Water Resources Engineering

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Lecture # 13

Today we will continue to discuss some of the abstractions from the precipitation. As we have seen, we can also call them as loss because these are the amounts which are taken out of the precipitation and the rest goes to run off. If you are interested in run off then these parts acts as losses. We have looked at evaporation, ways to measure it, ways to estimate it using some empirical or theoretical equations. Today we will look at transpirations, combine it with evaporation and we will also check evapotranspiration. We will also look at the infiltration.

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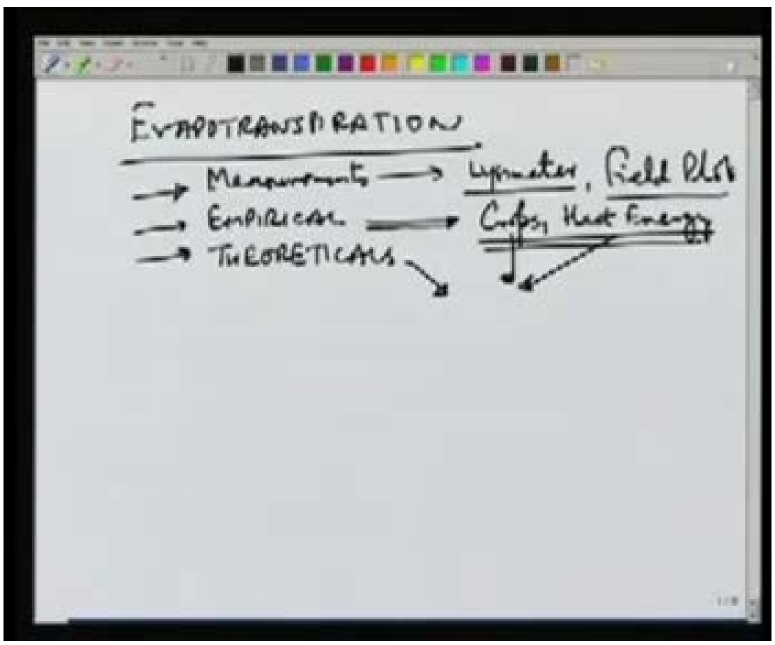

So let us start with the evapotranspiration which is also known as the consumptive use. It is the sum of evaporation and transpiration, evaporation from the land surface and transpiration from the plants. We can have evapotranspiration estimated by measurements or we can use some empirical equations and we may have some theoretical equations. In measurements, evapotranspiration is measured by using water balance, measuring other components and then estimating the evapotranspiration. There is an instrument which is known as a lysimeter. This is a closed tank in which some plants are also placed and then to maintain constant moisture, we need to supply some water periodically. The amount of water will repel the evapotranspiration in that time period or we can have some field plots in which under very controlled conditions, we can estimate what is the irrigation and what is the runoff. Then using a water balance, we can find out what evapotranspiration is. In empirical equations based on the crops and the amount of heat energy available, these are the two main factors which are taken into account when we derive an empirical equation which relates the evapotranspiration with the type of crop, the stage of growth of crop, and the amount of heat energy available which depends on the sunshine hours, it is the total amount of a number of hours in a day, for which the sun is shining and therefore heat energy is available to us. Some of these terms will be used in empirical equations, in theoretical equations and they also depend on the crop type and the heat energy. They have in addition some other parameter which we have to be estimated and using pure theoretical approach, we can derive these equations. Let us start with the measurement.

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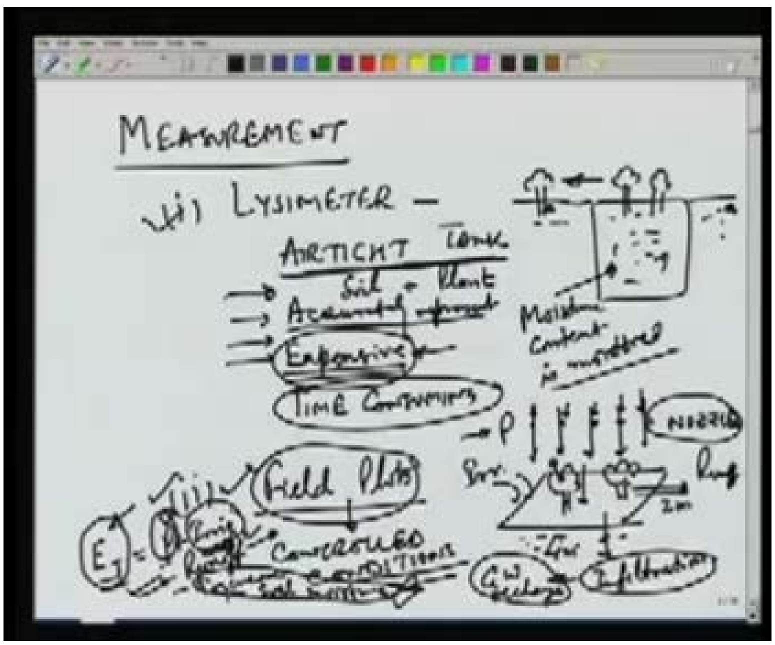

Measurement of evapotranspiration, the first method which is used, is known as a lysimeter. This is an air tight tank filled with soil and some plants and will be placed in the ground level. The level of soil in the lysimeter and the surrounding area is the same. The plants in the lysimeter should be similar to the plants which are outside the area, so that the transpiration is almost same. So the lysimeter or the air tight tank should represent the nearby conditions of the soil, plants and so on. The amount of moisture in this lysimeter is monitored. So moisture content is monitored and periodically we add water to maintain the soil at constant moisture and the amount of water which is added represents the evapotranspiration. There are some precautions which need to be taken. Firstly, it should accurately represent the surrounding area. Accurate representation of the surrounding soils is the requirement. The plants should be similar, the soil should be similar and it is naturally expensive to install and monitor. It is not used very often but if we are interested in high accurate results, and we are not concerned too much about money. We can install lysimeter in the field and with the amount of evapotranspiration from that. Time consumption of course, because we have to install lysimeter and keep on measuring the evapotranspiration on a daily basis or monthly basis or any time period we are interested in. The second method used is known as the method using field plots in which we have these plots which may be about 4 meter/ 2 meter size, 4 meter in length and 2 meter in width. There will be some nozzles which we will put water on this field plot and then there will be some run off which will be measured. The amount of water which is infiltrated can also be measured. The amount of water coming in will be followed by some transpiration from these plants and some evaporation. So the field plots are under very controlled conditions and if we measure other quantities then we can estimate the evapotranspiration E_t as p which is the precipitation plus irrigation. So if we know the amount of rainfall and these nozzles and perform it in the lab, we can do it like this (Refer Slide Time: 08:05). If we are in the field, we can measure the actual precipitation and the irrigation rate.

There is some irrigation water applied to this plot. The rainfall plus irrigation will be the net inflow into the field plot; we will then have to measure the runoff and if there is any increase in soil moisture. This increase in soil moisture is measured below this level. The amount of evapotranspiration can be obtained by water balance such that if we know the precipitation (we will know by using rain gauges) applied irrigation water that is also known, runoff will have to be measured and then increase in soil moisture also have to be measured. Then using this water budget we would a get the evapotranspiration. There is one more component which is used in this equation as I have shown in this infiltration. There is a loss to ground water or ground water recharge, so out of this infiltration, part of it will be retained in the soil that will increase. The soil moisture part of it will go down and recharge the ground water. This part is very difficult to estimate and that is why I have not shown it here. What we try to do is maintain the soil below the plot at the field capacity or below the field capacity, so that the ground water recharge is minimized. We will therefore ignore this and use only these terms, a precipitation, irrigation, run off and soil moisture which can be measured easily and evapotranspiration can be estimated. Using these two methods either lysimeter or field plot, we can estimate the evapotranspiration by measurement. Measurement is also not very easy. They are time consuming and they are expensive. So generally people have gone for empirical equations in which we have studied over a certain area, the amount of evapotranspiration and try to correlate it with the factors on which it depends, for example the crop, type of crop, the growth of crop and the sunshine hours. We will look at these empirical equations.

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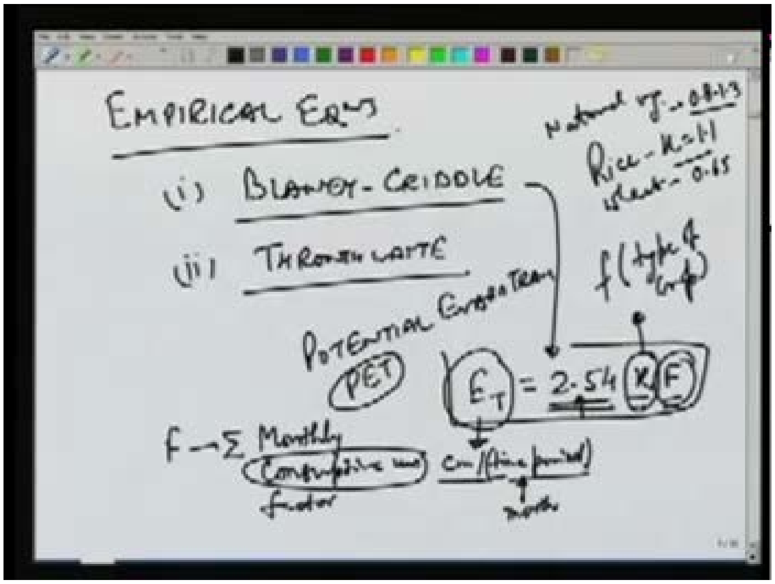

The two empirical equations which we will look at here, although there are various other equations, are the Blaney-Criddle and Thornthwaite equation. In the Blaney-Criddle equation, we have an equation which relates the evapotranspiration. This 2.54 factor comes because the original equation is in fps units and there are two terms K and F on which these evaporate. Whenever we talk about evapotranspiration we should keep in mind that this is potential evapotranspiration, which is denoted by PET. The actual evapotranspiration will be less than this depending on the amount of soil moisture available. This equation relates E_t with 2.54. As I said earlier, this originally was in inches per day and was then converted to centimeter. This is either per day or the time period. I will write per unit time period, so a month is taken. This time period would be in months. In the original equation, this 2.54, as I said was not present. But E_t was KF in inches. Now K is a factor which is a function of type of crop, for example for rice, K may be around 1.1and if you have wheat it would be about 0.65, for natural vegetation, it varies over a wide range of 0.8 – 1.3 depending on the density of the vegetation. This factor K can be obtained from the type of crop grown in that area or the H_m vegetation which is growing in that area. F is a factor which is known as monthly consumptive use factor. Consumptive use as we have seen is also another name for evapotranspiration and when we sum the monthly consumptive use factors for each month, we will get the value of F.

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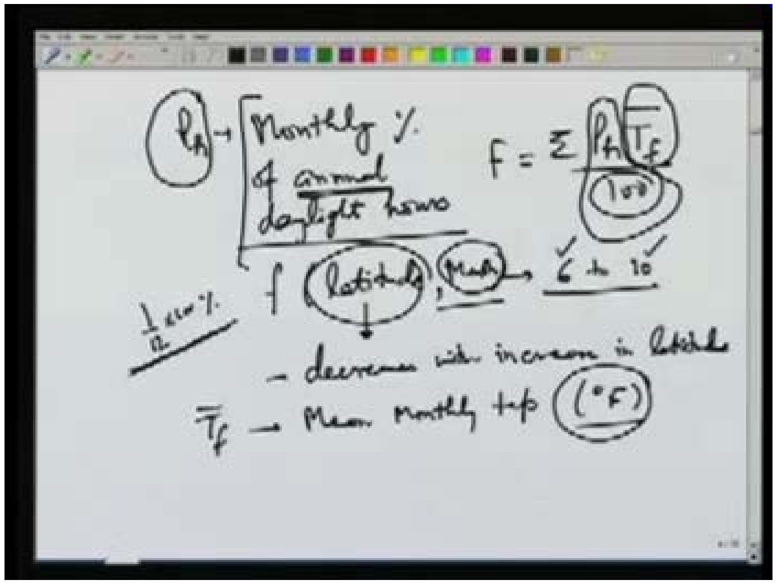

The formula for F is given as summation of $P_h T_f$ bar over 100.This 100 is there because P_h is a percent. This P_h by 100 is a fraction. The definition of these terms is P_h, is the monthly percent of the annual day light hours. Sometimes we call them sunshine hours if the amount of day light available in suppose a particular day or a month or annual (means in total, in the whole year). For each month we will have values of the day light hours in month expressed as a percentage of day light hours in the entire year. This again is a function of latitude. As we know, as we increase the latitude number of day light hours will decrease and its value is (Refer Slide Time: 15:26), so let me first say that this P_h decreases with increase in latitude. So at 0 degree we will have higher value and let us say at 40 degree north or 50 degree north we will have a lower value and the range of f is about 6 – 10. In a particular month it also depends on the month. For example for January it may be a smaller percentage, for summer months it will be a higher percentage and as you can see if you assume it to be uniform over the whole year, then the fraction will be 1/12 per hour into 100 percent.

So 8.33 percent would be, if the sunshine hours are uniformly distributed throughout the year then each month will have about 8 per cent of the annual sunshine hours. But since sunshine hours vary with months, some months will have smaller than 8, some will have a larger value than 8, so it will vary from 6 - 10 depending on the latitude and the month. Summer will have higher latitude, 0 degree latitude and this will be higher. So this fraction P_h and this t_f bar multiplied are summed up over the entire month or over all the months to get f. t_f is the mean monthly temperature and it was used in degree Fahrenheit in the original equation. We will keep that degree Fahrenheit. Using the mean monthly temperatures for each month, and the percentage P_h, we can find out this factor f and then using the Blaney-Criddle equation, we can find out the evapotranspiration, of course, this k has to be estimated based on the crop type and f is obtained from the formula. So this gives us an empirical method for finding out the evapotranspiration.

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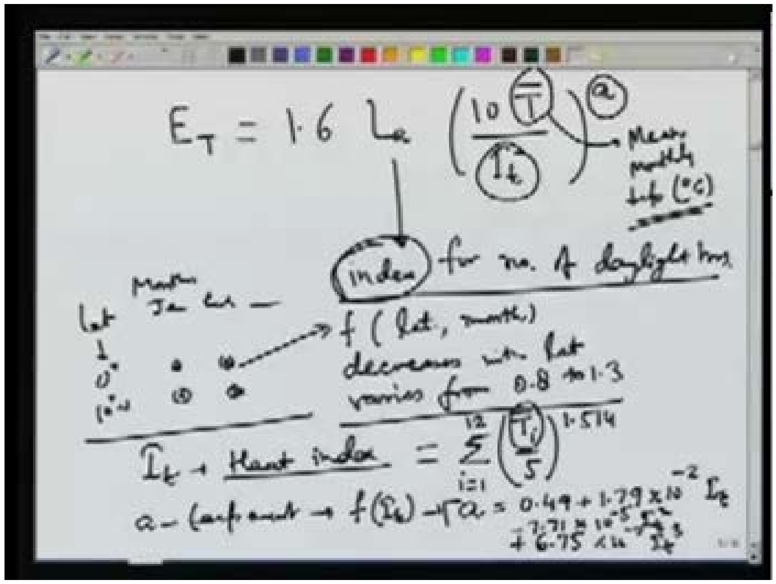

Thornthwaite equation is a similar equation where we have an equation like this $1.6L_a$ then t bar over I_t to the power a. So this also has similar kind of form with lot of these factors L_a is an index for number of day light hours which as you can see, is similar to what we had used earlier, day light hours. But here it is defined a little differently; again it will be a function of latitude and month. This also has similar tendency. It decreases with latitude and the typical variation is .8 - 1.3. There are tables available for different latitudes and different months, January, February and so on, Latitude, 0 degree, 10 degree north and so on. We will have these values of L_a given in a tabular form and you can look from here, the values. This is an index which denotes the amount or the number of day light hours for a particular month. T bar as we have used, before is mean monthly temperature. Now we use degree celsius rather than degree Fahrenheit. The other term I_t is a heat index and this is defined on the basis of the mean monthly temperature, summation over all the months. T bar again is the mean monthly temperature for the month i, so i will go from 1 to 12 for the entire year.

So I_t really is an index called the heat index, which tells you how many day light hours or how much will be the temperature, mean temperature for each month summed up for the whole year. There is a factor which is again an empirical index or we can say exponent which is a function of I_t. It has been found that a, can be given as a constant, about 0.49 + a cubic equation a linear term. Then we have a quadratic term and then we have a cubic term. Knowing the heat index, we can compute the value of a (Refer Slide Time: 22:03) from here. Mean monthly temperatures are known to us. L_a can be looked up from the table and this will give us the potential evapotranspiration using the Thornthwaite equation. The empirical equations are good but they are valid over a particular area and you apply them to some other area and we have to be careful. We have to look at these factors and take a different value, may be for a different area. So that is why equations which are based little more on theory are preferred.

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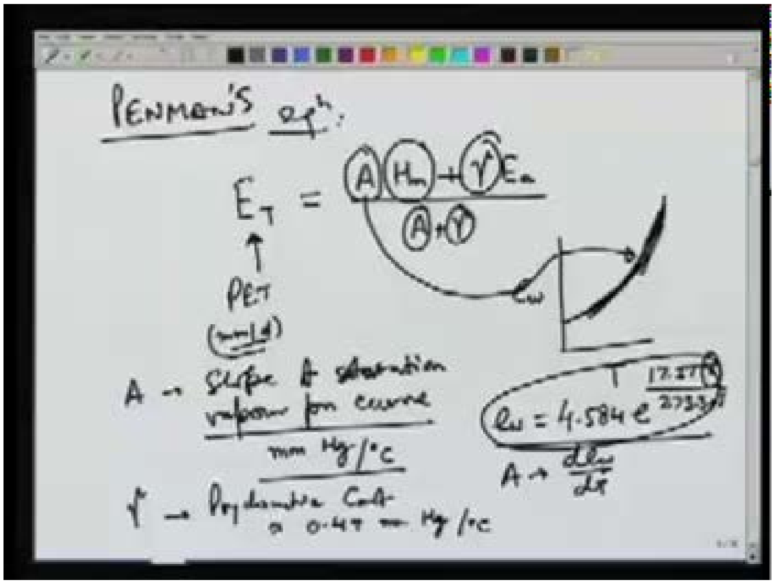

One of the theoretical equations which is commonly used is known as the Penman's equation. In the Penman's equation, the evapotranspiration is written as a com factor A times H_m + another factor gamma times E_a and divided by A + gamma. So this E_t is the potential evapotranspiration and again the units can be taken as a millimeter per day. The time units can be millimeter per day. Every day we can find out what is the potential evapotranspiration. H_m is the net radiation which we will see little later. A is the slope of the saturation, vapor pressure curve. As we have already seen, the saturation vapor pressure which is denoted by E_w is a function of temperature and follows the curve like this. The slope of this curve at any point is the factor A. Sometimes there is an equation or relation between E_w and t which can be used to obtain this factor A. So E_w can be written as 4.584, exponential of 17.27 over 2.3 + t. This t is the temperature and you can obtain this E_w in fitting this curve but most of the times, this curve will be given a tabular form and the slope A will also be given in tabular forms. So a slope of this line A which is d of dw/dt can be found from this equation. Using the tables or the graphs too, we can find the slope A. I will write it here, A is the slope of saturation, vapor pressure curve. The units of course will be millimeter of mercury per degree centigrade. The other factor which we use is the gamma, which is the psychometric constant and its value is taken as 0.49 millimeter of mercury per degree Celsius.

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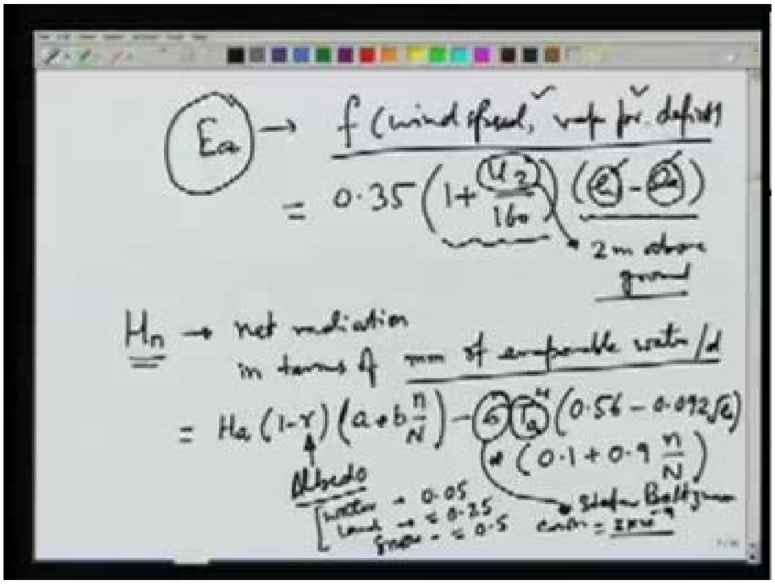

These are the two factors A and gamma E_a are the functions of wind speed and the vapor pressure deficit. As we have seen earlier in evaporation, the evaporation depends on wind speed and the difference in vapour pressure at water temperature, saturation vapor pressure at water temperature and the actual air vapor pressure. This can be related or this was given by an equation 0.35 into 1+ u_2/160 E_w – E_a. This u_2 represents the speed, 2 meter above ground. e_w and E_a we have already discussed, they are the saturation vapor pressure at water temperature, (the actual vapor pressure in the air), this is the vapor pressure deficit. This is wind speed factor which represents the amount or the speed with which we carry the saturation for the saturated air vapor away from the water body. So this E_a is the evaporation which is related with wind speed and the vapor pressure deficit. The important term here in the Penman's equation is H_n. H_n can be defined in terms of net radiation but not in terms of heat energy, but in terms of evaporation depth. So in terms of evaporation depth, there will be some millimeter, which can be used for depth units.

So millimeter of evaporable water per day means this is the net radiation. What is the depth of water that is required to evaporate in a day? It can be related with an equation like this, r is the reflectance or the albedo. Then we multiply it to the modified modification, a plus b into n/n then we have the Stefan Boltzmann constant, a square root of E_a which is the vapour pressure in the air and then we multiply this by another modifying factor 0.1 +0.9 m/n. r as we have seen is the reflectance or the albedo and the value for r is given for different materials. For example for water, r is about 0.05, for land it may vary depending on the land use but above 0.25 and if you have, let us say snow; it will have a very high reflectance and a value as high as 0.5. This sigma term represents the Stefan Boltzmanns constant and its value is given as around 2 times 10 to the power – 9, so this sigma value is used in combination with the absolute temperature.

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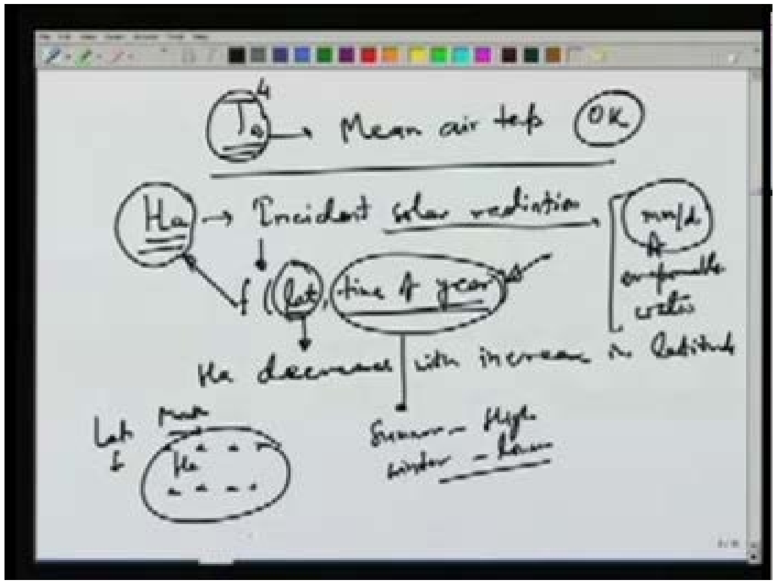

As we know it is T_a to the power 4, this T_a is the mean air temperature in degree Kelvin. As we know in the Stefan Boltzmann equation, the radiation radiated energy is proportional to the absolute temperature to the power 4. The other terms which are used in the equation, one of the most important terms is the incident solar radiation because this governs the amount of energy available for evaporation at that location. This will also be a function of latitude time of year. This is also expressed in millimeter per day of evaporable water, the amount of heat energy available, the depth of evaporation. It will cost in millimeter per day that is H_a, the function of latitude and time of year. As we have discussed already, this h_a will decrease with increase in latitude. At 0 degree it will have a higher value than 10 degree north, 20 degree north; it will have a lower value. Similarly during the time of year in summer, H_a will be higher and during winter it will be lower. Depending on the time of the year and latitude, we can obtain H_a, it will be given in tabular form and similar to what we have seen earlier, we have latitude month and we will have H_a values given in a table like this. So we can get the H_a value from there.

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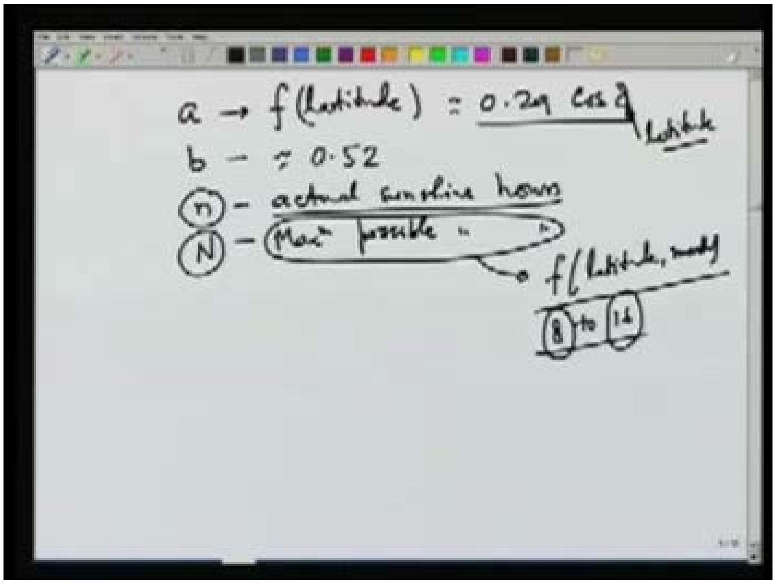

There are some constants used in this equation. For example a, b, n and capital N are some constants which have been defined by Penman's equation. a is the function of latitude and is given by about 0.29 cosine of phi, where phi is the latitude, b is generally taken as a constant and around 0.5 or 0.52 is the value. n is the actual sunshine hours. Number of actual sunshine hours and capital N is the maximum possible sunshine hours. So n is number of sun shine hours actually occurring at that time and n is maximum possible for that period, number of sunshine hours. N of course, is the maximum possible sun shine hours is again a function of latitude and the time latitude and month and varies from 8 – 16. For example, if you have winter months at high latitudes, number of day light hours may be as low as 8. If you have summer months near the equators, number of day light hours may be as high as 16.

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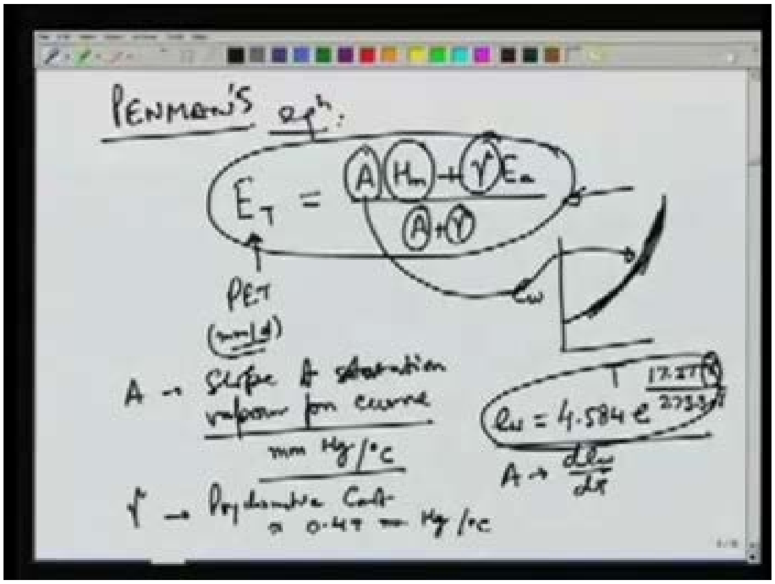

Knowing all these values, we can estimate the evapotranspiration using H_n and E_t using the penman's equation, so these are penman's equation. It is little more theoretical and from place to place you can estimate different parameters and obtain the evapotranspiration. Evaporation and evapotranspiration can be combined, evaporation as evapotranspiration or consumptive use. We have looked at different methods. It may be measurement, empirical equations or theoretical equations. In order to estimate the next component of abstraction, infiltration will be the next taken.

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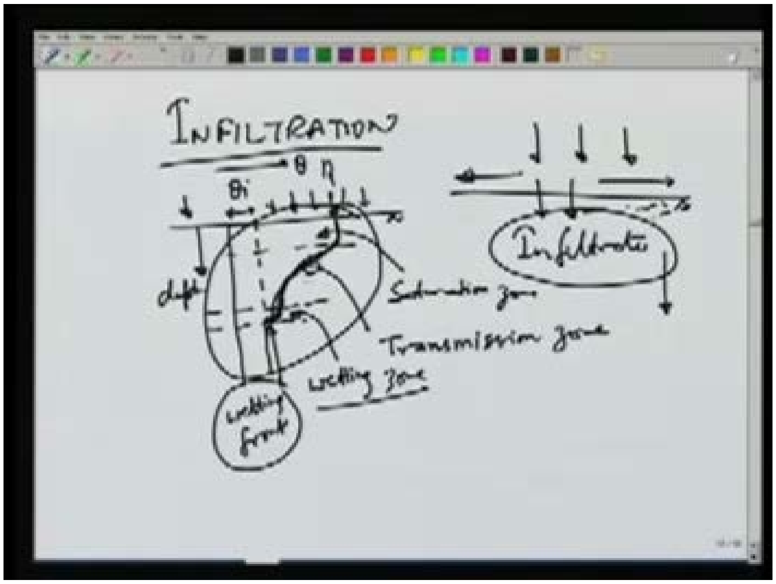

This is the component which is going below the surface of the earth and the amount of infiltration which goes or which infiltrates into the soil will be taken out of the precipitation. Evapotranspiration will be taken out of the precipitation and the rest will go as run off. But after satisfying some initial abstraction which is depression storage and some interception, infiltration measurement and its estimation using some empirical or semi theoretical equations will be our next topic. In infiltration we have seen, when precipitation occurs, a part of it will run off, a part of it will infiltrate. This infiltrated water will either stay in the top of soil layer or will go deeper and recharge the ground water as depercolation. When infiltration occurs and there exists some initial moisture content in the soil theta i, what we are plotting is theta axis and the depth below the ground level initially.

Let us say we have a constant value of the moisture content theta, i as water fall on this surface, and it would increase the moisture level near the surface. We will have a zone which we can call saturation zone in which the soil will be more or less saturated. We can say that the entire porosity may be filled with water. If porosity is plotted here, then the entire soil here is more or less saturated with water then there will be some unsaturated zone here and there will be a sudden drop. The second zone will be unsaturated. It will have partial air saturation partial water so this can call the transmission zone. So water is being transmitted or infiltrated and filled partially with air. The voids are partially filled with air and partially with water and then we have a third zone here which we can call the wetting zone and there will be a sharp front here which is a wetting front. Below this level, the soil will exist at its previous or original moisture contents. There is really no effect of the precipitation felt beyond the wetting zone or this wetting front is a very sharp change in the moisture content and beyond that the effect of precipitation is not felt. This is the mechanism of infiltration or this is the variation of the soil moisture below the ground surface. Once we want to estimate the infiltration, we should be able to solve this equation which governs the flow in this area but this is a very complicated equation because water is not filled or all the voids are not filled with water. There is some air also. The conductivity of this material depends on what the saturation is. So we call it unsaturated flow. There, the conductivity is the function of the moisture content and the equations are highly non- linear and therefore difficult to solve. We can use some measurements or we can use some semi theoretical equations to estimate the infiltration.

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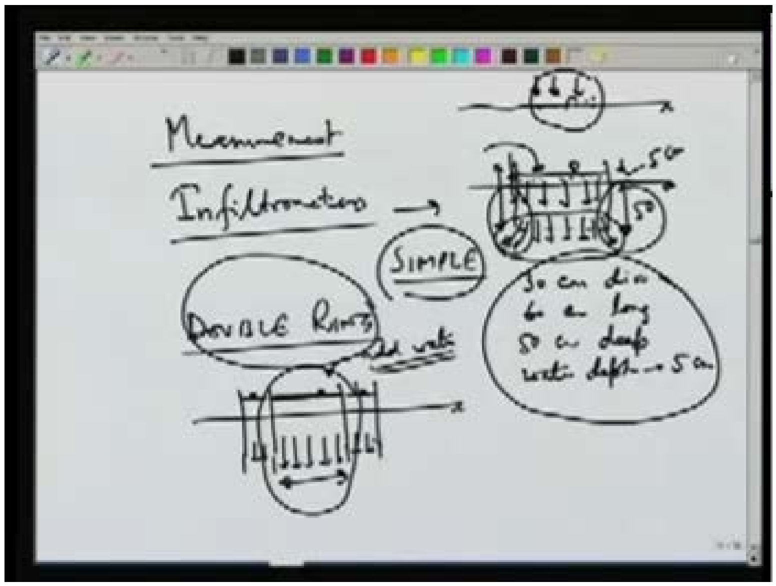

Measurement of infiltration is done by instruments which are known as infiltrometers. For example we can have the ground surface and we can put a ring in the ground we can fill it with water and then we note down how fast the water level is going down in the ring. We fill it or we can keep on filling it, adding more water to maintain the water level. The amount of water which is added to maintain the continuous constant level would be giving us the rate of infiltration and a simple infiltrometer. This we will call simple infiltrometer. The dimensions of the ring are given, for example a generally used ring may be of 30 centimeter diameter, 60 centimeter high or long and 50 centimeter deep. The total may be 60 centimeters. It may be driven 50 centimeter below the ground surface and the water level is generally around 5 centimeters. So water depth is around 5 centimeters. So using these standard sizes, we can fill it with water and note down the amount of water that is to be added in order to maintain this water level. The problem with this ring is that near the edges, the flow is not vertical. So the area of the ring will not represent the area of the flow.

There is a modification in the simple infiltrometer and sometimes we use what is known as double ring infiltrometers. In double ring we have an inner ring and an outer ring. This is the ground level. We have an outer ring and then we have an inner ring in which we will maintain a level. We will add more water to maintain a continuous constant water level here. The amount of water added will denote the infiltration. But here because of the presence of the outer ring, the flow will be nearly one directional or one dimensional in the entire area and therefore this will give us a better measure of the amount of infiltration which is taking place. These infiltrometers which are simple or double ring can be used to estimate the infiltration. One major objection with these infiltrometer is that they do not simulate the impact of rain. In field if you have, let us say this ground level, there are rain drops falling on the ground surface and because of the impact of these rain drops, the soil gets disturbed. Some of the fine particles may get washed away and get deposited into the pores, a bigger pore and that affects the infiltration. The other objection with the infiltrometer is that when we are driving them in the ground, it will disturb the nearby soil and therefore the amount of infiltration which we get may not represent actual infiltration. So one is, the impact of rain drop is not simulated. The other is that when we are driving these inside the ground, the soil in the nearby area gets affected and therefore it does not represent undisturbed conditions. Therefore there is another method which is commonly used all though, it is a little more expensive. It is known as the rainfall simulator.

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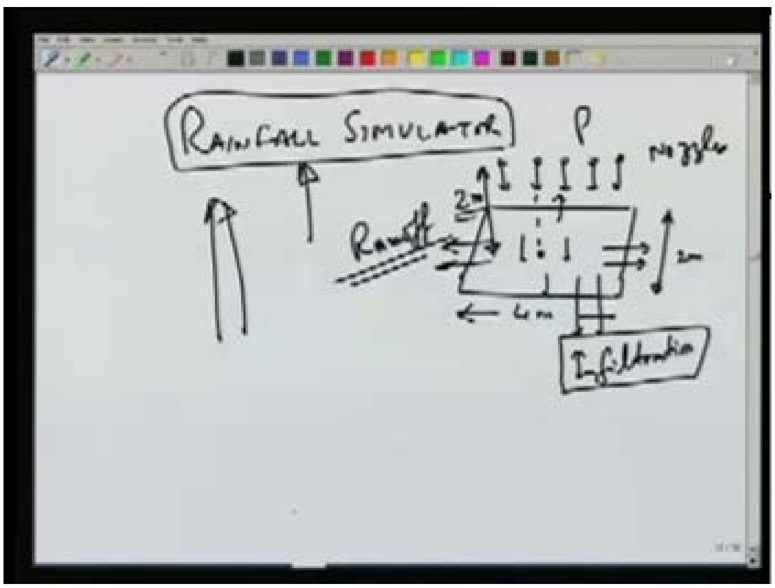

Similar to the field plot which we discussed for evapotranspiration, rainfall simulator is also carried out under controlled conditions. Sides generally would be about 4 meter/ 2 meter. The rain fall will be simulated by putting some nozzles above this area. As we saw, in evaporation experiment too we can do similar set up, where we put some plants even as we measure the evapotranspiration. But here our interest is in measuring the run off. So from this plot there will be some run off. There will be some precipitation which of course is known to us. The height of the nozzles from the plot is generally kept as 2 meters and this will also simulate some impact on the rain drop. When the rain drops fall on this plot, they will have impact an here and the other advantage is that since we are not driving anything into the ground, the soil is undisturbed. By measuring the precipitation and the runoff, we know what the infiltration is. This rainfall simulator takes care of the objections of the simple or double ring infiltrometer, includes that the rain drop impact is not similar to in the first case and the soil was disturbed. So both these are avoided in the rain fall simulator. This is preferred over the infiltrometer but of course, this is more expensive so depending on our aim, we can go for either this or we can go for double ring. Double ring is preferred over single or simple ring. Now the rate of infiltration is not constant.

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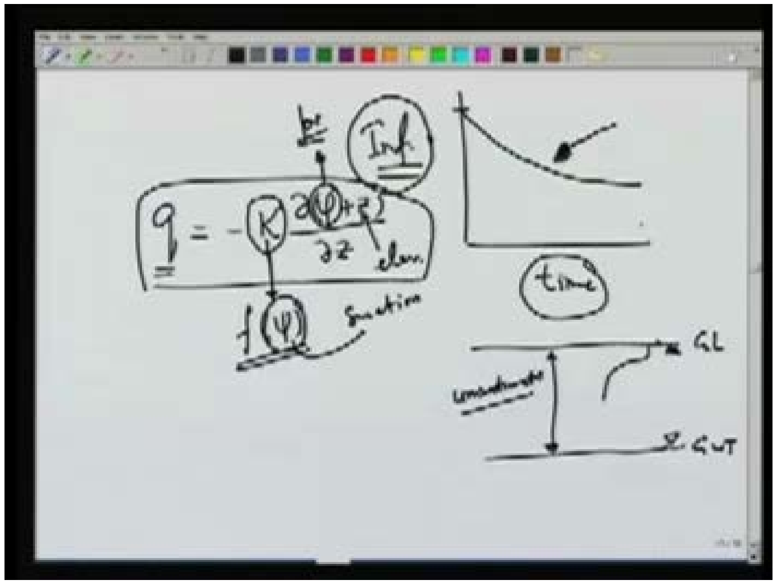

With time, the rate of infiltration decreases and there are various reasons for this. For example because of rain drop, the impact is the soil may get compacted. The pores may get filled with fine material therefore, the infiltration rate will decrease. The other issue is that as the soil gets more and more moisture, its capacity to infiltrate will also be reducing. We should be able to predict this infiltration rate, variation with time i.e., this curve, so as to know how much water will be lost in infiltration. There are various methods which can give us this curve. All are based on, if we look at the theory it says that the amount of water is the Darcy's law when written for a soil, we know that here we have ground level; here we have the ground water table so the soil in this area is unsaturated. During infiltration we have seen that part of the soil get saturated but most of it remains unsaturated.

The Darcy's law can still be used where phi is the pressure head and z is the elevation but the only problem is that now k instead of being constant, the conductivity is constant. When the soil was saturated, it is now a function of the pressure head. Phi in unsaturated condition, phi will have a negative value. We call it desuction, so negative pressure is called suction. This equation as we have discussed earlier, is non linear because k depends on phi and then we have a partial of phi here with respect to z. This is assuming a one dimensional vertical direction infiltration which will be generally the case. Theoretically solving this equation is not very easy and therefore lots of semi theoretical equations have been proposed by assuming something and then solving this equation.

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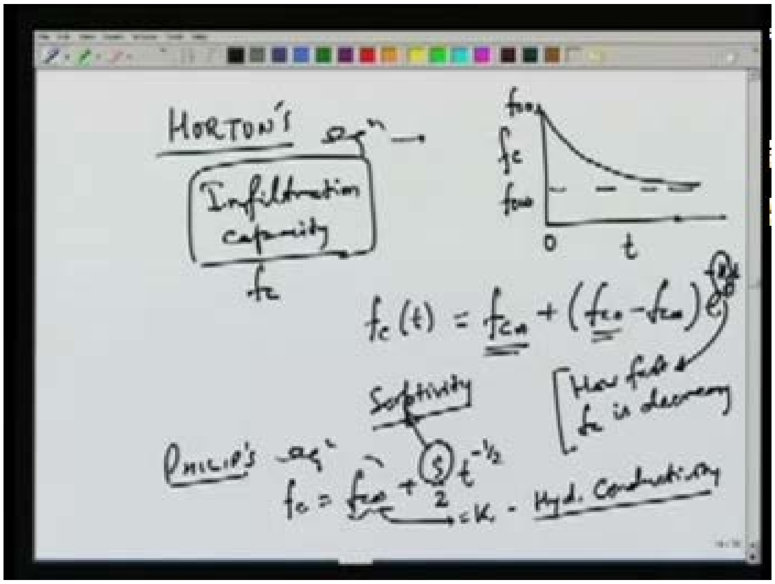

Some of these equations can be written like this. Horton's equation says that the decrease in the infiltration rate or the capacity, (let us first define this term infiltration capacity), we will call it f_c, so the capacity is the amount which can actually be infiltrated. The actual infiltration rate will depend on the amount of water available. If the precipitation is more than infiltration capacity, then rate of infiltration will be equal to infiltration capacity. But if precipitation is less than the capacity, then actual infiltration will be equal to the precipitation. Whatever equations are derived, they are derived for infiltration capacity. f_c is time and as we have seen, it decreases with time and in the Horton's equation, we write f_c at any time t. We relate it with its final value, a steady state value which we can call f_c infinity and an initial value f_c (0). So f_c (0) is that beginning and f_c infinity will be after a very long time.

This equation given by Horton, is an exponential equation where steady state value is this, initial value is this (Refer Slide Time: 53:18) k. f is a constant for this infiltration which will decide how fast f_c is decreasing. If kf is large, then f_c is decreasing very fast, f_x is small, then its decreasing slowly. So that will be a function of the soil type. There could be other equations, for example there is an equation which is known as Philip's equation which also relates the variation of f with time and is given as $f_c = f_c$ infinity. s is another soil property which is known as sorptivity, f_c infinity is generally taken as equal to k which is the saturated hydraulic conductivity. f_c can be given as k + s/ 2 t – 1/2.

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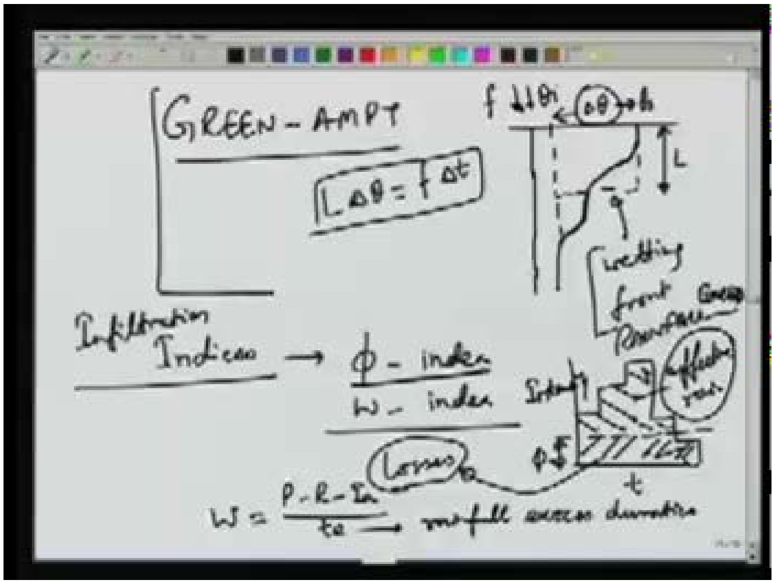

There could be lot of other equations, for example there is one model which is known as green AMPT model which assumes a plug flow. The moisture profile below the ground instead of being like this is assumed to be in the form of a plug flow or a sharp interface like this. This will be the wetting front idealized, wetting front because we are approximating the actual moisture profile by a sharp front. The length of the profile or the depth to which the soil is saturated will depend on what is the initial moisture theta i, what is the saturated moisture theta s, so difference of theta s and theta i delta theta into L so L delta theta should be equal to the infiltration rate. Let us call it f delta t. This will give us the depth of penetration of the moisture front but we will not discuss these models here. Horton's or Philip's model will be sufficient for our purpose.

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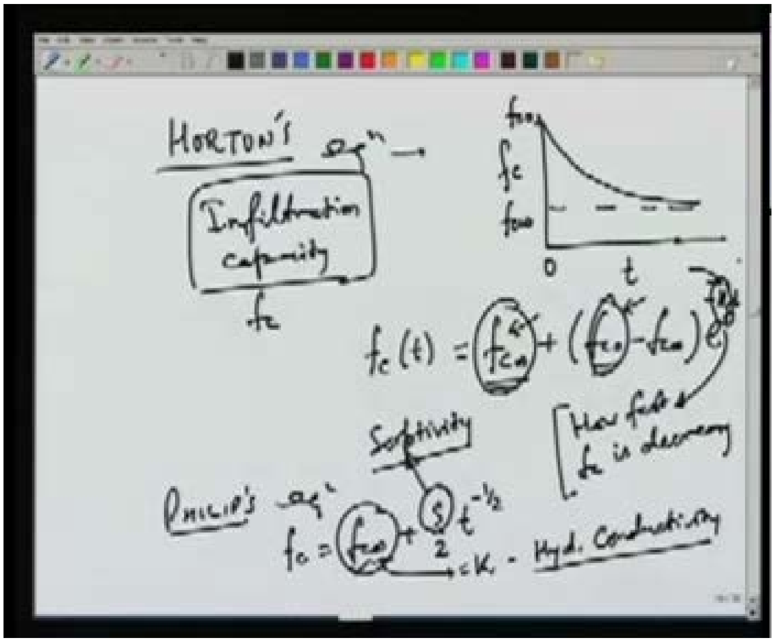

The only problem is that the parameters are difficult to estimate, for example in Horton's we need to estimate 1, 2 and 3. These 3 parameters need to be estimated similarly in Philips too sorptivity, add over the commitivity have to be estimated and estimation of these may not be very easy, so a number of times, some simplifying assumptions have been made. One of the assumptions uses infiltration indices and the two common indices which are used are known as the phi index and the w index. These represent the average infiltration rate. For example the phi index, if you have a rainfall hyetograph like this, time versus intensity and we know the losses then we draw a line here in such a way that this volume is equal to the losses. This line will be known as the phi index. The value will be known as the phi index and the effective rain. This will be the effective rain. Knowing the losses and knowing the height of graph, we can find out the phi index by making this area equal to the losses and then the remaining portion will be the effective rain and similarly we define a w index which is also based on the precipitation run off and the initial abstraction.

We divide it by an effective period which is rainfall excess duration. This can be called an effective rain or we can also sometimes call it rainfall excess which represents the amount of rainfall which causes run off in this case. These 2 indices phi and w indices, have been commonly used to represent the infiltration. In today's lecture we have looked at evapotranspiration and infiltration, various techniques for measuring them, some empirical theoretical or semi theoretical equations to estimate them. This finishes the abstraction part. We have looked at all the 3 or other initial losses also. We have looked at initial losses which consist of the depression storage and the interception loss then we have looked at evaporation, evapotranspiration and infiltration and then various methods of estimating or measuring them.