Surface Water Hydrology
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Lecture 62
Determination of Storage Capacity and Models in Reservoir Design

Hello students, welcome to this lecture. As you know that in this week we are discussing hydrologic design (part 2). In this particular lecture, we will be discussing the determination of storage capacity and models in reservoir design.

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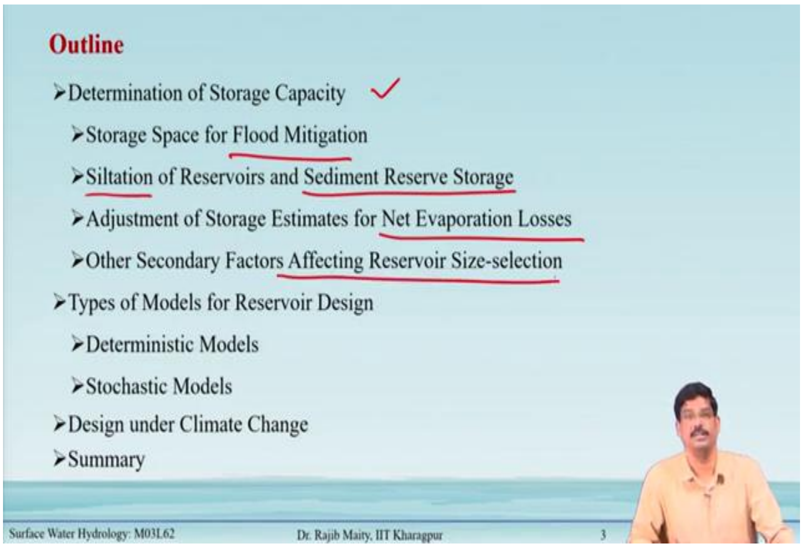

Following concept will be covered:

- Determination of Storage Capacity
- Models for Reservoir Design
- Design under Climate Change

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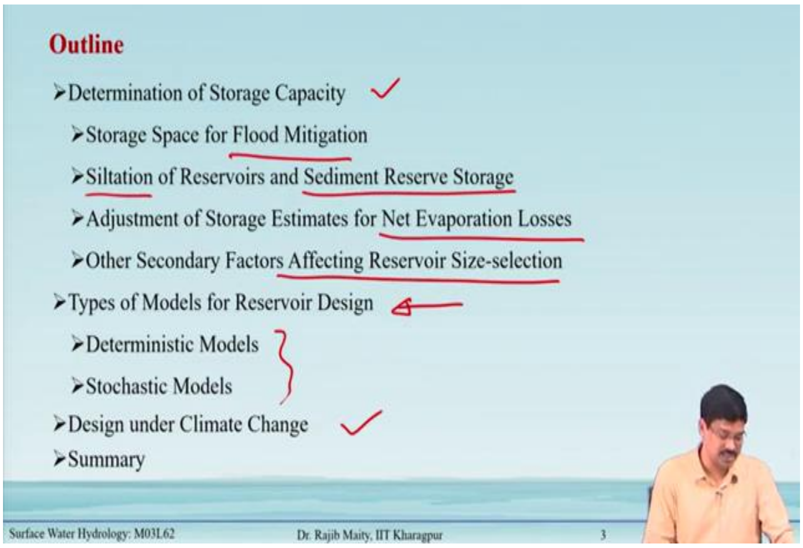

The outline of this lecture is as follows:

- Determination of Storage Capacity
  - Storage Space for Flood Mitigation
  - Siltation of Reservoirs and Sediment Reserve Storage
  - Adjustment of Storage Estimates for Net Evaporation Losses
  - Other Secondary Factors Affecting Reservoir Size-selection
- Types of Models for Reservoir Design
  - Deterministic Models
  - Stochastic Models
- Design under Climate Change
- Summary

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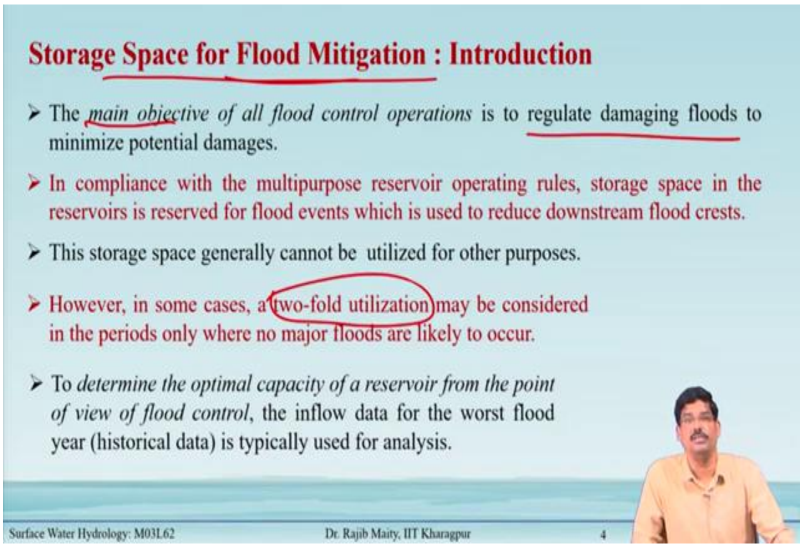

Storage Space for Flood Mitigation: Introduction

The main objective of all flood control operations is to regulate damaging floods to minimize potential damages. In compliance with the multipurpose reservoir operating rules, storage space in the reservoirs is reserved for flood events which is used to reduce downstream flood crests. This storage space generally cannot be utilized for other purposes.

However, in some cases, a two-fold utilization may be considered in the periods only where no major floods are likely to occur. To determine the optimal capacity of a reservoir from the point of view of flood control, the inflow data for the worst flood year (historical data) is typically used for analysis.

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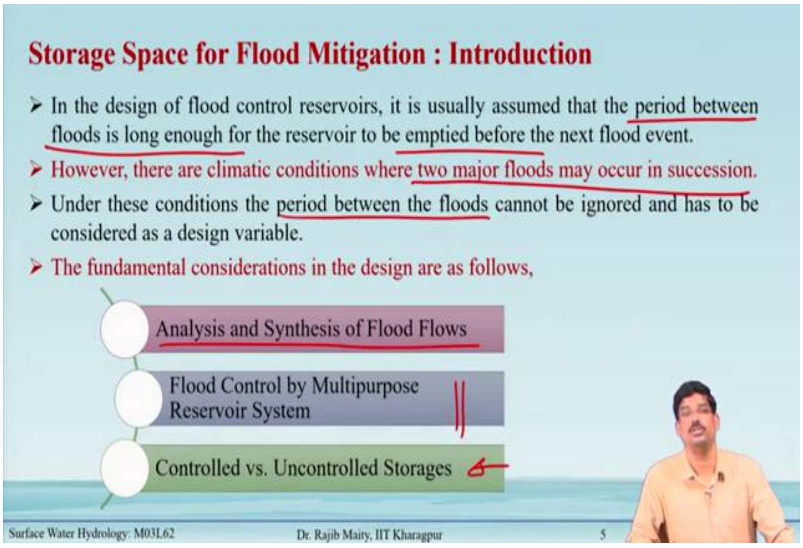

In the design of the flood control reservoir, it is usually assumed that the period between the floods is long enough, i.e. one flood occurrence does not have any effect on the immediate next one. So, there is a time and scope to empty the reservoir before the next flood occurs. However, there are several climatic conditions, where two major floods may occur in succession.

Under these conditions the period between the floods cannot be ignored and has to be considered as a design variable:

- Analysis and Synthesis of Flood Flows
- Flood Control by Multipurpose Reservoir System
- Controlled vs. Uncontrolled Storages.

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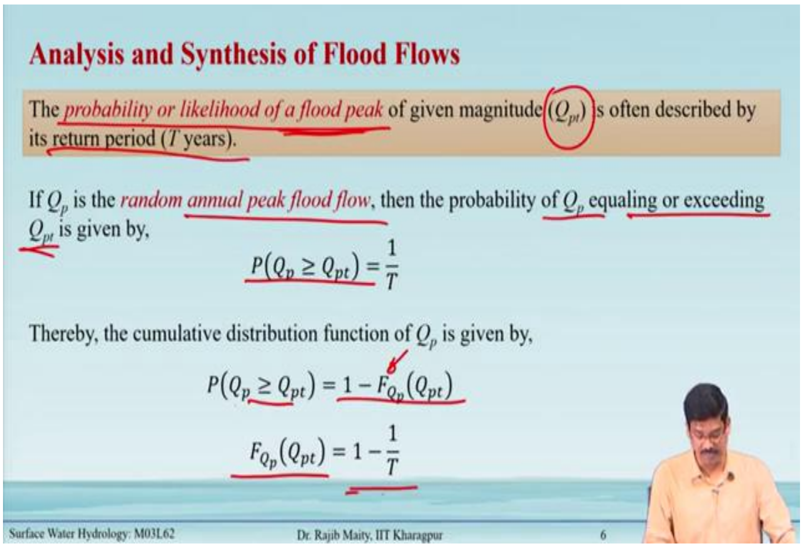

Analysis and Synthesis of Flood Flows

The probability or likelihood of a flood peak of a given magnitude (Q_{pt}) is often described by its return period (T *years*).

If Q_p is the random annual peak flood flow, then the probability of Q_p equaling or exceeding Q_{pt} is given by,

$$P(Q_p \geq Q_{pt}) = \frac{1}{T}$$

Thereby, the cumulative distribution function of Q_p is given by,

$$P(Q_p \geq Q_{pt}) = 1 - F_{Q_p}(Q_{pt})$$

$$F_{Q_p}(Q_{pt}) = 1 - \frac{1}{T}$$

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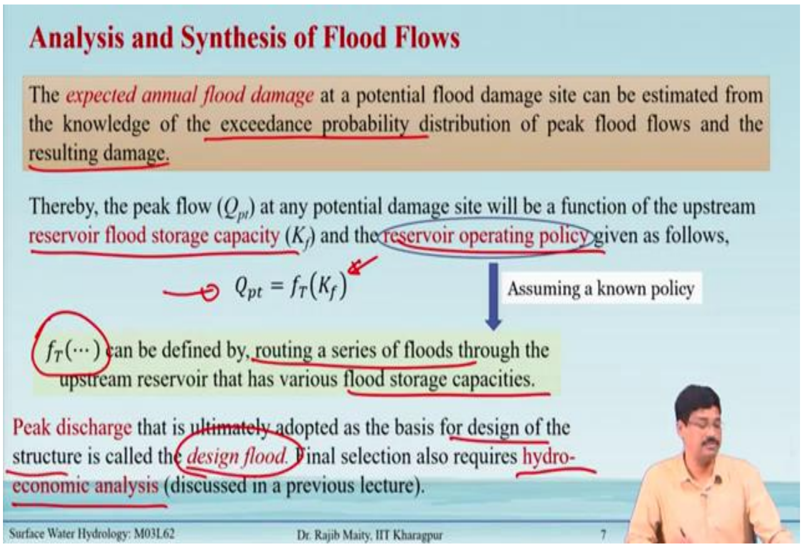

The *expected annual flood damage* at a potential flood damage site can be estimated from the knowledge of the exceedance probability distribution of peak flood flows and the resulting damage.

Thereby, the peak flow (Q_{pt}) at any potential damage site will be a function of the upstream reservoir flood storage capacity (K_f) and the reservoir operating policy given as follows,

$$Q_{pt} = f_T(K_f)$$

$f_T(\cdots)$ can be defined by, routing a series of floods through the upstream reservoir that has various flood storage capacities. Peak discharge that is ultimately adopted as the basis for the design of the structure is called the design flood.

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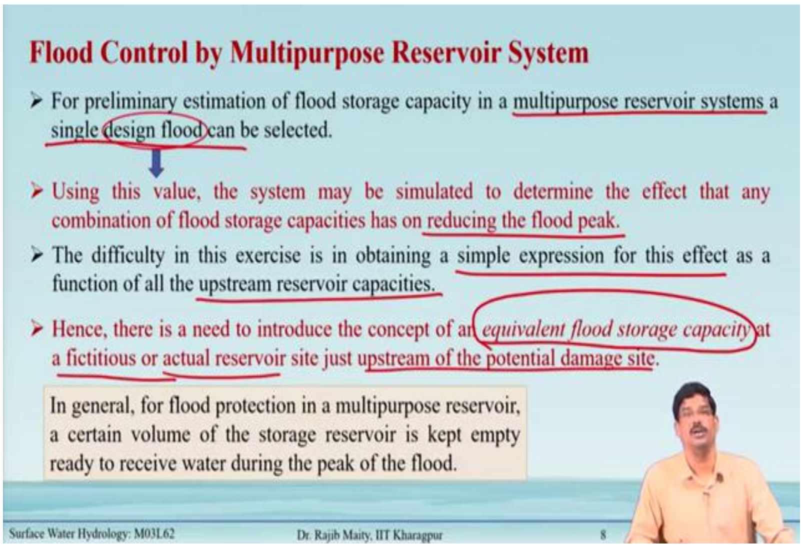

Flood Control by Multipurpose Reservoir System

For preliminary estimation of flood storage capacity in a multipurpose reservoir systems a single design flood can be selected. Using the value of design flood, the system may be simulated to determine the effect that any combination of flood storage capacities has on reducing the flood peak. The difficulty in this exercise is in obtaining a simple expression for this effect as a function of all the upstream reservoir capacities. Hence, there is a need to introduce the concept of an equivalent flood storage capacity at a fictitious or actual reservoir site just upstream of the potential damage site. In general, for flood protection in a multipurpose reservoir, a certain volume of the storage reservoir is kept empty ready to receive water during the peak of the flood.

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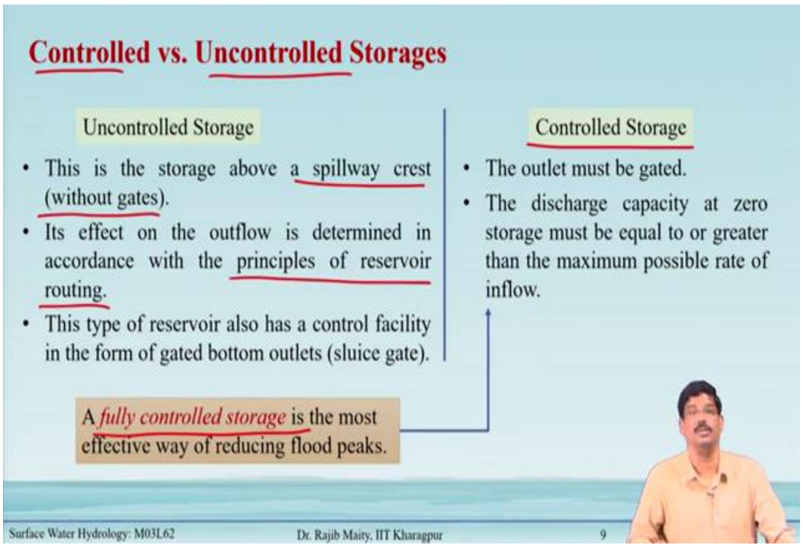

Controlled vs. Uncontrolled Storages

<u>Uncontrolled Storage</u>

- This is the storage above a spillway crest (without gates).
- Its effect on the outflow is determined in accordance with the principles of reservoir routing.
- This type of reservoir also has a control facility in the form of gated bottom outlets (sluice gate).

<u>Controlled Storage</u>

- The outlet must be gated.
- The discharge capacity at zero storage must be equal to or greater than the maximum possible rate of inflow.

A fully controlled storage is the most effective way of reducing flood peaks.

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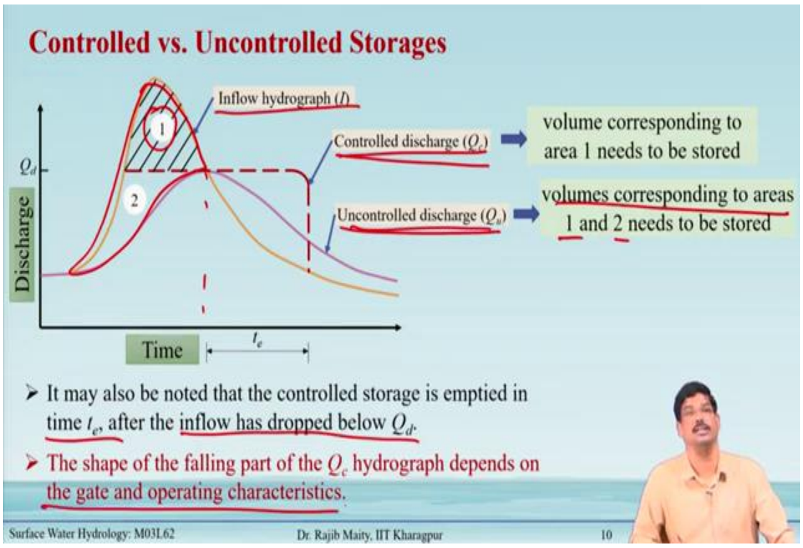

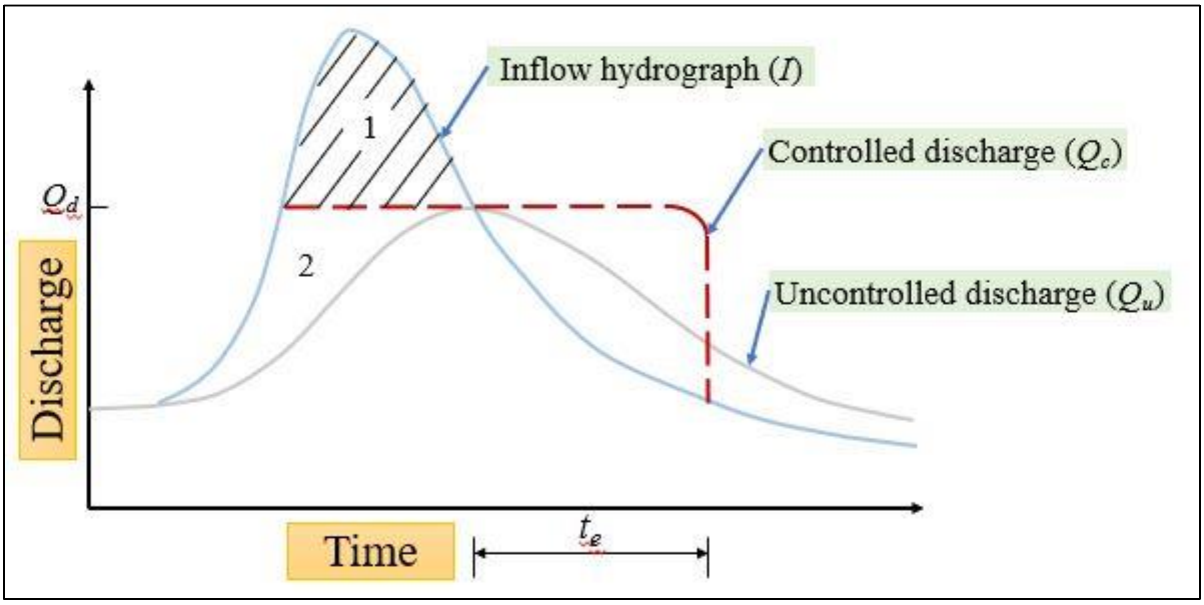

Figure 1: A typical diagram of an Inflow Hydrograph

In the case of controlled discharge volume corresponding to area 1(shown in fig.1) needs to be stored and in the case of uncontrolled discharge volumes corresponding to areas 1 and 2 (shown in fig.1) need to be stored.

It may also be noted that the controlled storage is emptied in time t_e after the inflow has dropped below Q_d.

The shape of the falling apart of the Q_c hydrograph depends on the gate and operating characteristics.

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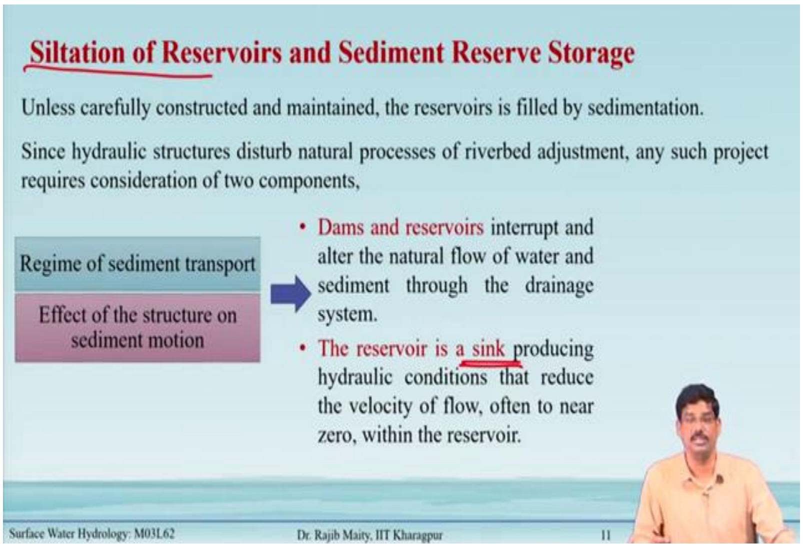

Siltation of Reservoirs and Sediment Reserve Storage

Unless carefully constructed and maintained, the reservoirs is filled by sedimentation. Since hydraulic structures disturb natural processes of riverbed adjustment, any such project requires consideration of two components. The first one is the dams and reservoirs interrupt and alter the natural flow of the water and sediment through the drainage system, and secondly, the reservoir acts like a sink and provide a hydraulic conditions that reduce the velocity of the flow. It may often very near to zero within the reservoirs that helps in siltation at the reservoir bottom.

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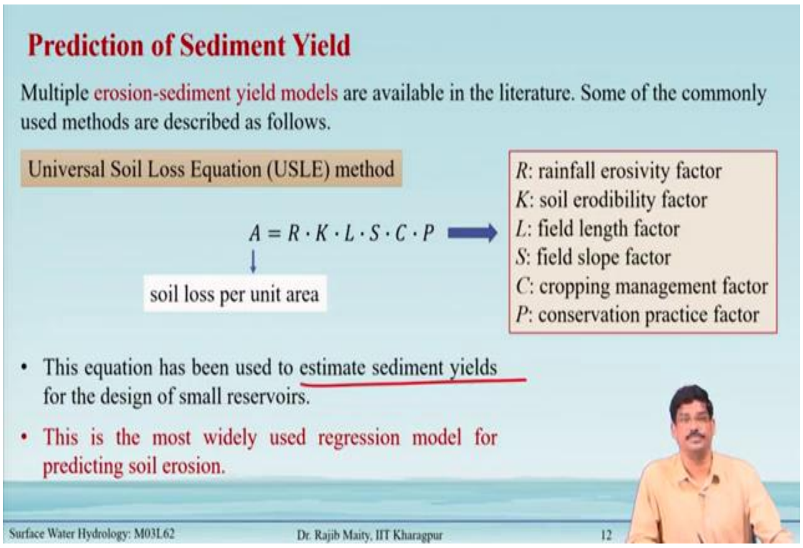

Prediction of Sediment Yield

Multiple erosion-sediment yield models are available in the literature. Some of the commonly used methods are described as follows.

Universal Soil Loss Equation (USLE) method

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P$$

Where A: soil loss per unit area

R: rainfall erosivity factor

K: soil erodibility factor

L: field length factor

S: field slope factor

C: cropping management factor

P: conservation practice factor

This equation has been used to estimate sediment yields for the design of small reservoirs.

This is the most widely used regression model for predicting soil erosion.

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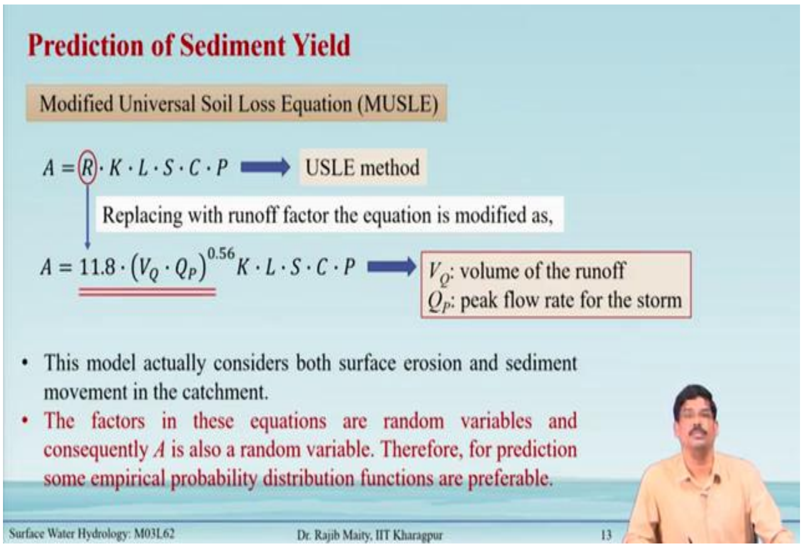

Prediction of Sediment Yield

Modified Universal Soil Loss Equation (MUSLE)

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P$$

The above equation is known as the USLE method. Replacing with runoff factor the equation is modified as

$$A = 11.8 \cdot (V_Q \cdot Q_P)^{0.56} K \cdot L \cdot S \cdot C \cdot P$$

Where, V_Q: volume of the runoff

Q_P: peak flow rate for the storm

This model considers both surface erosion and sediment movement in the catchment.

The factors in these equations are random variables and consequently, A is also a random variable. Therefore, for prediction some empirical probability distribution functions are preferable.

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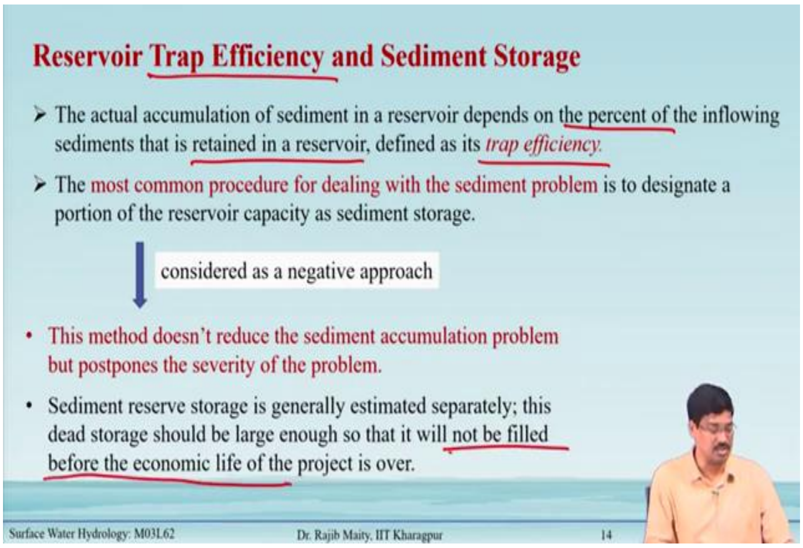

Reservoir Trap Efficiency and Sediment Storage

Another important term is called trap efficiency. The actual accumulation of sediment in a reservoir depends on the percent of the inflowing sediments that is retained in a reservoir, defined as its trap efficiency. The most common procedure for dealing with the sediment problem is to designate a portion of the reservoir capacity as sediment storage. It is considered as a negative approach. This method doesn’t reduce the sediment accumulation problem but postpones the severity of the problem. Sediment reserve storage is generally estimated separately; this dead storage should be large enough so that it will not be filled before the economic life of the project is over.

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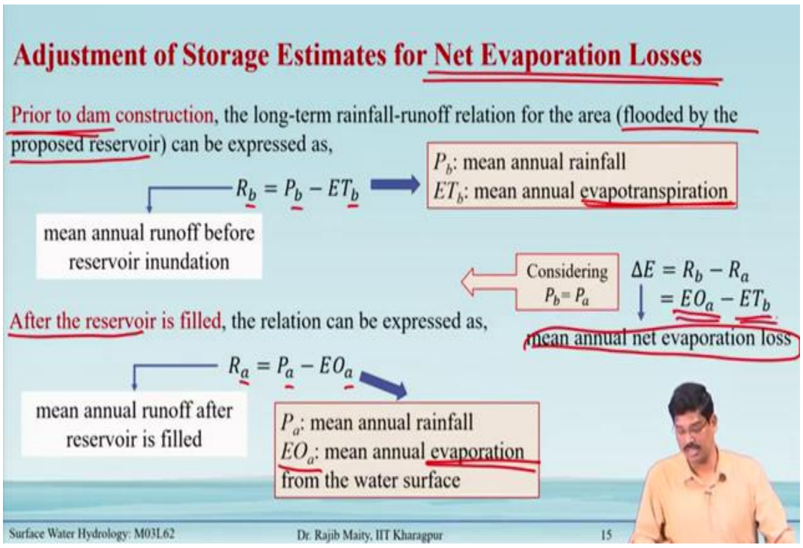

Adjustment of Storage Estimates for Net Evaporation Losses

Before dam construction, the long-term rainfall-runoff relation for the area (flooded by the proposed reservoir) can be expressed as,

$$R_b = P_b - ET_b$$

Where, P_b: mean annual rainfall

ET_b: mean annual evapotranspiration

R_b: mean annual runoff before reservoir inundation

Considering $P_b = P_a$

Mean annual net evaporation loss $\Delta E = R_b - R_a$

$$= EO_a - ET_b$$

After the reservoir is filled, the relation can be expressed as,

$$R_a = P_a - EO_a$$

Where, R_a: mean annual runoff after the reservoir is filled

P_a: mean annual rainfall

EO_a: mean annual evaporation from the water surface

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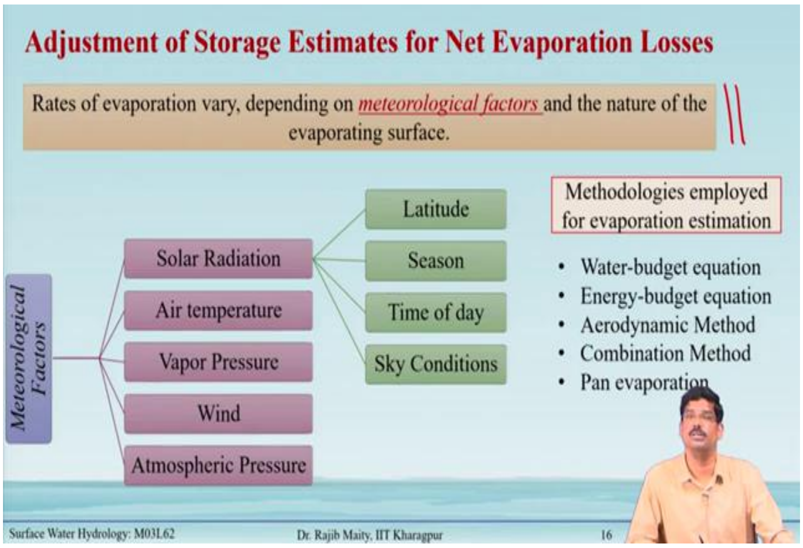

Rates of the evaporation vary depending on the meteorological factor and the nature of the evaporating surface. The Meteorological Factors are as follows:

- Solar Radiation
- Air temperature
- Vapor Pressure
- Wind
- Atmospheric Pressure

Under the solar radiation, the latitude, season, time of the day and condition of the sky may influence the rate of evaporation.

Methodologies employed for evaporation estimation are as follows:

- Water-budget equation
- Energy-budget equation
- Aerodynamic Method
- Combination Method
- Pan evaporation

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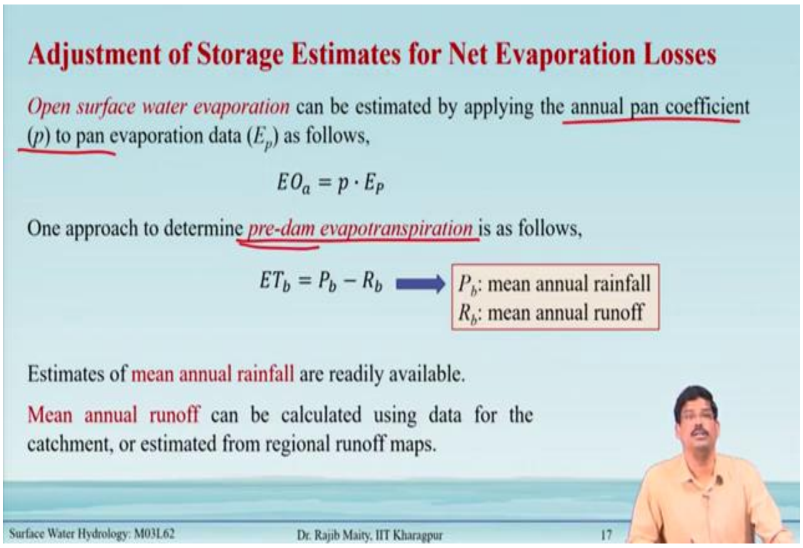

The open surface water evaporation can be estimated by applying the annual pan coefficient (p) to pan evaporation data (E_P) as follows,

$$EO_a = p \cdot E_P$$

One approach to determine pre-dam evapotranspiration is as follows,

$$ET_b = P_b - R_b$$

P_b: mean annual rainfall

R_b: mean annual runoff

Estimates of mean annual rainfall are readily available.

Mean annual runoff can be calculated using data for the catchment or estimated from regional runoff maps.

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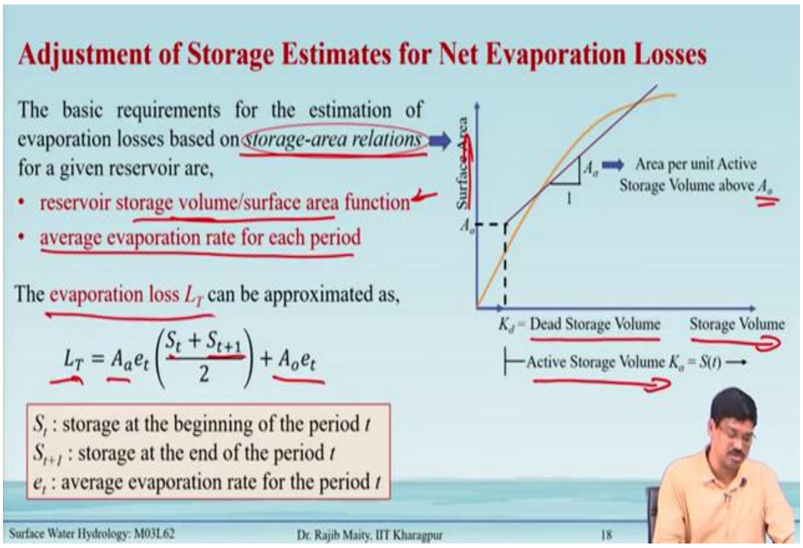

The basic requirements for the estimation of evaporation losses based on storage-area relations as shown in fig. 2 for a given reservoir are,

- reservoir storage volume/surface area function
- average evaporation rate for each period

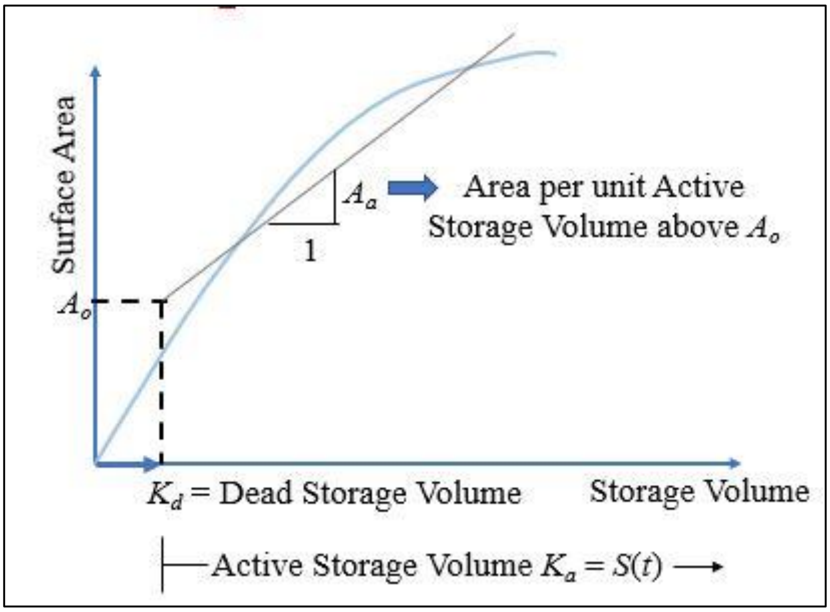

Figure 2: The storage area relationship

The evaporation loss L_T can be approximated as,

$$L_T = A_a e_t \left(\frac{S_t + S_{t+1}}{2}\right) + A_o e_t$$

Where, S_t : storage at the beginning of the period t

S_{t+1} : storage at the end of the period t

e_t : average evaporation rate for the period t

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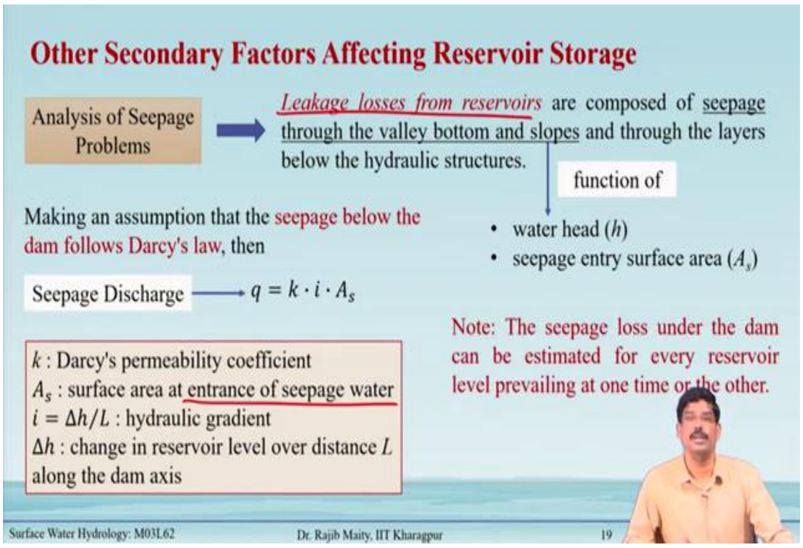

Other Secondary Factors Affecting Reservoir Storage

Other secondary factors include the leakage loss from the reservoir. The leakage losses from reservoirs are composed of seepage through the valley bottom and slopes and through the layers below the hydraulic structures. It is a function of water head (h) and seepage entry surface area (A_s). Assuming that the seepage loss below the dam follows Darcy's law, the seepage discharge is estimated as:

$$q = k \cdot i \cdot A_s$$

where, k: Darcy's permeability coefficient, A_s : Surface area at the entrance of seepage water

$i = \Delta h/L$: Hydraulic gradient, Δh : Change in reservoir level over distance L along the dam axis.

It may be noted that the seepage loss under the dam can be estimated for every reservoir level prevailing at one time or the other.

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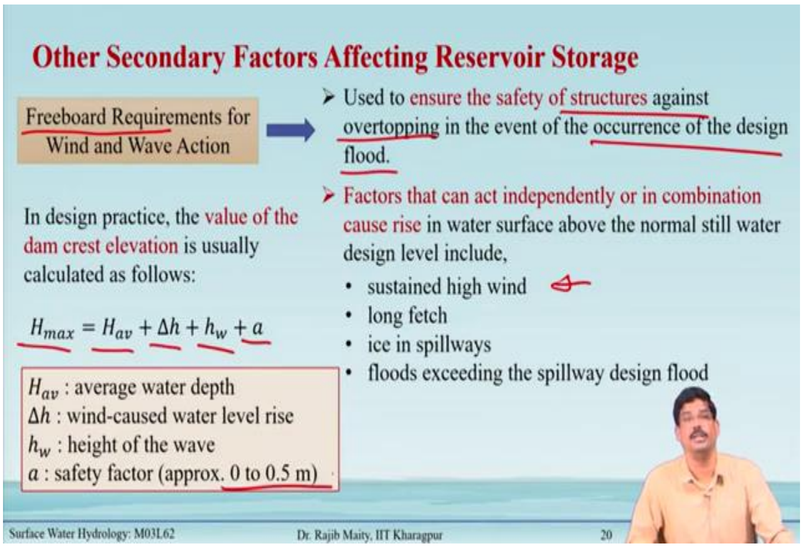

Freeboard Requirements for Wind and Wave Action

Used to ensure the safety of structures against overtopping in the event of the occurrence of the design flood.

Factors that can act independently or in combination to cause a rise in water surface above the normal still water design level include,

- sustained high wind
- long fetch
- ice in spillways
- floods exceeding the spillway design flood

In design practice, the value of the dam crest elevation is usually calculated as follows:

$$H_{max} = H_{av} + \Delta h + h_w + a$$

Where, H_{av} : average water depth

Δh : Wind-caused water level rise

h_w : Height of the wave

a : Safety factor (approx. 0 to 0.5 m)

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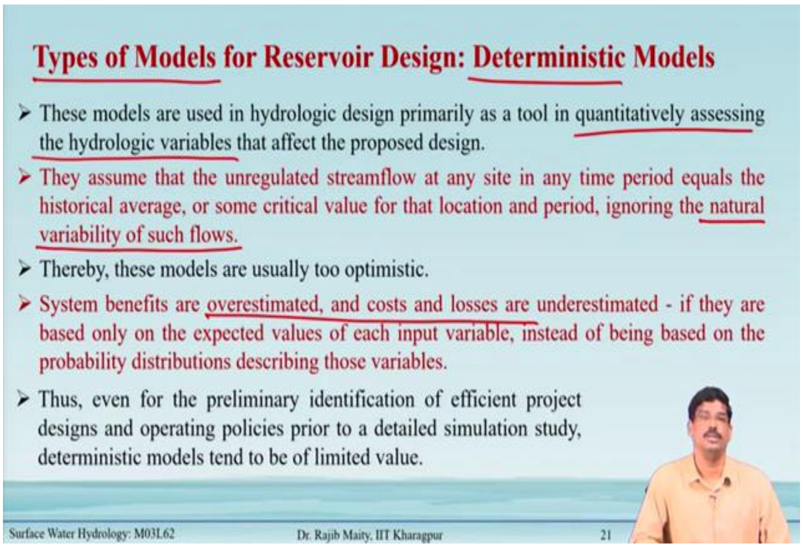

Types of Models for Reservoir Design: Deterministic Models

These models are used in hydrologic design primarily as a tool in quantitatively assessing the hydrologic variables that affect the proposed design. They assume that the unregulated streamflow at any site in any time period equals the historical average, or some critical value for that location and period, ignoring the natural variability of such flows. Thereby, these models are usually too optimistic. System benefits are overestimated, and costs and losses are underestimated - if they are based only on the expected values of each input variable, instead of being based on the probability distributions describing those variables. Thus, even for the preliminary identification of efficient project designs and operating policies prior to a detailed simulation study, deterministic models tend to be of limited value.

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Types of Models for Reservoir Design: Stochastic Models

The design of reservoirs must ideally take into account the stochastic aspect of the inflows and outflows. These methods typically come into use when the deterministic approach is found to be deficient. Stochastic processes are often analyzed in such a manner, and conclusions associated with them drawn and treated as if the process was deterministic. In any case, stochastic data do not improve poor records, but merely improve the quality of designs made with whatever records are available and the processes involved provide an idea of the confidence that can be placed on the adopted design value.

Some shortcomings of such models are operational bias and lack of knowledge concerning the underlying stochastic processes which may cause decisions to be less optimal than had the phenomena been treated as deterministic.

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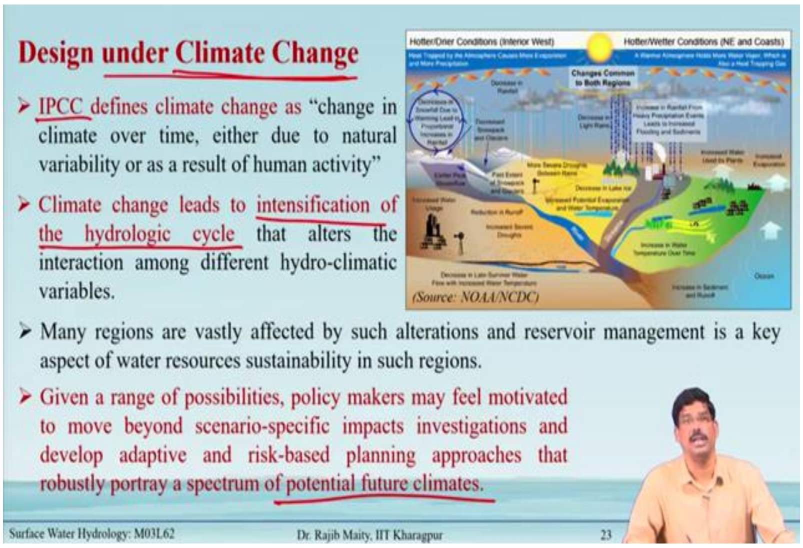

Design under Climate Change

IPCC defines climate change as "change in climate over time, either due to natural variability or as a result of human activity". Climate change leads to intensification of the hydrologic cycle that alters the interaction among different hydro-climatic variables. Many regions are vastly affected by such alterations and reservoir management is a key aspect of water resources sustainability in such regions. Given a range of possibilities, policy makers may feel motivated to move beyond scenario-specific impacts investigations and develop adaptive and risk-based planning approaches that robustly portray a spectrum of potential future climates.

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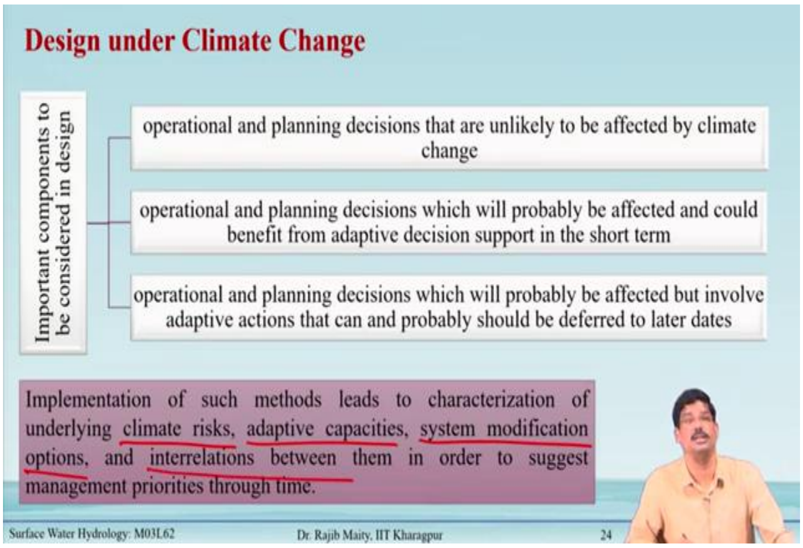

The important components that should be considered in the design may be grouped into three different major heads,

I. operational and planning decisions that are unlikely to be affected by climate change

II. operational and planning decisions which will probably be affected and could benefit from adaptive decision support in the short term

III. operational and planning decisions which will probably be affected but involve adaptive actions that can and probably should be deferred to later dates

Implementation of such methods leads to a characterization of underlying climate risks, adaptive capacities, system modification options, and interrelations between them to suggest management priorities over time.

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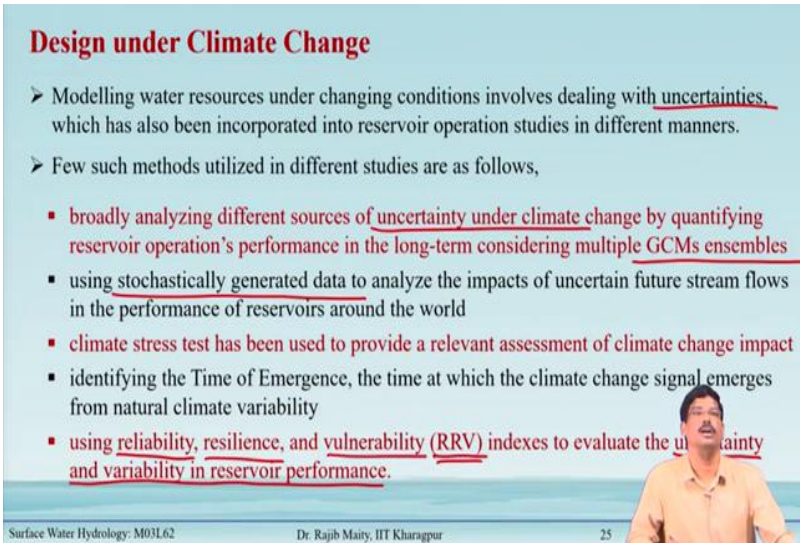

Modeling water resources under changing conditions involves dealing with uncertainties, which have also been incorporated into reservoir operation studies in different manners.

Few such methods utilized in different studies are as follows,

- broadly analyzing different sources of uncertainty under climate change by quantifying reservoir operation's performance in the long-term considering multiple GCMs ensembles

➢ using stochastically generated data to analyze the impacts of uncertain future stream flows on the performance of reservoirs around the world

➢ the climate stress test has been used to provide a relevant assessment of climate change impact

➢ identifying the Time of Emergence, the time at which the climate change signal emerges from natural climate variability

➢ Using reliability, resilience, and vulnerability (RRV) indexes to evaluate the uncertainty and variability in reservoir performance.

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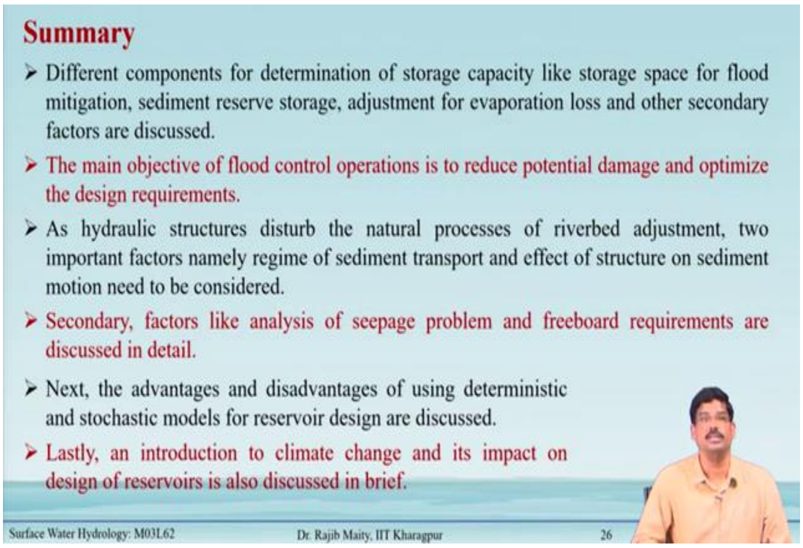

Summary

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

➢ Different components for the determination of storage capacity like storage space for flood mitigation, sediment reserve storage, adjustment for evaporation loss, and other secondary factors are discussed.

➢ The main objective of flood control operations is to reduce potential damage and optimize the design requirements.

➢ As hydraulic structures disturb the natural processes of riverbed adjustment, two important factors namely the regime of sediment transport and the effect of structure on sediment motion need to be considered.

- Secondary, factors like analysis of seepage problem and freeboard requirements are discussed in detail.
- Next, the advantages and disadvantages of using deterministic and stochastic models for reservoir design are discussed.
- Lastly, an introduction to climate change and its impact on the design of reservoirs is also discussed in brief.