Course Name: Watershed Hydrology

Professor Name: Prof. Rajendra Singh

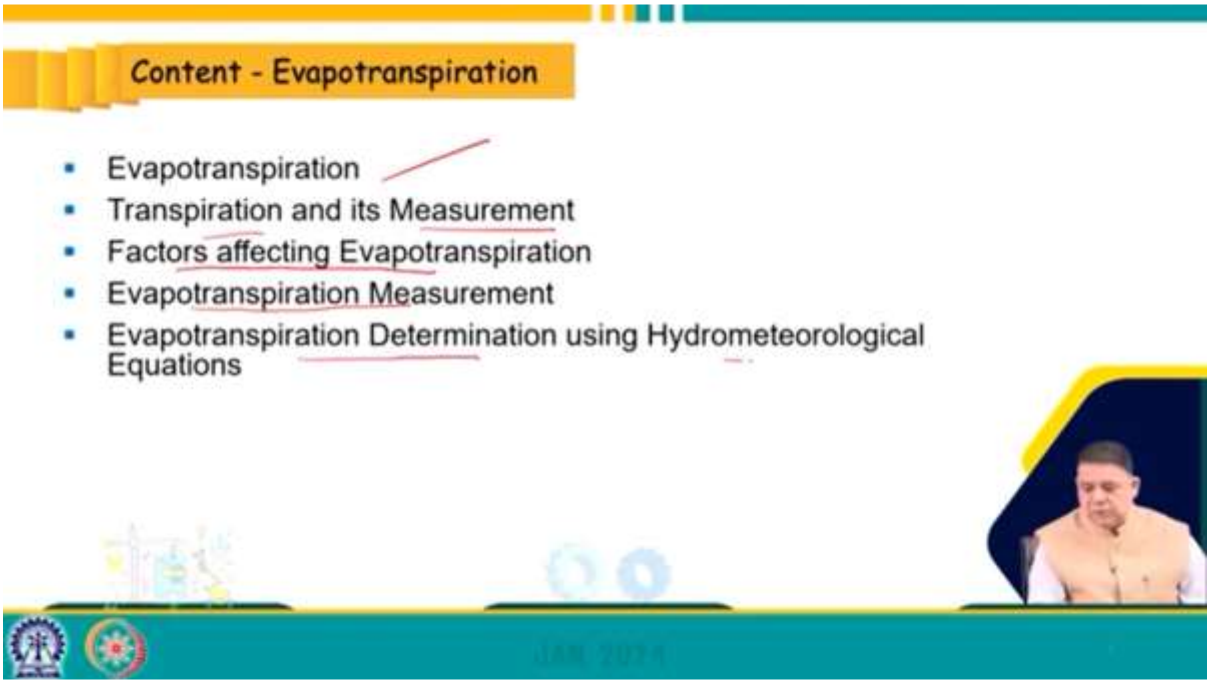
Department Name: Agricultural and Food Engineering

Institute Name: Indian Institute of Technology Kharagpur

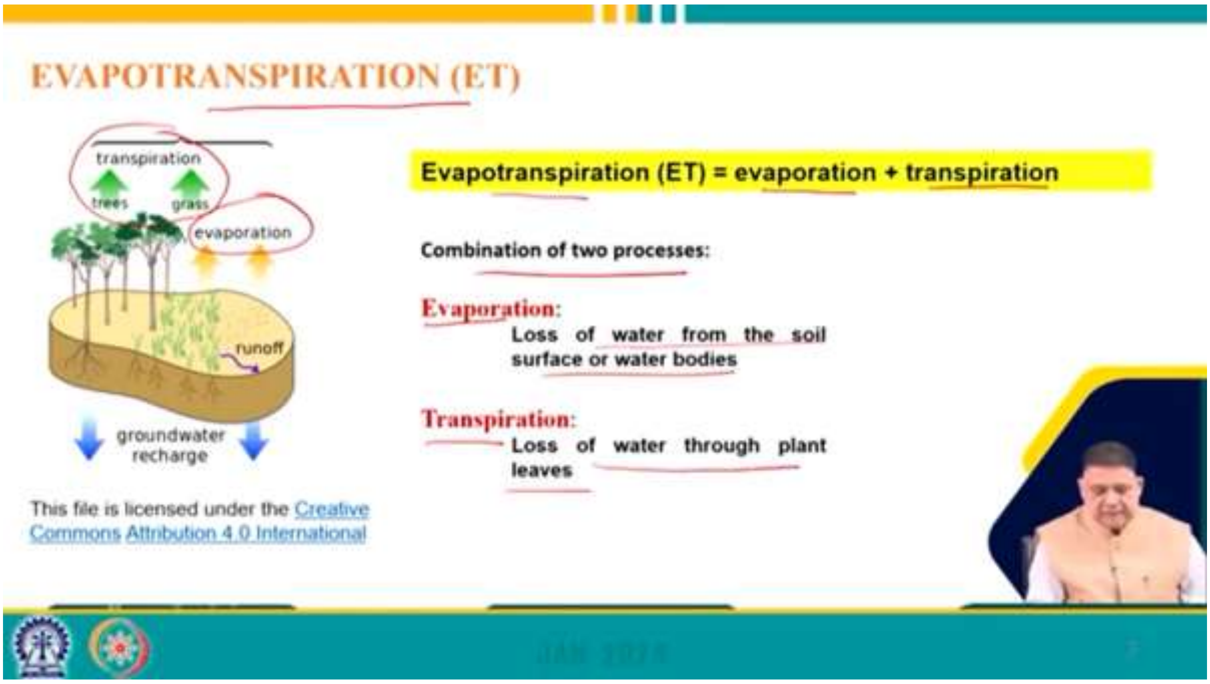
Week: 02

Lecture 08: Evapotranspiration

Hello friends. Welcome back to this online certification course on Watershed Hydrology. I am Rajendra Singh, a professor in the Department of Agriculture and Food Engineering at the Indian Institute of Technology, Kharagpur. We are in module 2. This is lecture number 3, and the topic is Evapotranspiration.

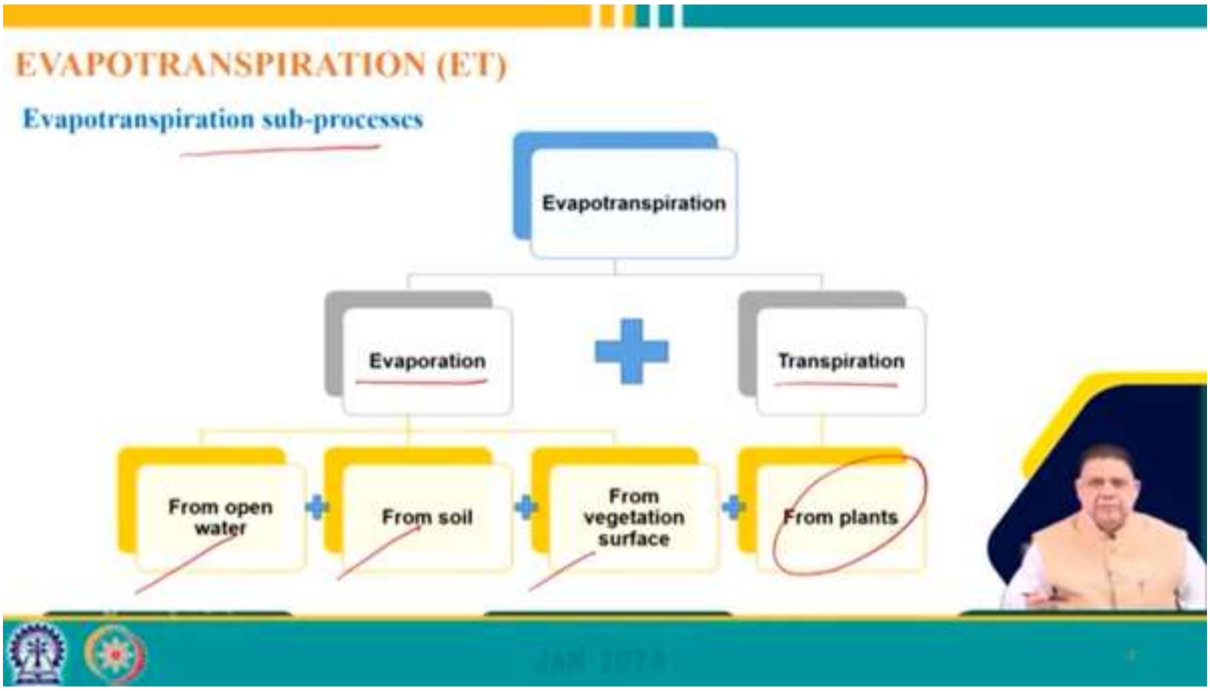


And this lecture will introduce evapotranspiration. We will have a look at transpiration and its measurement. We will talk about factors affecting evapotranspiration. We will then go into the measurement of evapotranspiration and then we will talk about evaporation evapotranspiration determination using hydrometallurgical equations.

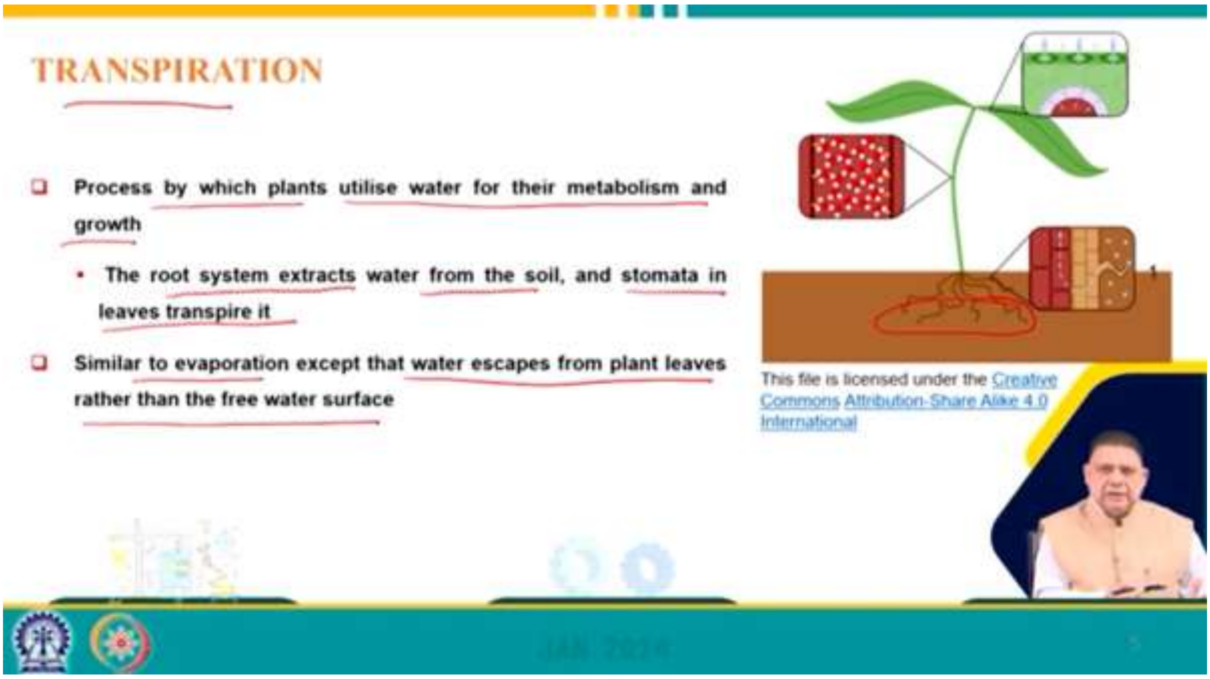


Let us start with evapotranspiration. So, if we remember the hydrological cycle which we introduced in earlier classes. So, obviously, we know evaporation occurs from water bodies, and that is how the water is transferred from land to the atmospheric system. Also, transpiration occurs from the canopies of trees, plants, or crops, and that is transpiration. Evapotranspiration is the sum of evaporation and transpiration; it is a combination of two processes: evaporation and transpiration, where evaporation is the loss of water from the soil surface or water bodies.

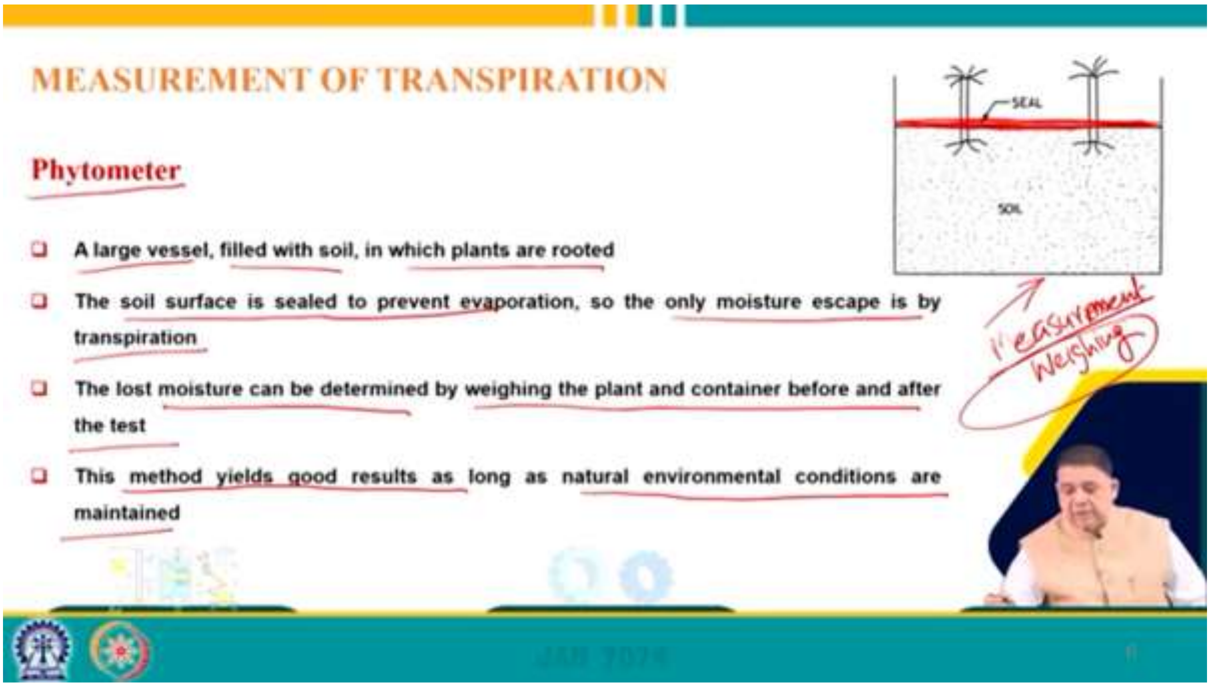
It can mainly occur from water bodies, but even if it is irrigated lands or saturated soils, then evaporation will still take place. Transpiration is the loss of water through plant leaves. So, this combination of these two processes is known as evapotranspiration.



If we look into the sub-processes of evapotranspiration, then we know that evapotranspiration is the sum of evaporation and transpiration. Transpiration, of course, takes place from plants or crops or whatever, and evaporation occurs; it could occur from open water bodies, from soil, and also from vegetation surfaces. That means, we see that when rainfall occurs, a part of it is intercepted by plants and buildings or other abstract objects. So, obviously, evaporation will also take place from vegetation surfaces and buildings.

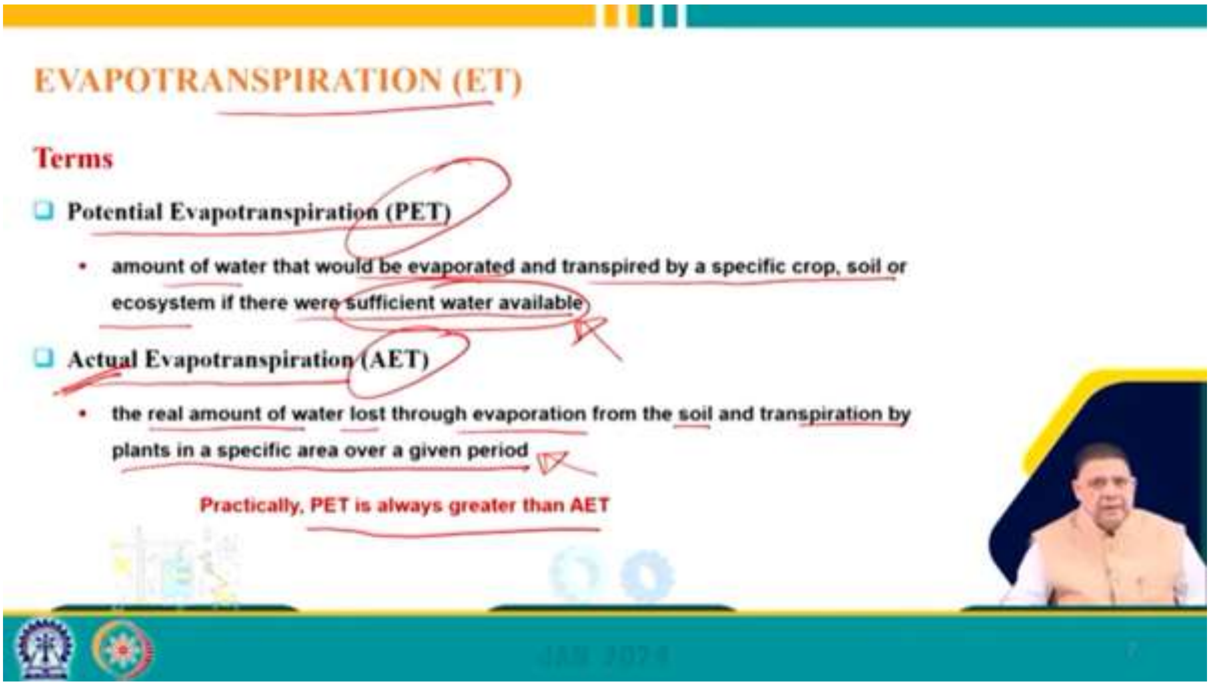


Now, let us talk about transpiration first. So, we have already discussed evaporation; now we will talk about transpiration here. It is a process by which plants utilize water for their metabolism and growth. So, we have already learned in our junior science classes that the root system extracts water from the soil and stomata in leaves transfer it. Basically, the roots extract water and nutrients from the soil, then through stems, it reaches leaves, where it is used by plants for their growth and metabolic activity. Of course, the stomata, which are there on plant leaves, are the pathways through which this water transpires. Similar to evaporation, except that water escapes from plant leaves rather than the free water surface. So, process-wise, it is more or less similar, but in the case of evaporation, we saw that it could take place from water bodies or from soil, as we discussed, but in this case, it is exclusively limited to the plant leaves.



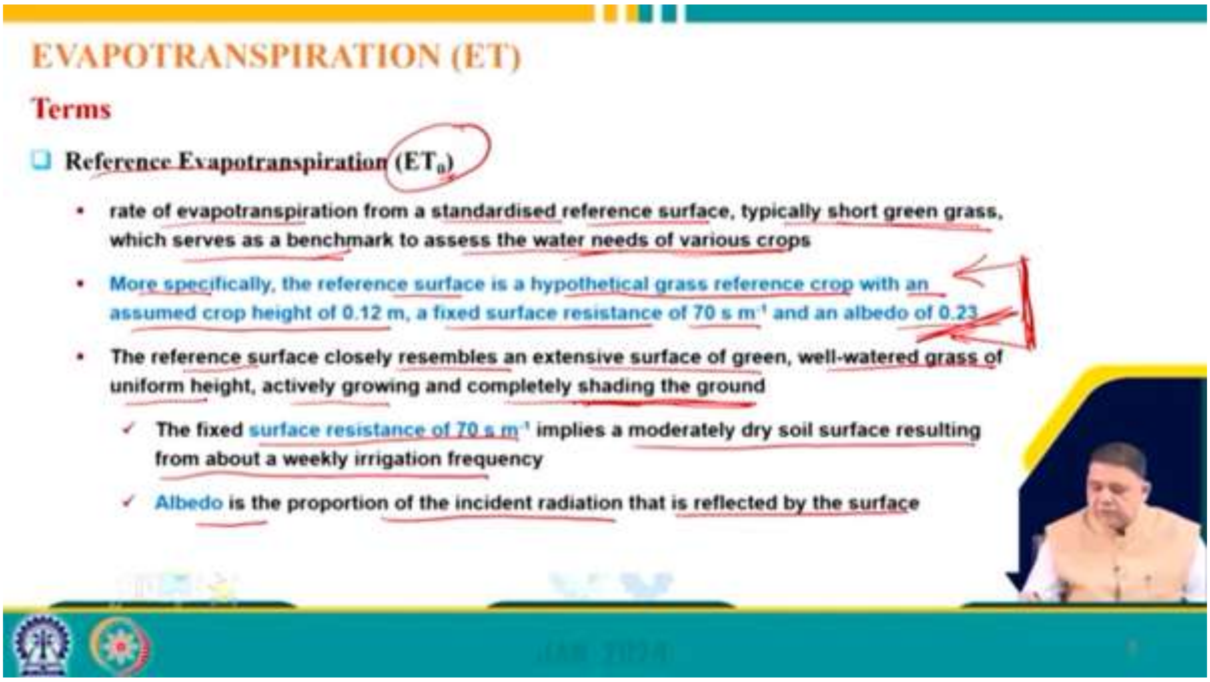
Now, coming to the measurement of transpiration, it is measured using equipment called a phytometer, which is basically a large vessel filled with soil in which plants are rooted. So, basically, it is a large vessel; sometimes, it could have measurement facilities. Basically, when we say measurement, this basically refers to wing-type equipment, where some kind of weight measurement is possible. In this case, the soil surface is filled and sealed to prevent evaporation, so that only moisture escape is through transpiration. What happens is that we put the plants in this soil, irrigate them, and then we seal the surface completely.

This simply means that we are stopping or checking the evaporation taking place from this vessel. So, the only loss of water that could take place is through transpiration, that is, through the plant system, and the lost moisture can be determined by weighing the plant in the container before and after the test. So, if it is a weighing type of measurement, then obviously, when we put the water, we know the initial weight, and after running the experiment for a certain period of time, say 24 hours or so, we will know how much water has been lost or how much weight loss has taken place. So, we can determine that this much water has transpired through the plants. This method yields good results as long as natural environmental conditions are maintained. Basically, if you maintain the natural environmental conditions, that means the air and temperature conditions are similar to natural conditions, then obviously, we will get a good estimation or measurement of transpiration value using this method.



Now, coming to evapotranspiration, there are several terms that are popularly used, and it is better to know or understand those terms. The first and foremost is potential evapotranspiration, which is known as PET. This is defined as the amount of water that could be evaporated and transpired by a specific crop, soil, or ecosystem if there were sufficient water available. So, that means if you have a system where a particular crop is growing or a natural system, and if water is not a limiting factor, then if sufficient water is available, then whatever evapotranspiration occurs, that is the sum of evaporation and transpiration from water bodies, soil, as well as plants, then that is referred to as potential evapotranspiration. Because it is potential, that means that is the maximum possible under given environmental conditions, the maximum possible value of evapotranspiration.

Then the second term comes is actual evapotranspiration, AET, which is the real amount of water lost through evaporation from soil and transpiration by plants in a specific area over a given period. So, obviously, as you can see, both definitions are more or less similar, except for in the case of PET, we are ensuring that there is sufficient water availability, that water is not a limiting factor. But in this case, no such guarantee is given, no such statement is there. So, it is a natural water, meaning you do not know how much water is available. So, under such circumstances, whatever evapotranspiration occurs is referred to as actual evapotranspiration, and obviously, as you can guess, PET is always greater than AET. So, these are the two very common terms which are in PET and AET, which you will find in textbooks or general papers if you refer.

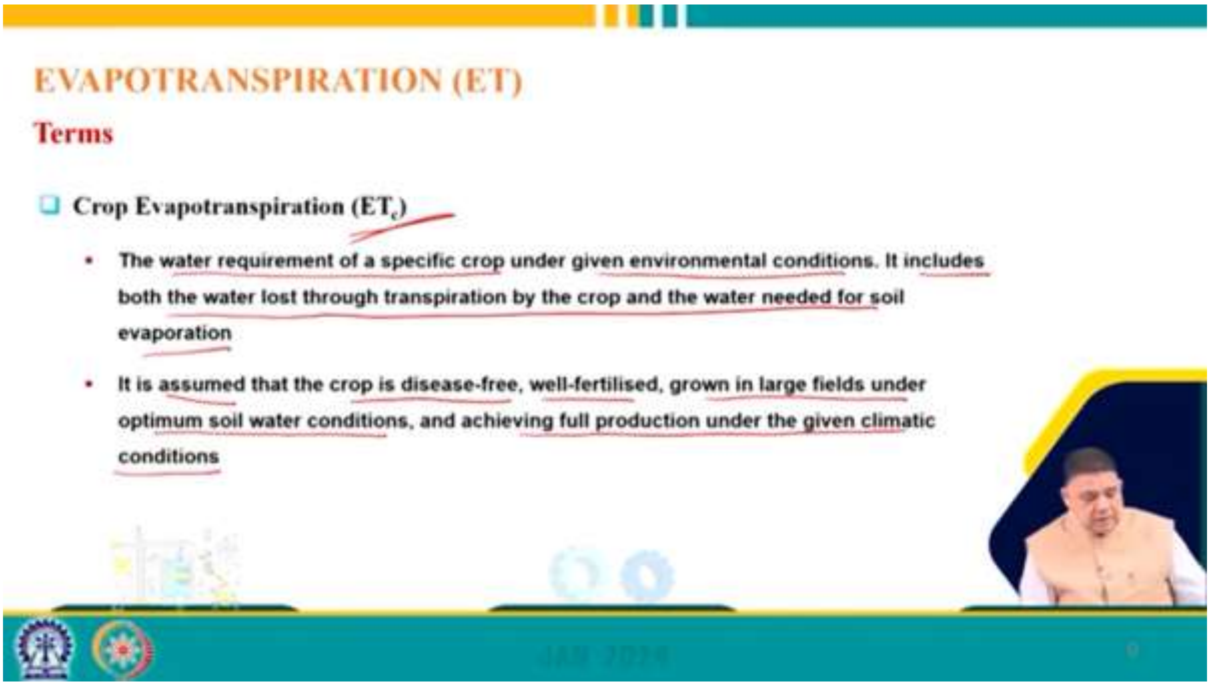


Then another important term which is used is reference evapotranspiration, ET0 or ET0 where 0 or naught is used as a suffix, ET naught or ET0, reference evapotranspiration, which is defined as the rate of evapotranspiration from a standardized reference surface, typically short green grass, which serves as a benchmark to assess the water needs of various crops. So, obviously, because the evapotranspiration differs from one crop to the other, from one condition to the other.

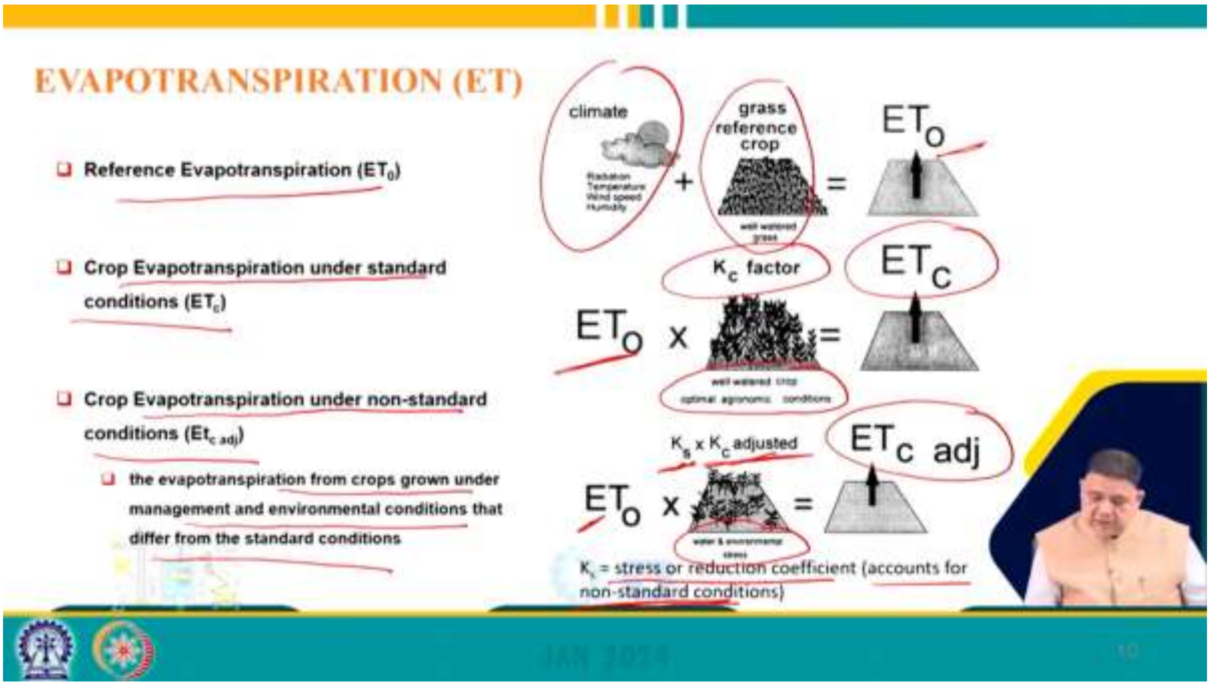
In order to standardize the evapotranspiration estimation, this reference evapotranspiration is defined, which is with reference to a typical reference crop, which is short green grass, which is used as a benchmark to assess the water requirements of various other crops. More specifically, the reference surface is a hypothetical grass reference crop with an assumed crop height of 0.12 meters, a fixed surface resistance of 70 seconds per meter, and an albedo of 0.23. So, these are the specific conditions which are defined for the short green grass, which is used as a reference crop.

And the reference surface closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing, and completely shading the ground. So, that means it is assumed that this green grass is being grown in a large area and all other factors like water, nutrient, environmental conditions, and growth factors are all ideal. It is assumed that the growth is uniform and active, and it is completely shading the ground.

Two other values which are referred to here are the fixed reference surface resistance of 70 seconds per meter, which implies a moderately dry soil surface resulting from about a weekly irrigation frequency. So, if in a particular field you follow a weekly irrigation schedule, then obviously, at the end of the schedule, this is the typical surface resistance that will be available. And similarly, albedo is the proportion of incident radiation that is reflected by the surface, and its value is 0.23, meaning 23 percent of incident radiation is reflected while defining the reference evapotranspiration.

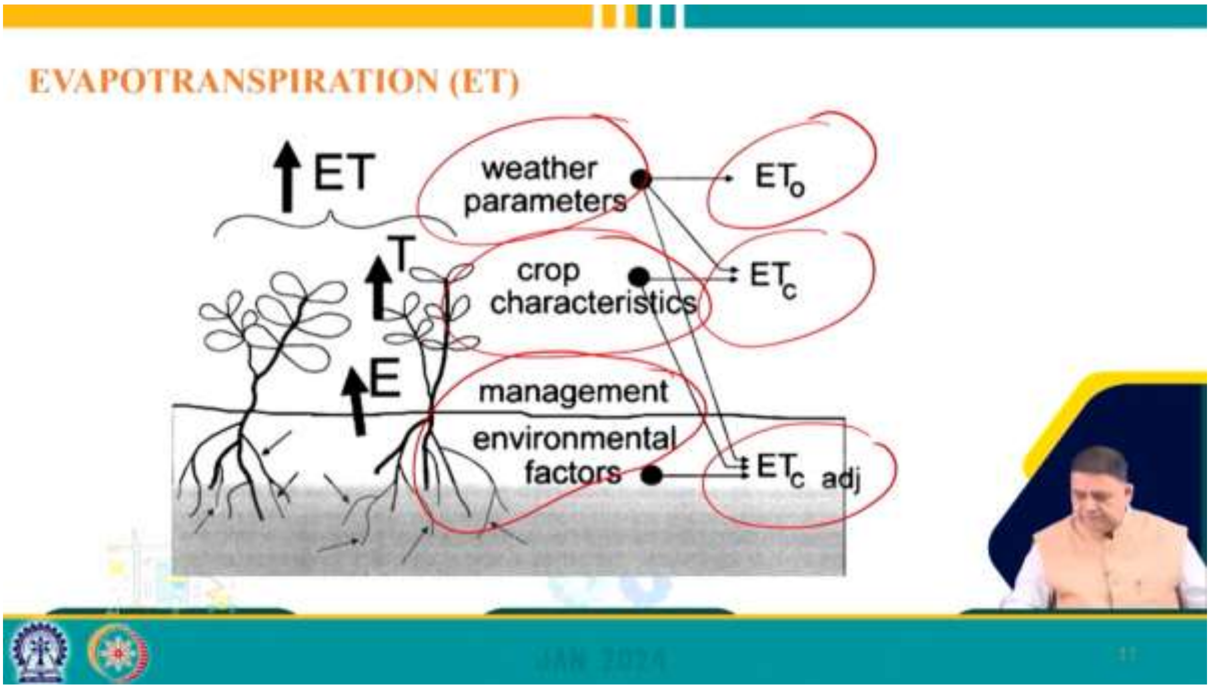


Now, with reference to that, we have crop evapotranspiration, ETC, which is defined as the water requirement of a specific crop under given environmental conditions, including both the water loss through transpiration by the crop and the water needed for soil evaporation. It is assumed that the crop is disease-free, well-fertilized, grown in large fields under optimum soil water conditions, and achieving full production under the given climatic conditions. So, first, we talk about the reference. Now, instead of a reference grass, if you put a typical crop like wheat, maize, paddy, whatever, and then you grow it under similar circumstances, the ideal conditions for crop growth, then whatever evapotranspiration value we get will be reflecting the value of crop evapotranspiration, ETC.

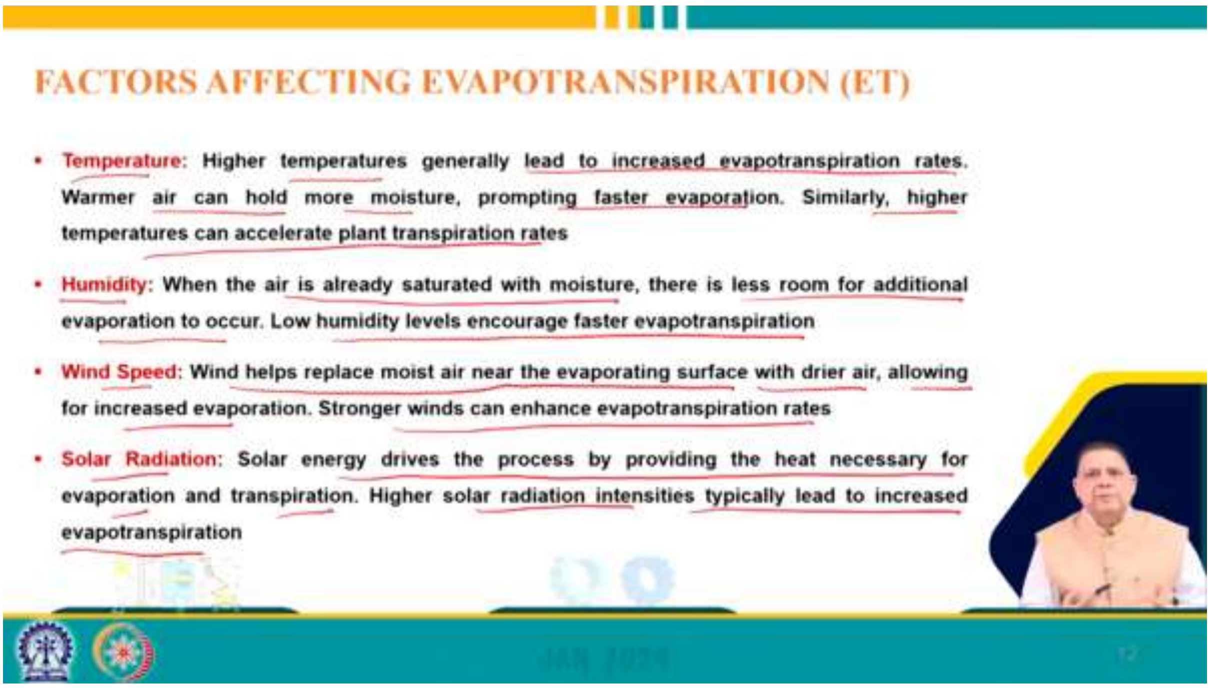


So, ET0 and ET naught, ET0 and ETC, these are two, one is for reference, the other is for a particular crop. So, basically, we can say that we have a reference evapotranspiration, ET0, which is for a reference crop under ideal conditions. That simply means if these ideal conditions are all maintained, then ET0 depends only on the climatic conditions. Then we have the next one, which is the crop evapotranspiration under standard conditions. So, if all standard conditions are met, such as a well-watered crop, optimum agronomic conditions, then whatever we get for that particular crop, that is crop evapotranspiration. This value can be obtained by multiplying this ET0, ET naught, the reference crop, by a crop coefficient, KC factor, which will be typical for a particular crop.

Then another term that comes up is crop evapotranspiration under non-standard conditions. So, we saw that crops could be grown under well-watered, optimal agronomic conditions, but in natural conditions, there could be slight differences. There could be water and environmental stress, and in that case, the evapotranspiration of crops grown under management and environmental conditions that differ from standard conditions is called ETC adjusted, which is crop evapotranspiration adjusted. Of course, we have to use KC adjusted and also KS, which is referred to as stress or reduction coefficient, which accounts for non-standard conditions. So, obviously, with ET0, if you multiply it with KS and KC, then we will get the actual crop or adjusted crop evapotranspiration, which is for crops growing under water and environmental stress.



So, basically, ET0 we can say depends on whether parameters, ETC depends on crop characteristics, and ETC adjusted depends additionally on management and environmental factors as well.

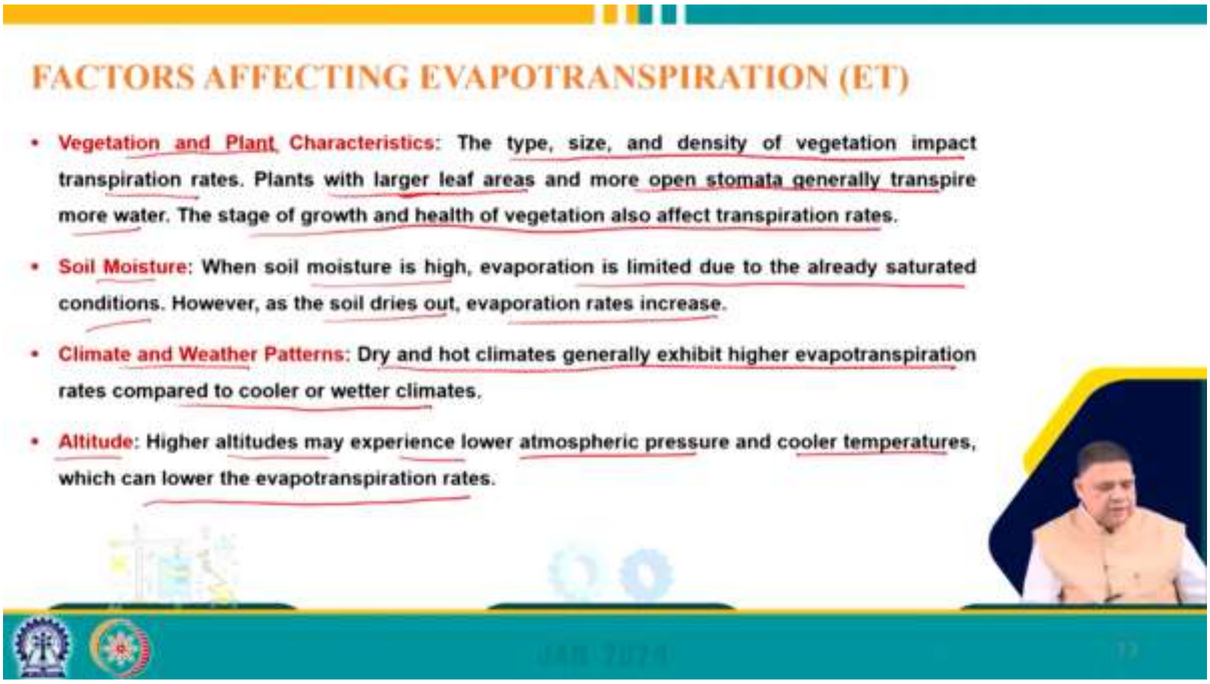


Now, let us come to factors affecting evapotranspiration, and there are several factors that affect evapotranspiration. Some of the factors we have seen already while discussing evaporation; more or less similar factors remain here.

For example, temperature: higher temperatures generally lead to increased evapotranspiration rates; warmer air can hold more moisture, prompting faster evaporation. Similarly, higher temperatures can accelerate plant transpiration rates. We also saw that if there is a vapor pressure difference, which also depends on water temperature and surrounding conditions. So, obviously, this is how temperature affects evapotranspiration. Then humidity: when the air is already saturated with moisture, there is less room for additional evaporation to occur; low humidity levels encourage faster evaporation.

So, if it is a humid condition, obviously, the vapor pressure difference will be very low; that means, evapotranspiration value will be low. But if the humidity is low, that means, there is a larger difference between Ew and Ea, and larger evapotranspiration could occur. Wind speed, we already know, wind helps replace moist air near the evaporating surface with dry air, allowing for increased evaporation. So, if wind speed is high, evaporation is large, as we already saw, and stronger winds can enhance evapotranspiration rates. So, obviously, when evaporation is more, evapotranspiration will be more.

Solar radiation, solar energy drives the process by providing the heat necessary for evaporation and transpiration; higher solar radiation intensity typically leads to increased evapotranspiration. So, if solar radiation or the heat necessary is higher, then evaporation will be more, transpiration will be more, so some of evaporation and transpiration, that is, evapotranspiration, will also likely be more.



Then, of course, the vegetation and plant characteristics, the type, size, and density of vegetation, impact transpiration rates. Plants with larger leaf areas and more openness transpire more water, and the stage of growth and health of vegetation also affect transpiration rate. So, if growth is more, and of course, if vegetation is healthy, then evapotranspiration or transpiration loss will be more.

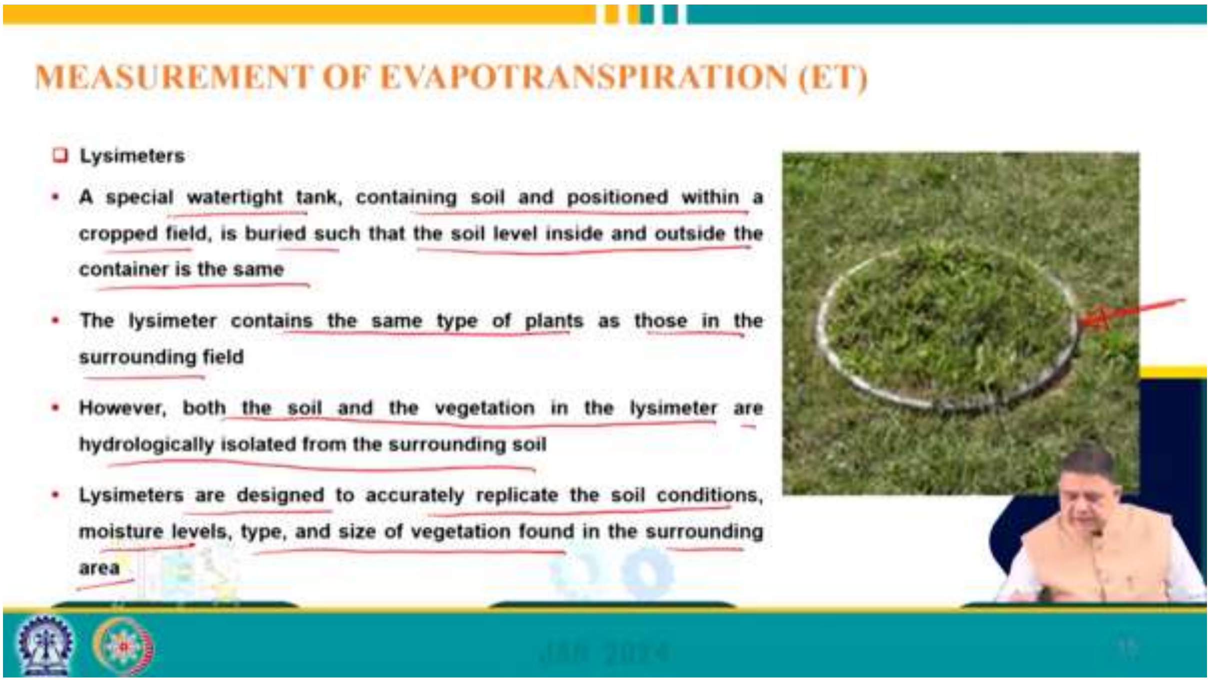
Similarly, if the plants have a larger leaf area, so more stomata, that means more openings, more transpiration. Soil moisture, when soil moisture is high, evaporation is limited due to already saturated conditions; however, as soil dries out, evaporation rates increase. So, obviously, when soil moisture is high, the environmental condition is more humid or moist, that means evaporation will be lower. But if it is relatively dry, then evaporation will be more.

Climate, weather patterns, dry and hot climates generally exhibit higher evapotranspiration compared to cooler or wetter climates. So, regions, we already know, if it is hot, then obviously, evaporation will be more, transpiration will be more, and the vice versa condition will be in cooler and wetter climates.

Altitude, already we have seen that higher altitudes may experience lower atmospheric pressure and cooler temperatures, which can lower the evaporation and evapotranspiration rate. So, at higher altitudes, evapotranspiration will be lower, as was the case for evaporation.

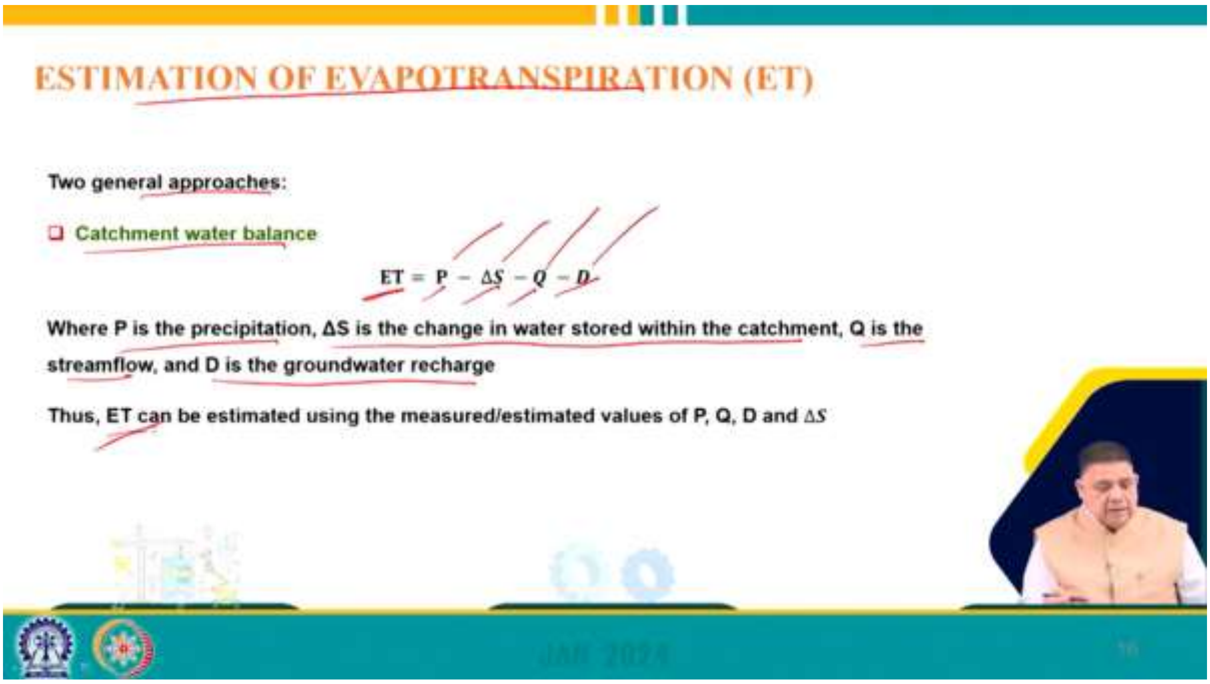
Now, coming to the measurement of evapotranspiration, typically, evapotranspiration is measured using lysimeters or in-field plots. So, lysimeter studies involve growing crops in large containers, as you can see here, these are the containers put in the field. So, growing crops in these large containers and measuring the water losses and gains.

ET can be estimated by determining the amount of water required to maintain constant soil moisture conditions within the tank container. So, typically, these lysimeters have a weighing facility. So, these weighing-type lysimeters are generally preferred.



They are put in the field, and a special watertight tank containing soil in position within a crop field is buried, such that the soil level inside and outside the container is the same. So, it is buried in the field exactly where the similar crop and similar conditions are being grown. It is buried in the sense that soil and plant conditions inside and outside are the same, and they contain the same type of plants as those in the surrounding field, obviously.

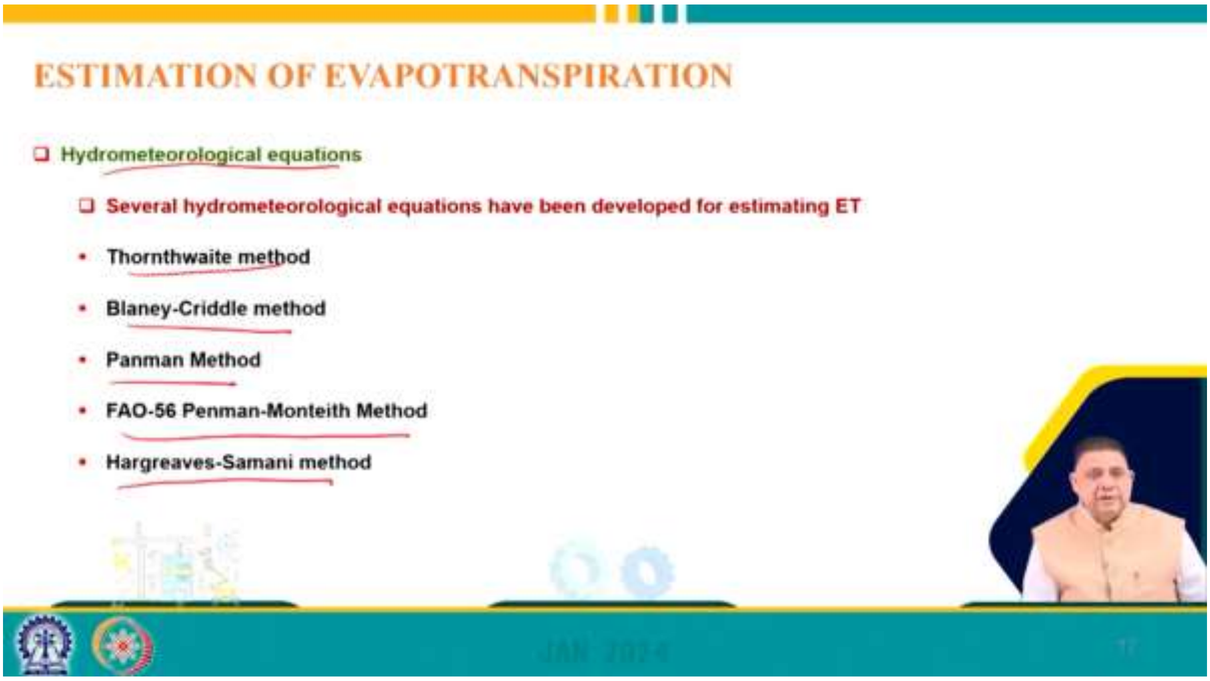
However, both the soil and vegetation in the lysimeter are hydrologically isolated from the surrounding soil. So, of course, as it is a metallic container, there is no exchange from the field and the soil or crop which is being grown inside the container. And they are designed to accurately replicate the soil conditions, moisture levels, type, and size of vegetation found in the surrounding area. So, all conditions remain the same, and of course, they are weighing-type, so basically, most of them have a facility to measure various components of the hydrological cycle and thus they can very easily give us a value of evapotranspiration.



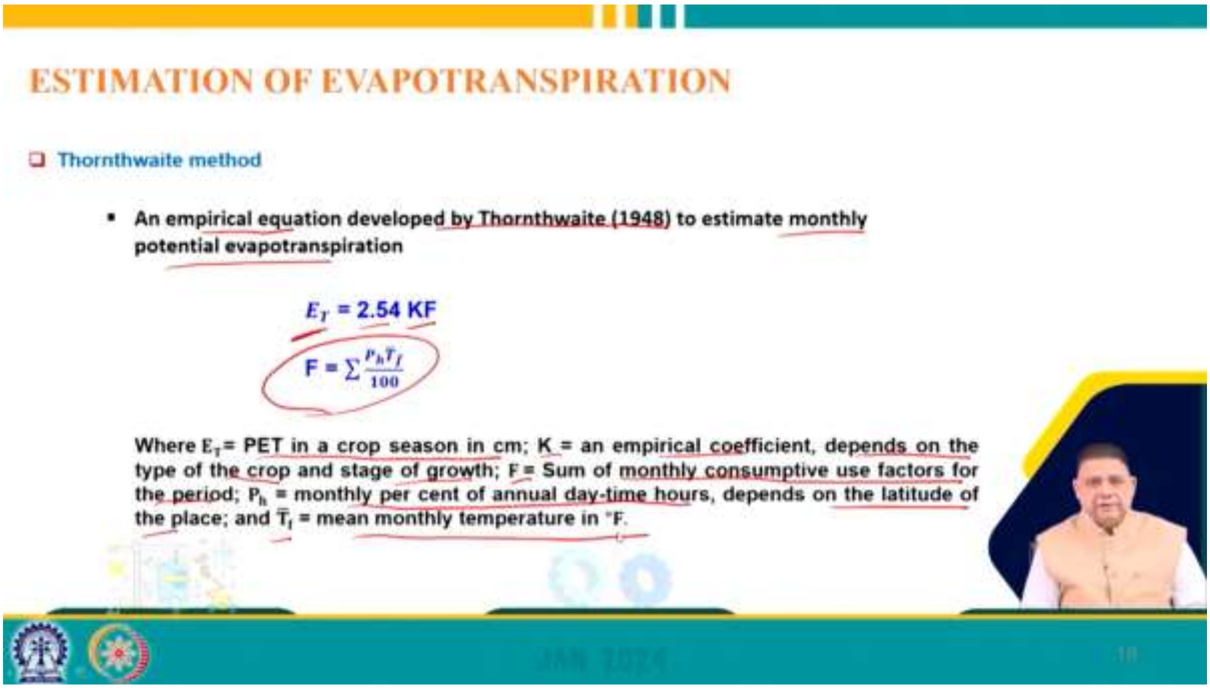
Now, other than measurement, we can also estimate evapotranspiration, and two general approaches are used. One is by using catchment water balance, which we have seen in almost all abstractions. So, the equation which is preferred here is

$$ET = P - \Delta S - Q - D$$

where P is the precipitation, delta S is the change in water stored within the catchment, Q is the stream flow, and D is the groundwater recharge. So, if we know precipitation, if we know the change in water storage, if we know discharge, if we know groundwater recharge, then we can estimate the value of ET from a given catchment.



Besides water balance, there are several hydrometallurgical equations which are used for estimating evapotranspiration, and some popular ones are the Thornthwaite method, Blaney-criddle method, Panman method, FAO 56 Panman-Monteith method, Hargreaves-samani method, and the list can go on and on. There are more than 30 hydrometallurgical equations that have been derived, and we will see only a limited ones and discuss about these a little bit here.



So, first one let us talk about Thorne-Tawit method, developed in 1948, to estimates monthly potential evapotranspiration (ET) as:

$$TF = 2.54 \times k \times F$$

where:

ET is the potential evapotranspiration in the crop season in centimetres,

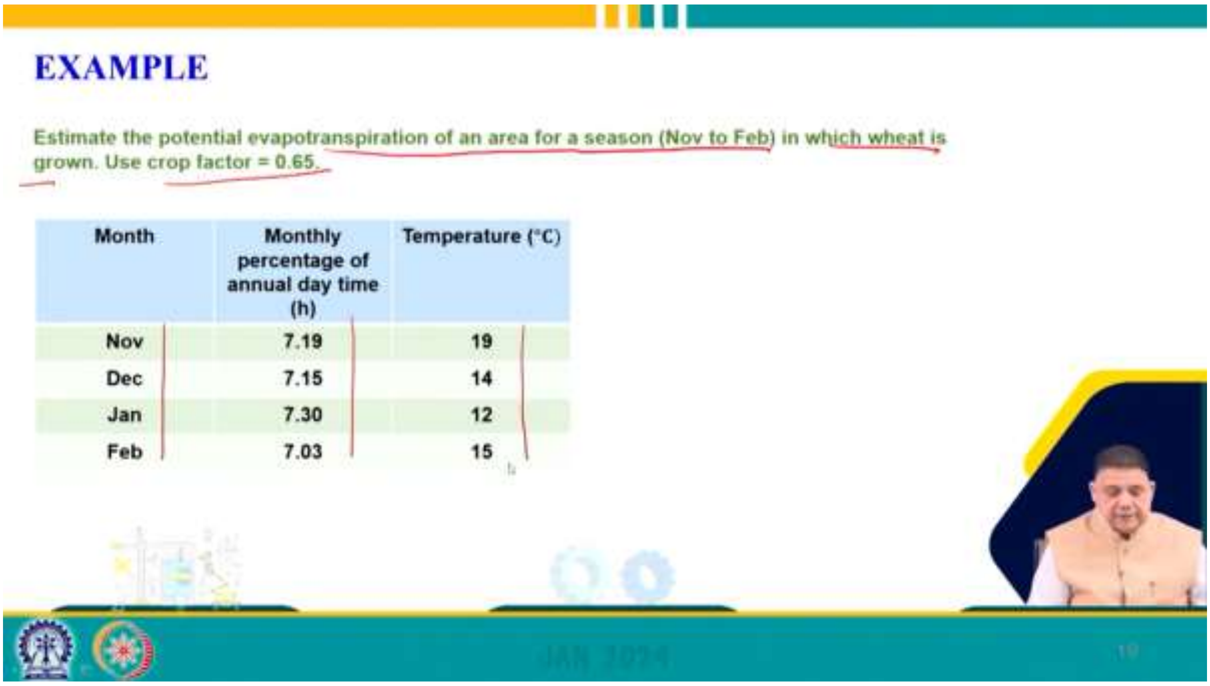
k is an empirical coefficient depending on the type of crop and stage of growth,

F is the sum of monthly consumptive use factors for the period.

F can be estimated as the sum of P$h \times \overline{T_f}$ divided by 100, where:

Ph is the monthly percent of annual daytime hours, depending on the latitude of the place,

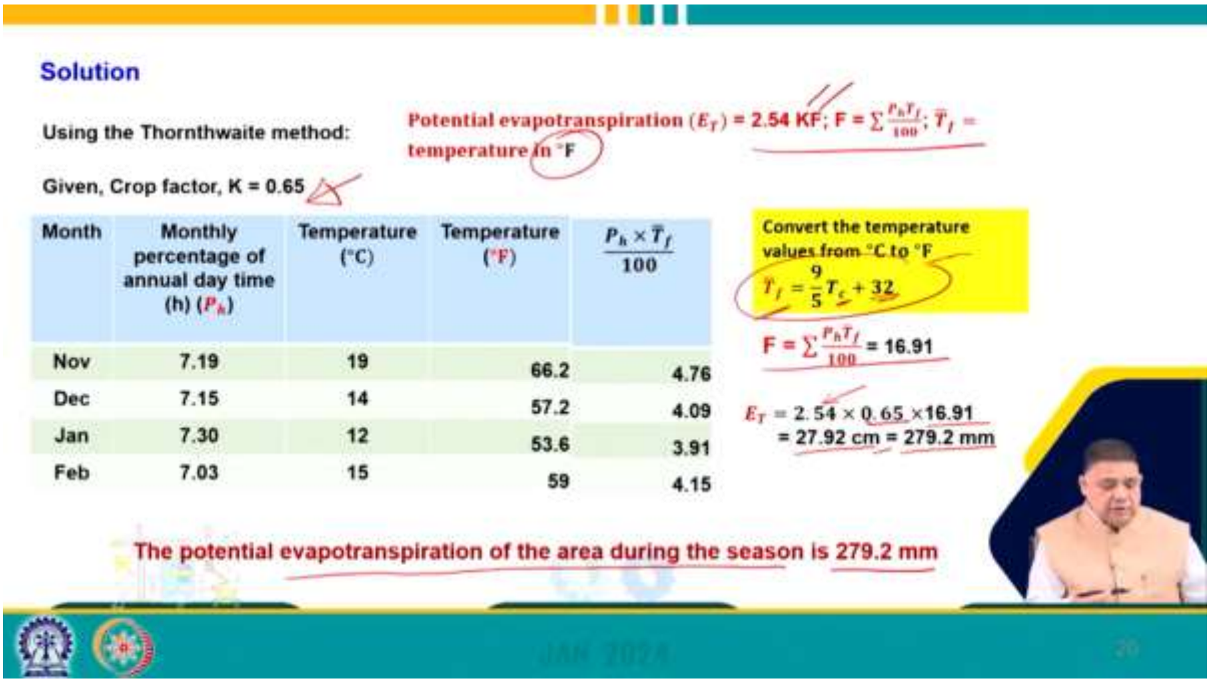
$\overline{T_f}$ is the mean monthly temperature in degrees Fahrenheit.



let's take an example estimate the potential evapotranspiration of area for a season Nov to February, in which wheat is grown, using a crop factor of 0.65. The monthly percentage of annual daytime hours and temperature are provided. Since the temperature is in degrees Fahrenheit, we need to convert Celsius to Fahrenheit using the formula:

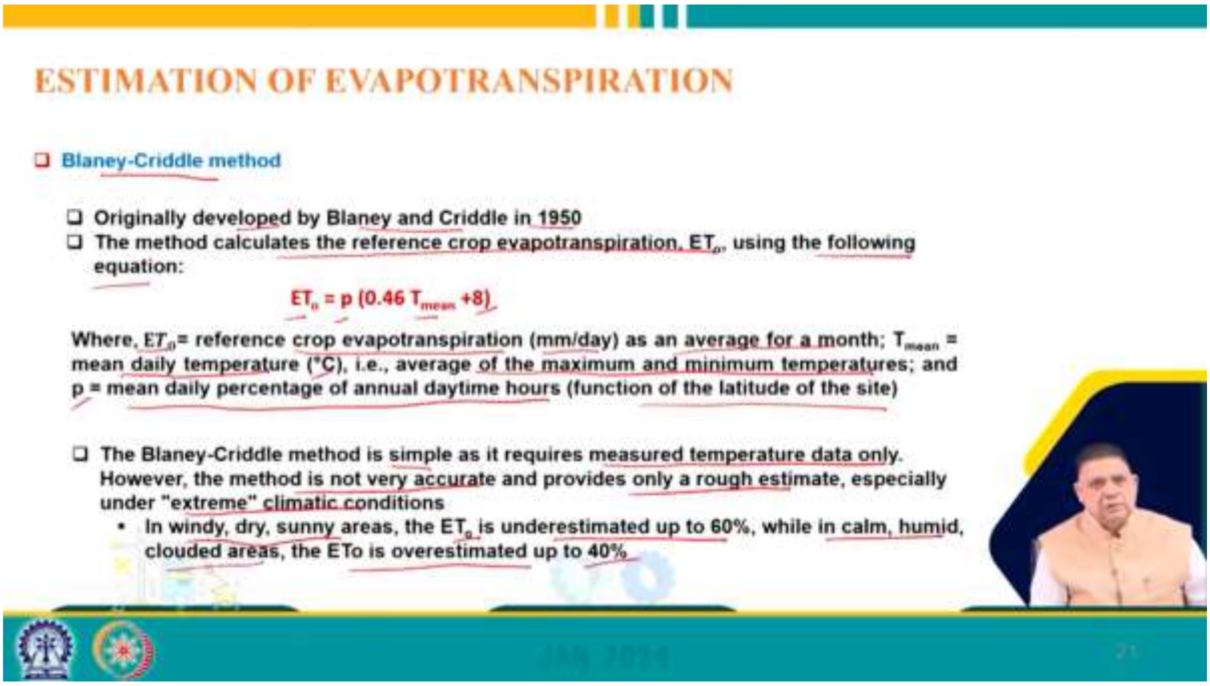
$$F = \frac{9}{5}T_C + 32$$

where T_C is the temperature in degrees Celsius. Using this relationship, we can find the temperature in different months.



The value of F is calculated as $Ph \times T_f/100$, and the sum of F comes out to be 16.91.

Given that k is 0.65 and F is 16.91 (a constant), the potential evapotranspiration(E_t) can be calculated as 2.54$\times$ $k \times F$, which equals 27.92 centimetres or 279.2 millimetres. Therefore, the potential evapotranspiration of the area during the season is 279 millimetres.



The Thornbeth formula can be used to find out the evapotranspiration, which equals 2 millimetres. Next, the Blaney-Cleeder method, originally developed by Blaney and Cleedle in 1950, calculates the reference crop evapotranspiration (E_t0) using the following equation:

$$E_t0 = P \times 0.46 \times T_{mean} + 8$$

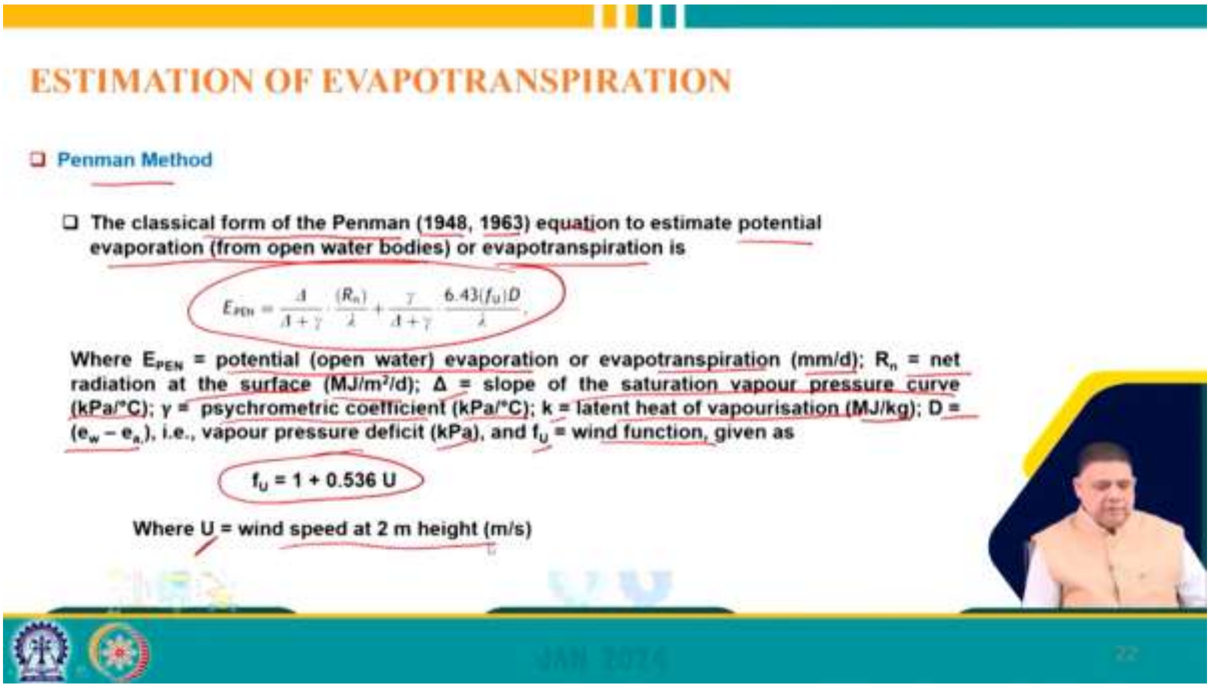
Where: E_t0 is the reference crop evapotranspiration in millimeters per day, as an average for a month.

T_{mean} is the mean daily temperature in degrees Celsius, which is the average of the maximum and minimum temperatures.

P is the mean daily percentage of annual daytime hours, which is a function of the latitude of the site, similar to the factor in the Thornbeth equation.

If you know the values of T_{mean} and P, you can find out E_t0 using the Blaney-Cleeder method.

This method is simple as it requires measured temperature data only. However, the method is not accurate and provides only a rough estimate of evapotranspiration, especially under extreme climate conditions. It has been found that in windy, dry, sunny areas, E_t0 is underestimated by up to 60 percent, and in calm, humid, clouded areas, E_t0 is overestimated by up to 40 percent. So, one has to use the Blaney-Cleeder method with caution, as it could underestimate or overestimate evapotranspiration depending on the conditions under which you are using this method.



Now, we come to the Penman method, which is the classical form of the Penman equation. It was first given in 1948 and then modified in 1963 to estimate potential evaporation from open water bodies or evapotranspiration, as given by this relationship.

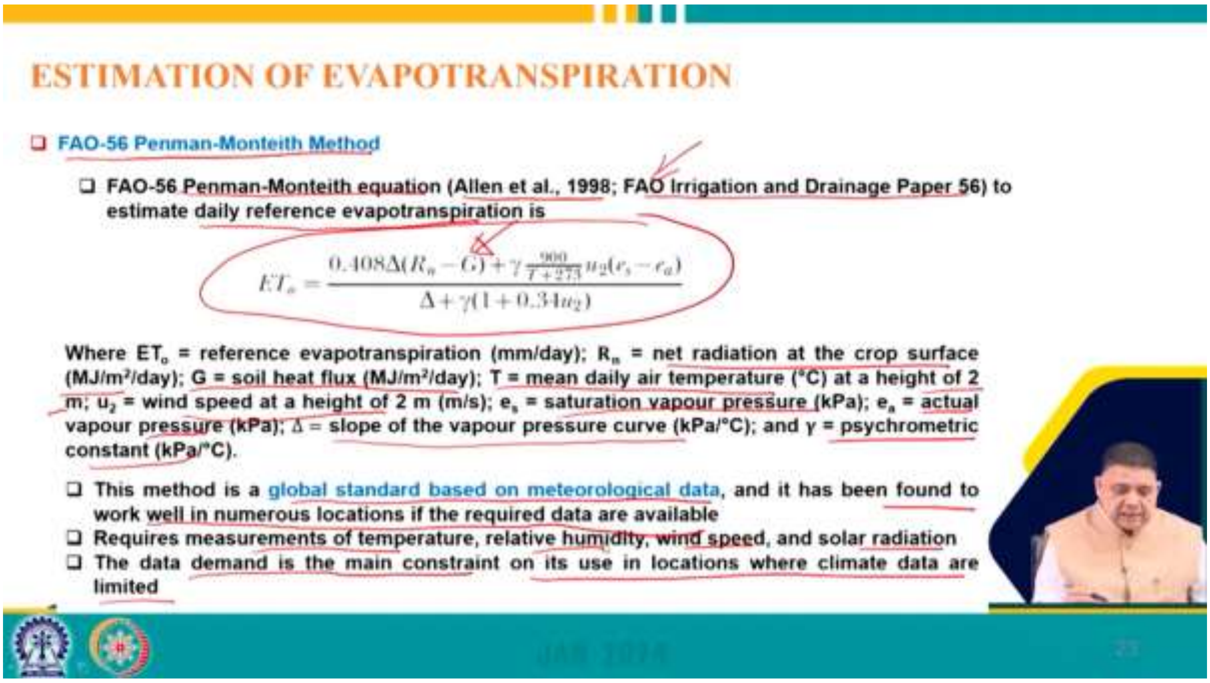
$$E_{PEN} = \frac{\Delta}{\Delta + \gamma} \cdot \frac{(R_n)}{\lambda} + \frac{\gamma}{\Delta + \gamma} \cdot \frac{6.43(f_u)D}{\lambda}$$

As you can see, E_{pen}represents potential evaporation or evapotranspiration in millimetres per day.R_n is the net radiation at the surface in mega joules per square meter per day. δ is the slope of the saturation vapor pressure curve in kilo Pascal per degree Celsius. γ is the psychometric coefficient in kilo Pascal per degree Celsius. k is the latent heat of vaporization in mega joules per kg. d is the vapor pressure deficit $(E_w - E_a)$ in kilo Pascal. f_u is the wind function, given by the relationship

$$f_u = 1 + 0.536\, U$$

where u is the wind velocity or wind speed at 2 meters height in meters per second.

A large amount of data is needed to use the Penman method, but its accuracy is definitely much higher than the Blaney-Credle method or the Thornthwaite method we discussed, or in fact, many other methods.

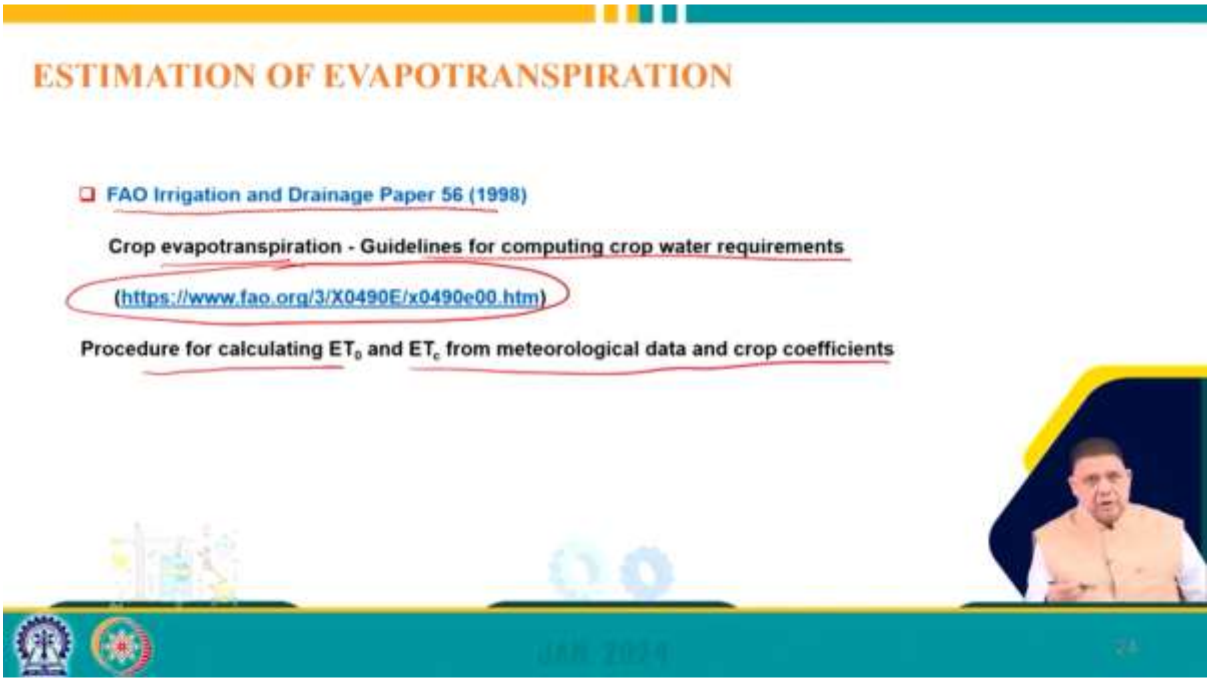


Now, let's move on to the FAO 56 Penman-Monteith method. The FAO 56 Penman-Monteith method or equation was developed by Allen and others in 1998 and is an integral part of FAO irrigation drainage paper number 56. It helps estimate daily reference evapotranspiration. The equation is more or less similar to the Penman method, with a few modifications.

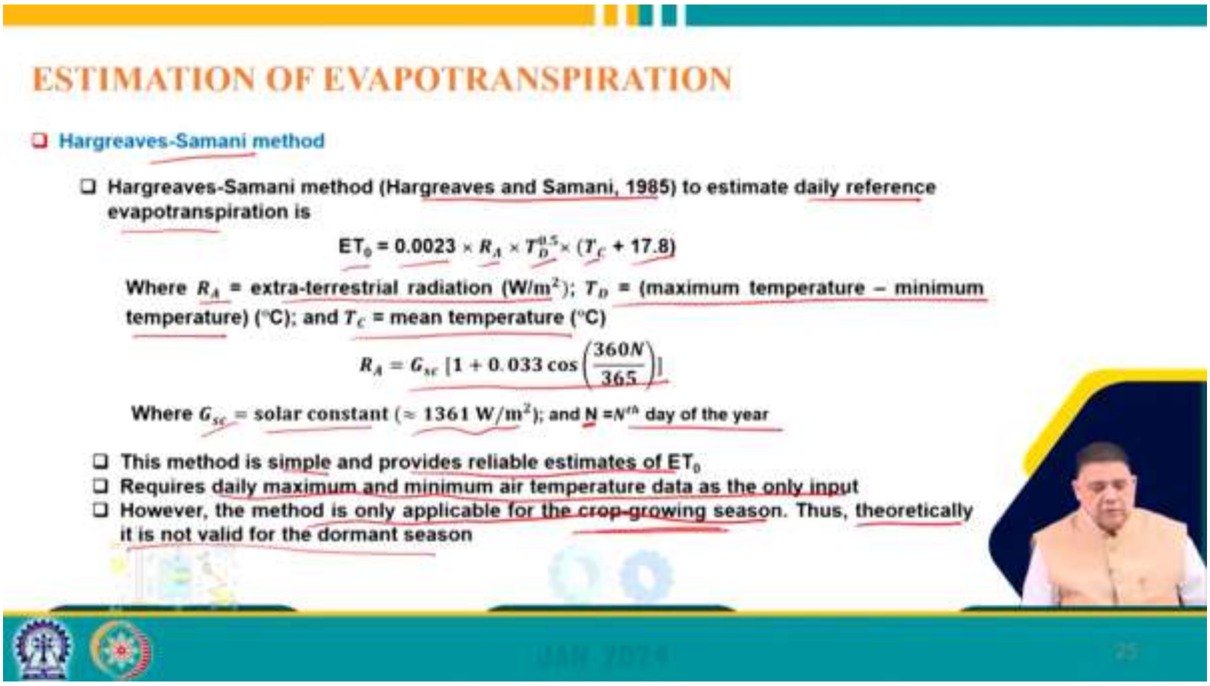
$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

Here, two important changes are made. First, G,which is the soil heat flux in mega joules per square meter per day, is considered. Second, the variables are mostly the same, with R_n representing net radiation at the crop surface, T as the mean daily air temperature at a height of 2 meters, U_2as the wind speed at 2 meters height,E_s as the saturation vapor pressure, E_a as the actual vapor pressure, δ as the slope of the vapor pressure curve, and γ as the psychrometric constant in kilo Pascal per degree Celsius.

This equation is used as a global standard based on meteorological data. After a significant amount of experimentation conducted under the Food and Agriculture Organization (FAO) by a team led by Richard Allen in 1998, it was found that this method works well in numerous locations if the required data are available.



So, it requires measurements of temperature, relative humidity, wind speed, solar radiation. So, the data demand is the main constraint on its use in locations where climate data are limited. Otherwise, if the data are available, then it gives the best estimate of evapotranspiration, and that is why it is referred to as a global standard based on meteorological data recommended for use around the world. And this is the reference of this FAO irrigation and drainage paper 56, 1998, crop evapotranspiration guidelines for computing crop water requirements. And this is the site from which you can download this report, and it includes the procedure for calculating E_t0 and E_tC from meteorological data and crop coefficient.



So, all the required steps are given in this particular paper. Then lastly, we will discuss Hargreaves and Samani method, which was given by Hargreaves and Samani in 1985 to estimate daily reference evapotranspiration. The equation is

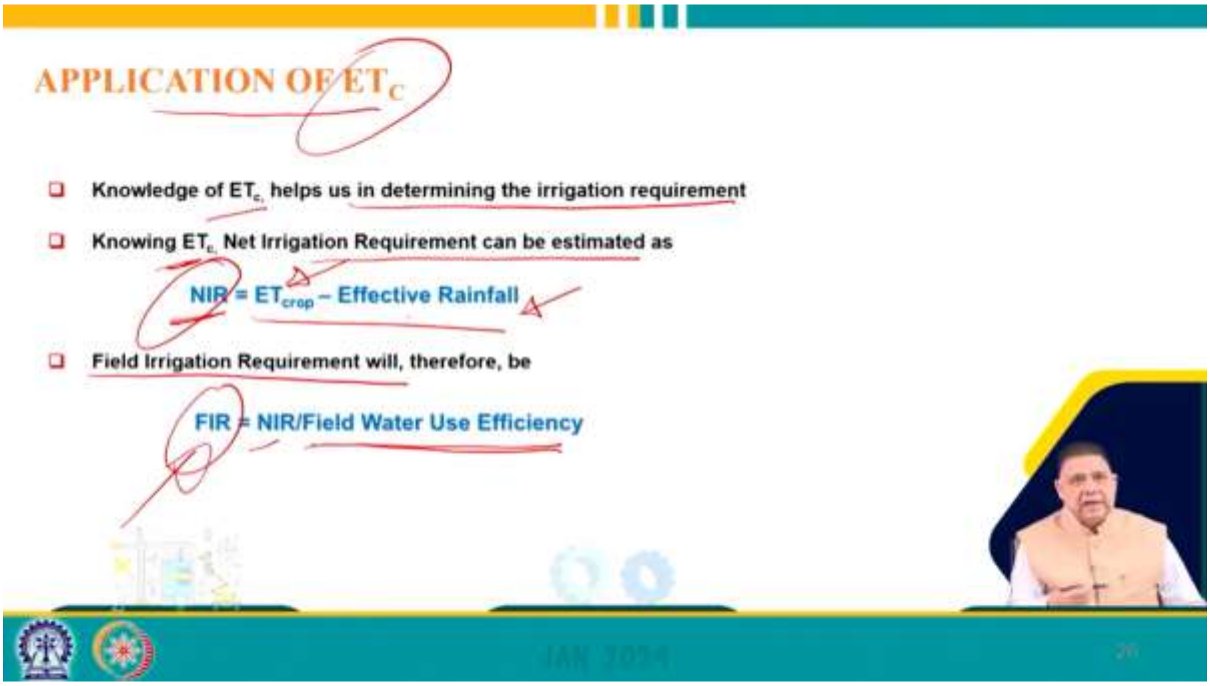
$$ET_0 = 0.0023R_a(T_d)^{0.5}(T_C + 17.8)$$

where R_a is the extra-terrestrial radiation watt per square meter, T_d is the maximum temperature minus minimum temperature, and T_C is the mean temperature. R_a can be estimated for a particular location using this relationship,

$$R_A = G_{SC}\left[1 + 0.033\cos\left(\frac{360N}{365}\right)\right]$$

where G_{SC} is the solar constant, which is approximately 1360 or 1361 watt per square meter, and n is the nth day of the year. So, for a location and for a given day of the year, one can estimate this. This method is simple and provides reliable estimates of ET_0 and requires daily maximum and minimum air temperature data as the only input. And that is why this is very popular and used in several research studies and several models.

However, there is a catch that this method is only applicable for the crop growing season. So, theoretically, it is not valid for the dormant season. So, if you are using this method in a continuous model, one has to be a little careful. But as far as only the crop growing season is concerned, this gives a very good estimation of evapotranspiration with minimum data, and that has been shown by research around the world.



So, with this, we come to study the application of E_tC. Why do we study E_tC or why do we determine E_tC? So, knowledge of E_tC helps us in determining the irrigation requirements because knowing E_tC, net irrigation requirement can be estimated using this relationship:

$$NIR = ET_{crop} - Effective\ Rainfall$$

So, if effective rainfall is known (that is, rainfall minus losses), the difference in these two is the net irrigation requirement. That means, that much water is needed by the crop to meet this evapotranspiration requirement. And of course, if you consider the field water use efficiency, then the field irrigation requirement can also be estimated by taking that into account. So,

$$FIR = \frac{N_{iR}}{field\ water\ use\ efficiency}$$

If we estimate E_tC for a crop, then we can find out what will be the total field irrigation requirement. So, that is the practical application of evapotranspiration. With this, we come to the end of this lecture. Please feel free to give your feedback and also raise your questions in the forum so that they can be answered. Thank you very much.