Surface Water Hydrology
Professor. Rajib Maity
Department of Civil Engineering
Indian Institute of Technology, Kharagpur
Lecture – 12
Estimation of Evaporation and Control Measures

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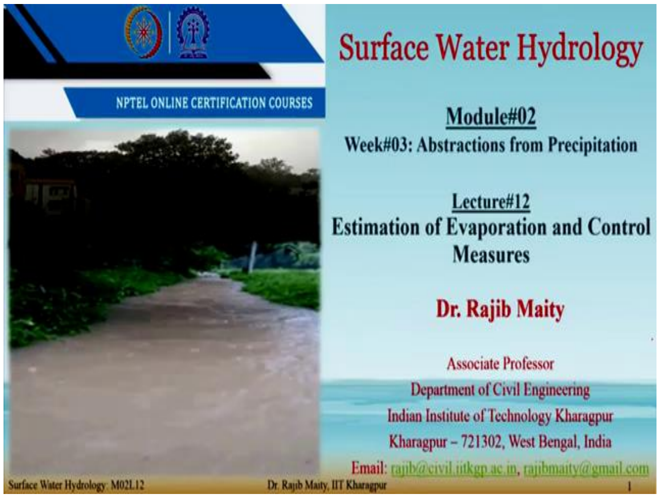

In lecture 12, we will discuss the estimation of evaporation and different control measures, so, that we can minimize the loss due to evaporation.

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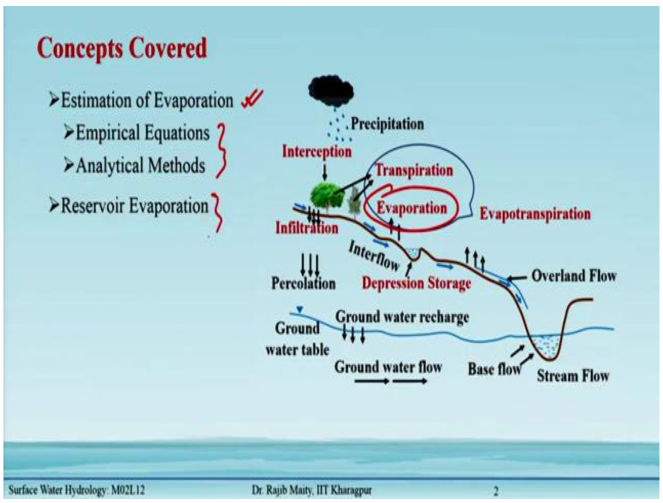

The concept covered in this lecture is the different estimation methods of this evaporation. There are two major things that we are considering one is the empirical equation and analytical methods, and also, we will discuss something about reservoir evaporation.

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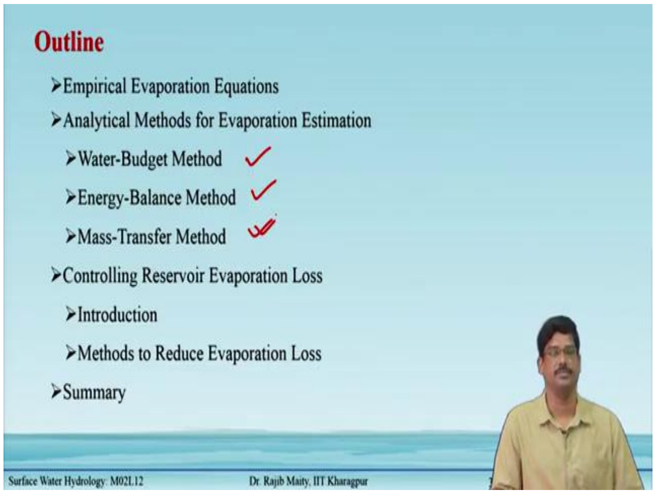

The outline for this lecture is empirical evaporation equations, what are they being utilized, and then, under the category of analytical methods of evaporation estimation, there are three majors methods, one is the water budget method, energy balance method, and mass transfer method and how to control the reservoir evaporation loss, some introduction and method to reduce evaporation loss will be discussed.

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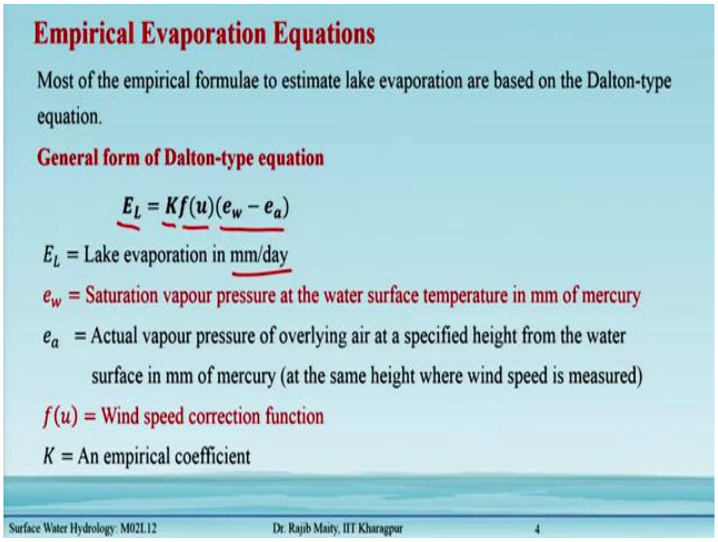

Empirical Evaporation Equations

Most of the empirical formulae to estimate lake evaporation are based on the Dalton-type equation.

General form of Dalton-type equation

$$\boldsymbol{E_L = Kf(u)(e_w - e_a)}$$

E_L= Lake evaporation in mm/day

e_w= Saturation vapour pressure at the water surface temperature in mm of mercury

e_a= Actual vapour pressure of overlying air at a specified height from the water surface in mm of mercury (at the same height where wind speed is measured)

$f(u)$= Wind speed correction function

K= An empirical coefficient

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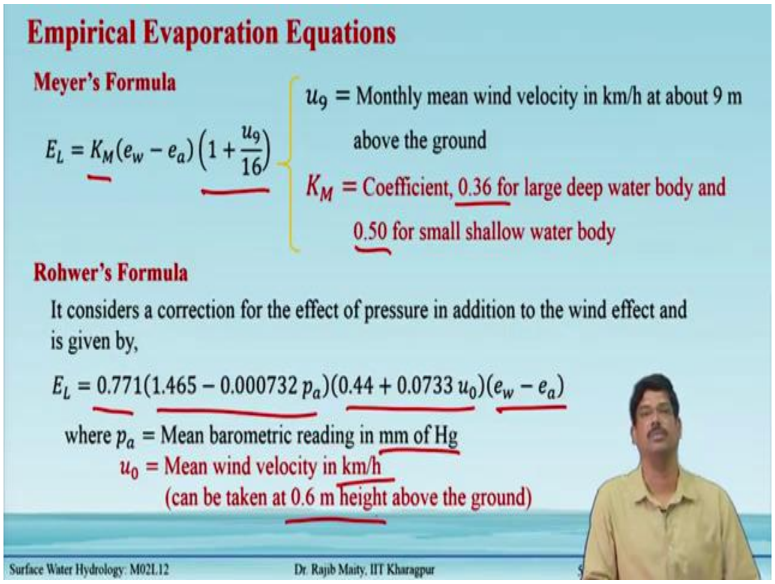

Meyer's Formula

$$E_L = K_M(e_w - e_a)\left(1 + \frac{u_9}{16}\right)$$

u_9= Monthly mean wind velocity in km/h at about 9 m above the ground

K_M= Coefficient, 0.36 for large deep-water bodies and 0.50 for a small shallow water body.

Rohwer's Formula

It considers a correction for the effect of pressure in addition to the wind effect and is given by,

$$E_L = 0.771(1.465 - 0.000732\, p_a)(0.44 + 0.0733\, u_0)(e_w - e_a)$$

Where p_a= Mean barometric reading in mm of Hg

u_0= Mean wind velocity in km/h

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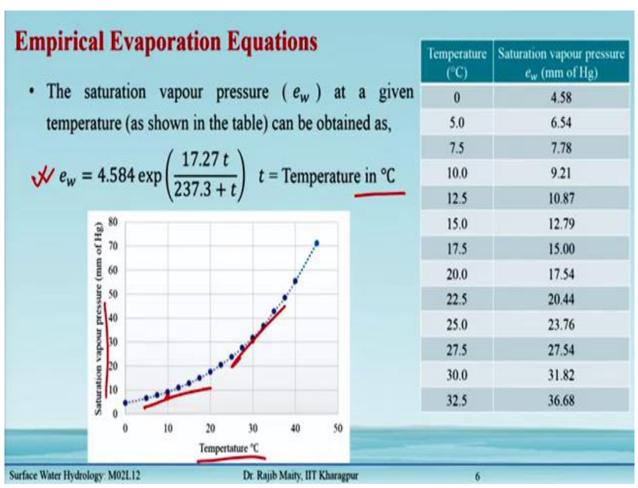

The saturation vapour pressure e_w at a given temperature (as shown in table 1) can be obtained as

$$e_w = 4.584 \exp\left(\frac{17.27\, t}{237.3 + t}\right)$$

t = Temperature in °C

Table 1: shows the saturation vapour pressure for different temperature

Temperature (°C)	Saturation vapour pressure e_w (mm of Hg)
0	4.58
5.0	6.54
7.5	7.78
10.0	9.21
12.5	10.87
15.0	12.79
17.5	15.00
20.0	17.54
22.5	20.44
25.0	23.76
27.5	27.54
30.0	31.82
32.5	36.68

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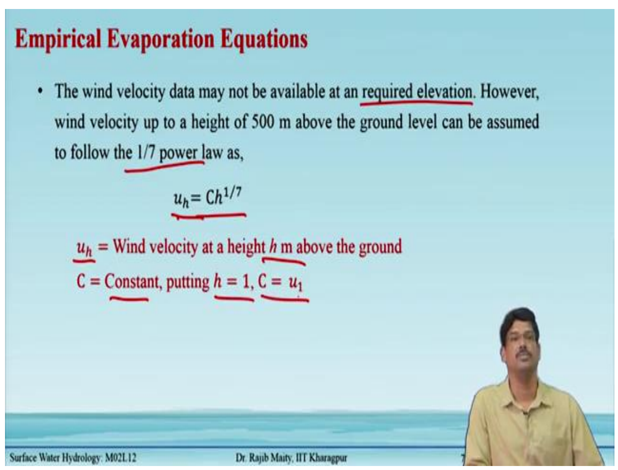

The wind velocity data may not be available at a required elevation. However, wind velocity up to a height of 500 m above the ground level can be assumed to follow the 1/7 power law as,

$$u_h = Ch^{1/7}$$

u_h = Wind velocity at a height h m above the ground

C= Constant, putting h =1, C=u_1

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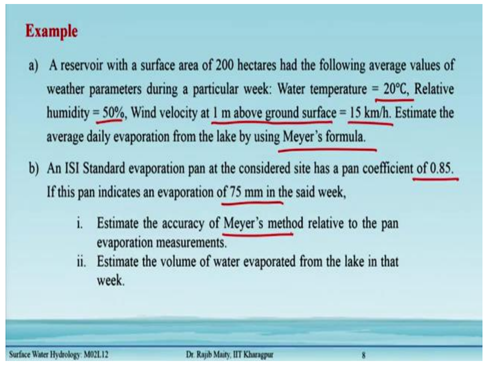

Example

a) A reservoir with a surface area of 200 hectares had the following average values of weather parameters during a particular week: Water temperature = 20℃, Relative humidity = 50%, Wind velocity at 1 m above ground surface = 15 km/h. Estimate the average daily evaporation from the lake by using Meyer's formula.

b) An ISI Standard evaporation pan at the considered site has a pan coefficient of 0.85. If this pan indicates evaporation of 75 mm in the said week,

   I. Estimate the accuracy of Meyer's method relative to the pan evaporation measurements.

   II. Estimate the volume of water evaporated from the lake in that week.

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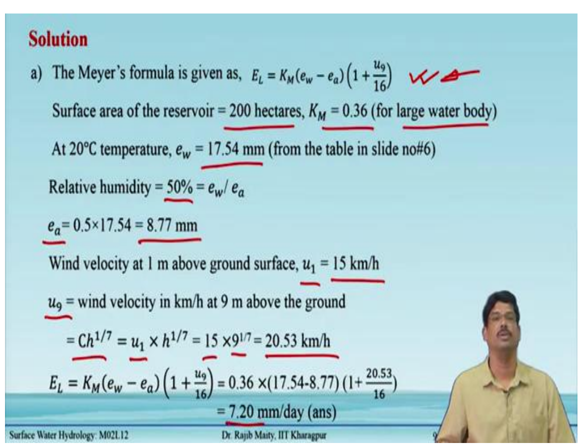

Solution

a) The Meyer's formula is given as,

$$E_L = K_M(e_w - e_a)\left(1 + \frac{u_9}{16}\right)$$

Surface area of the reservoir = 200 hectares, K_M = 0.36 (for large water body)

At 20°C temperatures, e_w = 17.54 mm (from the table in slide no#6)

Relative humidity = 50% = e_w/ e_a

e_a = 0.5×17.54 = 8.77 mm

Wind velocity at 1 m above ground surface, u_1 = 15 km/h

u_9 = wind velocity in km/h at 9 m above the ground

= C$h^{1/7}$= u_1×$h^{1/7}$= 15 ×91/7 = 20.53 km/h

$$E_L = K_M(e_w - e_a)\left(1 + \frac{u_9}{16}\right)$$

= 0.36 × (17.54-8.77) (1+ 20.53/16

= 7.20 mm/day (Ans)

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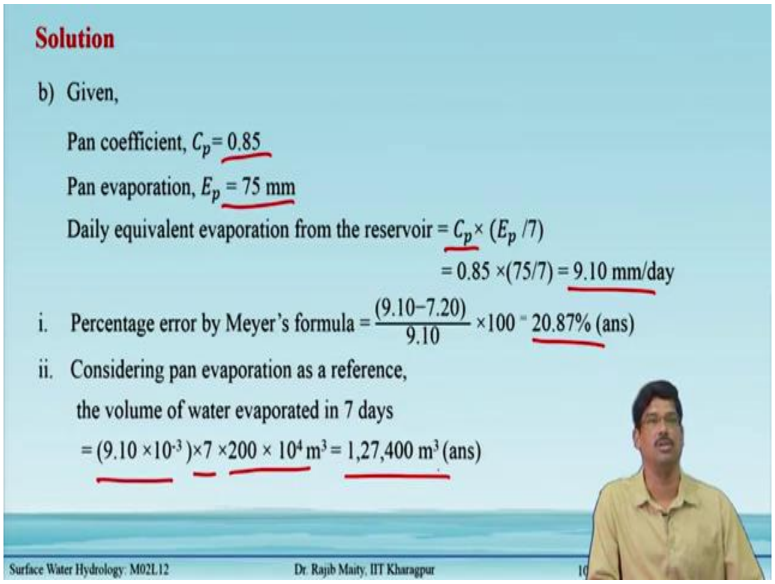

Solution

Given,

Pan coefficient, C_p= 0.85

Pan evaporation, E_p = 75 mm

Daily equivalent evaporation from the reservoir = C_{p} x E_p /7)

= 0.85 × (75/7) = 9.10 mm/day

Percentage error by Meyer's formula = {(9.10−7.20) /9.10} ×100 = 20.87% (Ans)

Considering pan evaporation as a reference,

The volume of water evaporated in 7 days

= $(9.10 \times 10^{-3}) \times 7 \times 200 \times 104\ m^3 = 1, 27{,}400\ m^3$ (Ans)

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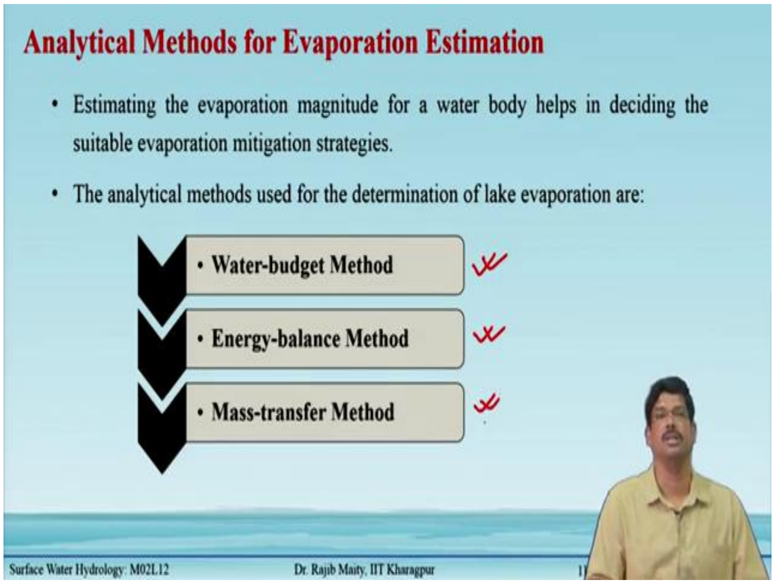

Analytical Methods for Evaporation Estimation

Estimating the evaporation magnitude for a water body helps in deciding the suitable evaporation mitigation strategies

The analytical methods used for the determination of the lake universe are majorly 3 categories first one is the water-budget method and then energy balance method and then must transfer method.

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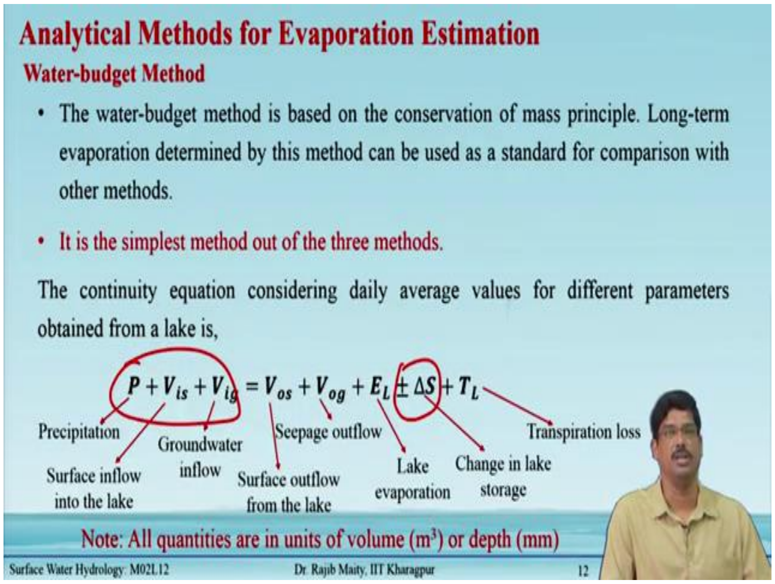
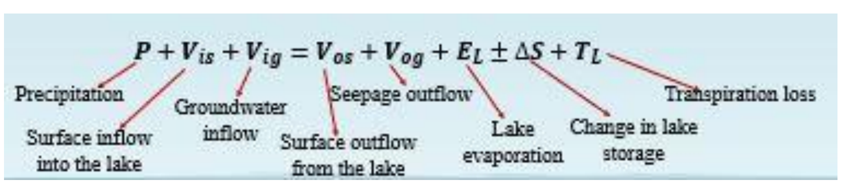


Water-budget Method

The water-budget method is based on the conservation of mass principle. Long-term evaporation determined by this method can be used as a standard for comparison with other methods. It is the simplest method out of the three methods.

The continuity equation considering daily average values for different parameters obtained from a lake is,



It may be noted quantities are in units of volume (m^3) or depth (mm)

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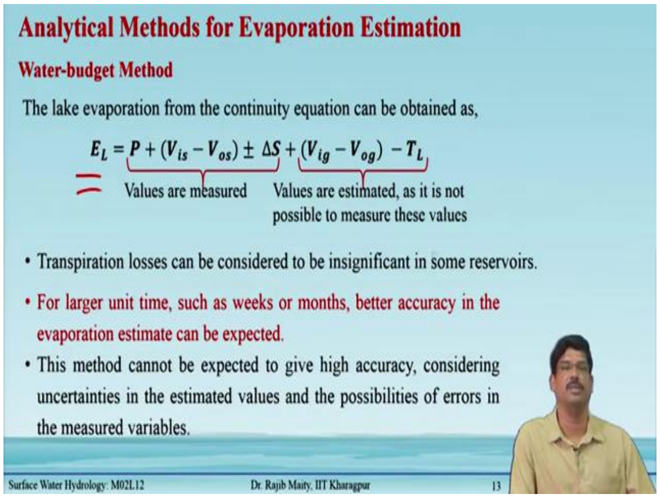

The lake evaporation from the continuity equation can be obtained as,

$$E_L = \underbrace{P + (V_{is} - V_{os}) \pm \Delta S}_{\text{Values are measured}} + \underbrace{(V_{ig} - V_{og}) - T_L}_{\text{Values are estimated, as it is not possible to measure these values}}$$

Transpiration losses can be considered to be insignificant in some reservoirs. For a larger unit time, such as weeks or months, better accuracy in the evaporation estimate can be expected. This method cannot be expected to give high accuracy, considering uncertainties in the estimated values and the possibilities of errors in the measured variables.

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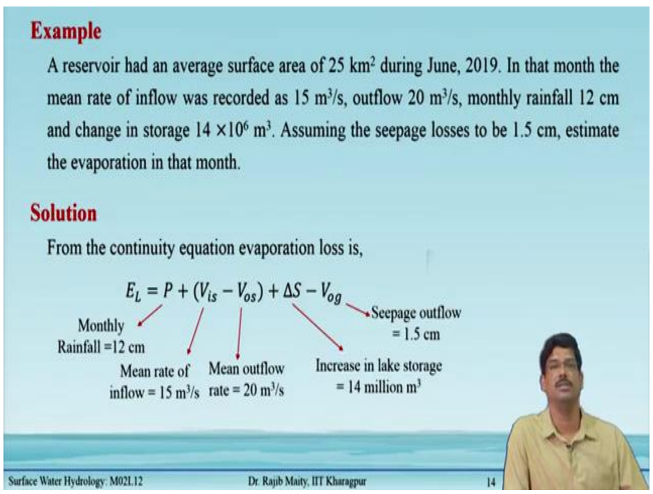
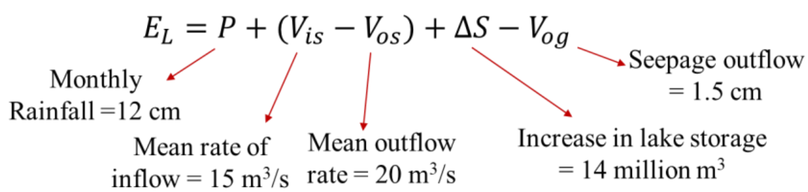


Example

A reservoir had an average surface area of 25 km^2 during June, 2019. In that month the mean rate of inflow was recorded as 15 m^3/s, outflow 20 m^3/s, monthly rainfall 12 cm, and change in storage 14 $\times 10^6$ m^3. Assuming the seepage losses to be 1.5 cm, estimate the evaporation in that month.

From the continuity equation evaporation loss is,



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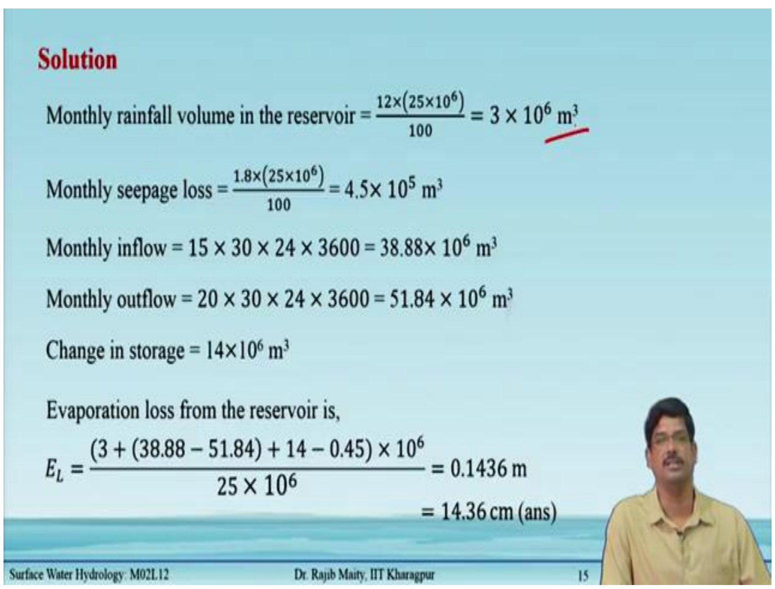

Solution

Monthly rainfall volume in the reservoir = $(12\times (25\times10^6))/100 = 3\times10^6$ m^3

Monthly seepage loss = $(1.8\times (25\times10^6))/100 = 4.5\times10^5$ m^3

Monthly inflow = $15\times30\times24\times3600 = 38.88\times10^6$ m^3

Monthly outflow = $20\times30\times24\times3600 = 51.84\times10^6$ m^3

Change in storage = 14×10^6 m^3

Evaporation loss from the reservoir is,

$$E_L = \frac{(3 + (38.88 - 51.84) + 14 - 0.45) \times 10^6}{25 \times 10^6} = 0.1436 \text{ m}$$
$$= 14.36 \text{ cm (Ans)}$$

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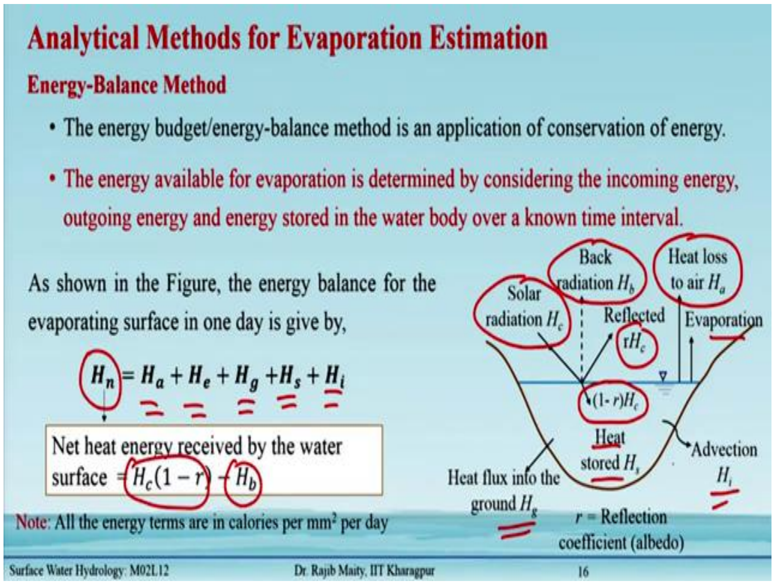

Energy-Balance Method

The energy budget/energy-balance method is an application of conservation of energy. The energy available for evaporation is determined by considering the incoming energy, outgoing energy, and energy stored in the water body over a known time interval.

As shown in Fig.1, the energy balance for the evaporating surface in one day is given by,

$$H_n = H_a + H_e + H_g + H_s + H_i$$

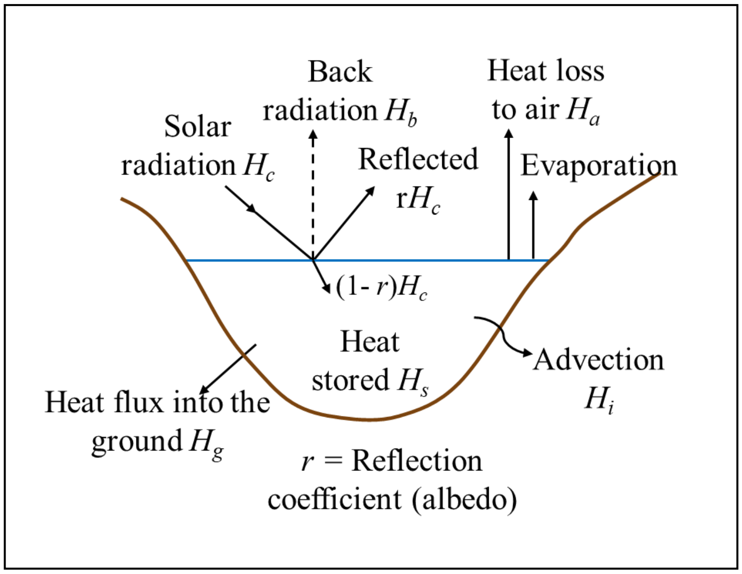

Fig.1 shows the Energy Balance in a Water Body

H_n=Net heat energy received by the water surface = $H_c(1-r)-H_b$

Note: All the energy terms are in calories per mm^2 per day

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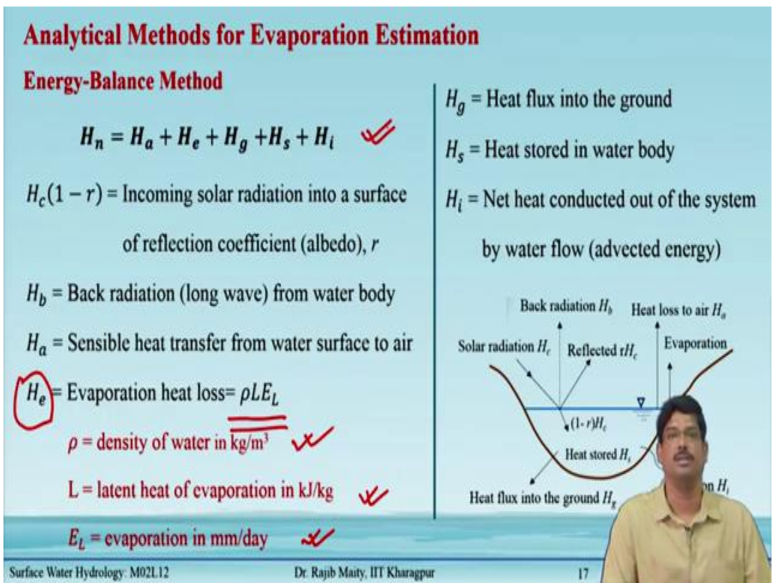

$$\boldsymbol{H_n = H_a + H_e + H_g + H_s + H_i}$$

$H_c(1-r)$ = Incoming solar radiation into a surface of reflection coefficient (albedo), r

H_b = Back radiation (long wave) from water body

H_a = Sensible heat transfer from water surface to air

H_e = Evaporation heat loss= $\rho L E_L$

H_g = Heat flux into the ground

H_s = Heat stored in water body

H_i = Net heat conducted out of the system by water flow (advected energy)

ρ = density of water in kg/m3

L = latent heat of evaporation in kJ/kg

E_L = evaporation in mm/day

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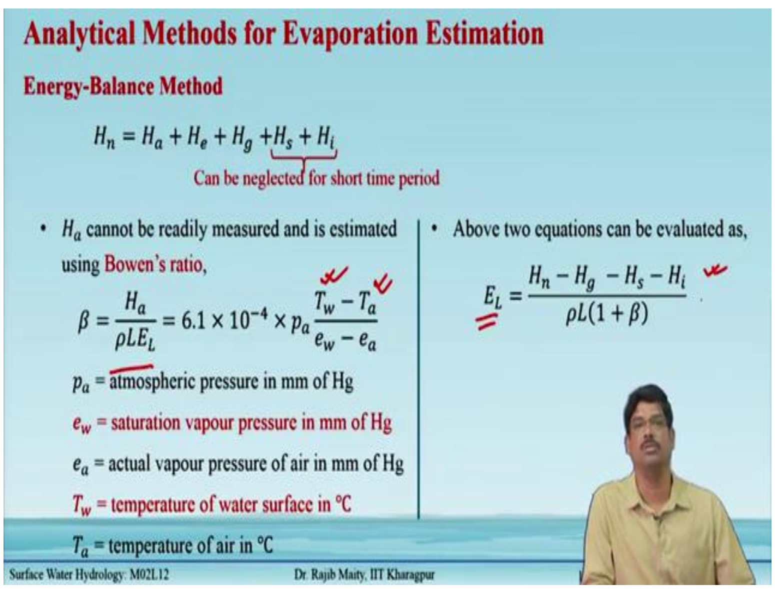

$$H_n = H_a + H_e + H_g + \underbrace{H_s + H_i}$$

Can be neglected for short time period

H_a cannot be readily measured and is estimated using Bowen's ratio,

$$\beta = \frac{H_a}{\rho L E_L} = 6.1 \times 10^{-4} \times p_a \frac{T_w - T_a}{e_w - e_a}$$

p_a = atmospheric pressure in mm of Hg

e_w = saturation vapour pressure in mm of Hg

e_a = actual vapour pressure of air in mm of Hg

T_w = temperature of water surface in ℃

T_a = temperature of the air in ℃

The above two equations can be evaluated as,

$$E_L = \frac{H_n - H_g \; - H_s - H_i}{\rho L(1+\beta)}$$

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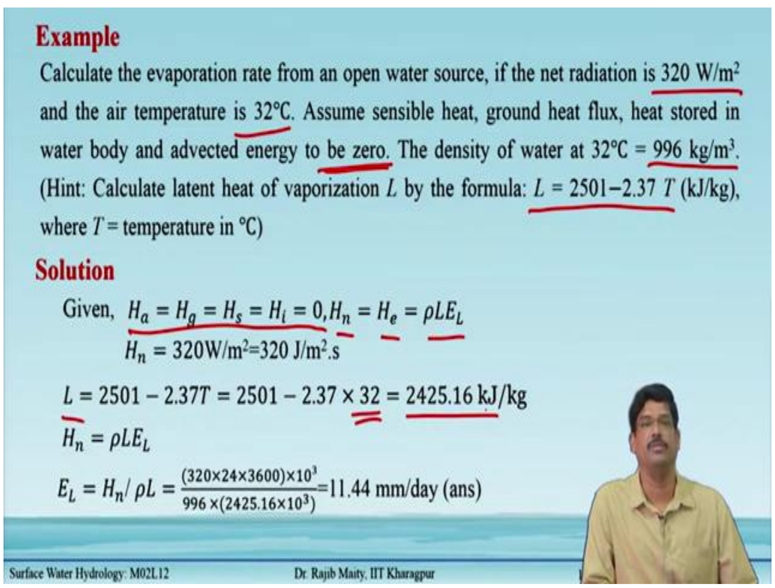

Example

Calculate the evaporation rate from an open water source, if the net radiation is 320 W/m^2 and the air temperature is 32℃. Assume sensible heat, ground heat flux, the heat stored in the water body, and advected energy to be zero. The density of water at 32℃ = 996 kg/m^3. (Hint: Calculate latent heat of vaporization L by the formula: L = 2501-2.37 T (kJ/kg), where T = temperature in ℃)

Solution

Given,

$H_a = H_g = H_s = H_i = 0$, $H_n = H_e = \rho L E_L$

$H_n = 320 \text{W/m}^2 = 320 \text{ J/m}^2\text{. S}$

$L = 2501 - 2.37T = 2501 - 2.37 \times 32 = 2425.16$ kJ/kg

$H_n = \rho L E_L$

$E_L = H_n / \rho L = ((320 \times 24 \times 3600) \times 10^3) / (996 \times (2425.16 \times 10^3)) = 11.44 \text{ mm/day}$ (Ans)

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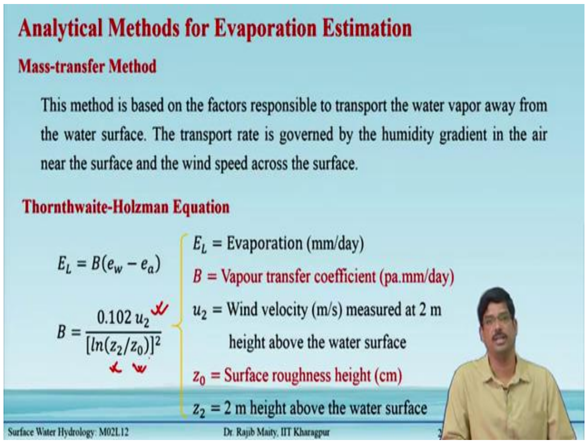

Mass-transfer Method

This method is based on the factors responsible to transport the water vapor away from the water surface. The transport rate is governed by the humidity gradient in the air near the surface and the wind speed across the surface.

Thornthwaite-Holzman Equation

$$E_L = B(e_w - e_a)$$

$$B = \frac{0.102\, u_2}{[ln(z_2/z_0)]^2}$$

E_L=Evaporation (mm/day)

B= Vapour transfer coefficient (pa.mm/day)

u_2= Wind velocity (m/s) measured at 2 m height above the water surface

z_0= Surface roughness height (cm)

z_2= 2 m height above the water surface

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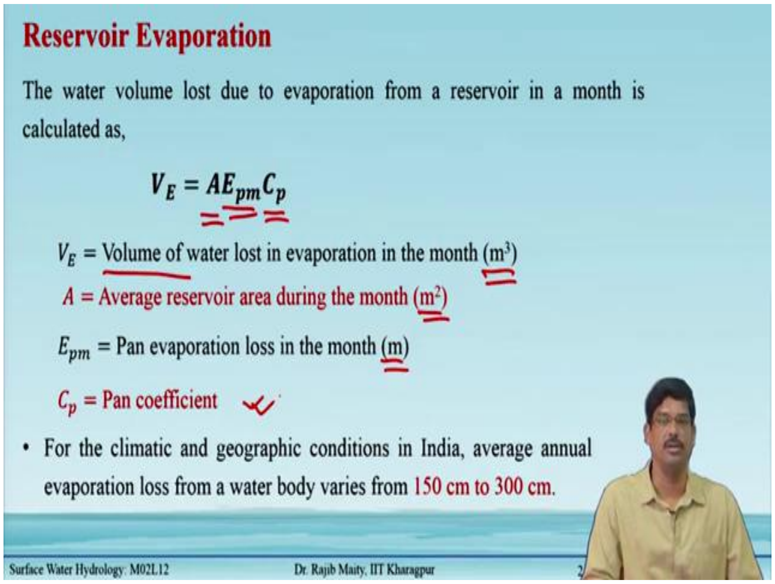

Reservoir Evaporation

The water volume lost due to evaporation from a reservoir in a month is calculated as,

$$V_E = AE_{pm}C_p$$

V_E= Volume of water lost in evaporation in the month (m3)

A= Average reservoir area during the month (m2)

E_{pm}= Pan evaporation loss in the month (m)

C_p= Pan Coefficient

For the climatic and geographic conditions in India, the average annual evaporation loss from a water body varies from 150 cm to 300 cm.

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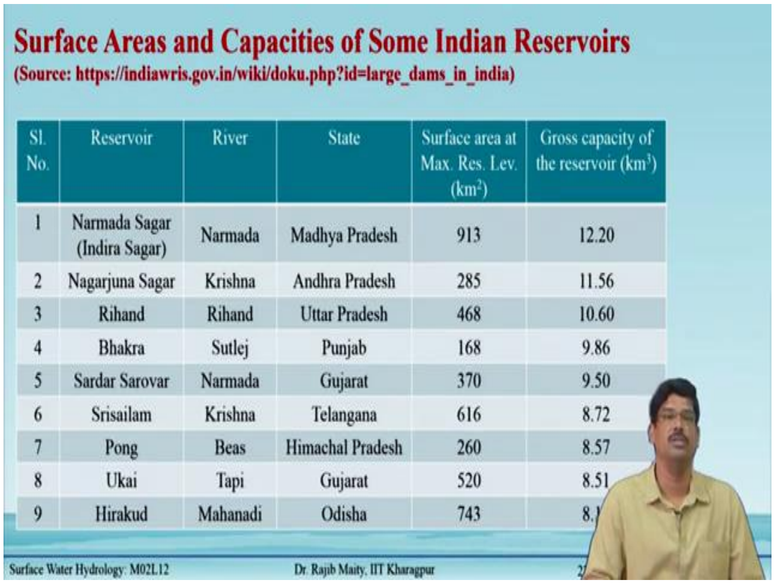

Surface Areas and Capacities of Some Indian Reservoirs

(Source: https://indiawris.gov.in/wiki/doku.php?id=large_dams_in_india)

Sl. No.	Reservoir	River	State	Surface area at Max. Res. Lev. (km^2)	Gross capacity of the reservoir (km^3)
1	Narmada Sagar (Indira Sagar)	Narmada	Madhya Pradesh	913	12.20
2	Nagarjuna Sagar	Krishna	Andhra Pradesh	285	11.56
3	Rihand	Rihand	Uttar Pradesh	468	10.60
4	Bhakra	Sutlej	Punjab	168	9.86
5	Sardar Sarovar	Narmada	Gujarat	370	9.50
6	Srisailam	Krishna	Telangana	616	8.72
7	Pong	Beas	Himachal Pradesh	260	8.57
8	Ukai	Tapi	Gujarat	520	8.51
9	Hirakud	Mahanadi	Odisha	743	8.14

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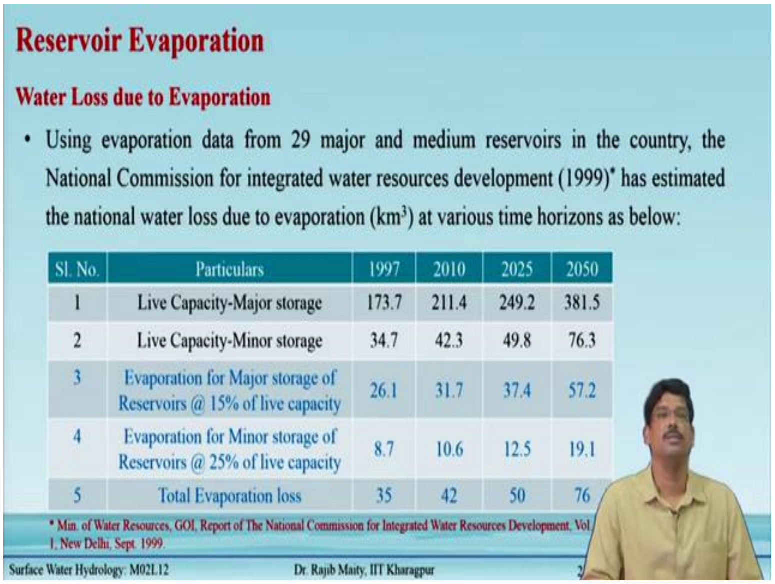

Reservoir Evaporation

Water Loss due to Evaporation

Using evaporation data from 29 major and medium reservoirs in the country, the National Commission for integrated water resources development (1999) * has estimated the national water loss due to evaporation (km3) at various time horizons as below:

Sl. No.	Particulars	1997	2010	2025	2050
1	Live Capacity-Major storage	173.7	211.4	249.2	381.5
2	Live Capacity-Minor storage	34.7	42.3	49.8	76.3
3	Evaporation for Major storage of Reservoirs @ 15% of live capacity	26.1	31.7	37.4	57.2
4	Evaporation for Minor storage of Reservoirs @ 25% of live capacity	8.7	10.6	12.5	19.1
5	Total Evaporation loss	35	42	50	76

* Min. of Water Resources, GOI, Report of the National Commission for Integrated Water Resources Development, Vol.-1, New Delhi, Sept. 1999.

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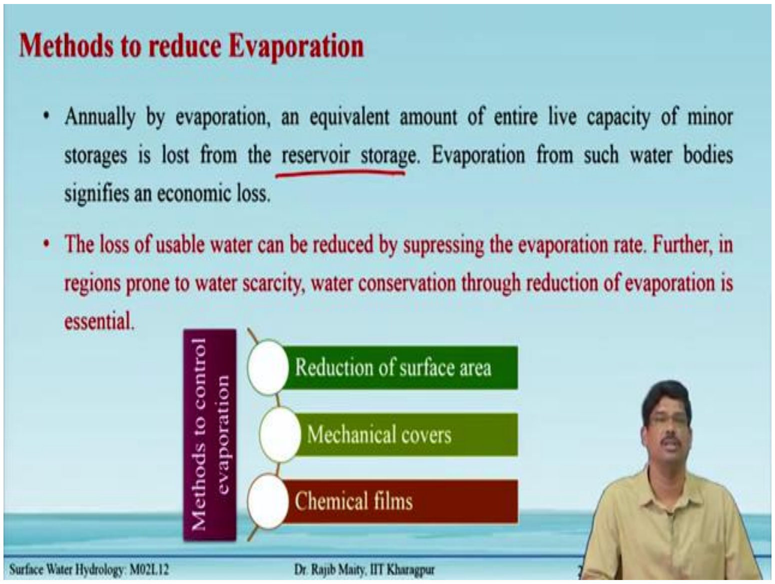

Methods to reduce Evaporation

Annually by evaporation, an equivalent amount of the entire live capacity of minor storage is lost from the reservoir storage. Evaporation from such water bodies signifies an economic loss. The loss of usable water can be reduced by suppressing the evaporation rate. Further, in regions prone to water scarcity, water conservation through the reduction of evaporation is essential.

There are 3 major methods are there through which we can control the rate of evaporation. The first one is the reduction of surface area, as we know that the surface area is directly proportional to the total amount or total volume of this evaporation loss. So, if we just reduce the surface area, there is a possibility of reducing the evaporation loss. There are some mechanical covers we can create to avoid direct exposure to the sun. And thirdly, there could be some chemical films that can be put over the water surface to reduce the evaporation loss we will take up these three things one after another.

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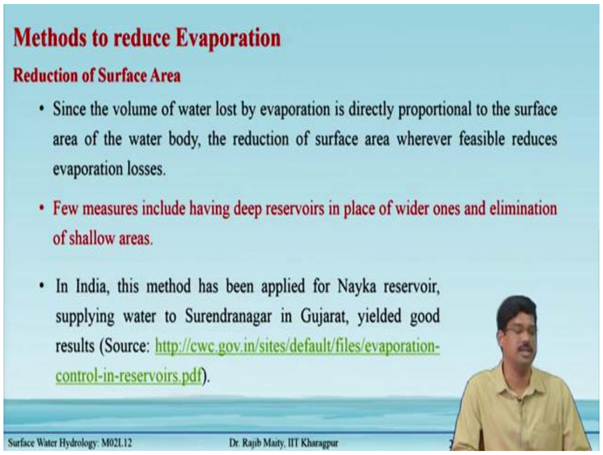

Reduction of Surface Area

Since the volume of water lost by evaporation is directly proportional to the surface area of the water body, the reduction of surface area wherever feasible reduces evaporation losses. Few measures include having deep reservoirs in place of wider ones and elimination of shallow areas.

In India, this method has been applied for Nayka reservoir, supplying water to Surendranagar in Gujarat, which yielded good results.

(Source: http://cwc.gov.in/sites/default/files/evaporation-control-in-reservoirs.pdf).

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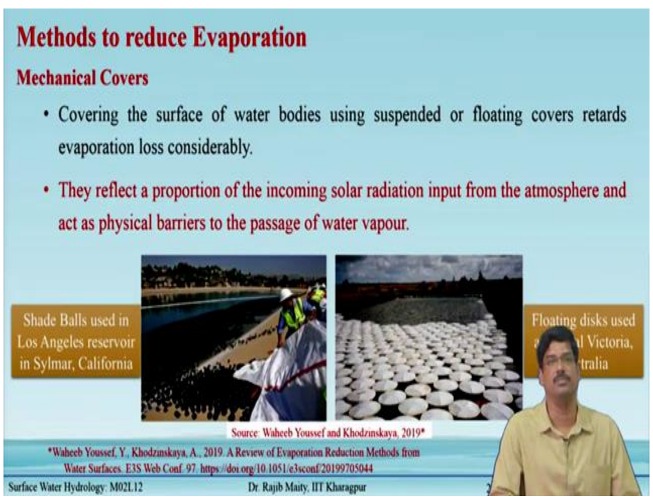

Mechanical Covers

The mechanical covers covering the surface of the water bodies using suspended or floating covers return evaporation loss considerably. They reflect a portion of the incoming solar radiation input from the atmosphere and act as a physical barrier to the passage of water vapor. The shade balls used in the Los Angeles Reservoir in Sylmar, California, and the floating disc are used in Victoria, Australia helps to reduce the evaporation loss.

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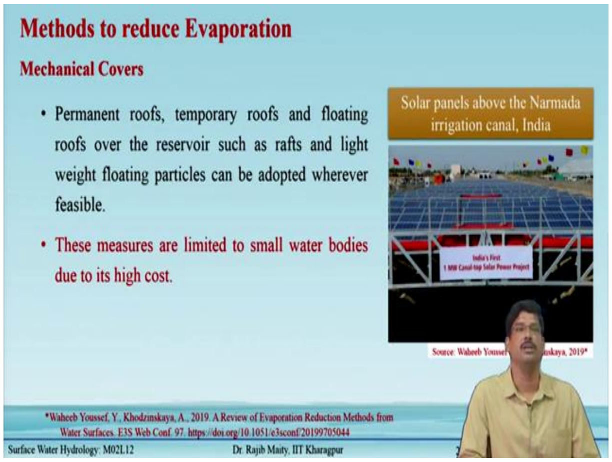

Under the same mechanical covers, sometimes the permanent roofs or temporary roofs and floating roofs, over the reservoirs such as the raft and lightweight floating particles can be adopted wherever feasible, these measures are limited to the small water bodies due to its high cost.

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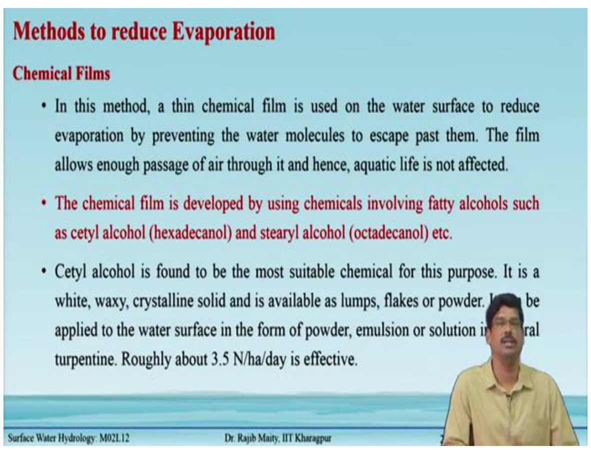

Chemical Films

In this method, a thin chemical film is used on the water surface to reduce evaporation by preventing the water molecules to escape past them. The film allows enough passage of air through it and hence, aquatic life is not affected.

The chemical film is developed by using chemicals involving fatty alcohols such as cetyl alcohol (hexadecanol) and stearyl alcohol (octadecanol) etc. Cetyl alcohol is found to be the most suitable chemical for this purpose. It is a white, waxy, crystalline solid and is available as lumps, flakes, or powder. It can be applied to the water surface in the form of powder, emulsion, or solution in mineral turpentine. Roughly about 3.5 N/ha/day is effective.

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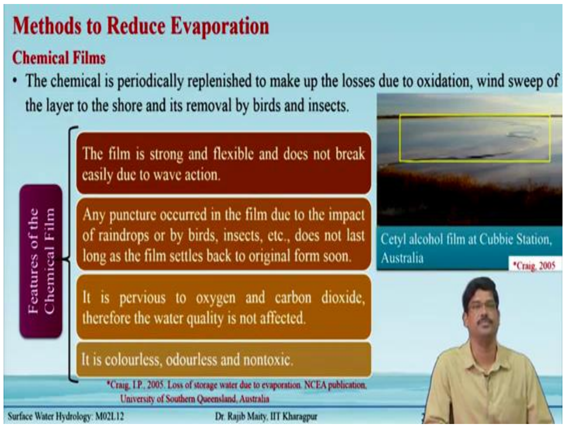

The chemical is periodically replenished to make up the losses due to oxidation, wind sweep of the layer to the shore, and its removal by birds and insects.

Features of the Chemical Films:

- The film is strong and flexible and does not break easily due to wave action.
- Any puncture that occurred in the film due to the impact of raindrops or by birds, insects, etc., does not last long as the film settles back to its original form soon.
- It is pervious to oxygen and carbon dioxide; therefore, the water quality is not affected.
- It is colourless, odourless, and nontoxic.

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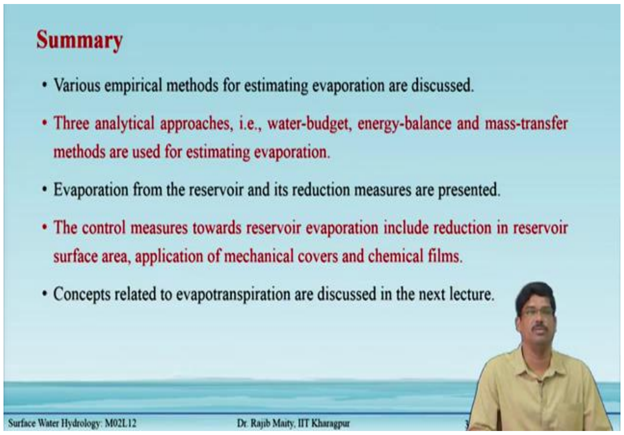

Summary

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

- Various empirical methods for estimating evaporation are discussed.
- Three analytical approaches, i.e., water-budget, energy-balance, and mass-transfer methods are used for estimating evaporation.
- Evaporation from the reservoir and its reduction measures are presented.
- The control measures towards reservoir evaporation include reduction in reservoir surface area, application of mechanical covers, and chemical films.
- Concepts related to evapotranspiration are discussed in the next lecture.