Water Resources Engineering

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Lecture No # 12

In the previous lecture we had seen abstractions from the precipitation and we also call it loss because we are interested in the surface runoff. So whatever is not going to surface runoff would be called losses. We have looked at different kinds of losses or abstractions. They are interception, and then we have depression storage, evaporation, transpiration and infiltration. The interception and depression storage are combined and called initial loss and similarly evaporation and transpiration are together called evapotranspiration or consumptive use.
So we have looked at some of the processes, such as mechanism of these processes and today we will look at a method to estimate these quantities. Let us start with the estimation of evaporation.

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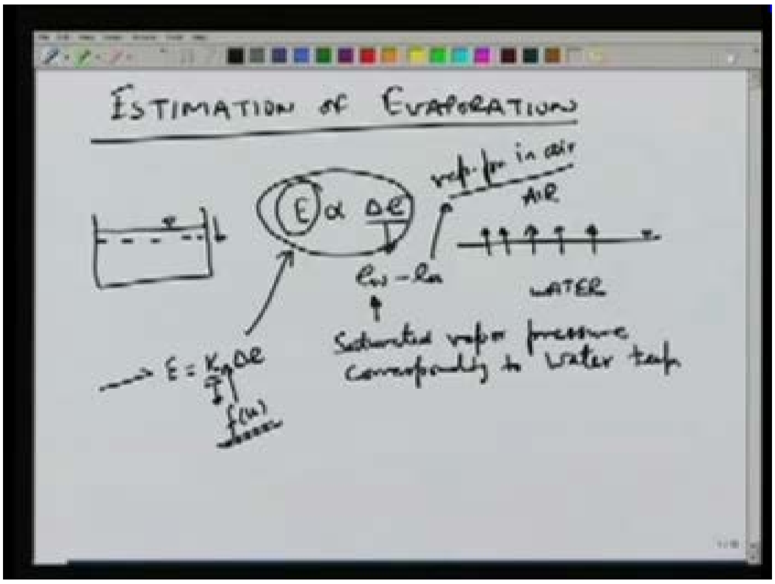

As we have discussed evaporation is transfer of water vapor into the air from a water surface below the boiling point. This is known as the evaporation and as we have already seen it is proportional to the rate of evaporation. It will be proportional to delta E which is the vapor pressure difference. This is the vapor pressure corresponding to water temperature and e_a is the vapor pressure in the air. The difference of these two vapor pressures will drive the evaporation. There are lots of methods of estimating evaporation. We can directly measure the evaporation. For example we can put some vessel and then we can see how this water level is going down with time and that will give us some idea about the evaporation. We can correlate this evaporation with evaporation of a nearby water body, so measurement is one method of estimating evaporation. We can also use some empirical equations for example; we know that e is proportional to delta e, so we can use some empirical equations like e = to some constant k into delta e. This constant may be a constant for a particular area or it may also depend on some other factors, for example we have seen that the wind speed is important, so k may be dependent on wind speed. We can have another function here which is the function of the wind speed, sometimes atmospheric pressure and so on. These kind of empirical equations have been derived for various locations but they would be valid only in that area. Universal acceptance of these empirical equations is not very common, and then we can apply some theoretical analysis and estimate the evaporation. Today we will look at these techniques of measurement, empirical equations and some theoretical equations.

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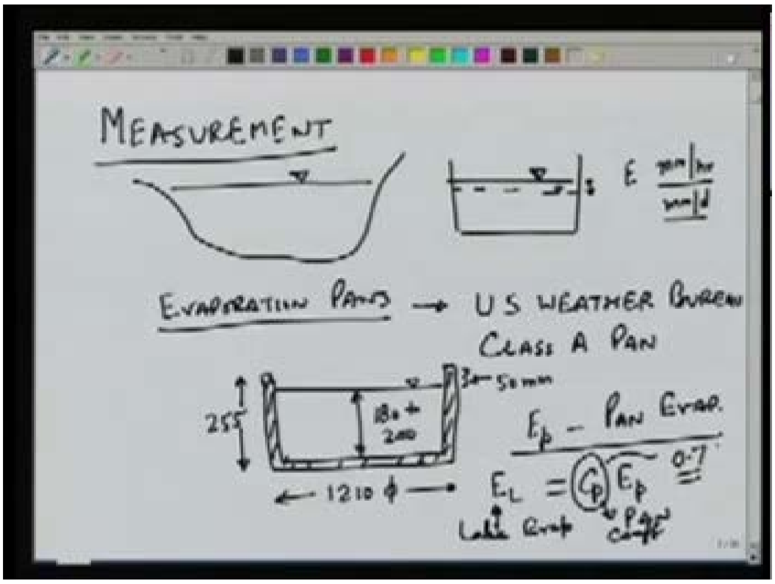

Now measurement of evaporation is quite straight forward, that we put a pan, let us say we want to estimate the evaporation from a lake. On the surrounding area or nearby this lake we can put a pan and we measure the water level at different times. This will give us an idea about the depth of evaporation and then knowing the time we can find out the rate of evaporation in let us say millimeter per hour or millimeter per day. The evaporation pan is sometimes called evaporometer because they measure the evaporation. One of the centered evaporation pans was used by U.S Weather Bureau and is known as class A pan. The dimension of this pan is made of galvanized iron. The dimensions would be the diameter of 1210 millimeter. This is circular pan with diameter of 1210 millimeter and a height of 255 millimeter. The water level typically is 50 millimeter below the top. We try to maintain the depth of water within the pan to 180 - 200 millimeter. We start with above 200 and then when the water level goes deeper at about 180, we again fill it up to this level and make this level up to the original level below 50meters from the top.

The evaporation depth is measured and we call that pan evaporation E_p. The lake evaporation is nothing but the evaporation from a nearby water body and this will not be equal to the pan evaporation and therefore we write the lake evaporation as some fraction multiplied by the pan evaporation. C_p is the pan coefficient and its value will depend on the type of pan which we use. For example for a U.S. Weather Bureau class A pan C_p value, are generally around 0.7. This means that whatever evaporation is obtained from the pan is multiplied with 0.7, to get the lake evaporation which implies that the pan evaporation is generally higher than the lake evaporation and there are lots of reasons for the same.

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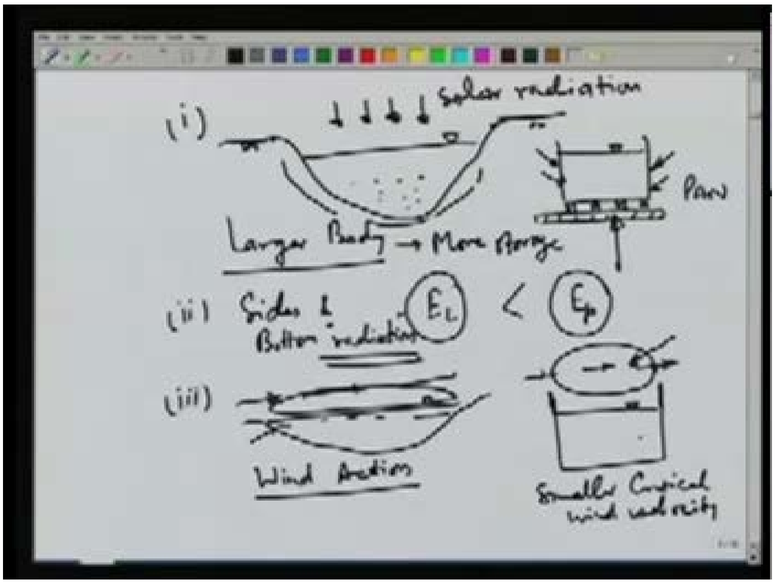

Firstly, if we have a pan and we have a nearby water body. The effect of size is important as we have seen that larger body stores a lot of heat. The solar radiation is the driving force for the evaporation. The radiation coming in from it will get absorbed into the water body and will not cause evaporation. It will not be available for evaporation but for a small pan radiation will be available for evaporation and therefore the pan evaporation will be larger than lake evaporation. Effect of the size or you can say heat storage within the body causes pan evaporation to be larger, so E_p will be larger than E_L because of the storage capacity of the body. The pan is generally on the ground surface so there is a wooden frame on which this pan is kept. There is heat transfer from the sides, there is some solar radiation occurring from the sides and from the bottom, while in a lake whose ground surface is here, in the lake from the sides and the bottom, there is hardly any solar radiation coming in. Most of the radiation is coming from the surface. Therefore again since more radiation is available in the pan, more heat energy will be available. E_P will again be greater than E_L. The sides and bottom will get some solar radiation and because of that the heat energy available will be larger.

So larger body has more storage and therefore less heat is available for evaporation pan. The sides and bottom are open to atmosphere so they also get some solar radiation which will directly contribute to larger evaporation. Another reason that in a pan there is rim above the water level and this will affect the wind action while in the lake whether the water level is here or here, the wind action will be almost same. But in the pan the wind action will get affected by the presence of the rim and because of the smaller size, also a smaller wind velocity will be able to remove the saturated air from this. The critical wind velocity is smaller because the size is small. A smaller wind velocity will be able to carry the moisture from above the pan but for a lake larger wind velocity is needed to remove the saturated air from above the water level. Therefore for a wind velocity which is more than the critical wind velocity for the pan but less than the critical wind velocity for the lake, the pan evaporation will be higher than the lake evaporation. Another reason for pan evaporation being higher is that the pan material is different.

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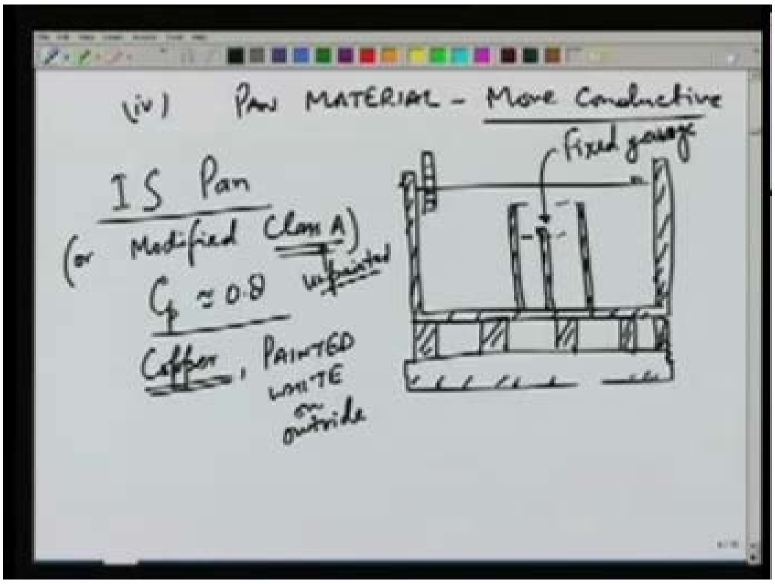

It is more conductive. For example, galvanized iron for class A pan will conduct more heat and evaporation will be larger and because of all these factors, size, the material, wind action, and being open to atmosphere, because of all these factors, the pan evaporation is higher and therefore we need to use a coefficient of 0.7 for class A pan. In India there is a modification in the U.S Weather Bureau class A pan. It has been slightly modified and we use a pan which is known as the Indian Standard pan or modified class A pan. The class A pan which was used by U.S Weather Bureau was slightly modified by the Indian Standard Institute. The dimensions are very similar, so we have the dimensions 1220 instead of 1210. The height of water is measured by using this stilling well, so there is a stilling well here which will damp out any fluctuations in the water level and the stilling well has a water gauge here, a fixed gauge to measure the water level. The water level will be measured on this gauge. There will be a thermometer also which will measure the temperature. There will be some temperature measuring device here.

Again this is also put on a wooden frame. There is a frame here and then wooden blocks in perpendicular direction, so that air circulates freely around the bottom. This pan has a coefficient C_p of about 0.8 and the material, the error modification which is done in class A pan. We had used galvanized iron in class A pan but in IS pan we use copper as the construction material. It is also painted white on the outside while class A pan is unpainted. There is minor difference in the size, in the painting of the surface and in the material of the pan because of which the pan coefficient instead of 0.7 for class A pan, the modified class A pan has a coefficient of 0.8. There are other types of pans, which are used but some of them are very expensive, for example one of the major objections in using the evaporation pan is that it is not representing the actual behaviors of the lake. This is open to radiation from all sides while the lake is not.

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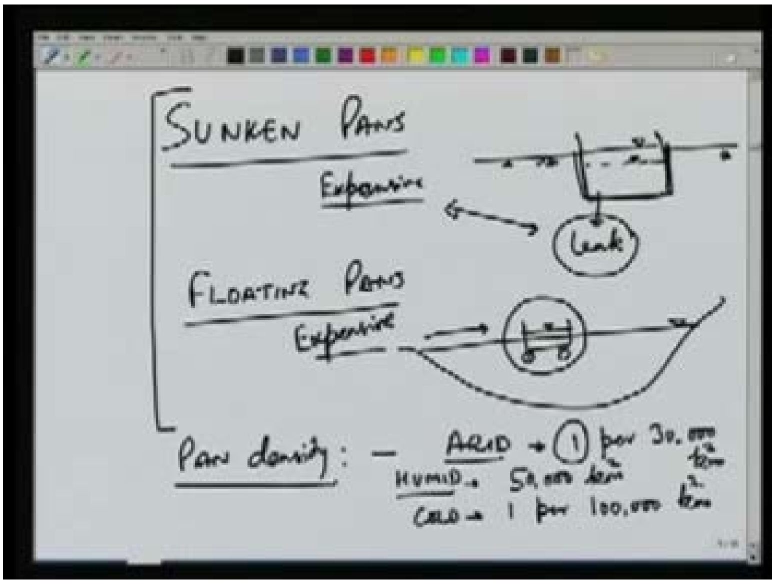

Sometimes we use pans which are known as sunken pans which are put underground. There is some part extending above the ground. Water level corresponds to the ground level and since this is sunk, the sides and the bottom are not exposed to solar radiation and therefore this will be closer to the lake condition than the class A pan or the IS pan. The disadvantage in case of leakage, it is very difficult to find out the leak because in above surface pans, it is very easy to see the leaks, because it is all above the surface. But since this is sunk below the ground if there is a leak, we will not be able to know about it and therefore the estimate of evaporation which we get will be water level going down, but part of this may be because of the leak. So we may over estimate the evaporation compared to the actual evaporation because of the leak. Also it is expensive because we have to dig and install it. Due to these 2 factors, cost and inability to estimate the location of leak or presence of leak, it is not typically used in India. The other types of pan which are used are known as floating pans and they as the name suggests, are some floating drums on which these pans are put and then since these pans are floating in the lake, they will represent the lake conditions quite accurately.

Again the problem is that they are expensive and the second problem is that measurement is quite cumbersome because since they are floating in the lake it is difficult for people to go in there and then take the reading. The reading procedure is quite cumbersome and because of expense they are not very commonly used. These pans are the common method for measuring the evaporation. If the evaporation pan is not available, there is a requirement or density. So pan density is suggested for by World Meteorological Organization forest arid area, where we expect high evaporation. We should have one evaporation pan in an area of about 30,000 kilometer square. So 30,000 square kilometer area should have one pan. But if we have cold areas where we do not expect very high evaporation then we can have a smaller density. Up to 100,000 square kilometer, we can put one pan and in between humid areas (which will be somewhere in the intermediate range) and we can have one pan in 50,000 kilometer square area. This area is quite large and evaporation pan may not be available near a water body for which we want to estimate the evaporation. Under these cases we may have to go for some theoretical or empirical models. We will look at some empirical equations.

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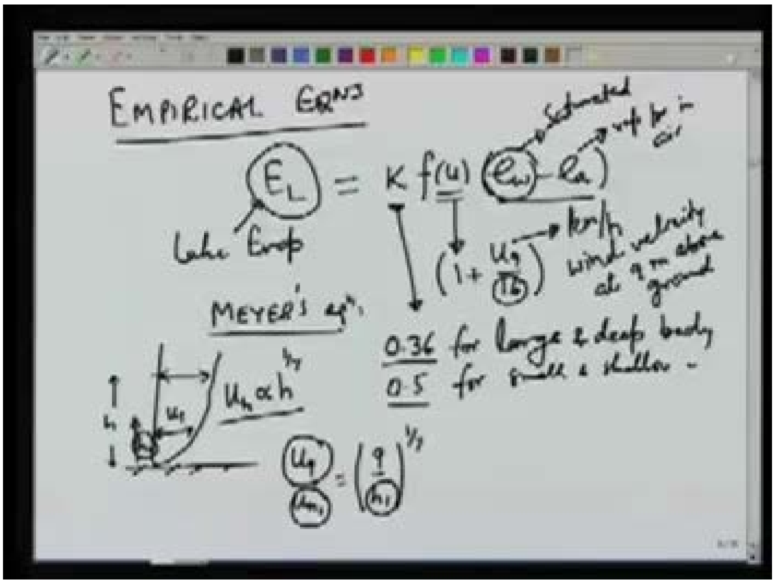

As we have discussed, they are of the form that evaporation is proportional to the change or difference in the vapor pressure. We write E_L which is the leak evaporation, some constant K times will be some function of wind velocity because we know that the wind velocity is an important parameter governing the evaporation and delta e which we can write as $e_w - e_a$. Most of the empirical equations are based on the particular area in which the experiments have been conducted. E_L has been measured, wind speed has been measured, the delta e has been measured and K has been obtained from that experiment. 2 very common empirical equations have been used. One is known as the Meyers equation which says that the value of K is around 0.36 for large and deep body and is above 0.5 for shallow or a small shallow. Whether the water body is large or deep, we can use 0.36 otherwise 0.5. fu is a function of the wind velocity and in Meyer's equation it has been given as u_9 over u_{16}. Most of these equations were derived in the fps units and therefore this 16 term comes because instead of being in miles per hour, we use the wind velocity at 9 meter above the ground. u_9 indicates that the wind velocity is measured at a distance of 9 meters from the ground. As we know the wind velocity shows a variation like this at the ground level. It will be almost 0 and as we move from the ground, let us say at a height of h, the wind velocity will be proportional to 1/7 power of h.

This is known as the one seventh power law in the boundary layer. It is proportional to 1/7 power of the height. This 16 comes in the original equation. This was 0.1 that means this was 10 but since we are converting miles per hour to kilometer per hour, this factor of 16 also comes there. Once we know the kind of water body it is, we know the K, we can measure the wind velocity. Wind velocity measurement is generally done at some particular elevation so this 9 meters or 30 feet was the commonly used elevation. If we measure at some other height, h_1, we can always convert it to any other measurement. Suppose we measure u_1 by h_1, we can convert it to u_9, so u_9 over uh_1 would be = 9 over h_1 to the power 1/7, so by measuring uh_1 and h_1 we can obtain u_9 from this equation and use that in Meyers equation. The other 2 terms which we need are saturated vapor pressure and this is vapor pressure in air. The saturated vapor pressure, e_w is the function of temperature.

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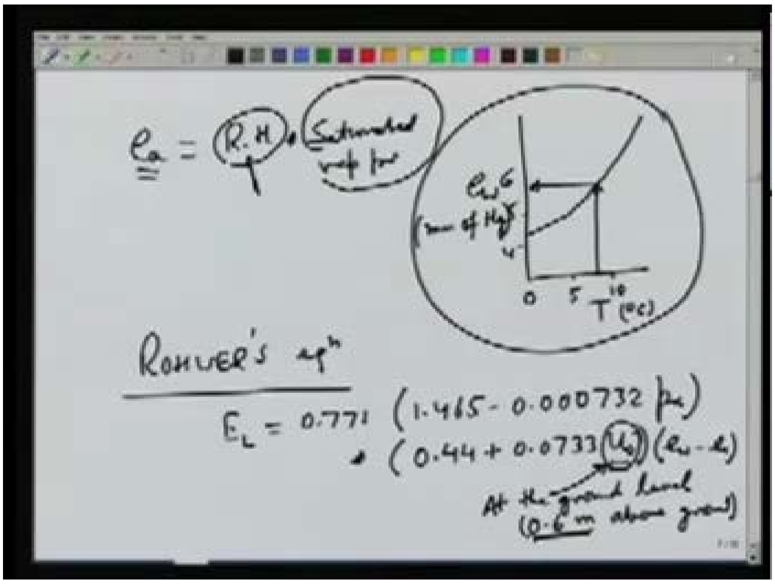

A curve like temperature versus e_w would be available to us. For example t = 0 degrees, 5 degrees, 10 degrees centigrade. e_w is typically expressed in millimeters of mercury and its value may be 4, 5 or 6. Once this graph is available to us, knowing the water temperature we can obtain the value of e_w and e_a would be relative humidity times saturated vapor pressure. Relative humidity measurement is done in weather stations. This will be known to us and knowing saturated vapor pressure, we can estimate the ea and therefore in Meyer's equation, we would have all the quantities available to us which will give us the lake evaporation. Another empirical equation which is common is known as the Rohwer's equation in which the atmospheric pressure is also being taken into account. P_a is the atmospheric pressure into wind velocity factor which is taken as 0.44, $0.0733u_0$ and then you have delta e term. We will notice that we are using u_0 rather than u_9, so in Meyer's equation, the velocity was measured at 9 meters above the ground surface. This u_0 indicates the velocity should be at the ground surface.

The ground level typically about 2 feet above the ground or 0.6 meter because immediately at the ground level no slip condition will say that the velocity should be 0, so velocity at the ground level typically is taken 0.6 meter above the ground level. This can be measured or we measure some other height and convert it using 1/7 power law.. We have already seen how to obtain e_w and e_a. P_a is atmospheric pressure and this P_a is also expressed in millimeters of mercury. Measurement of P_a is also done regularly on weather stations. This gives us an estimate of the lake evaporation using empirical formula. Empirical equations are good but typically they are valid only in the area for which they have been derived and not universally. Therefore we should look for some theoretical equations which we will now do.

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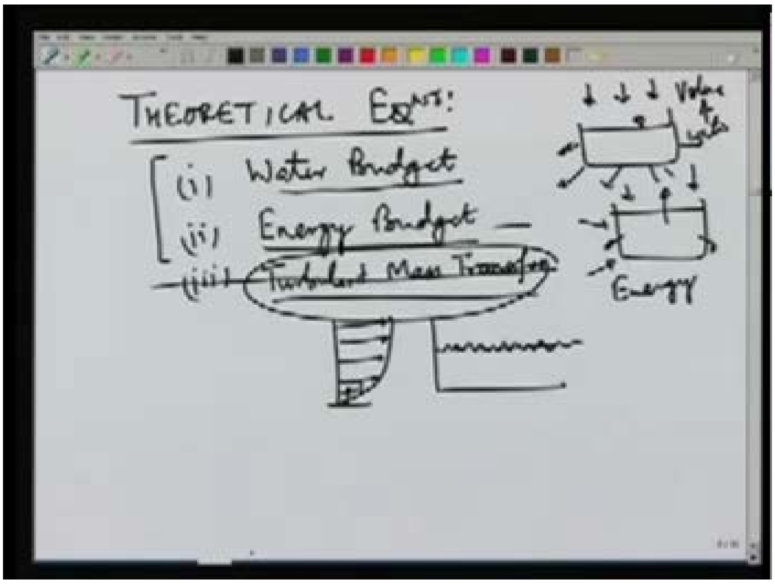

The theoretical equations are generally based on balance of some quantity, for example, water, volume or heat energy or they will be based on turbulent boundary layer mass transfer. So, 3 different kinds have been used. The first one is based on the water budget, the second one is based on energy budget and the third type of theoretical equations can be derived based on mass transfer through turbulent boundary layers. In water budget we look at a water body and find out the inflow, outflow except evaporation. If we obtain everything other than evaporation then we can obtain evaporation by water balance. This is the idea behind the water budget equations for estimating the evaporation. In energy budget we look at the energy that comes. This was volume of water. Here we look at energy (Refer Slide Time: 32:49), the solar radiation on this body is being radiated back or reflected back. We know the amount transferred to the ground, to the air and then we can say that the remaining portion will be used for evaporation and once we know the amount of energy being used for evaporation, we can find out the volume of water which is being evaporated. In the turbulent mass transfer, we use the boundary layer theory. In the boundary layer, the velocities vary and there is a turbulent motion that means there will be fluctuations of velocities. If we look at the velocity at any point, it is fluctuating with time. There is some mean velocity but there lots of fluctuations and these fluctuations cause a mass transfer from one layer to the other. Looking at the theoretical behavior of mass transfer, we can evaluate the concentration of water vapor in the water, in the air and that gradient will be affected or the gradient and the fluctuations will cause the mass transfer or will cause evaporation. These theories are little more advanced so we shall not deal with them. Here only these two, water budget and energy budget will be dealt with.

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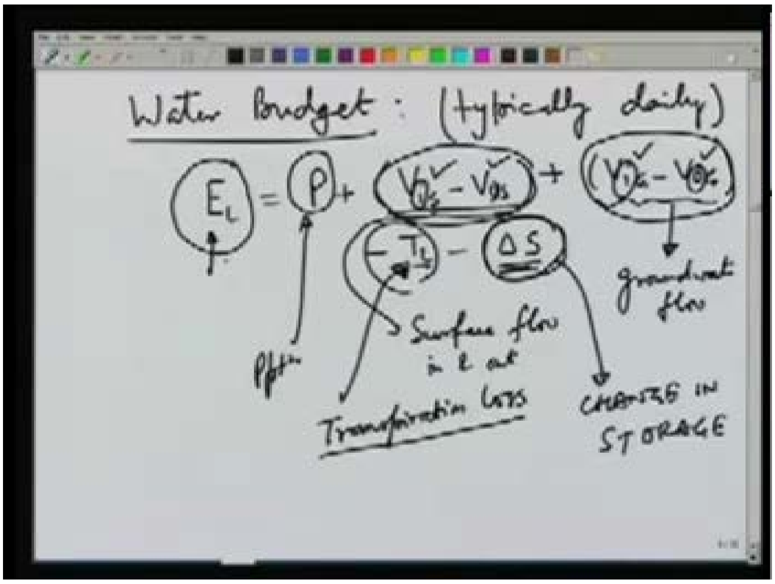

In the water budget, we take a time period of a day or a week or a month. A day is usually taken. The amount of water coming in and going out in a day, using the water budget, can be written like this. This lake evaporation or evaporation from the water body can be related to the precipitation Vsino, these are the volume inflow and outflow from the surface water so surface flow in and out. The subscript, i represent in and o represents out, s means surface. Volume of water which is coming through surface flow in and out will give the net inflow. This is ground water again in and out, so this term gives the net ground water inflow into the lake T_L is transpiration loss. It is very small for a layer but just to be more accurate, we consider T_L also and delta s is a change in storage. What water budget tells us is that, if we know the amount of rain falling on the lake, if we know the net inflow through surface water, the net inflow through ground water, the transpiration loss and the change in storage, we can find out the evaporation from the lake, because that will be the net result of all the other processes. Precipitation is easy to measure and surface inflow and outflow are also comparatively easier to measure, but the component which includes ground water flow, inflow and outflow is not so easy to measure. Transpiration loss is also not easy but sometimes since it is very small, most of the times we can ignore it. Delta s is easier to measure. Ground water flow is a very uncertain parameter, measurement of this ground water inflow and outflow is not very accurate which is why this water budget may not be able to give very accurate results for the lake evaporation. Therefore we can go for an energy budget approach.

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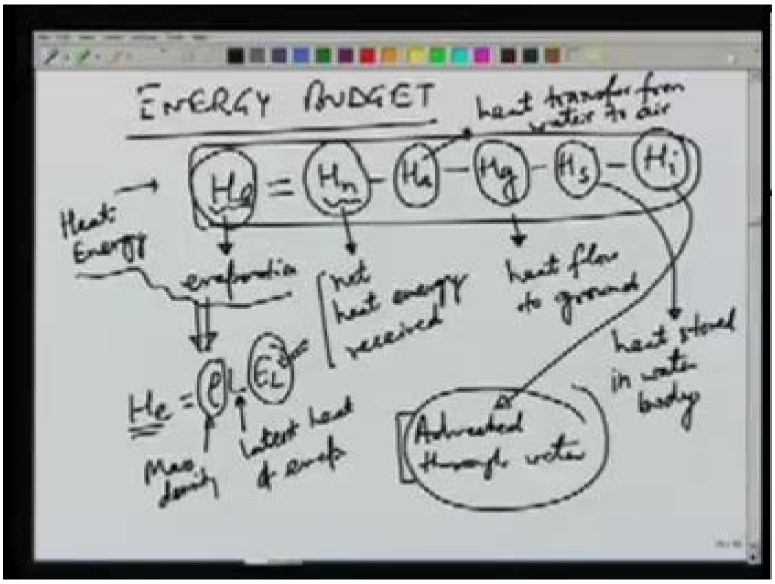

We look at the total energy coming to the body and the amount which is lost and therefore the remaining is used for evaporation. If you look at various components, we can write the heat energy which is used for evaporation as $H_n – H_a – H_g – H_s – H_i$. This is the heat energy used for evaporation. All of these H are energies which is really heat energy. H_e represents the heat energy used in evaporation. H_n is the net heat energy which is received by the water body or the lake. H_a is the heat which is transferred to air or lost to air, so we can say that this is the heat transferred from water to air or we can say sensible heat transfer from water to air.
This is the heat transfer to ground, so after total heat energy received by the body, a part of is transferred to air. Part of it goes to ground; two other losses are heat transfers. One is storage, so there is some heat out of the total net radiations. Some of the heat will be stored in the water body and then there is some part which is advected through water, so the energy budget relates the energies which are used for different purposes. H_e as we have seen is for evaporation
H_n is the net energy received
H_a transferred to air
H_g transferred to ground
H_s stored in the water body and H_i is the adverted through water.

What it means is that there is some water which may be going out of the water body and it carries some heat energy that will be the advected heat energy through water and it goes out of the water body and therefore has to be accounted for in the water in the energy budget. If we know all the quantities other than H_e, we can obtain the value of H_e and the amount of heat energy used for evaporation can be used to obtain the lake evaporation. If we know the H_e value, then it will depend on the lake evaporation we have. So we know the mass density of water, latent heat of evaporation and this is the lake evaporation (Refer Slide Time: 42: 35) as we have discussed. If we know the heat energy used for evaporation, knowing the mass density and the latent heat, we can find out the lake evaporation.

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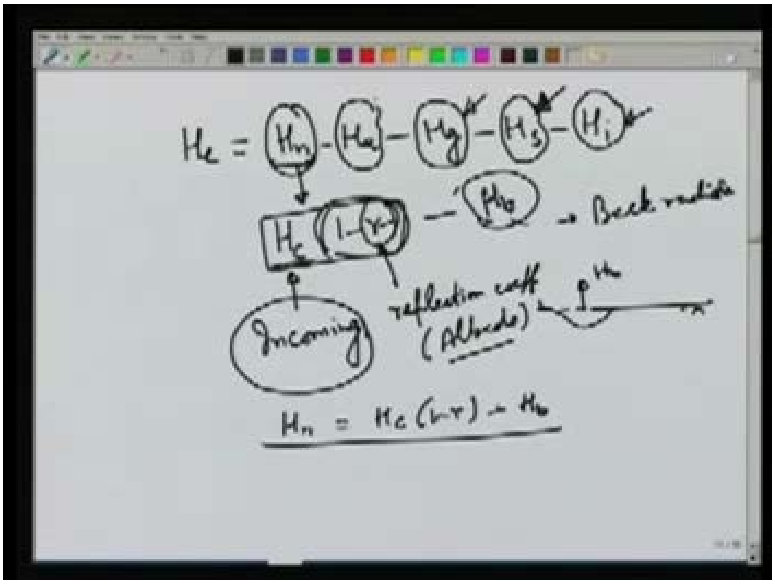

So let us look at some other terms and see how we can obtain them. Let us rewrite the equation, net radiation coming in loss to air to the ground, the storage and advected out.
The net radiation coming in will depend on the total radiation coming in and the reflected back radiation. We can write this as H_c into 1 – r. This H_c is incoming total. r is reflection coefficient also popularly called Albedo. The Albedo value will show how much is reflected back to the atmosphere, out of the total incoming radiation. We will have to add some back radiation, rather subtract some. So we can write this as – $H_{P.}$ This part is radiated from the water surface. There is a lake here, the amount of heat radiated back will be H_b and r repellent the reflection back to the atmosphere. The net heat coming in or received by the water body can be written as incoming solar radiation which we can obtain, 1 – r, so this is the amount reflected. That means this is the amount which is absorbed, H_c (1 – r) and out of that H_b is again radiated back. This net heat inflow H_n is obtained as H_c (1 – r) – H_b. This can be obtained. H_g is the amount of heat which is transferred to the ground. H_n is easy to obtain,
H_g is the amount of heat which is transferred to the ground, knowing the ground temperature, and the water body temperature, this is also easy to obtain. H_s is the storage within the within the water body. Knowing the water body temperature and the change we can obtain this too quite easily. H_i heat advected out of the water body is again by getting to know the amount of water which is going out of the water body. We can estimate this too very easily. Other terms are easy to obtain except H_a.

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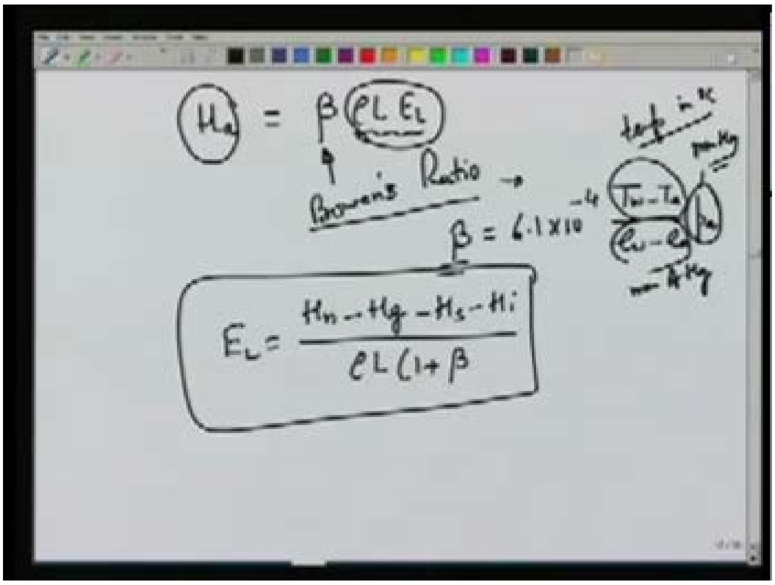

H_a is the sensible heat transferred from the water to air and it is very difficult to measure it which is why we relate it with the evaporation itself and the equation which we use is beta times where this rho L E_L is nothing but the heat energy being used for evaporation and beta is known as the Bowen's ratio. In other words, you can say that this is the ratio of the sensible heat transfer between water and air and the heat used for evaporation and this has been obtained empirically as difference of the water and air temperature multiplied by atmospheric pressure divided by delta e. These units of course will be centigrade for temperature. This is temperature in degree Celsius. Temperature of water and air e_w and e_a, We have already seen these will be in millimeters of mercury and p_a is the atmospheric pressure millimeter of mercury, so once we obtain beta, we can obtain H_a or we can write H_a in terms of the heat of evaporation and the Bowen's ratio. Using these, all these vales can finally be obtained to get an equation for E_L as H_n – H_g – H_s H_i. As we have discussed all these 4 quantities are comparatively easier to measure and therefore obtaining E_L from this equation is quite a straight forward, so using water balance or energy balance we can obtain the lake evaporation E_1. We have seen 3 different methods, one measurement using a pan, one based on some empirical equation derived for some local conditions. But empirical equations could be derived for our own interest and also the theoretical equations which are based on water balance or energy balance. They will need measurement of certain quantities but these quantities are not very difficult to measure, so we can use one of these equations to find out the evaporation.

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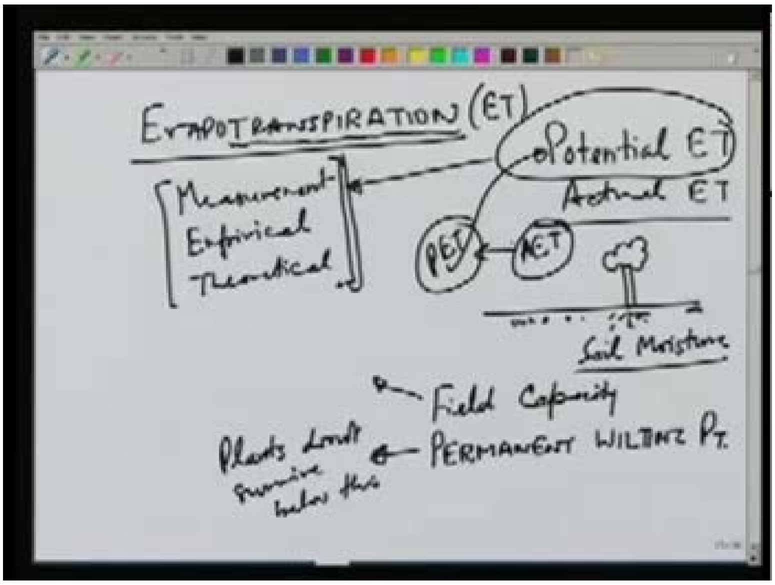

The next term which we want is evapotranspiration. Evapotranspiration, as we have seen is the combination of some of evaporation and transpiration and therefore there are some additional complications involved in determination because transpiration depends on the plant's growth, their water required, and the stage of growth. Evapotranspiration is comparatively difficult to measure or estimate compared to evaporation. There are techniques which are similar to what we have used for evaporation. We can have measurement or empirical equations or theoretical equations same as in evaporation. But in evapotranspiration, there is a very fine distinction between what we call potential evapotranspiration and the actual evapotranspiration. The potential evapotranspiration is the evapotranspiration which will be occurring if water is available. But sometimes if we look at the ground and the soil below, in the root zone of the plants, there will be some soil moisture. If soil moisture is not available, then transpiration will not take place below certain soil moisture. The plants will not be transpiring and in the soil, we have looked at the terms field capacity and there is another term related to the type of vegetation, which we call Permanent Wilting Point.

Permanent Wilting Point is the amount of soil moisture below which plants will not survive and field capacity as we have seen is the maximum amount of water which the soil can hold under gravity. So potential evapotranspiration is the one which we can estimate using these methods. Actual evapotranspiration will depend on the field conditions, so we will look at some of the methods of estimating the PET and the actual evapotranspiration AET, when compared with PET. We will decide on whether plants are able to get to enough water or not. The evapotranspiration and some measurement of infiltration and equations for infiltration will be dealt with in the next lecture. In today's lecture we have looked at various methods of estimating evaporation, we have looked at some methods which are based on measurement, so we measure the evaporation from a pan and we correlate the evaporation from a nearby water body with the evaporation in the pan (There is a pan coefficient which we use for this purpose). We looked at two different pans, one used by U S Weather Bureau and the other in India. We looked at their pan coefficients. They are 0.7 and 0.8. We use some empirical equations to obtain evaporation for a particular area. We also relate the evaporation with the wind velocity and the vapor pressure difference. We also looked at some theoretical methods which are based on water balance or energy balance. Next time we will look at similar methods used for evapotranspiration and methods used for infiltration.