Surface Water Hydrology
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Lecture – 13
Evapotranspiration

In lecture 13, we will discuss one of the most important abstractions from precipitation, which is known as Evapotranspiration.

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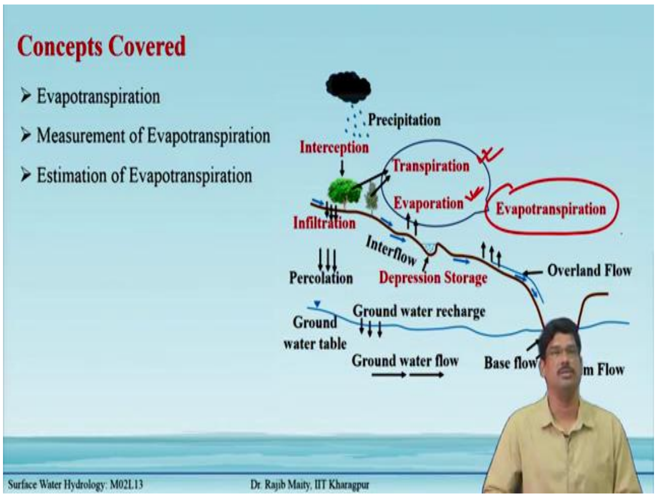

In this lecture, we are covering evapotranspiration, measurement of evapotranspiration, and estimation of evapotranspiration.

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The outline goes as follows the introduction to evapotranspiration, measurement of evapotranspiration. Three major methods will be focused, on is lysimeters, field plots, and soil moisture depletion method. Then, we take up some equations for evapotranspiration. And the concept of the reference crop evapotranspiration, then potential evapotranspiration and actual evapotranspiration before we go to the summary.

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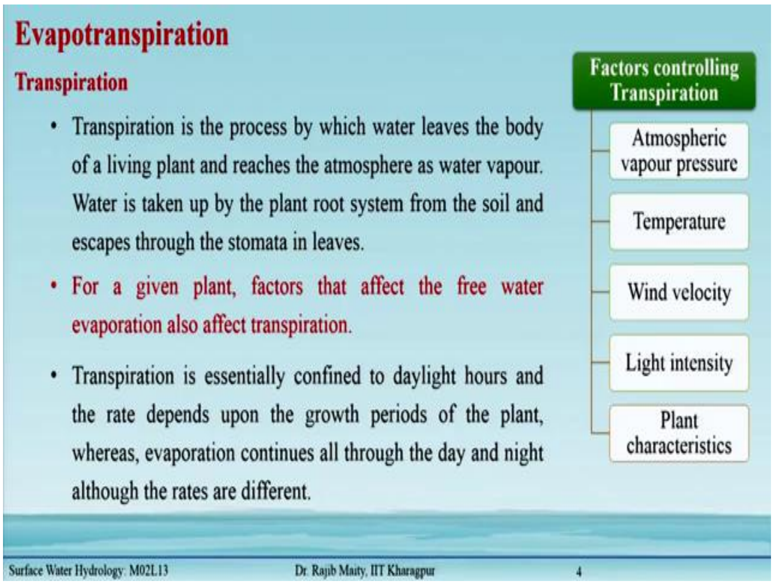

Evapotranspiration

Transpiration

Transpiration is the process by which water leaves the body of a living plant and reaches the atmosphere as water vapour. Water is taken up by the plant root system from the soil and escapes through the stomata in leaves.

For a given plant, factors that affect the free water evaporation also affect transpiration. Transpiration is essentially confined to daylight hours and the rate depends upon the growth periods of the plant, whereas, evaporation continues all through the day and night although the rates are different.

There are some of the factors controlling evaporation, the controlling transpiration. The first one is atmospheric vapour pressure, temperature, wind velocity, light intensity and plant characteristics.

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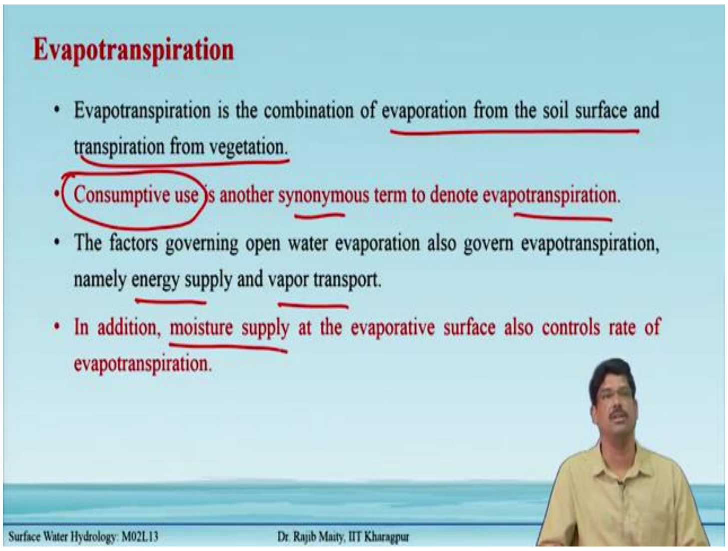

Evapotranspiration

Evapotranspiration is the combination of evaporation from the soil surface and transpiration from vegetation. There is another word, which is known as the consumptive use, or consumptive use of water is also synonymous with the evapotranspiration. The factors governing open water evaporation is also governing evapotranspiration namely the energy supply and vapour transport.

So, these are the two major things that control the total amount of evapotranspiration. In addition, the moisture supply at the evaporative surface also controls the rate of evapotranspiration.

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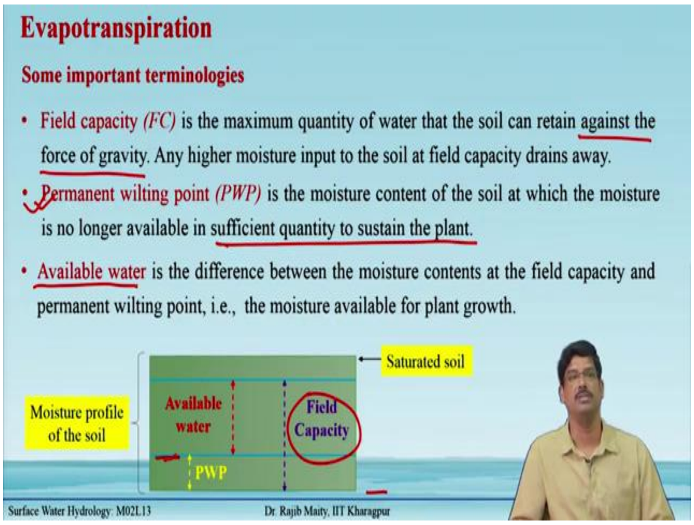

Some important terminologies

Field capacity (FC) is the maximum quantity of water that the soil can retain against the force of gravity. Any higher moisture input to the soil at field capacity drains away.

Permanent wilting point (PWP) is the moisture content of the soil at which the moisture is no longer available in sufficient quantity to sustain the plant.

Available water is the difference between the moisture contents at the field capacity and permanent wilting point, i.e., the moisture available for plant growth.

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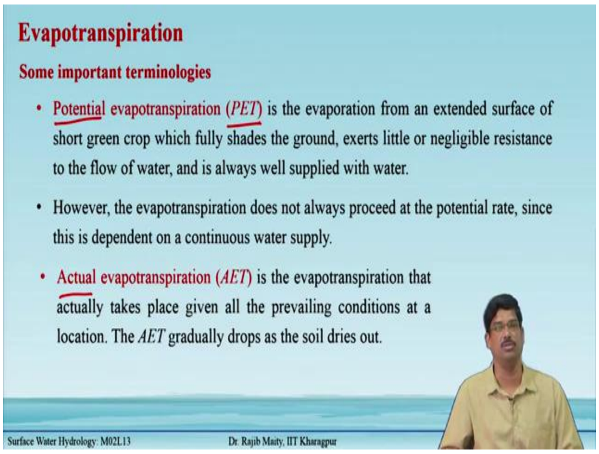

Potential evapotranspiration (PET) is the evaporation from an extended surface of a short green crop that fully shades the ground, exerts little or negligible resistance to the flow of water, and is always well supplied with water.

However, the evapotranspiration does not always proceed at the potential rate, since this is dependent on a continuous water supply.

Actual evapotranspiration (AET) is the evapotranspiration that takes place given all the prevailing conditions at a location. The *AET* gradually drops as the soil dries out.

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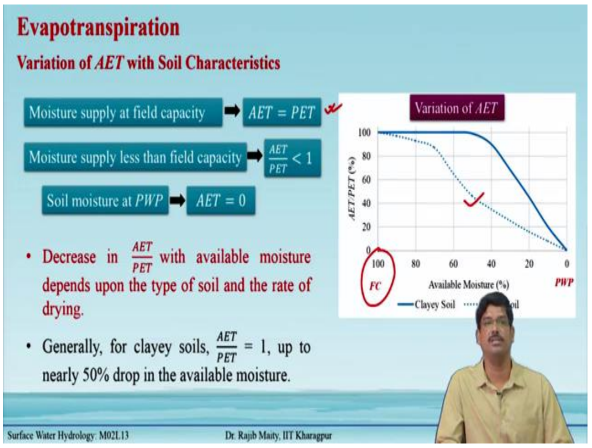

The Variation of AET with Soil Characteristics

- The moisture supply at the field capacity, if it is available, then AET = PET.
- The moisture supply when it is less than the field capacity that is AET/ PET<1,
- When the soil, moisture is at PWP, that time AET = 0.

Decrease in AET/PET with available moisture depends upon the type of soil and the rate of drying. It drops quickly in the case of the sandy soil and for the clay soil, it has a more, it goes up to a certain extent as compared to the sandy soil when it is still the AET and PET are same and then gradually drops to 0. Both of them drop to 0 when it reaches the permanent wilting point that is the available moisture becomes 0 percent.

So, a decrease in the AET by PET with the available moisture depends on the type of the soil and rate of the drying. Generally, for clayey soils, AET/PET = 1, up to nearly 50% drop in the available moisture.

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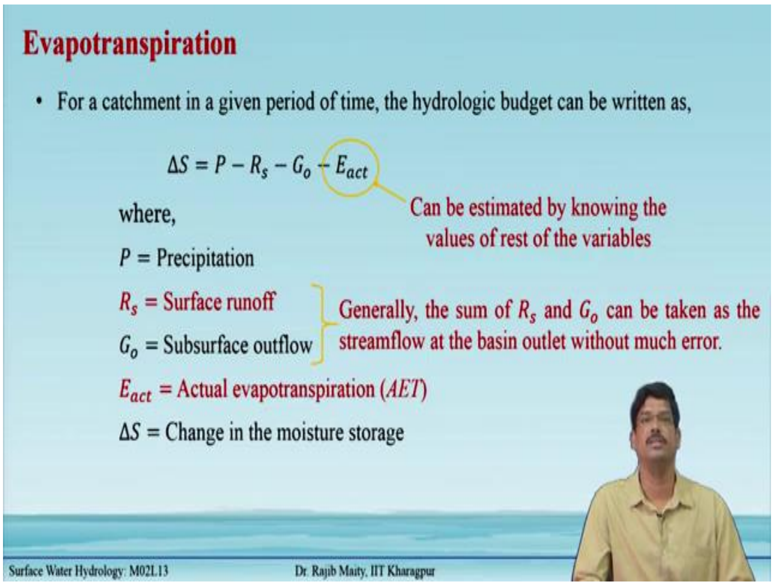

For a catchment in a given period of time, the hydrologic budget can be written as

$$\Delta S = P - R_s - G_o - E_{act}$$

Can be estimated by knowing the values of rest of the variables

Where, P=Precipitation

R_s= Surface runoff

G_o= Subsurface outflow

E_{act}= Actual evapotranspiration (AET)

ΔS= Change in the moisture storage

Generally, the sum of R_s and G_o can be taken as the streamflow at the basin outlet without much error.

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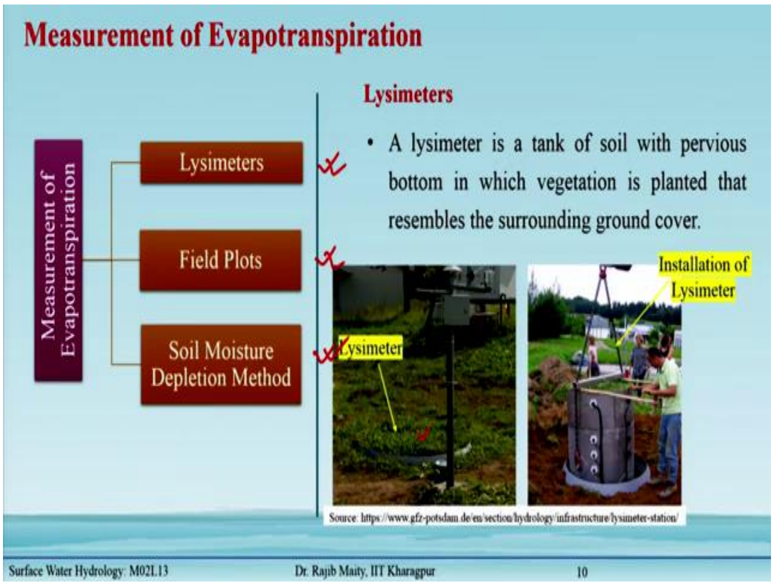

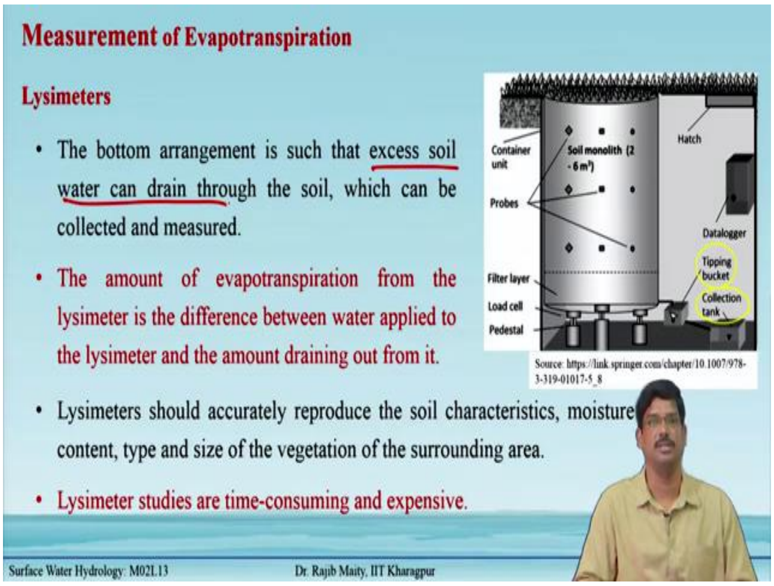

Measurement of Evapotranspiration

The measurement of the evapotranspiration can be done in three major ways. The first instrument is called the Lysimeter. Then the second category is the field plots and the third one is a soil moisture depletion method.

Lysimeters

A lysimeter is a tank of soil with pervious bottom in which vegetation is planted that resembles the surrounding ground cover.

The bottom arrangement is such that excess soil water can drain through the soil, which can be collected and measured. The amount of evapotranspiration from the lysimeter is the difference between water applied to the lysimeter and the amount draining out from it.

Lysimeters should accurately reproduce the soil characteristics, moisture content, type, and size of the vegetation of the surrounding area. Lysimeter studies are time-consuming and expensive.

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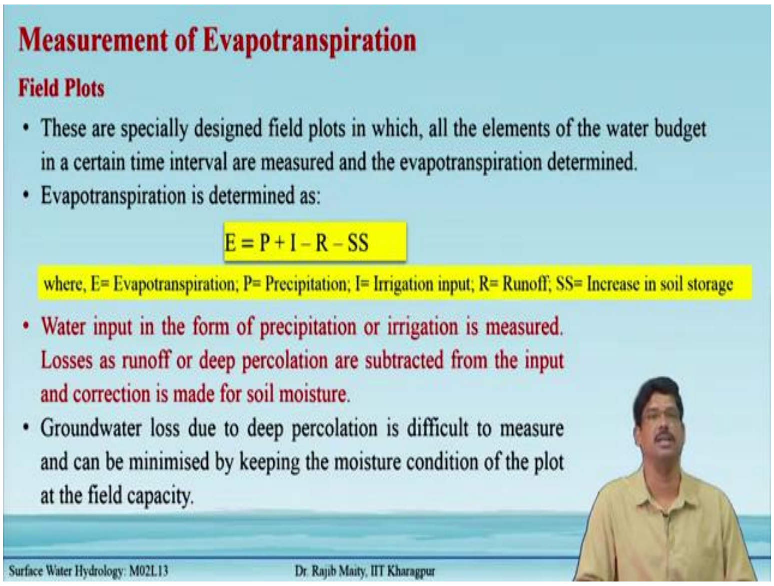

Field Plots

These are specially designed field plots in which, all the elements of the water budget in a certain time interval are measured and the evapotranspiration determined. Evapotranspiration is determined as:

$$E = P + I - R - SS$$

Where, E= Evapotranspiration; P= Precipitation; I= Irrigation input; R= Runoff; SS= Increase in soil storage

Water input in the form of precipitation or irrigation is measured. Losses as runoff or deep percolation are subtracted from the input and correction is made for soil moisture. Groundwater loss due to deep percolation is difficult to measure and can be minimized by keeping the moisture condition of the plot at the field capacity.

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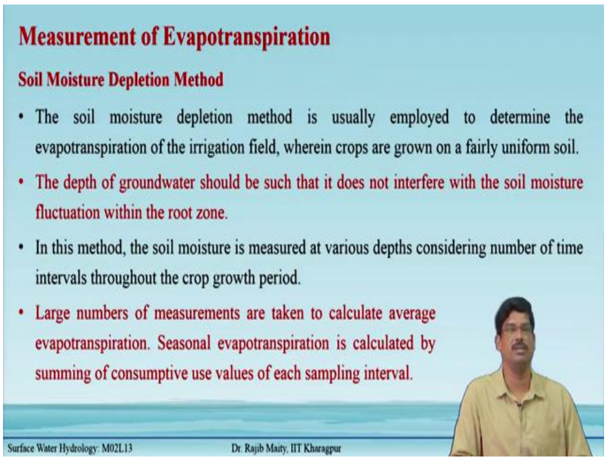

Soil Moisture Depletion Method

The soil moisture depletion method is usually employed to determine the evapotranspiration of the irrigation field, wherein crops are grown on fairly uniform soil. The depth of groundwater should be such that it does not interfere with the soil moisture fluctuation within the root zone.

In this method, the soil moisture is measured at various depths considering several time intervals throughout the crop growth period. Large numbers of measurements are taken to calculate average evapotranspiration. Seasonal evapotranspiration is calculated by summing of consumptive use values of each sampling interval.

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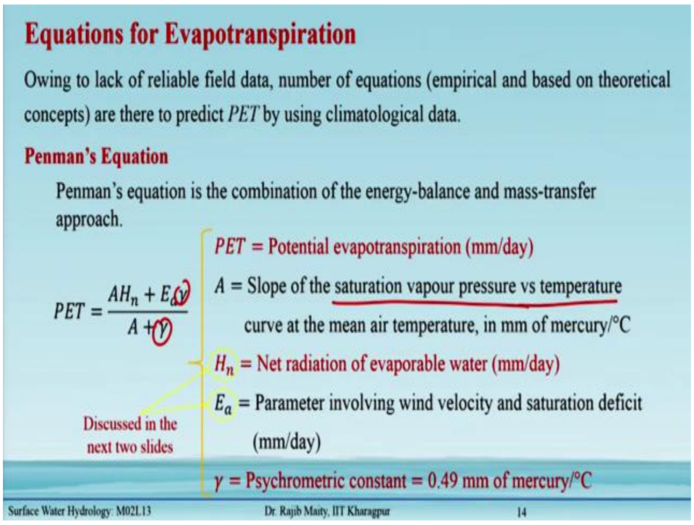

Equations for Evapotranspiration

Owing to the lack of reliable field data, several equations (empirical and based on theoretical concepts) are there to predict PET by using climatological data.

Penman's Equation

Penman's equation is the combination of the energy-balance and mass-transfer approach.

$$PET = \frac{AH_n + E_a\gamma}{A + \gamma}$$

PET= Potential evapotranspiration (mm/day)

A= Slope of the saturation vapour pressure vs temperature curve at the mean air temperature, in mm of mercury/°C

H_n= Net radiation of evaporable water (mm/day)

E_a= Parameter involving wind velocity and saturation deficit (mm/day)

γ= Psychometric constant = 0.49 mm of mercury/°C

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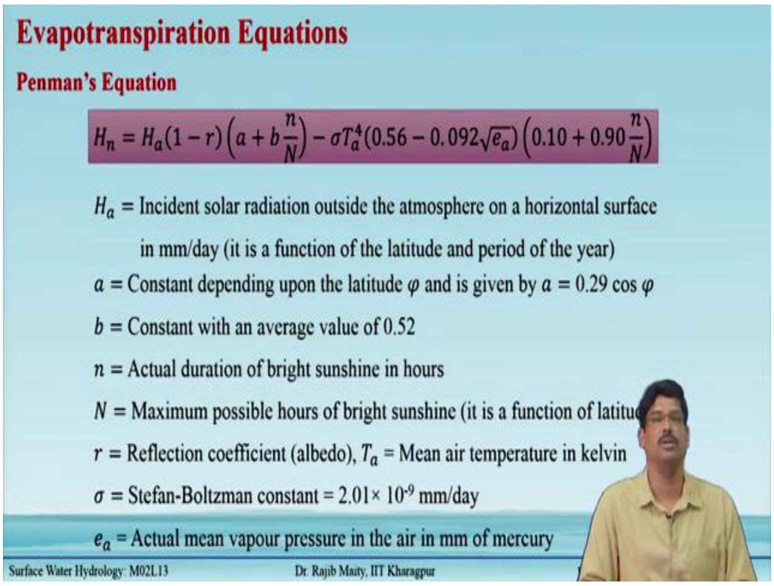

Penman's Equation

$$H_n = H_a(1-r)\left(a + b\frac{n}{N}\right) - \sigma T_a^4(0.56 - 0.092\sqrt{e_a})\left(0.10 + 0.90\frac{n}{N}\right)$$

H_a= Incident solar radiation outside the atmosphere on a horizontal surface in mm/day (it is a function of the latitude and period of the year)

a= Constant depending upon the latitude φ and is given by a= 0.29 cos φ

b= Constant with an average value of 0.52

n= Actual duration of bright sunshine in hours

N= Maximum possible hours of bright sunshine (it is a function of latitude)

r= Reflection coefficient (albedo),

T_a = Mean air temperature in kelvin

σ= Stefan-Boltzman constant = 2.01× 10-9 mm/day

e_a = Actual mean vapour pressure in the air in mm of mercury

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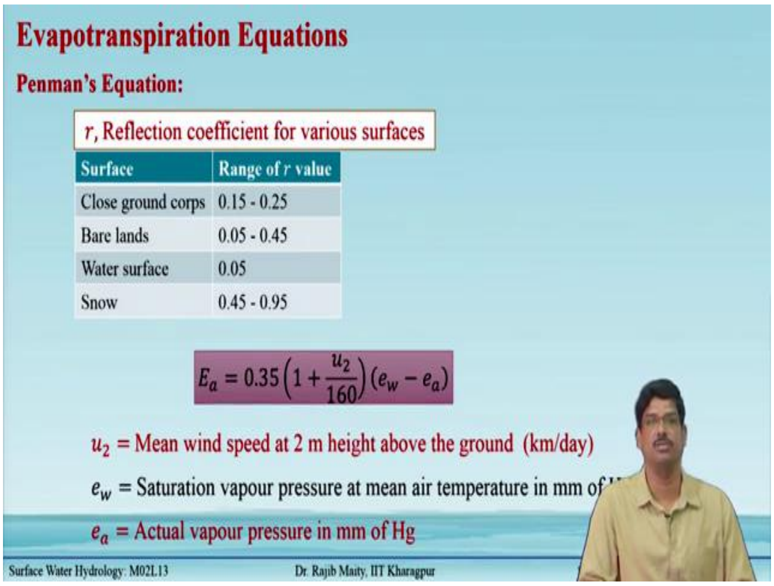

R is the reflection that we will call it albedo. And it depends on the different surface conditions.

Surface	Range of r value
Close ground corps	0.15 - 0.25
Bare lands	0.05 - 0.45
Water surface	0.05
Snow	0.45 - 0.95

Now, E_a can be estimated from the following expression

$$E_a = 0.35\left(1+\frac{u_2}{160}\right)(e_w - e_a)$$

u_2= Mean wind speed at 2 m height above the ground (km/day)

e_w= Saturation vapour pressure at mean air temperature in mm of Hg

e_a= Actual vapour pressure in mm of Hg

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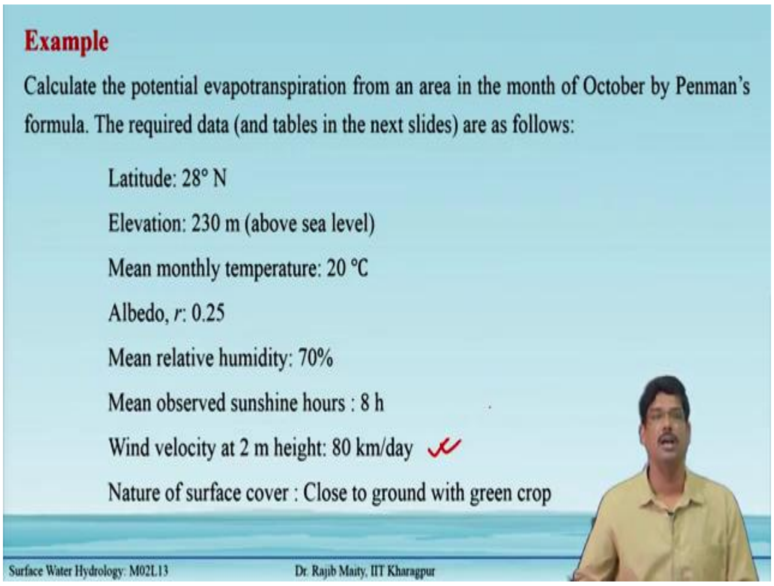

Example

Calculate the potential evapotranspiration from an area in the month of October by Penman's formula. The required data (and tables in the next slides) are as follows:

Latitude: 28° N

Elevation: 230 m (above sea level)

Mean monthly temperature: 20 °C

Albedo, r: 0.25

Mean relative humidity: 70%

Mean observed sunshine hours: 8 h

Wind velocity at 2 m height: 80 km/day

Nature of surface cover: Close to ground with green crop

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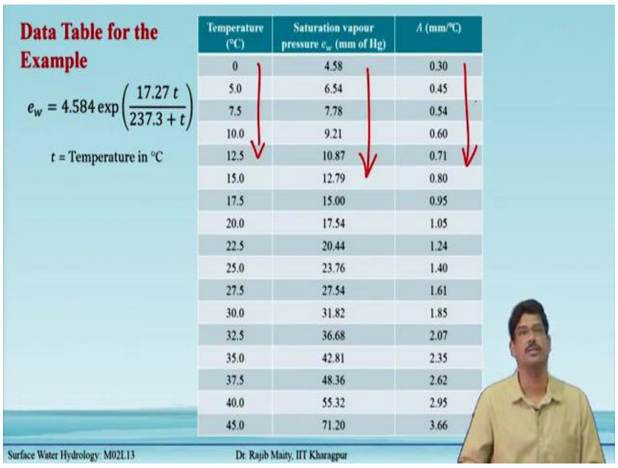

Data Table for the Example

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

t = Temperature in °C

Temperature (°C)	Saturation vapour pressure e_w (mm of Hg)	A (mm/°C)
0	4.58	0.30
5.0	6.54	0.45
7.5	7.78	0.54
10.0	9.21	0.60
12.5	10.87	0.71
15.0	12.79	0.80
17.5	15.00	0.95
20.0	17.54	1.05
22.5	20.44	1.24
25.0	23.76	1.40
27.5	27.54	1.61
30.0	31.82	1.85
32.5	36.68	2.07
35.0	42.81	2.35
37.5	48.36	2.62
40.0	55.32	2.95
45.0	71.20	3.66

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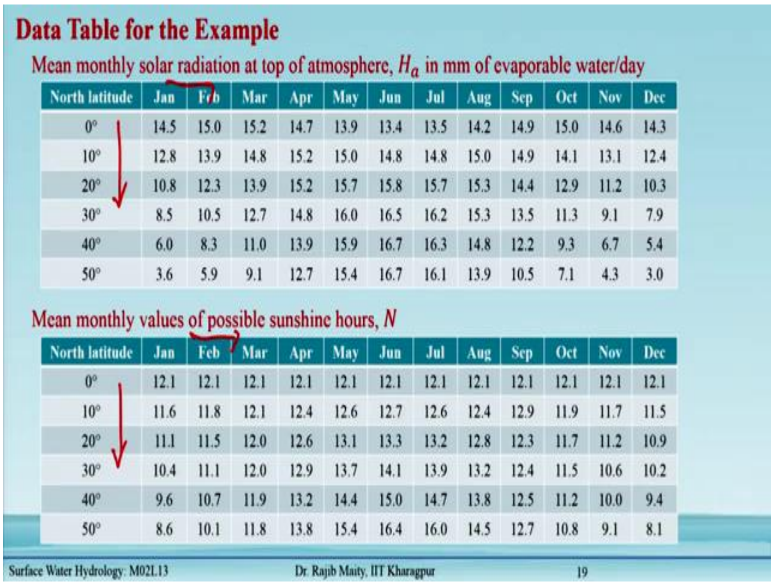

Data Table for the Example

Mean monthly solar radiation at top of the atmosphere, H_a in mm of evaporable water/day

North latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0°	14.5	15.0	15.2	14.7	13.9	13.4	13.5	14.2	14.9	15.0	14.6	14.3
10°	12.8	13.9	14.8	15.2	15.0	14.8	14.8	15.0	14.9	14.1	13.1	12.4
20°	10.8	12.3	13.9	15.2	15.7	15.8	15.7	15.3	14.4	12.9	11.2	10.3
30°	8.5	10.5	12.7	14.8	16.0	16.5	16.2	15.3	13.5	11.3	9.1	7.9
40°	6.0	8.3	11.0	13.9	15.9	16.7	16.3	14.8	12.2	9.3	6.7	5.4
50°	3.6	5.9	9.1	12.7	15.4	16.7	16.1	13.9	10.5	7.1	4.3	3.0

Mean monthly values of possible sunshine hours, N

North latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0°	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1
10°	11.6	11.8	12.1	12.4	12.6	12.7	12.6	12.4	12.9	11.9	11.7	11.5
20°	11.1	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
30°	10.4	11.1	12.0	12.9	13.7	14.1	13.9	13.2	12.4	11.5	10.6	10.2
40°	9.6	10.7	11.9	13.2	14.4	15.0	14.7	13.8	12.5	11.2	10.0	9.4
50°	8.6	10.1	11.8	13.8	15.4	16.4	16.0	14.5	12.7	10.8	9.1	8.1

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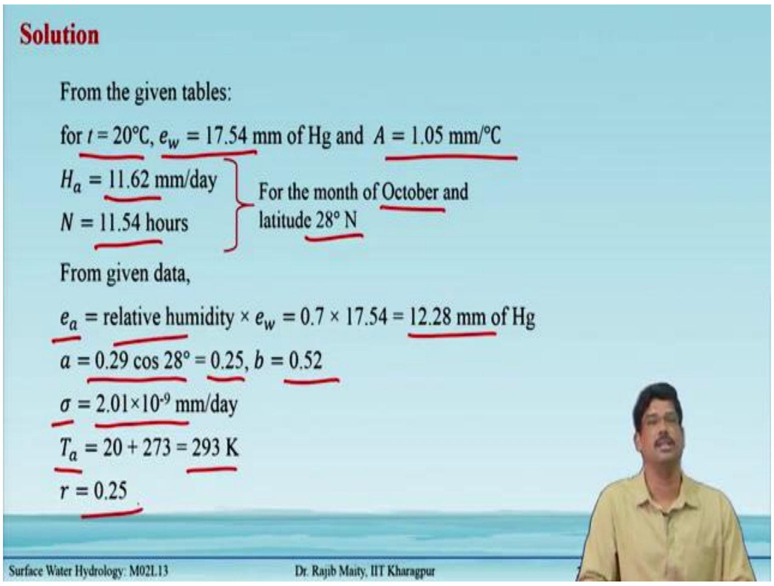

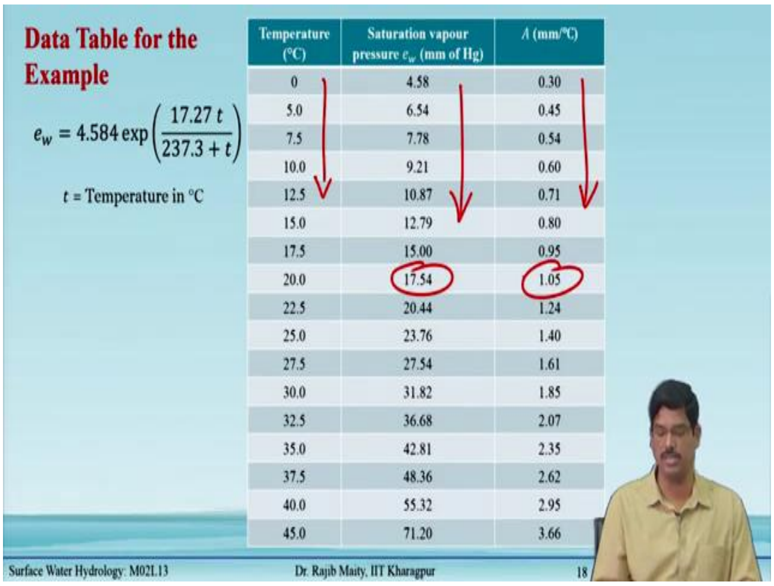

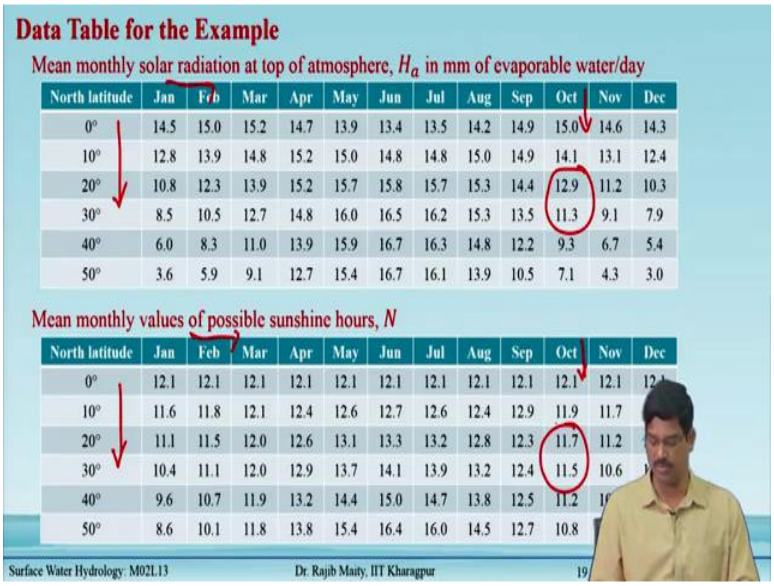

Solution

From the given tables:

for t = 20℃, e_w= 17.54 mm of Hg and A= 1.05 mm/℃

H_a= 11.62 mm/day [For the month of October and latitude 28° N]

N= 11.54 hours [For the month of October and latitude 28° N]

From given data,

e_a= relative humidity × e_w= 0.7 × 17.54 = 12.28 mm of Hg

a= 0.29 cos 28° = 0.25, b= 0.52

σ= 2.01×10-9 mm/day

T_a= 20 + 273 = 293 K

r= 0.25

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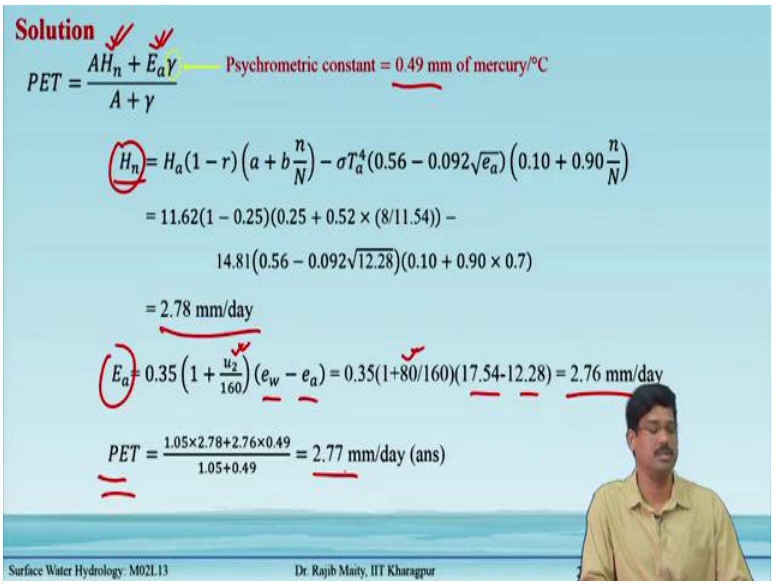

$$PET = \frac{AH_n + E_a\gamma}{A + \gamma}$$

γ= Psychrometric constant = 0.49 mm of mercury/°C

$$H_n = H_a(1-r)\left(a + b\frac{n}{N}\right) - \sigma T_a^4(0.56 - 0.092\sqrt{e_a})\left(0.10 + 0.90\frac{n}{N}\right)$$

$= 11.62\ (1-0.25)\ (0.25\ +0.52 \times (8/11.54) - 14.81\ (0.56-0.092 \times \sqrt{12.2})\ (0.10+0.90\times0.7)$

$= 2.78$ mm/day

$E_a = 0.35(1+u_2/160)\ (e_w - e_a) = 0.35(1+80/160)\ (17.54-12.28) = 2.76$ mm/day

$PET = \frac{1.05\times2.78+2.76\times0.49}{1.05+0.49} = 2.77$ mm/day (ans)

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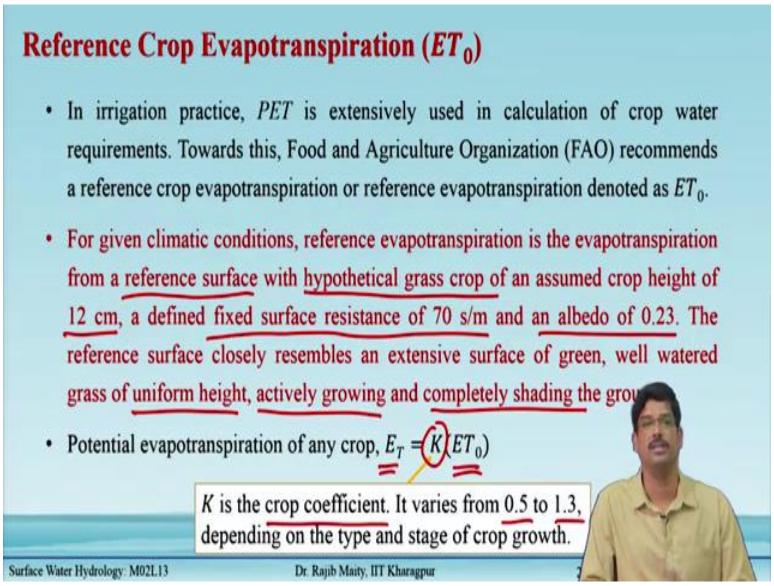

Reference Crop Evapotranspiration (ET_0)

In irrigation practice, PET is extensively used in the calculation of crop water requirements. Towards this, Food and Agriculture Organization (FAO) recommends a reference crop evapotranspiration or reference evapotranspiration denoted as ET_0.

For given climatic conditions, reference evapotranspiration is the evapotranspiration from a reference surface with a hypothetical grass crop of an assumed crop height of 12 cm, a defined fixed surface resistance of 70 s/m, and an albedo of 0.23. The reference surface closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground.

Potential evapotranspiration of any crop, $ET=K(ET_0)$

K are the crop coefficient. It varies from 0.5 to 1.3, depending on the type and stage of crop growth.

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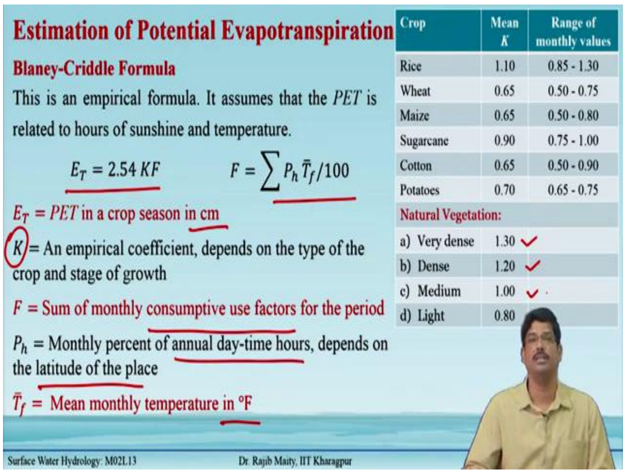

Blaney-Criddle Formula

This is an empirical formula. It assumes that the PET is related to hours of sunshine and temperature.

$$E_T = 2.54KF \qquad F = \sum P_h \bar{T}_f/100$$

E_T= PET in a crop season in cm

K= An empirical coefficient depends on the type of the crop and stage of growth

F= Sum of monthly consumptive use factors for the period

P_h = Monthly percent of annual day-time hours, depends on the latitude of the place

T_f= Mean monthly temperature in °F

In the following table, the different crops are mentioned here like rice, wheat, maize, sugarcane, cotton, potatoes. The mean value of K is given and their range is also given.

Crop	Mean K	Range of monthly values
Rice	1.10	0.85 - 1.30
Wheat	0.65	0.50 - 0.75
Maize	0.65	0.50 - 0.80
Sugarcane	0.90	0.75 - 1.00
Cotton	0.65	0.50 - 0.90
Potatoes	0.70	0.65 - 0.75
Natural Vegetation:		
a) Very dense	1.30	
b) Dense	1.20	
c) Medium	1.00	
d) Light	0.80	

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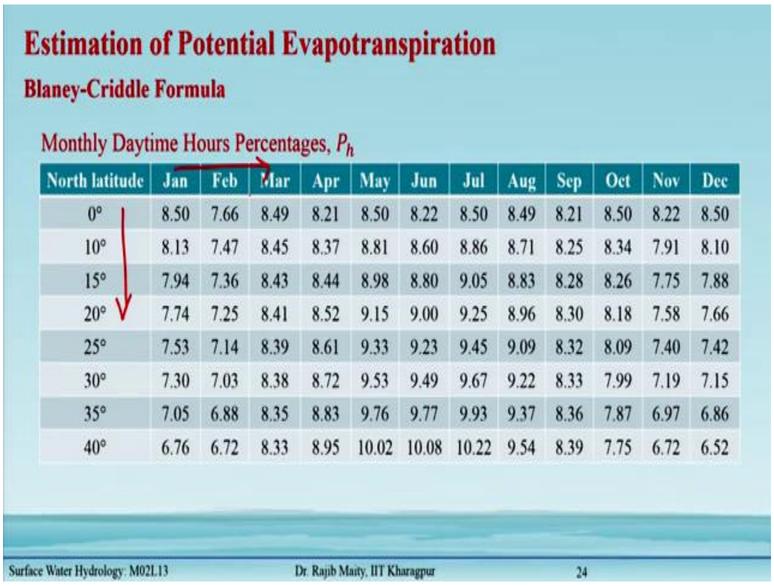

Monthly Daytime Hours Percentages, P_h

North latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0°	8.50	7.66	8.49	8.21	8.50	8.22	8.50	8.49	8.21	8.50	8.22	8.50
10°	8.13	7.47	8.45	8.37	8.81	8.60	8.86	8.71	8.25	8.34	7.91	8.10
15°	7.94	7.36	8.43	8.44	8.98	8.80	9.05	8.83	8.28	8.26	7.75	7.88
20°	7.74	7.25	8.41	8.52	9.15	9.00	9.25	8.96	8.30	8.18	7.58	7.66
25°	7.53	7.14	8.39	8.61	9.33	9.23	9.45	9.09	8.32	8.09	7.40	7.42
30°	7.30	7.03	8.38	8.72	9.53	9.49	9.67	9.22	8.33	7.99	7.19	7.15
35°	7.05	6.88	8.35	8.83	9.76	9.77	9.93	9.37	8.36	7.87	6.97	6.86
40°	6.76	6.72	8.33	8.95	10.02	10.08	10.22	9.54	8.39	7.75	6.72	6.52

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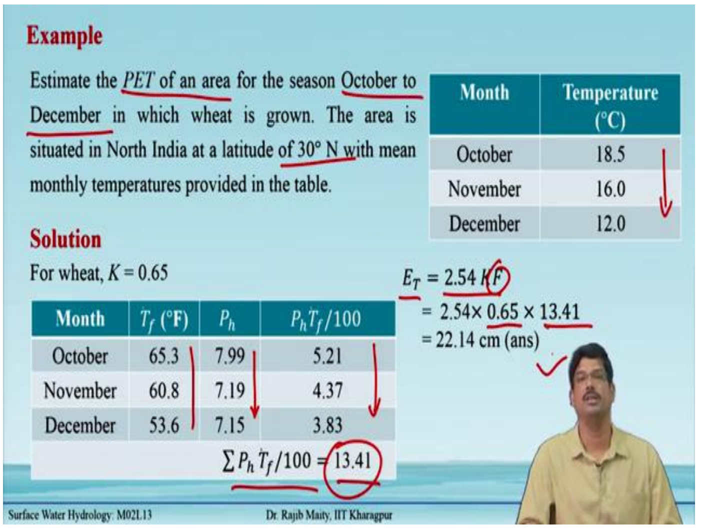

Example

Estimate the PET of an area for the season October to December in which wheat is grown. The area is situated in North India at a latitude of 30° N with mean monthly temperatures provided in the table.

Month	Temperature (°C)
October	18.5
November	16.0
December	12.0

Solution

For wheat, K = 0.65

Month	$\bar{T}_f$ (°F)	P_h	$P_h\bar{T}_f/100$
October	65.3	7.99	5.21
November	60.8	7.19	4.37
December	53.6	7.15	3.83
			$\sum P_h \bar{T}_f/100 = 13.41$

E_T=2.54 KF

= 2.54×0.65×13.41

= 22.14 cm (Ans)

So, we get the 22.14 centimeter as a PET for this for the season October to December.

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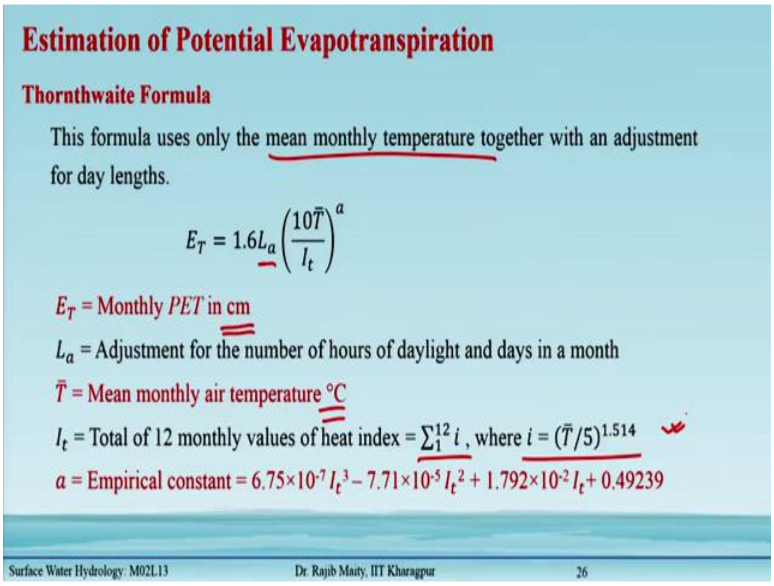

Thornthwaite Formula

This formula uses only the mean monthly temperature together with an adjustment for day lengths

$$E_T = 1.6L_a\left(\frac{10\bar{T}}{I_t}\right)^a$$

E_T = Monthly PET in cm

L_a = Adjustment for the number of hours of daylight and days in a month

$\bar{\mathbf{T}}$ = Mean monthly air temperature °C

I_t = Total of 12 monthly values of heat index $= \sum_1^{12} i$, where $i = (\bar{T}/5)^{1.514}$

a = Empirical constant = $6.75\times10^{-7} I_t^3 - 7.71\times10^{-5} I_t^2 + 1.792\times10^{-2} I_t + 0.49239$

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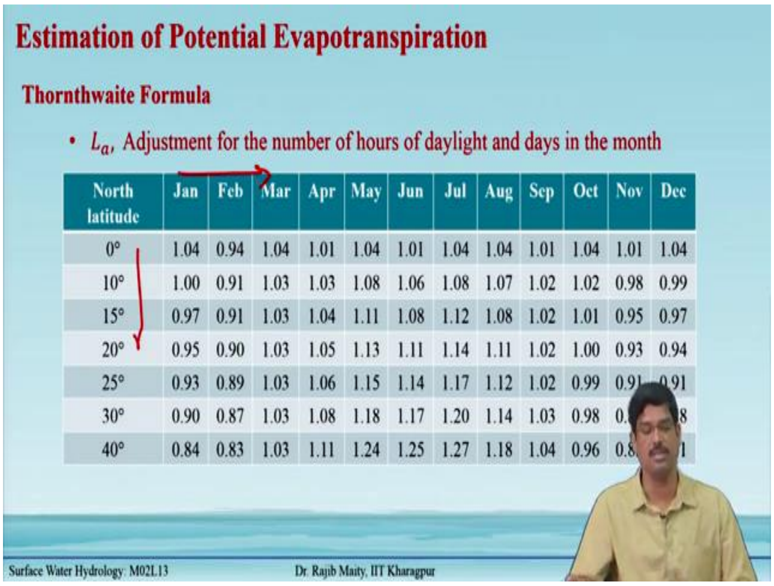

L_a, Adjustment for the number of hours of daylight and days in the month

North latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0°	1.04	0.94	1.04	1.01	1.04	1.01	1.04	1.04	1.01	1.04	1.01	1.04
10°	1.00	0.91	1.03	1.03	1.08	1.06	1.08	1.07	1.02	1.02	0.98	0.99
15°	0.97	0.91	1.03	1.04	1.11	1.08	1.12	1.08	1.02	1.01	0.95	0.97
20°	0.95	0.90	1.03	1.05	1.13	1.11	1.14	1.11	1.02	1.00	0.93	0.94
25°	0.93	0.89	1.03	1.06	1.15	1.14	1.17	1.12	1.02	0.99	0.91	0.91
30°	0.90	0.87	1.03	1.08	1.18	1.17	1.20	1.14	1.03	0.98	0.89	0.88
40°	0.84	0.83	1.03	1.11	1.24	1.25	1.27	1.18	1.04	0.96	0.83	0.81

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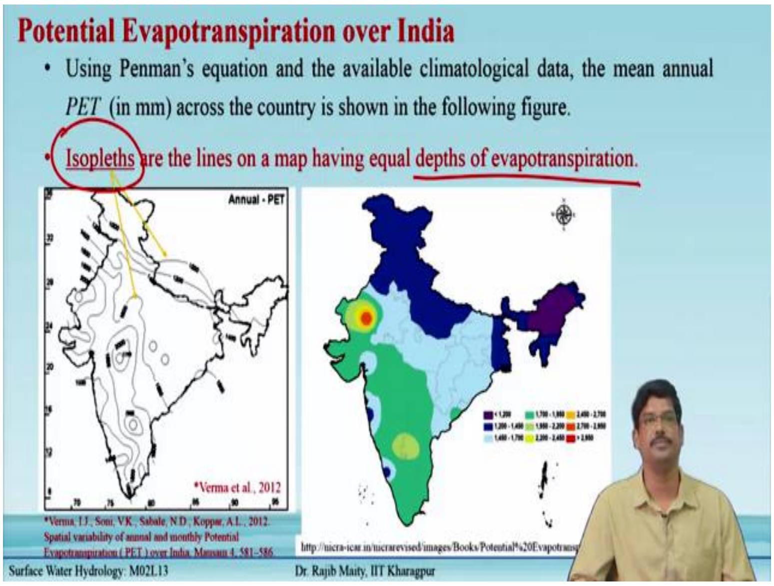

Potential Evapotranspiration over India

Using Penman's equation and the available climatological data, the mean annual PET (in mm) across the country is shown in the following figure 1.

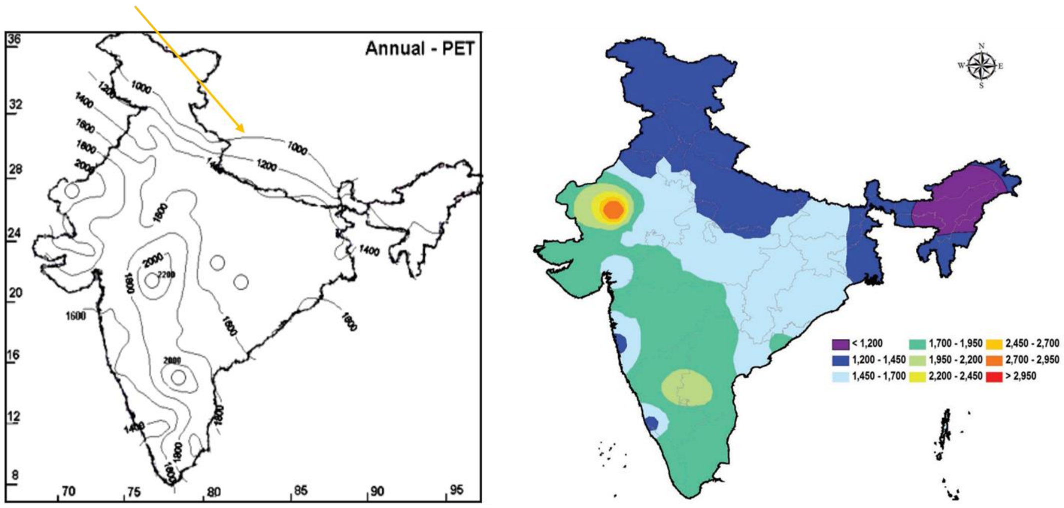

Fig.1 shows the Potential Evapotranspiration over India

Isopleths are the line on a map that has equal depths of your evapotranspiration. So, one typical example you can see fig.1, on the left-hand side, how is it shown that how the depths of the evapotranspiration are annual PET is shown through some contour plot And on the right-hand side also you can see that how this that using this Penman's equation and the available climatological data and the mean annual PET across the country.

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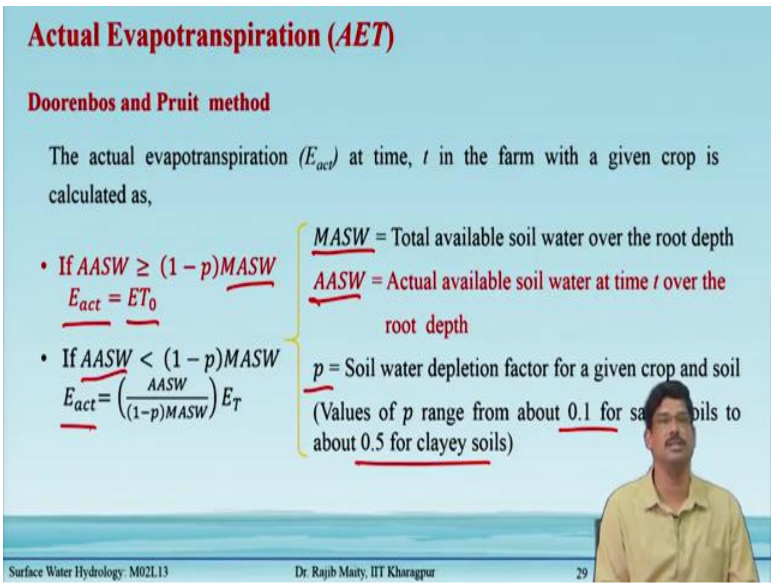

Actual Evapotranspiration (*AET*)

Doorenbos and Pruit method

The actual evapotranspiration (E_{act}) at a time, t in the farm with a given crop is calculated as,

If $AASW \geq (1-p)\ MASW$

$E_{act} = ET_0$

If $AASW < (1-p)\ MASW$

$$E_{act} = \left(\frac{AASW}{(1-p)MASW}\right) E_T$$

$MASW$ = Total available soil water over the root depth

$AASW$ = Actual available soil water at time t over the root depth

p = Soil water depletion factor for a given crop and soil

(Values of p range from about 0.1 for sandy soils to about 0.5 for clayey soils)

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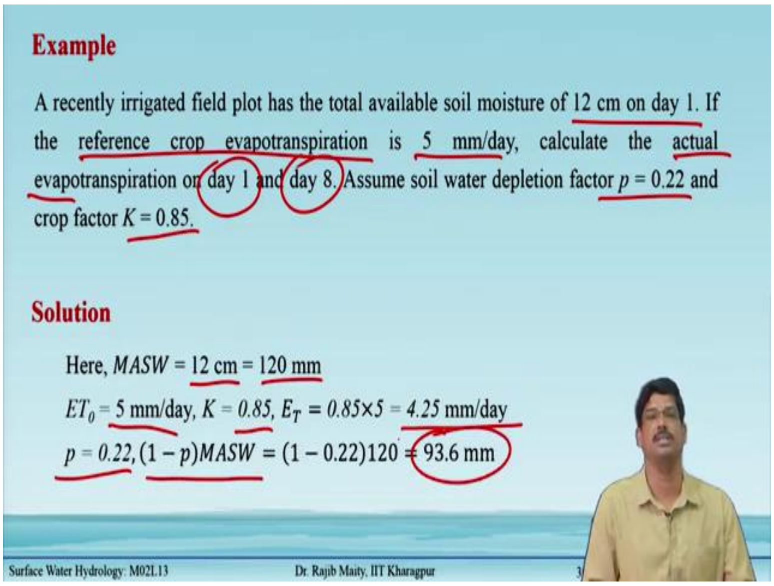

Example

A recently irrigated field plot has total available soil moisture of 12 cm on day 1. If the reference crop evapotranspiration is 5 mm/day, calculate the actual evapotranspiration on day 1 and day 8. Assume soil water depletion factor p = 0.22 and crop factor K = 0.85.

Solution

Here, $MASW$ = 12 cm = 120 mm

ET_0 = 5 mm/day, K = 0.85, E_T= 0.85×5 = 4.25 mm/day

p = 0.22, $(1-p)\ MASW$= (1−0.22)120=93.6 mm

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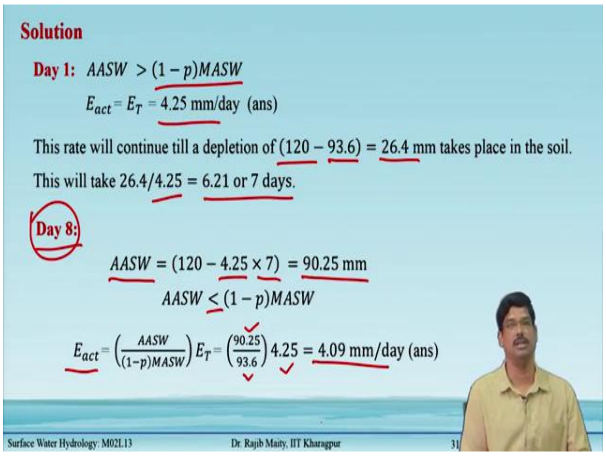

Day 1:

$AASW > (1-p)\ MASW$

E_{act}= E_T = 4.25 mm/day (Ans)

This rate will continue till a depletion of (120−93.6) =26.4 mm takes place in the soil.

This will take 26.4/4.25=6.21 or 7 days.

Day 8:

$AASW$= (120−4.25×7) =90.25 mm

$AASW < (1-p)\ MASW$

E_{act}= $(AASW/\ (1-p)\ MASW)\ E_T$= (90.25/93.6)4.25=4.09 mm/day (Ans)

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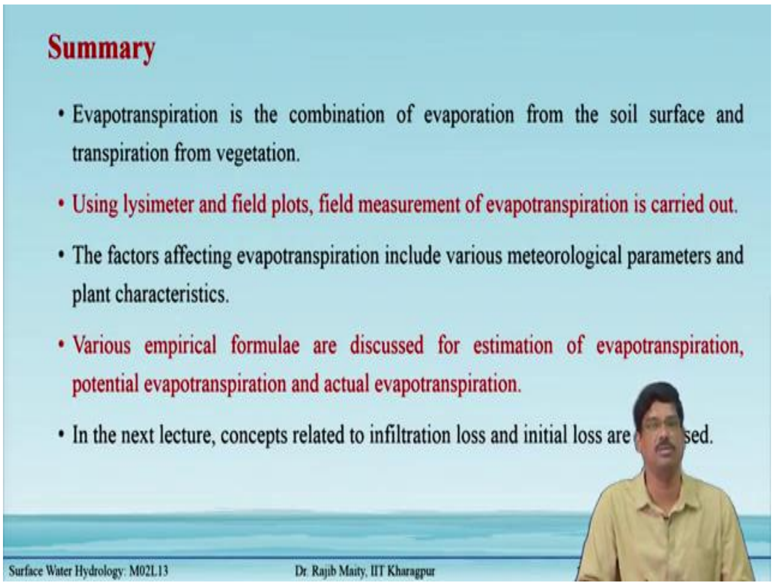

Summary

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

- Evapotranspiration is the combination of evaporation from the soil surface and transpiration from vegetation.
- Using lysimeter and field plots, field measurement of evapotranspiration is carried out.
- The factors affecting evapotranspiration include various meteorological parameters and plant characteristics.
- Various empirical formulae are discussed for the estimation of evapotranspiration, potential evapotranspiration, and actual evapotranspiration.
- In the next lecture, concepts related to infiltration loss and initial loss are discussed.