Course Name: Watershed Hydrology

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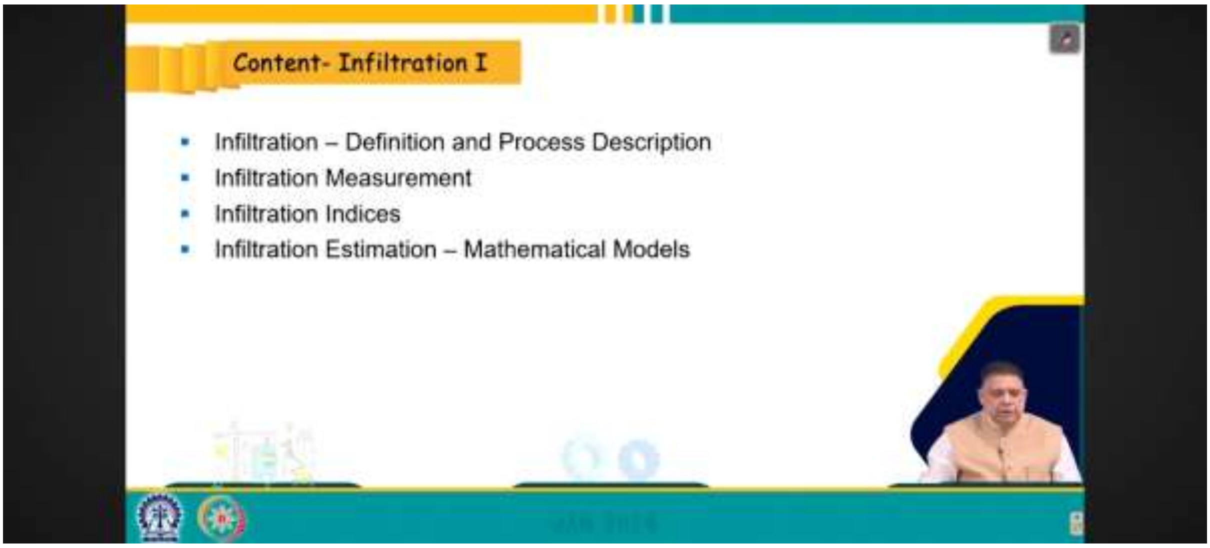
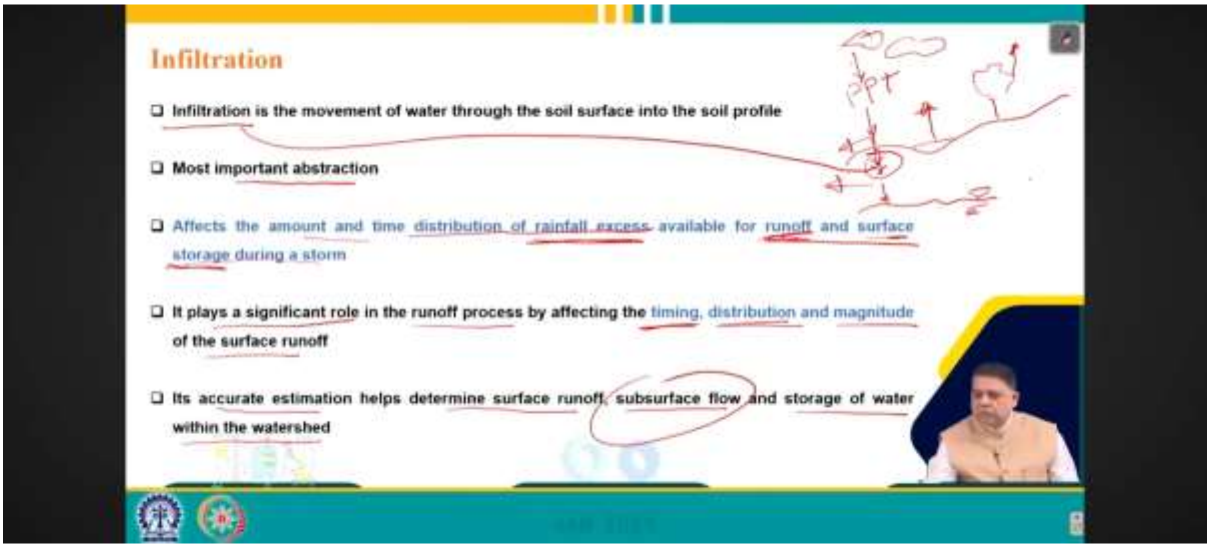
Week: 02

Lecture 09: Infiltration I

Hello, friends! Welcome back to the online certification course on Motor Street 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 4, and the topic is Infiltration Part 1.



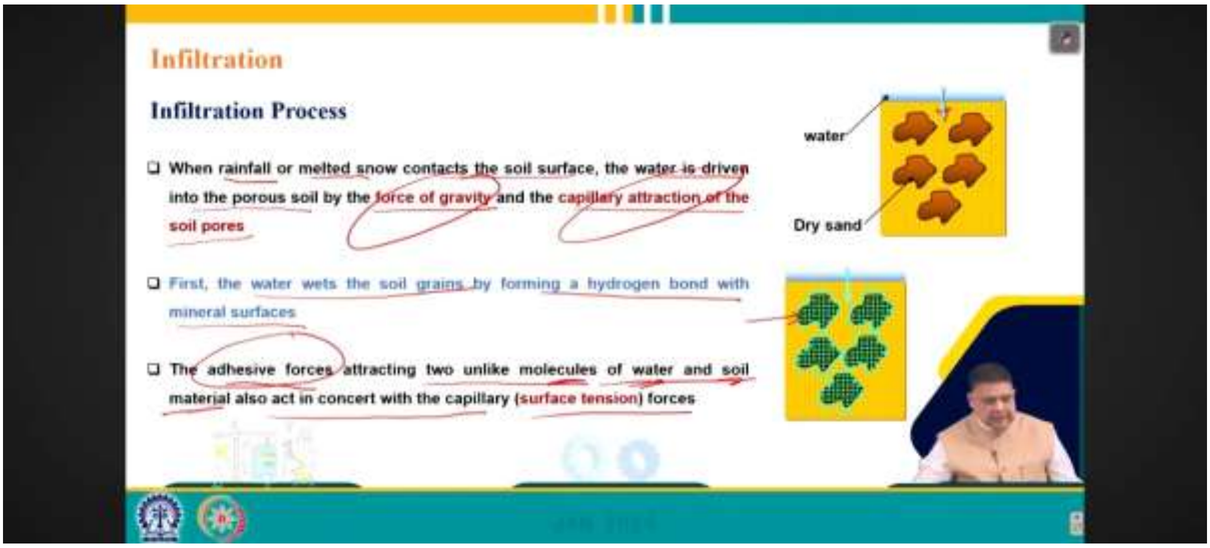
In this lecture, we will define and describe the infiltration process, then we will go for infiltration measurement. We will talk about infiltration indices and infiltration estimation using various mathematical models.



Coming to defining infiltration, is the movement of water from the soil surface into the soil profile, and it is the most important abstraction. We have already discussed various types of abstractions, and while defining or classifying abstractions also, I mentioned that infiltration is the most important abstraction.

And if you remember, when we discussed the hydrological cycle and then also, we also said that when evaporation or transpiration occurs, then crowd for formulation takes place, finally conditions occur and precipitation occurs. The precipitated water when reaches the soil surface, the very first process which starts is infiltration and that is what we are discussing today infiltration, the very first process which starts. It affects the amount and time distribution of rainfall excess available for runoff and surface storage during a storm, and we discussed also that once precipitation reaches the earth's surface, the first thing it must do is to satisfy the infiltration capacity of the soil. So, if the kind of infiltration capacity of the soil is higher, less water will be available for other processes, or rather than the next process is overland flow as we discussed in the hydrological cycle.

So, obviously, the amount of runoff or the amount of storage, because we know that when overland flow takes place when the flow starts in the form of a sheet, then if there are potholes, then water gets stored there. So, both the runoff and the surface storage will depend on the infiltration because of rainfall excess, if you remember, we also said that the total precipitation minus losses, we call that rainfall excess, and that is the part of precipitation or rainfall which is available for overland flow and other processes. Infiltration plays a significant role in the runoff process by affecting the timing, distribution, and magnitude of surface runoff.



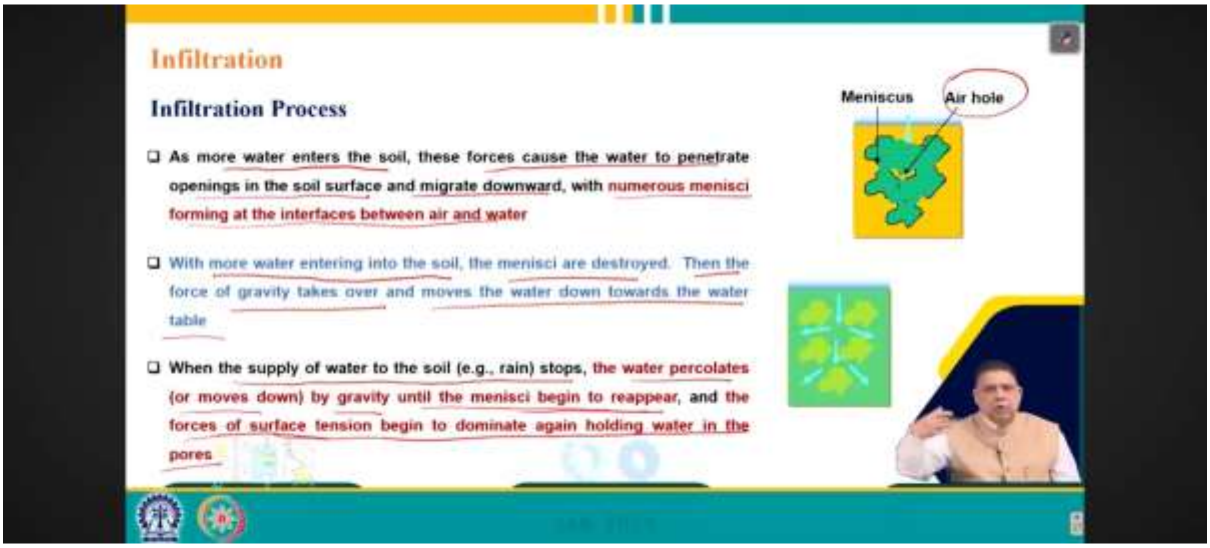
So, just now we discussed that once precipitation satisfies the infiltration capacity, then only precipitation overland flow or surface runoff starts, and, of course, the timing will be affected. So, there will be a distribution because the infiltration capacity of the soil along the way, along the path, will keep on changing, and as it changes, it will affect the runoff magnitude as well as its distribution.

The accurate estimation of infiltration helps determine surface runoff, subsurface flow, and storage of water within the watershed. So, just now we saw that obviously, once infiltration is known we know how much water is available for overland flow and, of course, we know the surface here, this separation etcetera, we know how much water could be stored. Also, once the water infiltrates, then there are possibility two possibilities one is that it flows if the soil profile or the profile is such, then it starts flowing parallel to the surface or it joins the groundwater level. So, if the groundwater level is here, so groundwater if its level is there, then it may join that. So, either it will affect the subsurface flow or the groundwater flow.

So, it all depends on the infiltration magnitude. Onto the infiltration process, it all starts as we discussed once rainfall or snow contacts the soil surface. So, whenever rainfall occurs or snowfall occurs, then only the infiltration process starts. Then when that happens, water is driven into the porous soil by the force of gravity and the capillary attraction of the soil force. So, as you can see here when the precipitation occurs or snowfall occurs, there will be water meeting the soil surface.

Then of course, depending on the magnitude of rainfall, depending on the head that is generated on the surface, the gravitational load through gravity, the water will start getting into and the capillary forces will act. The first the water wets the soil grains by forming a hydrogen bond with mineral surfaces. That is what happens here. As you can see that the soil grains are the chemicals or particles that are there in the soil, they will attract this water, and then a hydrogen bond will be formed. The adhesive forces attracting two unlike molecules of water and soil material also act in concert with capillary surface tension forces.

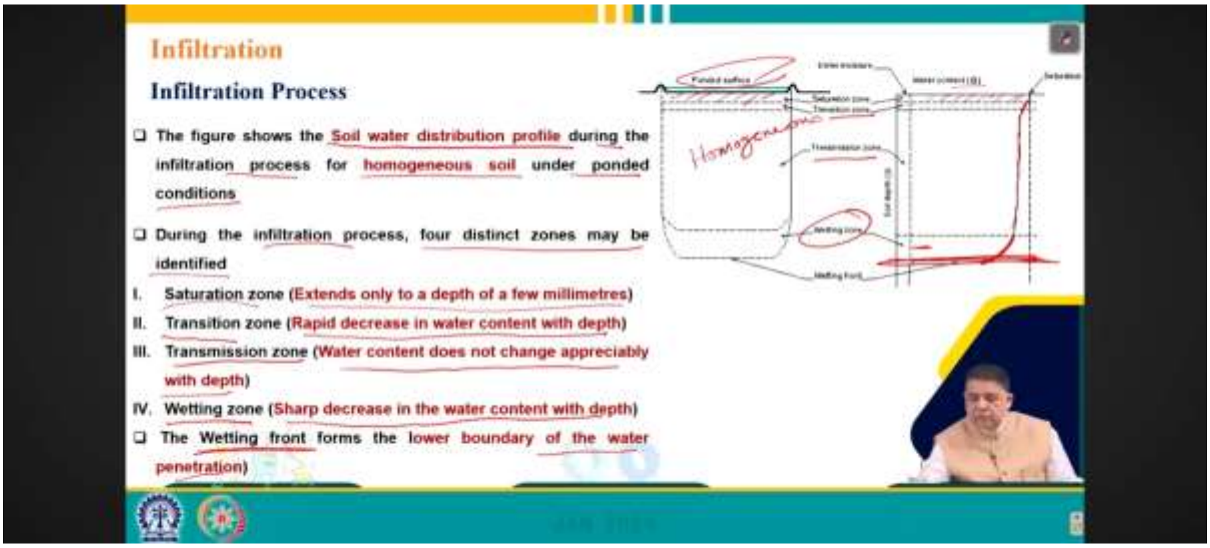
So, we already saw that there is a force of gravity. We also saw there is a capillary attraction, but in addition to these two, adhesive forces also come into the picture because there will be when two unlike molecules, that is of water and the soil particles, they come in contact, they will attract each other.



So, because of that adhesive forces also act. Now, as more water enters the soil, that means, if the precipitation continues, these forces cause the water to penetrate openings in the soil surface and migrate downward with numerous menisci forming at the interfaces between air and water so, as you can visualize that where if more and more water comes because of capillary forces more and more water will be entering the soil surface and obviously, it will be filling the soil pores, but because there are pocket holes of air or air holes also.

So, there might be some spaces where air remains in the beginning, and with more water entering the soil, the menisci are destroyed. Then the force of gravity takes over and moves the water down towards the water table. So, obviously, if this flow process continues, then menisci will disappear and of course, the water will start moving downwards because of the gravitational force and it will percolate down to the water table. When the supply of water to the soil, that is, rain stops, the water percolates or moves down by gravity until the menisci begin to reappear and the forces of surface tension begin to dominate again holding water in the pore. So, obviously, when the rainfall stops, the reverse process starts taking place and as a result, what happens that as long as there is enough water is there, gravity will take the water down, but once the supply is not there, gravitational forces will reduce and it will be the surface tension or capillary forces will take over and obviously, because of the surface tension, the menisci will start reappearing again.

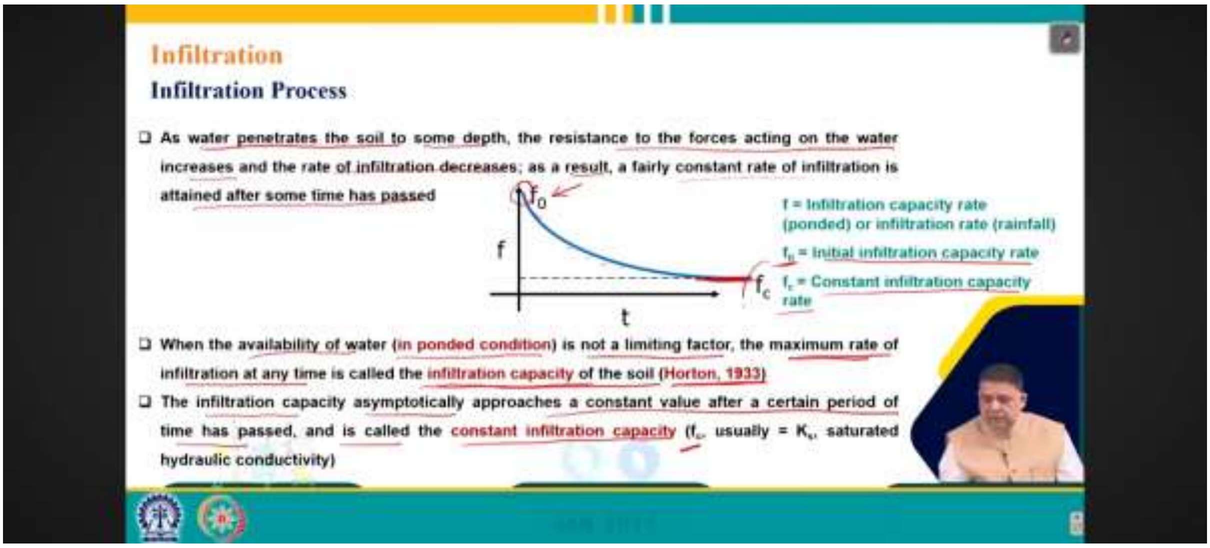
So, that means, the entire reverse process and the soil will go back to its natural condition where it was before the rainfall started.



Now, this figure shows the soil water distribution profile during the infiltration process for homogeneous soil under ponded conditions. So, this assumes that the soil here is homogeneous and there is a ponded water surface on the soil on the ground. So, what happens in such a case during the infiltration process, four distinct zones may be identified and these zones are saturated zone which extends only to a depth of a few millimeters. So, this is where it is taking place and this is basically, we are seeing the soil water distribution profile.

So, on the top, there is saturation because there is ponding water and then of course, the saturation zone which extends only to a few depths of millimeters This is this part here again because it is a saturated zone it will direct contact. So, obviously, this is also having this is also saturated. Then comes the transition zone where there is a rapid decrease in water content with depth. So, just below the saturation zone, there is a transition zone where you can see that there is a sharp decrease in the water content. The third is the transmission zone where water content does not change appreciably with depth.

So, obviously, as you can see here this zone the transmission zone that is which takes the water downwards there is for a much larger depth, and as you can see almost constant moisture content is almost constant in the entire profile. And lastly, there is a wetting zone where there is a sharp decrease in water content with depth. Again, you can see where this is here this is the wetting zone in this portion, and of course, the lower boundary condition is the lower boundary of the water penetration that is referred to as it wetting front. So, of course, on the surface on the top there is a ponded water on the bottom on the bottom there is a water wetting front, and of course, in between there is a saturated zone, transition zone, transmission zone, and wetting zone. So, all the zones can be distinctly identified in a soil profile.

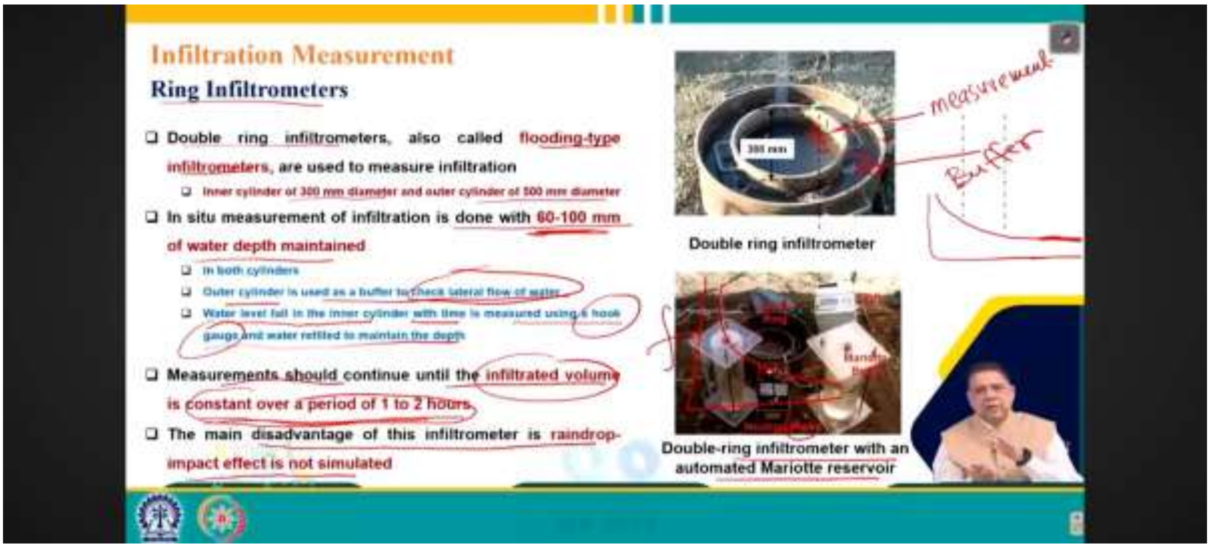


Coming to the infiltration process the rate at which water enters the soil at its surface is defined as the infiltration rate. So, the rate we already saw is that infiltration is the entry of water through the soil surface, and the rate at which it enters the soil is the infiltration rate. And infiltration rate as a function of time defines the infiltration curve. So, this is what we are seeing here that is nothing, but the infiltration curve which is an infiltration rate against time if we plot this is the kind of curve we will get and that is an infiltration curve. Under most conditions, the greatest rate of infiltration occurs when water first contacts into the soil surface that means, when the soil is completely dry and when the capillary forces are strongest.

So, that means, when the soil is dry the capillary forces are strong, and when the water comes into contact because of always you will find that infiltration starts at a very high rate. But as you can see that it gradually reduces and that happens is that water penetrates the soil to some depth the resistance to forces acting on the water increases and the rate of infiltration decreases. As a result, a constant rate of infiltration is attained after some time as fast. So, as you see here it starts at a very high rate and then it starts decreasing and then if the infiltration experiment is continued for a longer period, then it becomes almost constant as you can see here. So, here f_0 which is here that is the initial infiltration capacity rate and f_c which is the constant infiltration capacity rate if the infiltration experiment or infiltration continues for a longer period.

When the availability of water, which is the case when water is ponded on the surface, is not a limiting factor, then when there is a bonding water supply for a time, then the maximum rate of infiltration at any time is called the infiltration capacity of the soil, and this was defined by Haughton in 1933. So, when water is ponded on the surface, obviously, then that assumes that there is a continuous supply of water, then water is not a limiting factor and it is the capacity of the soil infiltration capacity of soil that determines how the infiltration rate will change. So, that is why the infiltration rate is the infiltration capacity of the soil. An infiltration capacity asymptotically approaches a constant value after a certain period as fast and is called the constant infiltration capacity Fc which is here you can see here and typically this value is almost equal to Ks which is saturated hydraulic conductivity of the soil. So, if you continue the experimentation then obviously, the constant infiltration capacity rate will be attained which is f_c and which is almost equal to saturated hydraulic conductivity.

One important thing is here that when it is a ponded condition then it is f is called infiltration capacity rate. If it is a rainfall where there is no ponded condition that is water this condition that water is not a limiting factor that does not hold good then it is called simple infiltration rate. So, infiltration rate or infiltration capacity rate that that nature of the curve will remain the same only thing is that the terminology we use in case of ponded condition we say it is capacity rate in the case of rainfall we call it infiltration rate.

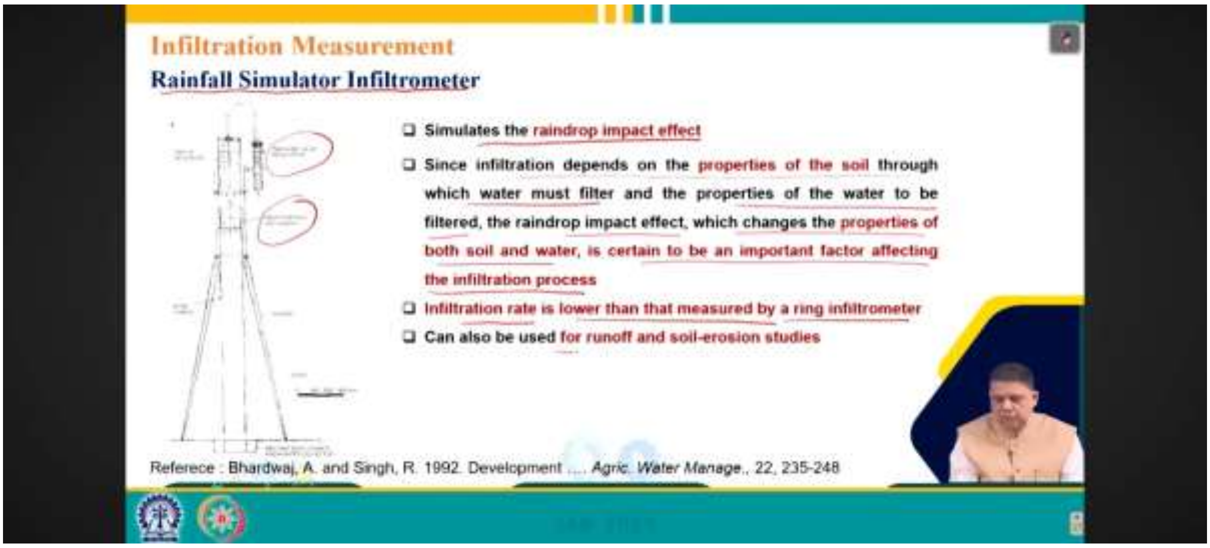


Now, we come to infiltration measurement and typically infiltration is measured by equipment called ring infiltrometers and typically we use what we call the double ring infiltrometer which is also called as flooding type infiltrometer that is used for measuring double ring because it has two co-centric cylinders as you can see here the inner cylinder has a diameter there are two say this is the inner cylinder this is the outer cylinder the inner cylinder has a diameter of 300 millimeters where is the outer cylinder has 500 millimeters diameter. So, diameters 300 and 500 that is a standard, and of course, for conducting the experiment we really put them into the soil, and up to the certain level they are put they are sunk into the soil basically and then the measurement is gone and when the in-situ measurement is done then basically we maintain a depth of 60 to 800 millimeters and in both the cylinders that is both the inner and outer.

So, while doing experiments on the water level here and here both places it is maintained in between 60 to 1600 millimeters, and the outer cylinder basically is used as a buffer to check the lateral flow of water. So, infiltration measurement is done in the inner cylinder that is this is used for measurement whereas in the outer cylinder is used for creating the buffer and that buffer is basically to check the lateral flow of water because as we have seen that infiltration means it is the water entry from the soil surface and typically that must be vertical. So, to avoid the lateral flow of water and keep the water moving vertically we use this outer cylinder, and the water level fall in the inner cylinder with time is measured using a hook gauge and water refill to maintain the depth. So, when the infiltration measurement is starts, we maintain the requisite or pre-decided water level say 100 millimeters and as the time passes as the infiltration starts taking place, of course, there will be a fall in the water level. So, that fall in the water level is recorded using any kind of measuring device it could be a hook gauge which could be used to measure the changes in the level and that is recorded with time.

So, time and the change in the water level water level in the inner cylinder that is recorded, and water is refilled to its original level and that is how we continue the experiments and then with time we of course, we know and we can plot this curve here for say time and this is the curve we normally get. But this measurement should continue until the infiltrated volume is constant over a period of 1 to 2 hours this is important because if we if you remember that we said that it starts with the high rate and then it decreases and attains a constant cost. So, to get this constant value, we must continue this experimentation for a longer period and unless and until the infiltration volume is constant over a period of 1 to 2 hours. So, when it remains constant for a significant period, we stop the experiment session and the main disadvantage of this infiltrometer is raindrop impact effect is not simulated. Before that, this picture shows the double-ring infiltrometer with an automated Mariotte reservoir and this Mariotte reservoir does nothing but maintain a constant water level in the inner cylinder.

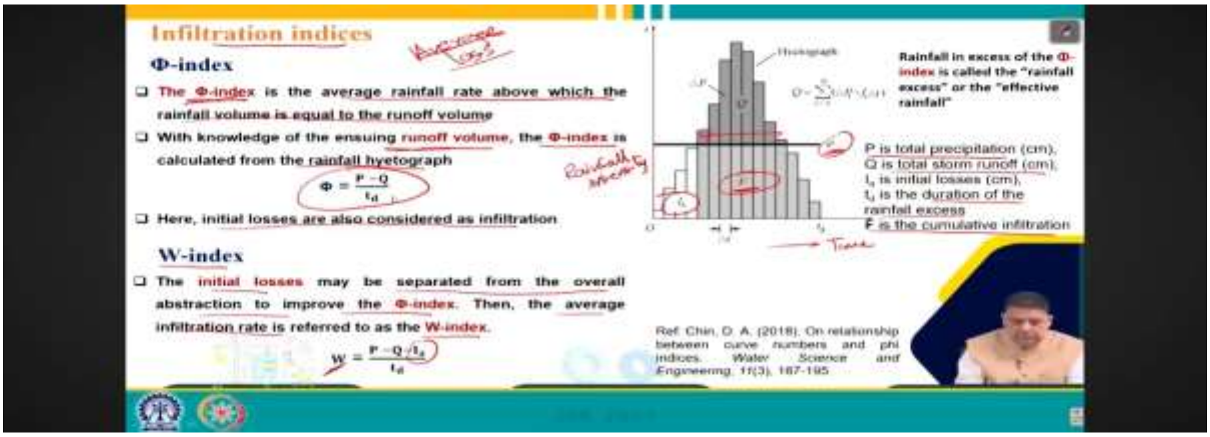
We, as I mentioned, use a hook gauge to measure the water level fall and then refill the inner cylinder, but if we use the Mariotte reservoir, then automatically the water level is maintained and through the cylinder, we know how much water has infiltrated. So, you do not have to really calculate; you automatically get that value. But what happens is that raindrop impact, when if you have red soil erosion, you know that when raindrop impacts the soil surface what happens is that there is a splash and because of that splash, the soil particles are I mean they are loosened and as a result, what happens the soil, the water becomes dirty number 1 and also after a certain period of time the surface gets sealed and because of the surface sealing effect, the infiltration rate is expected to be lower, but because in the case of double ring infiltrometer we the raindrop impact is missing and we always have clean water and a sufficient head buildup that is why typically it gives a higher rate of infiltration.



Then to take care there has been a device called rainfall simulator infiltrometer that has been developed which simulates the raindrop impact effect. So, of course, there is a drop forming mechanism and water is maintained here and then a constant head is maintained here basically and there is a pressure head regulator for maintaining a constant head and then there is a drop forming mechanism.

So, under constant head these drops, raindrops are formed and they fall on the soil surface. So, the process of the rainfall is simulated in this case. So, since infiltration depends on the properties of the soil through which water must be filtered and the properties of water to be filtered raindrop impact effect which changes the properties of both soil and water is certain to be an important factor affecting the infiltration process. So, that means, the water gets dirty also the surface sealing effect takes place because of the simulation of the raindrop impact and that is why the infiltration rate is lower than that measured by a ring infiltrometer because the surface sealing and the dirty water are there in this case. So, obviously, it gives a more reasonable value of infiltration compared to a ring infiltrometer which gives a higher value of infiltration as I already mentioned.

And besides measuring infiltration, this rainfall simulator infiltrometer it can also be used for runoff and soil erosion study. So, we can also estimate how much runoff will take place if a certain intensity of rainfall is maintained and how much soil erosion will take place. So, that gives us an additional advantage in this case.



Now, we come to infiltration indices and there are two types of indices which are used the ϕ--index and the W-index. The first one is a ϕ-- index which is the average rainfall rate above which the rainfall volume is equal to runoff volume.

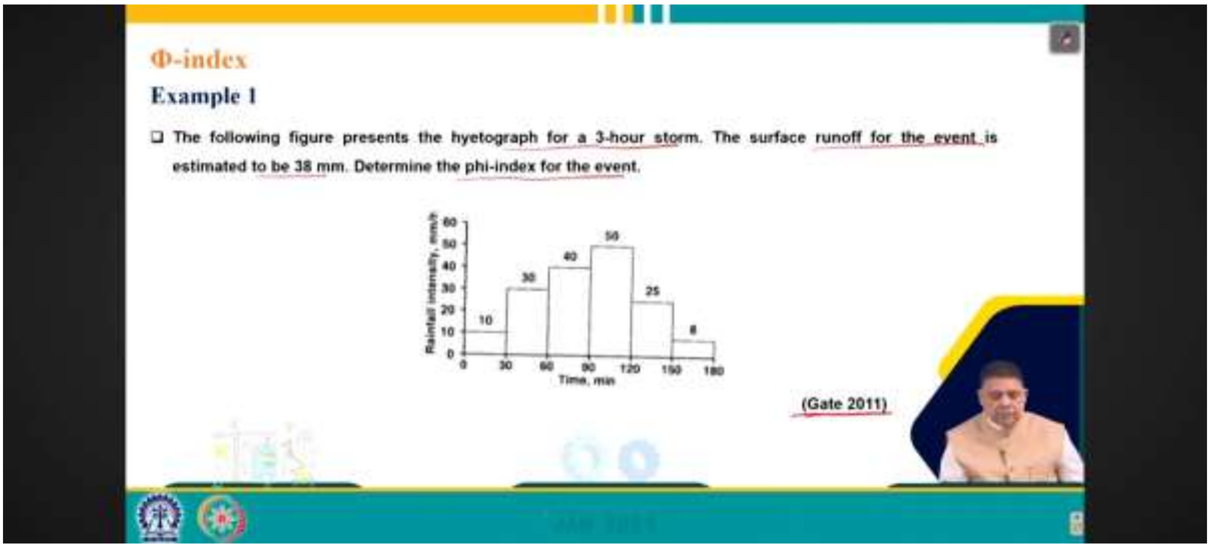
Basically, the ϕ--index or the indices are used to represent the average loss as we saw that the abstractions are lost nothing, but loss. So, basically, because the different abstractions will change with the with the with the location with the conditions within a particular basin itself. So, that is why and it is very difficult to estimate each one of them. So, that is why the concept of this average loss has been brought into the picture and that is what the ϕ- index does. The ϕ-index is the average rainfall rate above which the rainfall volume is equal to the runoff volume.

So, that simply means that you see this is a hyetograph you can see here. So, a hyetograph, as you remember, we plot rainfall intensity with time here. So, this is time here. So, rainfall intensity versus time, so obviously, when rainfall occurs there will be some initial losses and of course, after satisfying the initial infiltration will start, but at the same time the runoff, the overland flow will start. But at the same time infiltration will also continue.

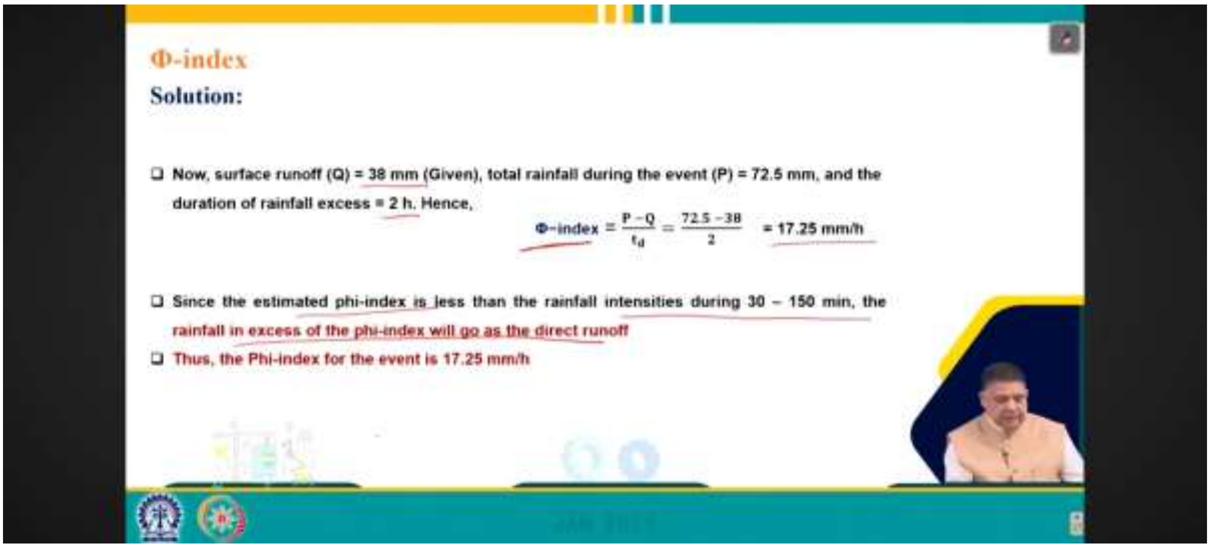
So, this is the entire process. So, if we consider this as the ϕ- index, representing the average losses over the basin, then obviously, whatever area of the curve is under the hyetograph and above the ϕ- index line that represents the runoff volume. So, that is how if we find out, we can find out what the total runoff volume is. So, if we measure the total runoff volume, the ϕ- index can be calculated from the rainfall hyetograph as $\phi = (P - Q)/t_d$, where P is the total precipitation, Q is the total storm runoff, and t_d is the duration of the rainfall excess, that is the period where the precipitation is greater than the losses, and losses here are being represented by the ϕ- index, and F here is the cumulative infiltration. So, obviously, there are initial losses and of course, when the overland flow occurs the also infiltration process continues. So, this is what this picture shows here and these initial losses are also considered as infiltration in the case of the ϕ- index, as we can see.

So, that is why there is another index that has been brought into the picture, that is the

W-index. Then initial losses may be separated from the overall abstraction to improve the ϕ-index, and then the average infiltration rate is referred to as the W index. So, the W index, as you can see here, there is a change with the ϕ- index that is initial abstraction is taken into consideration by calculating the value of the W index and that is why this W-index is likely to be slightly lower than the ϕ- index value because here the initial losses have been considered.



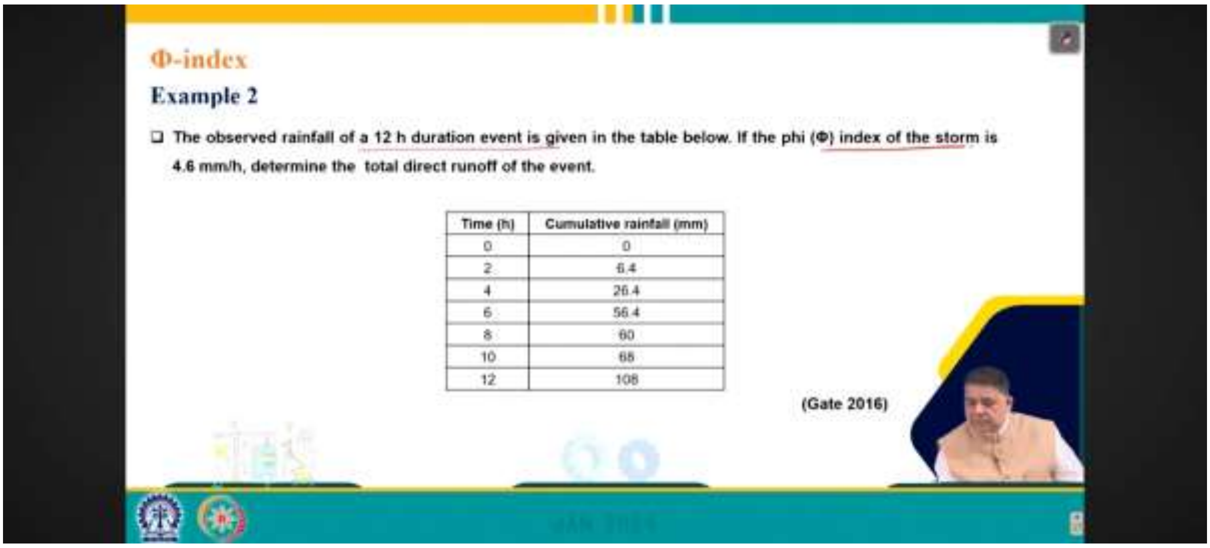
Let us take an example, example 1, the following figure presents the hyetograph for a 3-hour stop, the surface runoff for the event is estimated to be 38 mm, determining the ϕ- index for the event. So, we have a rainfall hyetograph given, a 30-minute interval and it continues for 160 minutes, which means 3 hours, and these are the intervals. At every 30 intervals, these are the rainfall intensities. And of course, this question is taken from the GATE examination 2011.



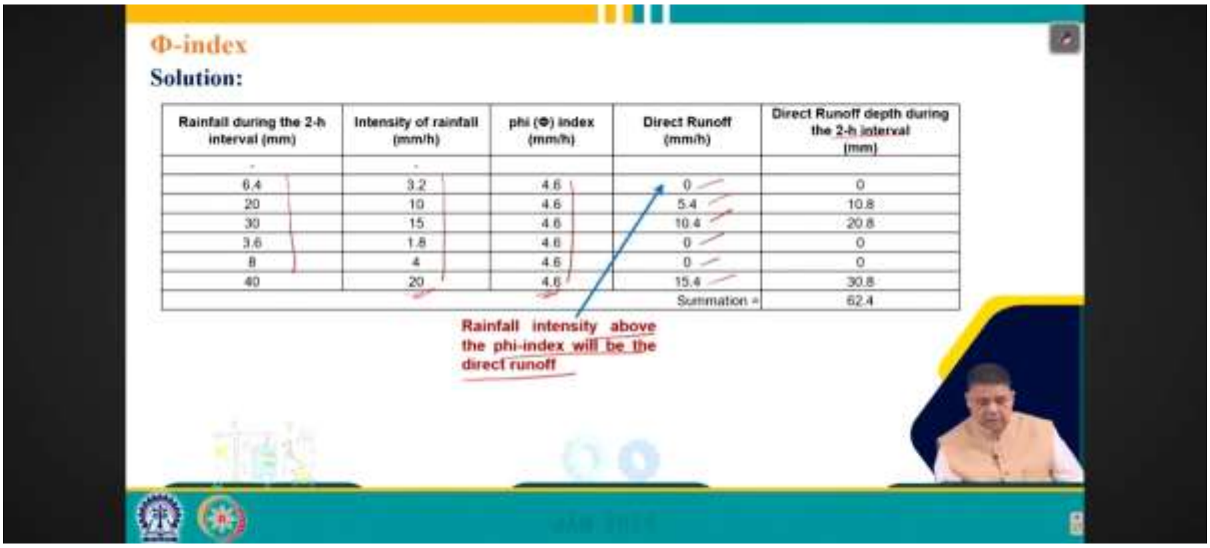
So, from the figure, we can tabulate the rainfall intensity, and cumulative rainfall is given here.

So, the surface runoff already given is 38 mm, and total rainfall during the event we found out is 81.5 mm. So, and the duration of rainfall excess is 3 hours. So, we can calculate the first x approximation of the ϕ- index is $(P-Q)/t_d$ and that value comes out to be 14.5 millimeters per hour. Now, if we say 14.5 millimeters per hour, that means this is where somewhere this ϕ- index value we will plot, but remember the figure we said that only the precipitation which is lying above this ϕ- index line, that is the effective rainfall and that is where the runoff will be generated. Now, if the ϕ- index is 14.5 mm, there will be no excess rainfall during 0 to 30 millimeters, as you can see here this is lower than the ϕ- index value and here 150 to 180 which is lower than the ϕ- index value, which simply means that we must reassess the total depth by excluding these durations these durations do not contribute to effective rainfall. So, that simply means that if we neglect this then the total rainfall value comes out to be 72.5 mm. And now with no known values of Q, our time also reduces to 2 hours because we have taken 1 hour on half an hour either side away so that means, the new estimation of ϕ- index value comes out to be 17.25 millimeters per hour. And if you look at the value here 17.5 that means, somewhere it will be somewhere here. So, obviously, we have only considered this portion as effective rainfall so that remains good.

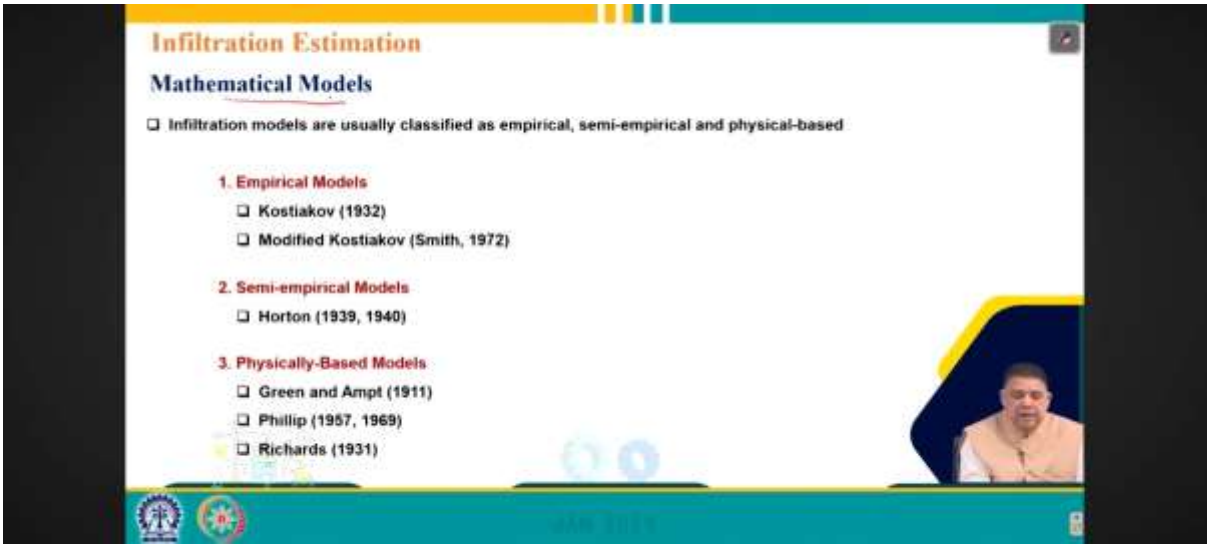
And so, since the estimated ϕ- index is less than the rain for instance during 30 to 150 minutes the rainfall more than the ϕ- index will go in direct runoff thus the ϕ- index of the event is 17.25 millimeter per hour.



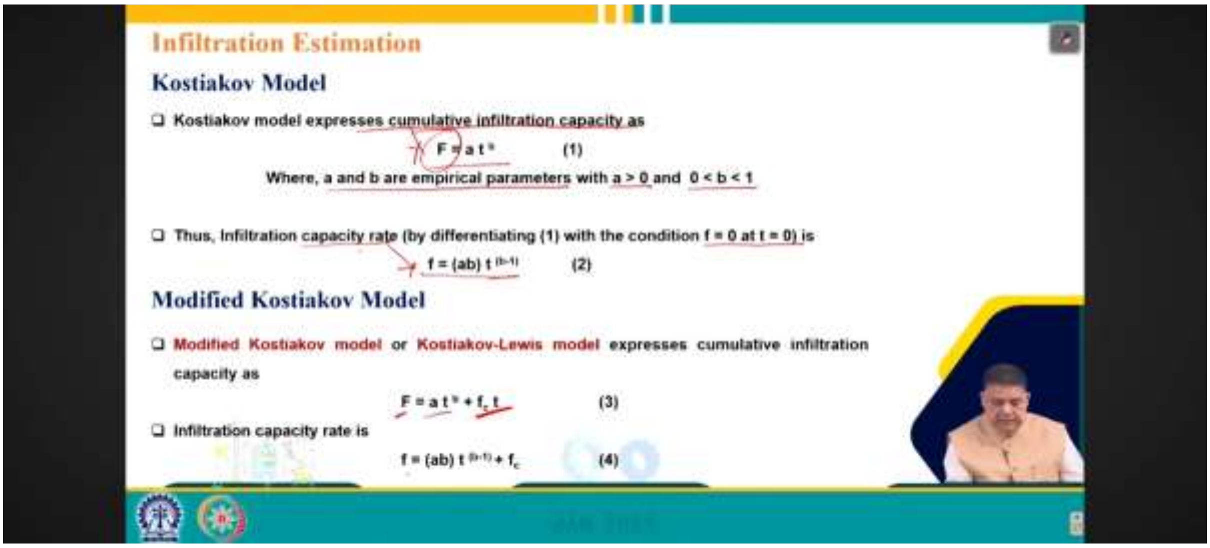
We can take another example quickly which is the observed rainfall of a 12-hour duration event given in the table below if the ϕ- index of the storm is 4.6 millimeters per hour determines the total direct runoff of the event. So, cumulative rainfall is given and different times and this question is from date 2016.



So, the same process will be rainfall during the 2-hour interval and intensity will find out so that means, basically, we need the ϕ- the hyetograph, and the ϕ- index value is given as 4.6. So, the same principle when the intensity of rainfall is lower than the ϕ- index then there will be rainfall intensity above the ϕ- index will be direct runoff and there will be no production. So, that means, direct runoff is 0, 0, 0 here and 5.4,10.4 and 15.4 which means this value minus this value will be the direct runoff millimeter per hour, and because this 2-hour interval we are talking about so obviously, it will be double of that is direct runoff depth. So, the total direct runoff depth comes out to be 62.4. So, the total direct runoff during the event will be 62.4 millimeters.

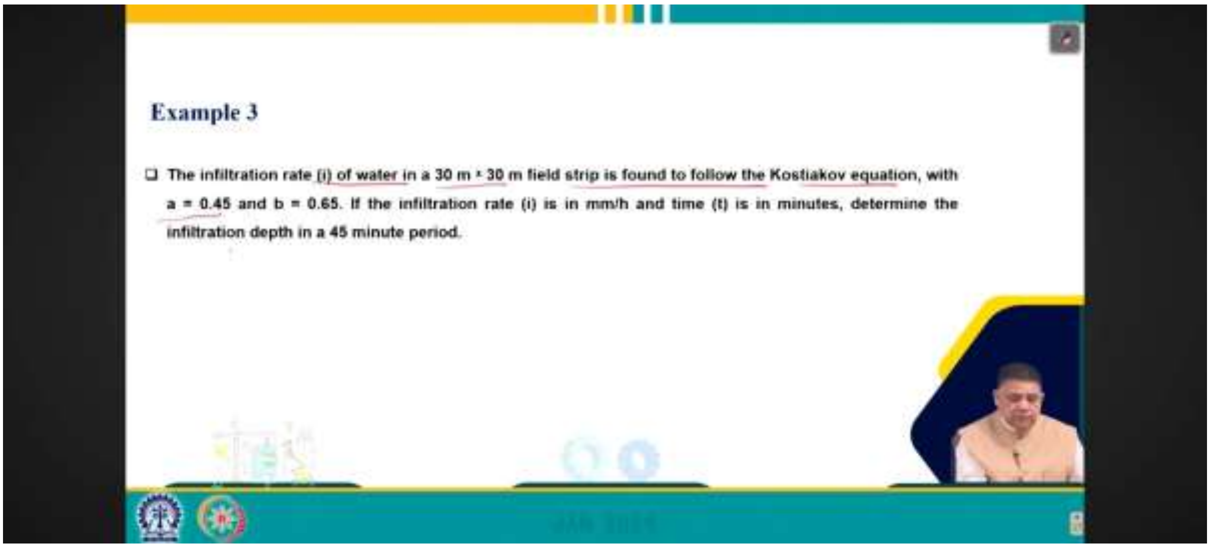


Now, we come to estimating infiltration using mathematical models, and usually, infiltration models are classified as empirical semi-empirical, and physically based and they are these are the different models in the different categories. For empirical models we have the Kostiakov equation developed in 1932, modified by Kostiakov by Smith in 1972, semi-empirical models Haughton 1939, 1940 and are physically based we have 3 different models renamed given in 1911, Phillip in 1957 in 1969 and the third one is Richard's equation in 1931. We will see these in the remainder of today's lecture and the next lecture.

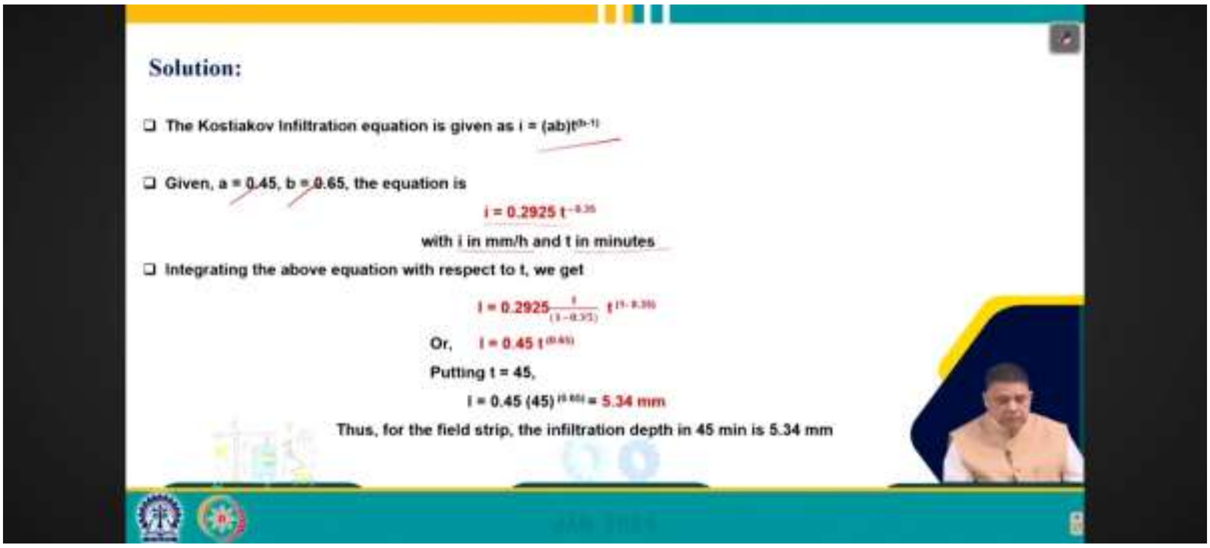


Starting with the Kostiakov model Kostiakov model expresses cumulative infiltration capacity in this form Of equals to a to the power t a t to the power b where a and b are empirical parameters with (a>0) and (0<b<1) and infiltration capacity rate this is cumulative infiltration capital F the rate can be expressed by differentiating above equation with the condition that f= 0 at t= 0 that is f= $(ab)t^{(b-1)}$ and this is the infiltration rate, this is the rate and this is cumulative infiltration.

Kostiakov modified Kostiakov model is just a modification here you can see that after attaining f_c also infiltration will continue that part is considered. So, F= at^b+f_ct is also there and the infiltration capacity rate is again f is given by equation number 4 which comes by differentiating equation number 3.



We will take a quick look at an equation a problem an infiltration rate of water in a 30 by 30-meter field step is found to follow Kostiakov equation with an equal to 0.45 and b equals to 0.65. If the infiltration rate is in millimeters per hour and time is in minutes determine the infiltration depth in 45 minutes period.



So, Kostiakov equation we already know I equal to a b t to the power b minus 1 we are given a we are given b. So, I in terms of t we can find out which comes out to be I equals to 0.2925 t to power -3.5 where I is in millimeter per hour and t in minutes. So, at 44 we want to get up. So, we can integrate that equation with reference to t because we want cumulative infiltration. So, we will get $I=0.45\ t^{0.65}$. So, it forts equal to 45 it we get a value of 5.34. So, for the fault field strip infiltration depth in 45 minutes is 5.34 millimeters.

So, with this we come to the end of this lecture. Thank you very much please give your feedback and raise your doubts so that can be answered on the forum. Thank you.