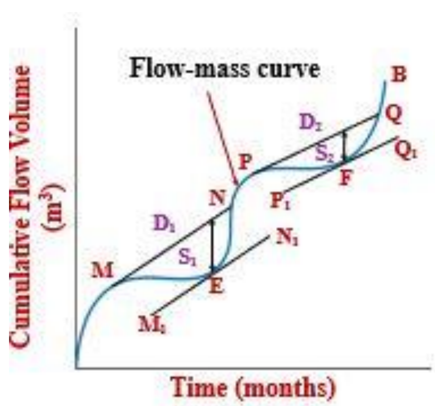

Fig.5 shows the flow mass curve

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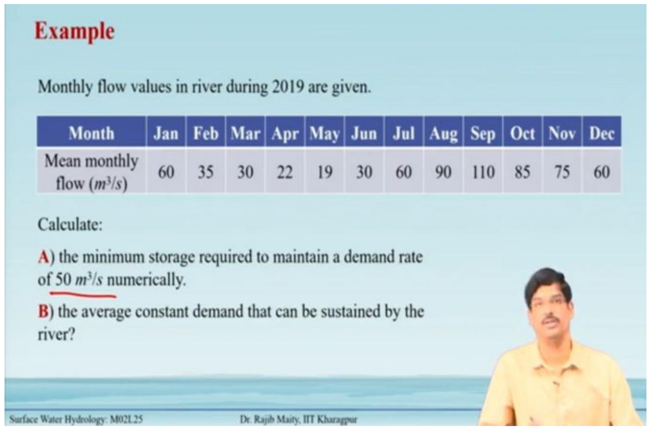

Example

Monthly flow values in river during 2019 are given.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean monthly flow (m^3/s)	60	35	30	22	19	30	60	90	110	85	75	60

Calculate:

A) the minimum storage required to maintain a demand rate of 50 m^3/s numerically.

B) the average constant demand that can be sustained by the river?

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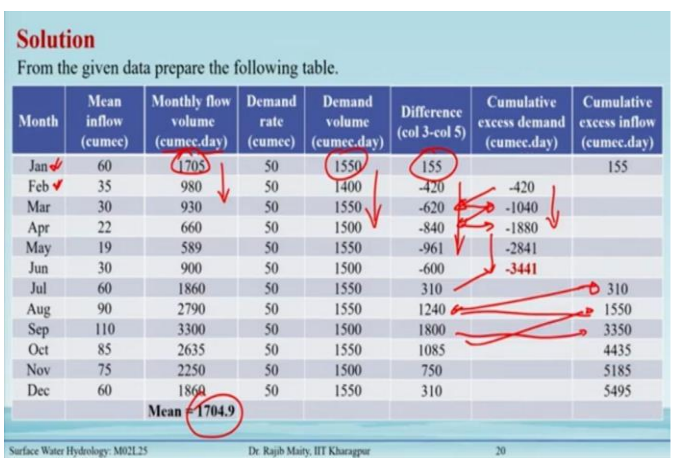

Month	Mean inflow (cumec)	Monthly flow volume (cumec.day)	Demand rate (cumec)	Demand volume (cumec.day)	Difference (col 3-col 5)	Cumulative excess demand (cumec.day)	Cumulative excess inflow (cumec.day)
Jan	60	1705	50	1550	155		155
Feb	35	980	50	1400	-420	-420	
Mar	30	930	50	1550	-620	-1040	
Apr	22	660	50	1500	-840	-1880	
May	19	589	50	1550	-961	-2841	
Jun	30	900	50	1500	-600	-3441	
Jul	60	1860	50	1550	310		310
Aug	90	2790	50	1550	1240		1550
Sep	110	3300	50	1500	1800		3350
Oct	85	2635	50	1550	1085		4435
Nov	75	2250	50	1500	750		5185
Dec	60	1860	50	1550	310		5495
		Mean = 1704.9					

Solution

From the given data prepare the following table.

Month	Mean inflow (cumec)	Monthly flow volume (cumec.day)	Demand rate (cumec)	Demand volume (cumec.day)	Difference (col 3-col 5)	Cumulative excess demand (cumec.day)	Cumulative excess inflow (cumec.day)
Jan	60	1705	50	1550	155		155
Feb	35	980	50	1400	-420	-420	
Mar	30	930	50	1550	-620	-1040	
Apr	22	660	50	1500	-840	-1880	
May	19	589	50	1550	-961	-2841	
Jun	30	900	50	1500	-600	**-3441**	
Jul	60	1860	50	1550	310		310
Aug	90	2790	50	1550	1240		1550
Sep	110	3300	50	1500	1800		3350
Oct	85	2635	50	1550	1085		4435
Nov	75	2250	50	1500	750		5185
Dec	60	1860	50	1550	310		5495
		Mean = 1704.9					

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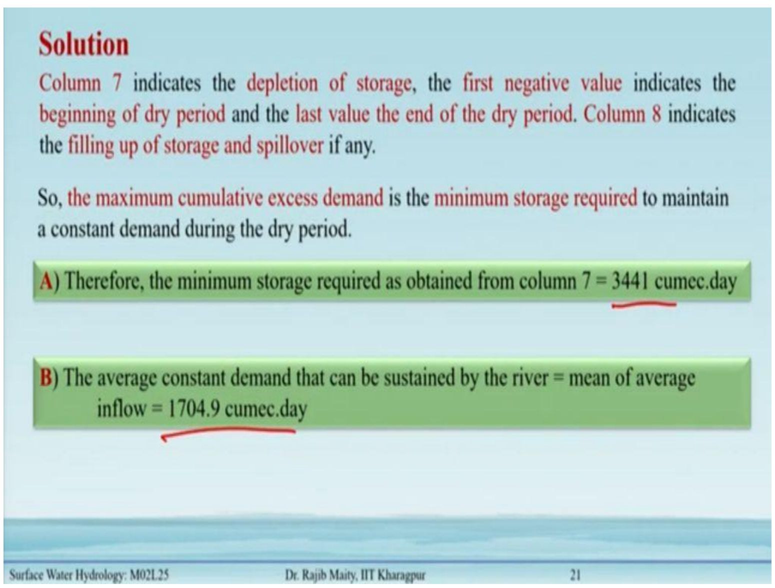

Solution

Column 7 indicates the depletion of storage; the first negative value indicates the beginning of a dry period and the last value the end of the dry period. Column 8 indicates the filling up of storage and spillover if any.

So, the maximum cumulative excess demand is the minimum storage required to maintain a constant demand during the dry period.

A) Therefore, the minimum storage required as obtained from column 7 = 3441 cumec. day

B) The average constant demand that can be sustained by the river = mean of average inflow = 1704.9 cumec. day

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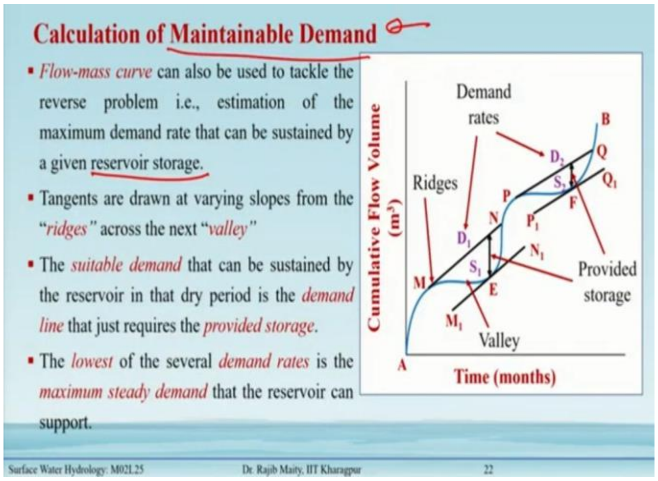

Calculation of Maintainable Demand

The flow-mass curve can also be used to tackle the reverse problem i.e., estimation of the maximum demand rate that can be sustained by given reservoir storage.

Tangents are drawn at varying slopes from the “ridges” across the next “valley”. The suitable demand that can be sustained by the reservoir in that dry period is the demand line that just requires the provided storage. The lowest of the several demand rates is the maximum steady demand that the reservoir can support.

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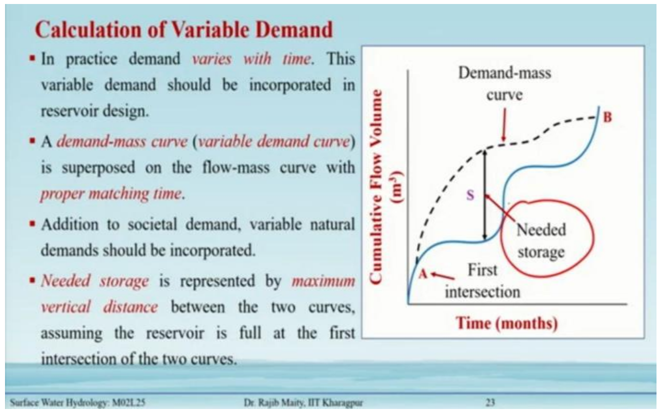

Calculation of Variable Demand

In practice, demand varies with time. This variable demand should be incorporated in reservoir design.

A demand-mass curve (variable demand curve) is superposed on the flow-mass curve with proper matching time. In addition to societal demand, variable natural demands should be incorporated. It depends on the different times of the year or the total time period, the demand can vary.

Needed storage is represented by the maximum vertical distance between the two curves, assuming the reservoir is full at the first intersection of the two curves.

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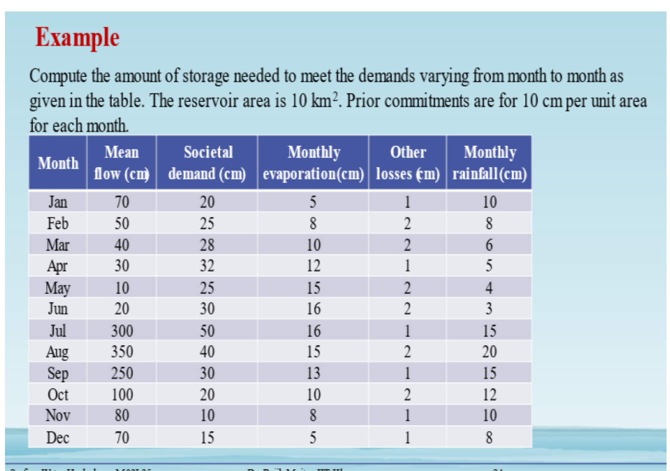
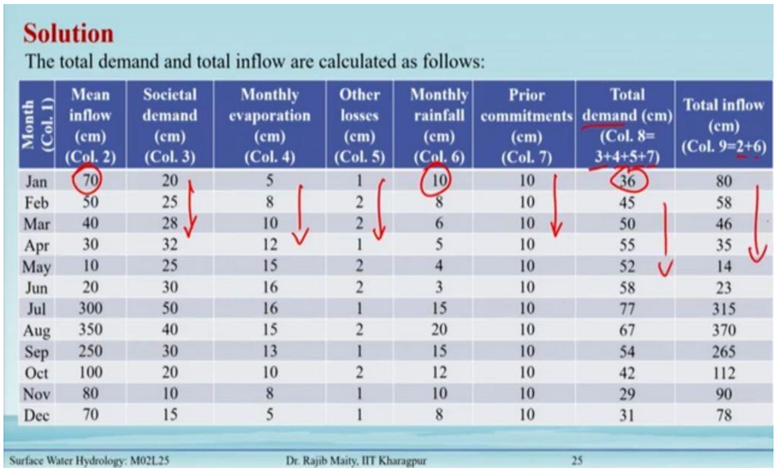


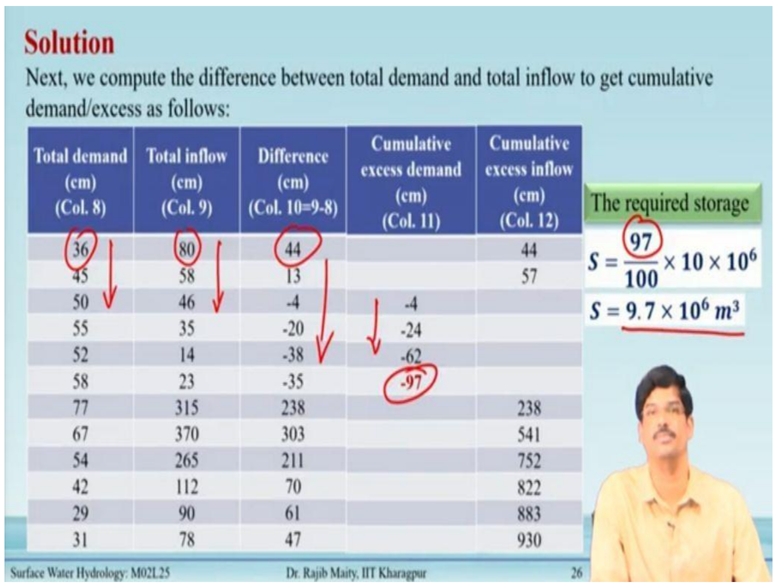
Month	Mean flow (cm)	Societal demand (cm)	Monthly evaporation(cm)	Other losses (cm)	Monthly rainfall(cm)
Jan	70	20	5	1	10
Feb	50	25	8	2	8
Mar	40	28	10	2	6
Apr	30	32	12	1	5
May	10	25	15	2	4
Jun	20	30	16	2	3
Jul	300	50	16	1	15
Aug	350	40	15	2	20
Sep	250	30	13	1	15
Oct	100	20	10	2	12
Nov	80	10	8	1	10
Dec	70	15	5	1	8



Solution

The total demand and total inflow are calculated as follows:

Month (Col. 1)	Mean inflow (cm) (Col. 2)	Societal demand (cm) (Col. 3)	Monthly evaporation (cm) (Col. 4)	Other losses (cm) (Col. 5)	Monthly rainfall (cm) (Col. 6)	Prior commitments (cm) (Col. 7)	Total demand (cm) (Col. 8= 3+4+5+7)	Total inflow (cm) (Col. 9=2+6)
Jan	70	20	5	1	10	10	36	80
Feb	50	25	8	2	8	10	45	58
Mar	40	28	10	2	6	10	50	46
Apr	30	32	12	1	5	10	55	35
May	10	25	15	2	4	10	52	14
Jun	20	30	16	2	3	10	58	23
Jul	300	50	16	1	15	10	77	315
Aug	350	40	15	2	20	10	67	370
Sep	250	30	13	1	15	10	54	265
Oct	100	20	10	2	12	10	42	112
Nov	80	10	8	1	10	10	29	90
Dec	70	15	5	1	8	10	31	78



Solution

Next, we compute the difference between total demand and total inflow to get cumulative demand/excess as follows:

Total demand (cm) (Col. 8)	Total inflow (cm) (Col. 9)	Difference (cm) (Col. 10=9-8)	Cumulative excess demand (cm) (Col. 11)	Cumulative excess inflow (cm) (Col. 12)
36	80	44		44
45	58	13		57
50	46	-4	-4	
55	35	-20	-24	
52	14	-38	-62	
58	23	-35	-97	
77	315	238		238
67	370	303		541
54	265	211		752
42	112	70		822
29	90	61		883
31	78	47		930

The required storage

$$S = \frac{97}{100} \times 10 \times 10^6$$

$$S = 9.7 \times 10^6\ m^3$$

Example

Compute the amount of storage needed to meet the demands varying from month to month as given in the table. The reservoir area is 10 km^2. Prior commitments are for 10 cm per unit area for each month.

Month	Mean flow (cm)	Societal demand (cm)	Monthly evaporation (cm)	Other losses (cm)	Monthly rainfall (cm)
Jan	70	20	5	1	10
Feb	50	25	8	2	8
Mar	40	28	10	2	6
Apr	30	32	12	1	5
May	10	25	15	2	4
Jun	20	30	16	2	3
Jul	300	50	16	1	15
Aug	350	40	15	2	20
Sep	250	30	13	1	15
Oct	100	20	10	2	12
Nov	80	10	8	1	10
Dec	70	15	5	1	8

Solution

Month (Col. 1)	Mean inflow (cm) (Col. 2)	Societal demand (cm) (Col. 3)	Monthly evaporation (cm) (Col. 4)	Other losses (cm) (Col. 5)	Monthly rainfall (cm) (Col. 6)	Prior commitments (cm) (Col. 7)	Total demand (cm) (Col. 8= 3+4+5+7)	Total inflow (cm) (Col. 9=2+6)
Jan	70	20	5	1	10	10	36	80
Feb	50	25	8	2	8	10	45	58
Mar	40	28	10	2	6	10	50	46
Apr	30	32	12	1	5	10	55	35
May	10	25	15	2	4	10	52	14
Jun	20	30	16	2	3	10	58	23
Jul	300	50	16	1	15	10	77	315
Aug	350	40	15	2	20	10	67	370
Sep	250	30	13	1	15	10	54	265
Oct	100	20	10	2	12	10	42	112
Nov	80	10	8	1	10	10	29	90
Dec	70	15	5	1	8	10	31	78

Next, we compute the difference between total demand and total inflow to get cumulative demand/excess as follows:

Total demand (cm) (Col. 8)	Total inflow (cm) (Col. 9)	Difference (cm) (Col. 10=9-8)	Cumulative excess demand (cm) (Col. 11)	Cumulative excess inflow (cm) (Col. 12)
36	80	44		44
45	58	13		57
50	46	-4	-4	
55	35	-20	-24	
52	14	-38	-62	
58	23	-35	**-97**	
77	315	238		238
67	370	303		541
54	265	211		752
42	112	70		822
29	90	61		883
31	78	47		930

The required storage

$$S = \frac{97}{100} \times 10 \times 10^6$$

$$S = 9.7 \times 10^6\ m^3$$

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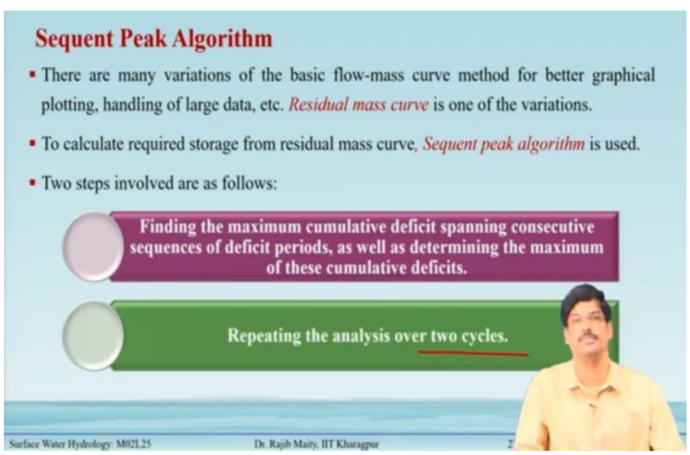

Sequent Peak Algorithm

Another algorithm is also utilized to determine the storage and that is using the residual mass curve. So, there are many variations are there in this basic flow-mass curve method for better graphical plotting; and handling large data sometimes, this method is useful. To calculate the required storage from the residual mass curve, the sequent peak algorithm is utilized; and there are mainly two steps;

I. Finding the maximum cumulative deficit spanning consecutive sequences of deficit periods, as well as determining the maximum of these cumulative deficits.

II. Repeating the analysis over two cycles.

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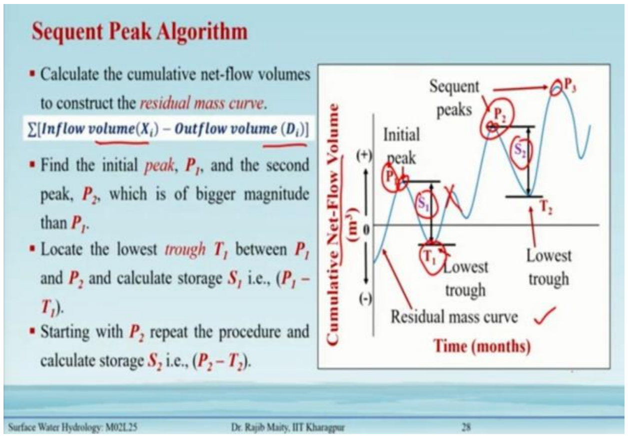

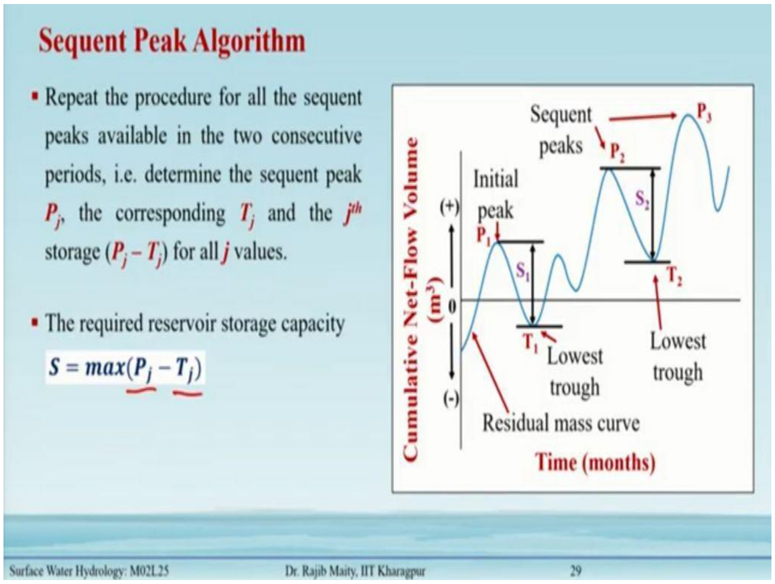

Sequent Peak Algorithm

- Calculate the cumulative net-flow volumes to construct the residual mass curve. A typical diagram is shown in fig.6

$$\sum[\boldsymbol{Inflow\ volume}(\boldsymbol{X_i}) - \boldsymbol{Outflow\ volume}\ (\boldsymbol{D_i})]$$

- Find the initial peak, P_1, and the second peak, P_2, which is of a bigger magnitude than P_1.
- Locate the lowest trough T_1 between P_1 and P_2 and calculate storage S_1 i.e., ($P_1 - T_1$).
- Starting with P_2 repeat the procedure and calculate storage S_2 i.e., ($P_2 - T_2$).
- Repeat the procedure for all the sequent peaks available in the two consecutive periods, i.e., determine the sequent peak P_j, the corresponding T_j, and the j^{th} storage ($P_j - T_j$) for all j values.
- The required reservoir storage capacity

$$\boldsymbol{S = max(P_j - T_j)}$$

This maximum value is we can use as a storage requirement for the reservoir using the sequent peak algorithm.

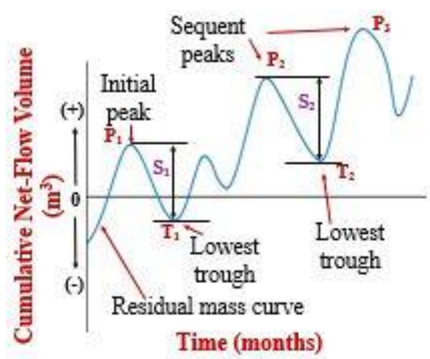

Fig.6 shows the residual mass curve

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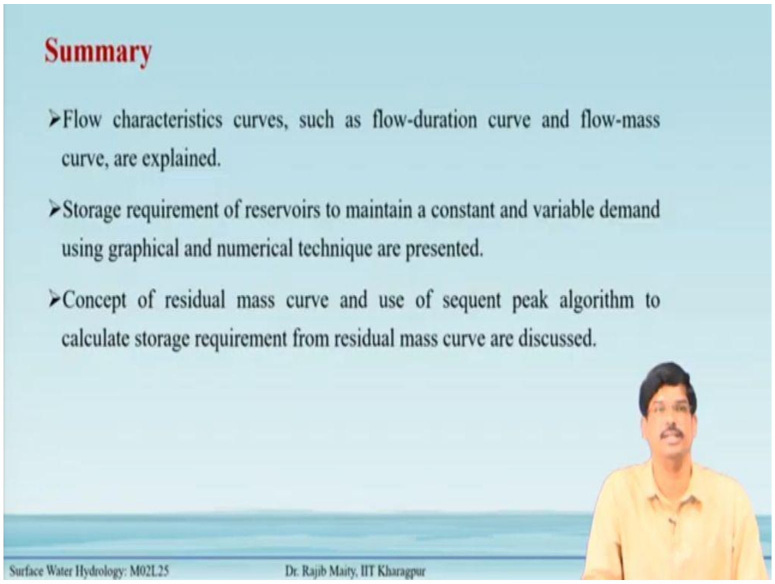

Summary

In summary, we learned the following points from this lecture:

- Flow characteristics curves, such as flow-duration curve and flow-mass curve, are explained.
- Storage requirements of reservoirs to maintain a constant and variable demand using the graphical and numerical techniques are presented.
- The concept of the residual mass curve and the use of sequent peak algorithm to calculate storage requirement from the residual mass curve are discussed.