Water Resources Engineering

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Lecture No. # 07

In today's lecture, we are going to talk about runoff. Runoff is the component of precipitation which runs off from the catchment through the streams or other drains. We will start by looking at the hydrologic cycle with runoff components in detail. So let us look at the cycle once again.

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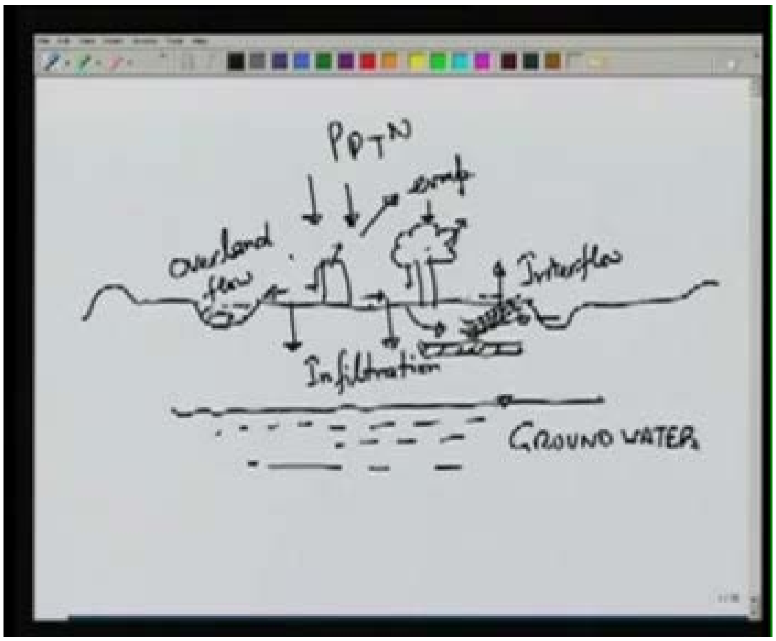

This is the ground surface. There may be drains, trees; there may be small depressions like lakes. So when precipitation occurs, part of it will evaporate directly, part of it will fall on the trees and other structures like roof of the buildings. From the roof of the buildings and trees, some part will evaporate directly without reaching the ground and some part will fall down to the ground. Now the part which falls on the ground, part of that will again evaporate from the ground surface and a part of it will go below the ground level and this is known as infiltration.

Now once this water goes underground, there is below the ground, a saturated soil layer and this is known as the ground water which moves very slowly. So once the water reaches the ground water, it will move again towards the drain but at a slow rate. Some part of infiltration, if the soil is pervious and there is an impermeable layer, will go to the stream or will appear on the surface. If the impermeable layer intersects the surface, this part is known as interflow. So this is the part which infiltrates and then comes back again on the surface or in the stream. So this interflow is also an important component. Now the part of precipitation which does not evaporate or infiltrate runs on the land. This is known as the over land flow. Over land flow will go into the lakes and once the depressions and lakes are filled then the rest of it runs off to the stream. What we will look at today is this component. How much water runs off into the stream from a particular precipitation?

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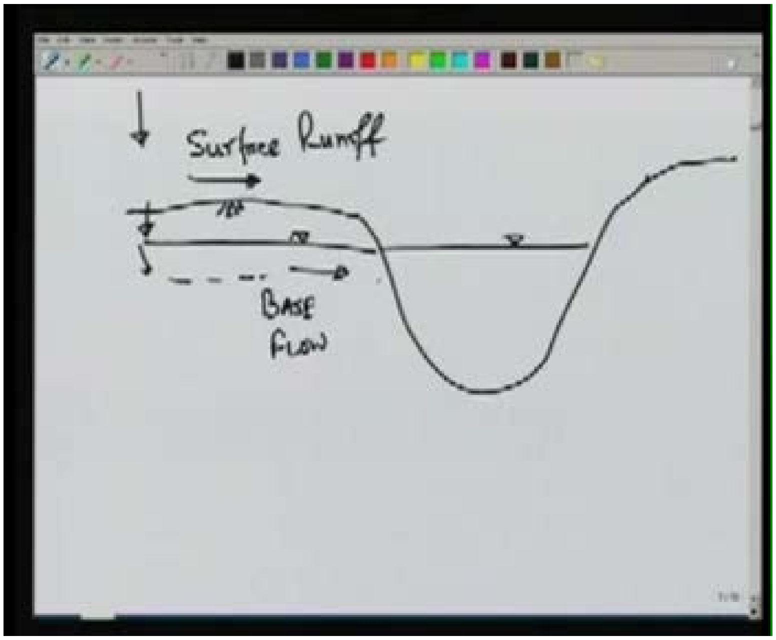

If we look at various components of the runoff, let us say a river cross section and let us say the ground surface is like this and the ground water is here. The part which comes over the surface is known as surface runoff and the part which comes from the ground water is called base flow. The difference between these two is that surface runoff comes immediately or very soon after the precipitation while base flow for the same precipitation to appear in the stream as base flow will take a longer time because, it will infiltrate into the water into the ground, reach the ground water and moves very slowly. This may take a few months or sometimes even years to reach the stream. So there is a fast component and there is a slow component.

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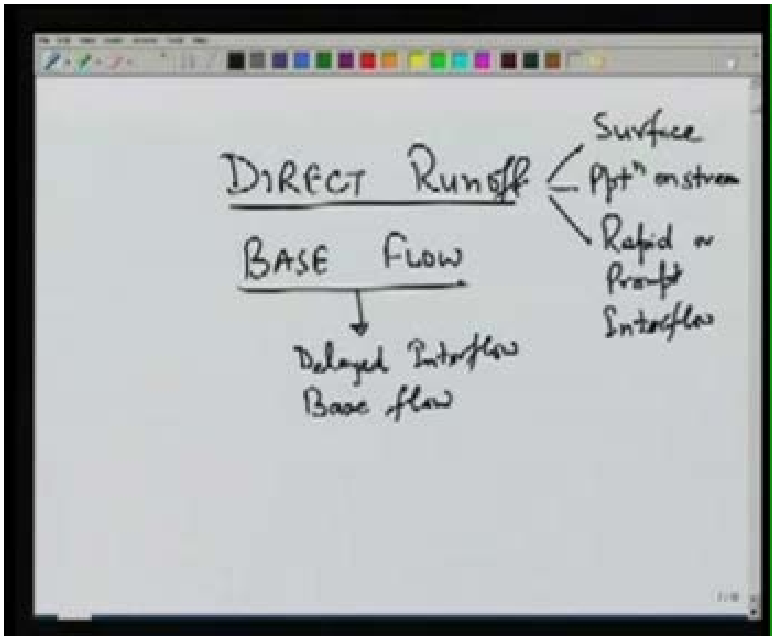

We can write down various components in two forms. Direct run off and base flow depending on how fast or how slow they reach the stream. In the direct run off, we can again have various components. For example surface runoff which comes over the surface. There is some rainfall which occurs directly on the stream surface so precipitation on stream, and there is some part of interflow which comes very fast and back to the stream and we can call this Prompt inter flow or rapid interflow. So the component of inter flow which goes in to the ground and then reappears in a short time is known as the rapid or prompt inter flow and that is also counted towards direct runoff. So this entire direct runoff component is the one which occurs a little while after the precipitation. The base flow component can again have two different parts. One, this will be a delayed interflow and two; this would be a base flow. So the delayed interflow is the component of interflow which goes into the ground and appears on the surface again, but not very fast, it takes a while sometimes a few days. Base flow is the component which comes from the ground water and typically it takes a few months or sometimes even years. So we will look at various aspects of these components and see how we can predict or estimate the runoff with or for a given event of precipitation.

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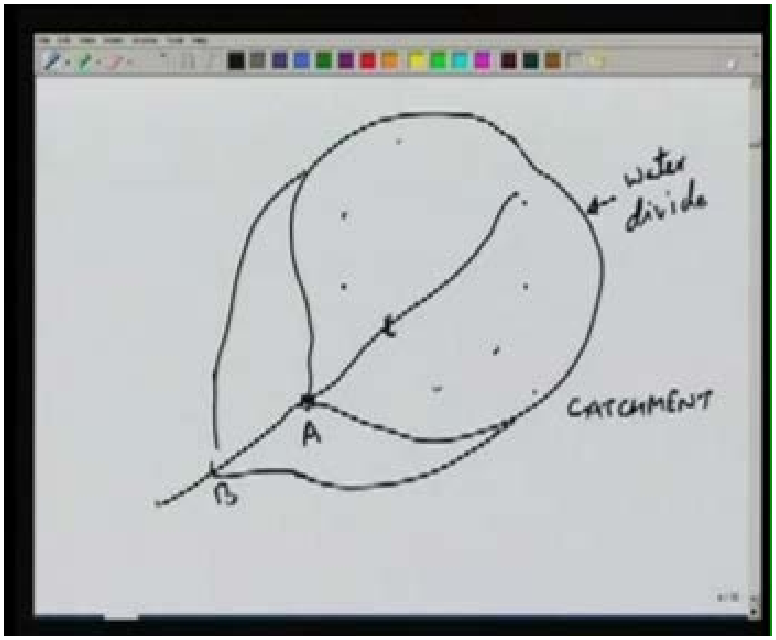

So let us look at a river which has its origin at some point. Now let us say that this point is A. This entire area is the one which contributes to the flow at the point A in the river. This area is known as the catchment area. So this is the catchment of the river at the point A. This means that that all the precipitation falling in this area will ultimately reach the point A and it will be taken out of this area through the stream at point A. So this catchment area has its boundary which is known as water divide or sometimes the catchment area is also called water shed. So the idea of this catchment area is that any precipitation falling anywhere in this area would go to the river and then will be carried out of this area or runoff from this area through point A. Now if we take another point B then naturally the catchment area of B would be larger and it may look like this.

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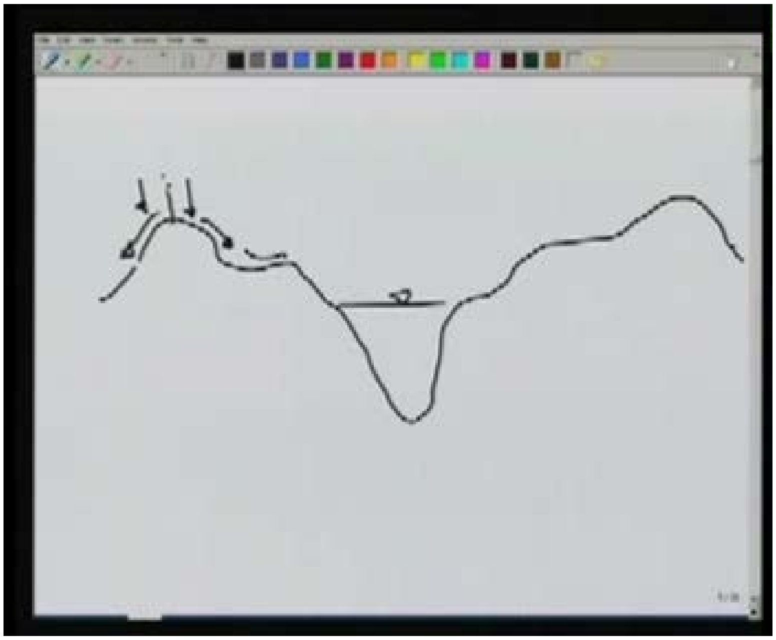

If we look at the elevation, then suppose the ground is like this and this is the river section then any water precipitation falling on this side may come to the river and a precipitation falling on this side may go out of this area. So this will be a water divide, defining the catchment area. Now how do we study the runoff in a river?

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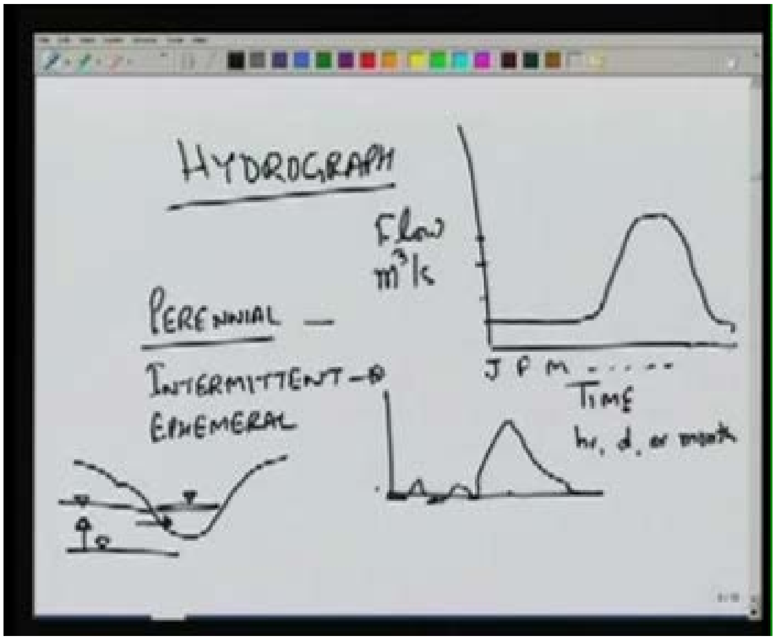

Typically what we do is plot what is known as a hydrograph, which tells us how the flow in a river or a stream varies with time. The flow typically would be in meter cube per second. The time may be in hours, days or even months depending on what scale we are talking about. If you look at the flow, let us say over the scale of a year we might say that it is a January, February, and March and so on. The flow in a river may be very small during the months of winter and until may be May. But when the monsoon arrives, the flow will increase and then again it will go down and then in January it will become very small. So this is the hydrograph of the stream and it is very important to know the hydrograph because it will tell us what is the maximum flow in the stream, what is the minimum flow in the stream and both these are very important because the maximum flow will affect the design of any flood control works. The minimum flow will affect the storage requirement or whatever water we can take out of the river on a consistent basis, it will affect that. So both these are important. What is the minimum flow? What is the maximum flow? If we look at typical streams, there may be three different kinds of streams.

One which runs throughout the year, i.e., perennial for which the hydrograph will look like this (Refer Slide Time: 11:56). Because it will run through the year and there is no part of the year where there is no flow in the river, so in this all the time there is at least some flow in the river. But the other kind of a stream is intermittent and ephemeral. They may not have flow during some part of the year. For example the intermittent stream may have a hydrograph which would look like this. So in some part of the year, there will be no flow and during most part of the year there would be some flow in the stream. In the absence of storm, when there is no precipitation falling on the area, ground water flow or the base flow are the ones which sustain the flow in the stream. So in a perennial stream the ground water level will be above the stream bed and therefore it will contribute water towards the stream ah throughout the year. But in intermittent streams the ground water level sometimes may fall below the stream bed and there will be no flow in the stream. But again during monsoons the water in the ground water level may rise and therefore it will have a continuous period of 6-7 months or so in which there will be always the flow. Contrasting behavior is observed in ephemeral streams in which there is almost 0 flow in most part of the year and there will be some isolated flows in response to storms. When there is rainfall, then there is some flow in the river and then there is no rain there will be no flow. So in these kinds of streams, the pattern of a stream is important to know in order to design storage or a flood control measure.

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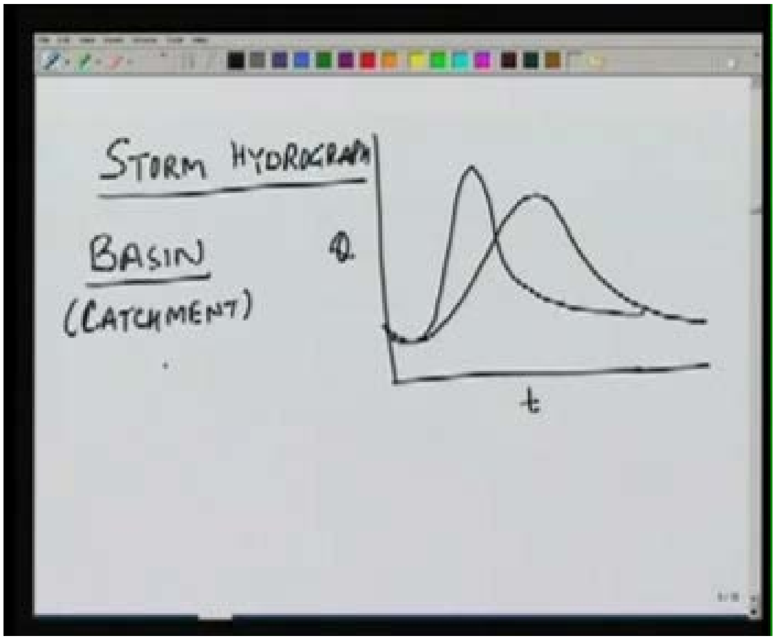

Now the runoff process or this hydrographs shifts it may have a flat peak it may have a very sharp peak the time base may be small the time base may be large this depends on a lot of factors. So next, we will see some of the factors which affect the shape of the hydrograph. We would start with a hydrograph which is of a smaller duration. So it is in response to some precipitation over the area and then we will go to the higher duration, behavior for example animal hydrograph. The hydrograph which is in response to a storm is typically called storm hydrograph or simply hydrograph. So in this uh lecture we will just use hydrograph for this term hydrographs. So let us see how the storm hydrograph shape is affected by different factors. The factors which affect the shape depend on the basin or the catchment basin and catchments that are used, they are synonymous. So some basin or catchment properties affect the shape of the hydrographs. So when a rain occurs how does the runoff change?

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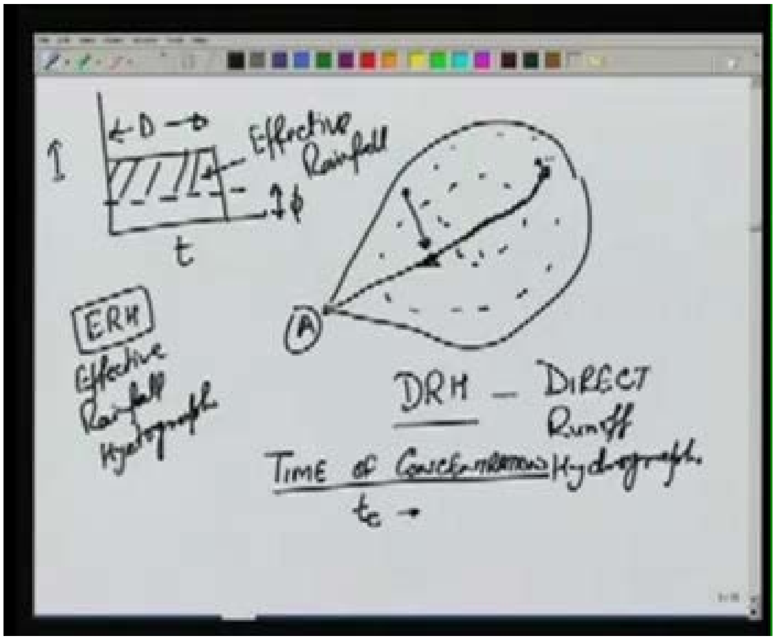

So over a certain area let us say, this is the catchment area. A river originating here and moving to the point A and now suppose there is some rain over this entire area, (we will assume that the rain is of uniform intensity), the hydrograph of the rainfall can be plotted as the intensity versus time and it may be of uniform intensity for certain duration D. Now if this intensity is less than the evaporation and infiltration from the basin, then there will be no runoff. So first it has to satisfy the evaporation, the infiltration and also depending on the presence of lakes and other small depressions, the depression storage. So some part of it will go in to satisfying the initial obstruction and we have already seen this in the chapter on infiltration that we can define an infiltration index phi which is taken out of the rain and then the effective rainfall is reduced. This hydrograph is called ERH, the effective rainfall hydrograph. So our interest is in looking for a given ERH, what will be the runoff hydrograph or DRH direct runoff hydrograph? In a hydrograph there will be some component which will have a base flow and that is not a direct result of the effective rainfall, therefore we must remove that component and then study the relation between effective rainfall and the direct runoff. So if you look at this catchment the one important factor is known as the time of concentration. Now this time of concentration typically denoted by t_c, is the maximum time it takes for a drop of water anywhere on the catchment to reach the outlet A.

Now if we look at this catchment area which does not have any tributaries, there is just one main channel and there is no tributary to this channel then a water drop falling on this point will first move over the land and then join the stream. A water drop falling here may move here and then follow the stream. Typically the velocity in the stream is much higher than the velocity over land. So what we say is that, over land flow typically moves at a smaller velocity compared to the stream flow, therefore a point which is farther from the outlet A, this point which is at a distance, is farther from the point A. It may reach A sooner then let us call this point B and this C. So a rain drop falling at B will first move over the land to the river and then it will follow the river to the point A. A rain drop falling at C will first have to travel over the land to this point on the stream and then move towards the point A in the stream. Now since the stream velocity is very high, the rain drop at B may reach A sooner than C. So it is not the distance which affects the time of concentration but it is how far it has to go over land and that how far than it will have to go to a stream. So this is the maximum time. In this case it may be a point somewhere here or here (Refer Slide Time: 21:15). So it will have to cover a lot of area over land and then will reach the stream and move to the point A. So time of concentration is an important parameter in the hydrographs. So let us now look at these factors.

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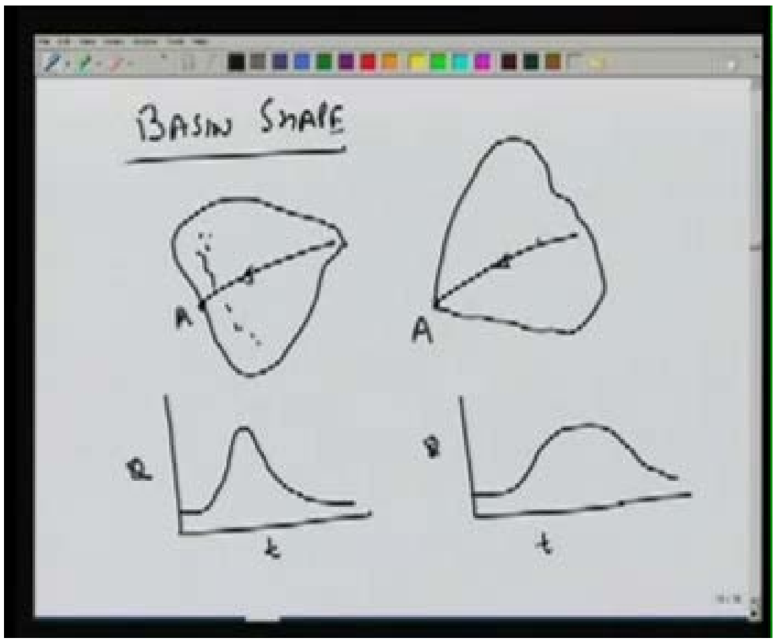

For example how does the basin shape will affect the hydrograph? Now let us look at two basins in which have everything identical. For example same length of river, same size, but the shapes of the catchment are different. So in one of them, the catchment is wider, near the outlet and narrower as we go away and in one, the catchment is narrow near the outlet and it is wider as we move away. If you look at the hydrograph, considering everything to be the same except the basin shape, we would expect the peak to come sooner. If you look at the curve, because most of the rain occurring near the outlet point will reach very fast at A and also since this area is large the peak will be higher. But in the other case, the hydrograph will be more flat because the rainfall which is occurring in the distant area would take some time to reach the point A. So the shape of the hydrograph will be affected by the shape of the basin. The next factor may be the basin size. Size of course decides the volume of rain occurring over the catchment.

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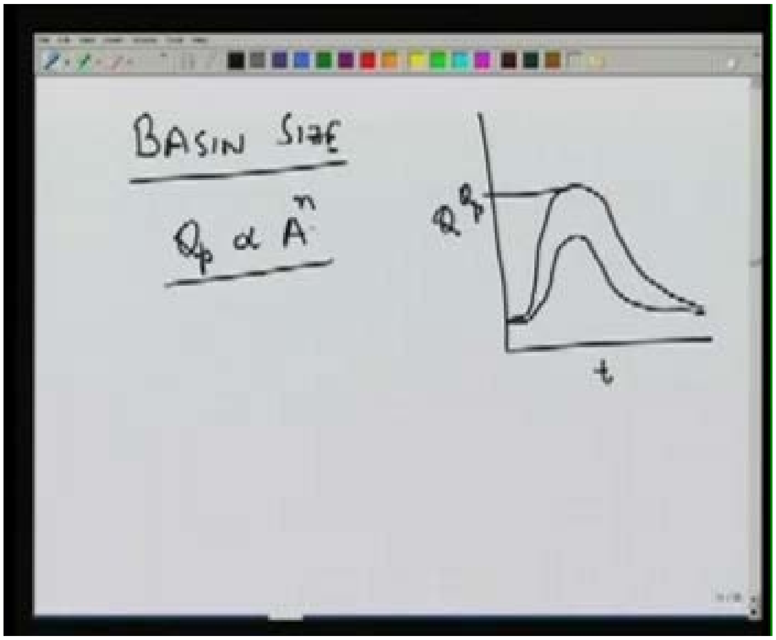

So if the size is more, the volume of rain will be more and therefore the runoff will be higher. So if you have a smaller size of catchment, the hydrograph may look like this, for a bigger size of catchment, the hydrograph may look like this (Refer Slide Time: 24:27) for the same rain because the same rain is occurring over the larger area, so it will contribute more volume to the runoff. Typically the peak flow is proportional to the basin area to some power n and n will vary from area to area. There are some typical values given in their S books for different areas in India and outside India.

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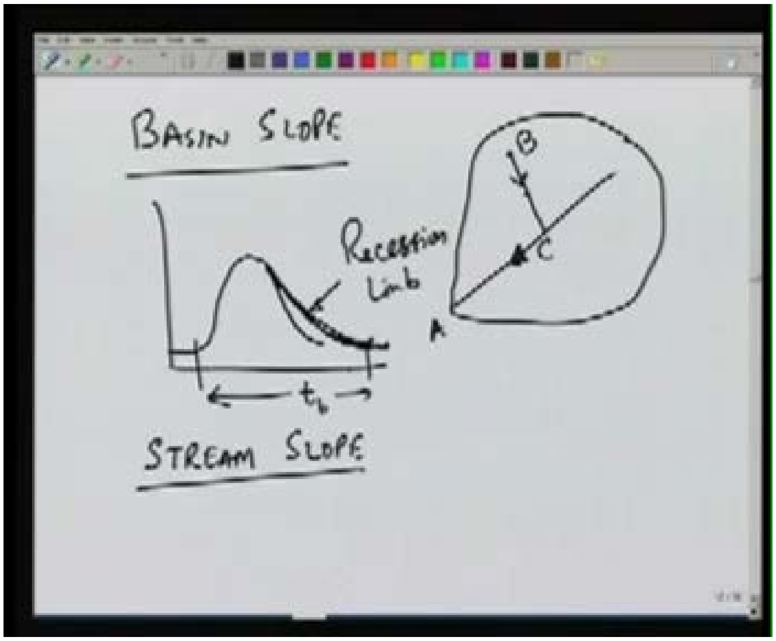
4 

The next factor we would look at is basin slope. Now basin slope will affect the time of over land flow. So if there is a channel and the catchment area. The time it takes for rain to drop or a water to travel from B to C will be dependent on the slope of the basin. Higher the slope, smaller will be the time taken in travelling from B to C. Therefore the time base of the hydrograph will depend on basin slope, typically larger slope will have a smaller t_b. Similarly the stream slope also is important because the stream slope decides the stream velocity. So higher slope again means higher velocity and therefore it will affect the falling part of the hydrograph. This part which is typically known as falling limb or recession limb denotes the water coming from the storage. It may be channel storage or it may be storage inside lakes or small depressions in the area. So this part will depend on what is the stream slope. If the stream slope is large, this part will be showing a rapid decline. If the stream slope is small it will show a flat decline. The next factor is land use.

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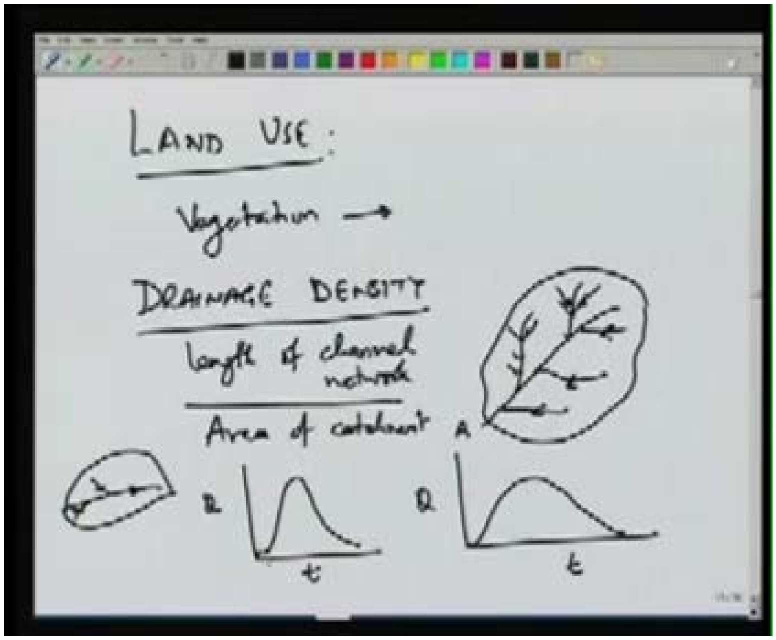

For the same rainfall, if the land is open, the soil is porous then most of the water will go inside the ground. Lot of infiltration and runoff will be smaller but if the land is paved, we have lot of roads, parking lots and other paved areas, and then there will be less infiltration and more runoffs. Similarly vegetation also affects the runoff. If there is more vegetation there will be more interception. There will be more transpiration and also the over land flow velocity will be reduced. So if there is more vegetation, typically the runoff volume will be smaller. Drainage density is another important parameter which affects the hydrograph. By drainage density we mean in the catchment area, what is the length of channel and again this is channel network which includes all the tributaries also. So if you have a tributary joining in here, and tributary joining in here, these tributaries may themselves have some smaller channels joining them. So this is the length of the entire channel network per unit area of the catchment. So divided by the area of catchment, this is known as the drainage density.

So this should also be straight forward to look at if we look at two hydrographs with different drainage density, for example this may correspond to a network which has a smaller drainage density and this may correspond to a network which has a larger drainage density. Now smaller drainage density means that most of the flow will be over land flow and higher density means that most of the flow will be through the streams. So it will reach the point A faster and the peak also would be affected by the drainage density in the area. Now when the rain occurs initially, there will be some flow because of the base flow component. So if we want to study the effect of the rain, we must separate out the base flow and the direct runoff. So let us look at the typical hydrograph and see how we can distinguish these components and separate various components.

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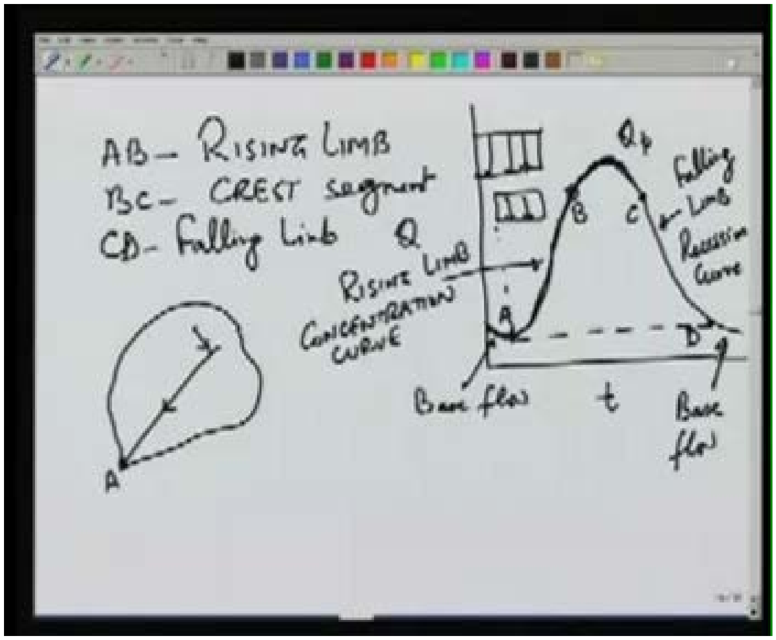

So if you look at this typical hydrographs, the rain has started and it is conventional to show the rain on the hydrograph itself. So the rain hydrograph is shown on the hydrograph itself to tell that this hydrograph is because of this rain. Now if you see from this figure, the flow in the river is decreasing even after starting of rainfall. So initially the flow in the river is base flow, the base flow will be decreasing with time because as water is taken from the ground water depending on the surrounding area and conductivity, the water level will be going down and therefore the flow in the channel will be reducing. Now once the rain occur the stream flow does not immediately start to increase because initially some part of the rain will be going into satisfying the river pollution and infiltration requirements. Let us say this is point A. At point A, the rainfall has satisfied the initial abstraction and now the runoff has started. So we call this as the start of the direct runoff. It will start increasing and will reach the peak. So this point is known as the peak point Qp. Now at Qp, we have reached a maximum flow and this will depend on the time of concentration. Suppose our rainfall is more than the time of concentration, after reaching Qp it might continue at Qp for some time and then come down but typically the rainfall is not for that long duration because the time of concentration is typically quite high and rainfall generally is for a shorter duration. So once it reaches Qp, it will not continue at that level. But it will fall down.

Now on the rising limb, this portion of the curve is called a rising limb or sometimes even concentration curve. If you look at this part, it is concave upwards at this point A and at the peak, it is convex upwards, so somewhere in the middle there is a point of inflection where the nature of the curve changes from concave to convex. Let us call this point of inflection as point B. Similarly when the rainfall has stopped and the flow is now reducing on the falling limb, which is also known as recession curve, because water is receding recession curve. So on the falling limb again the nature of curve is changing from convex upwards to concave upwards and there will be another point of inflection here where, before that the curve was convex upwards and after that was concave upwards.

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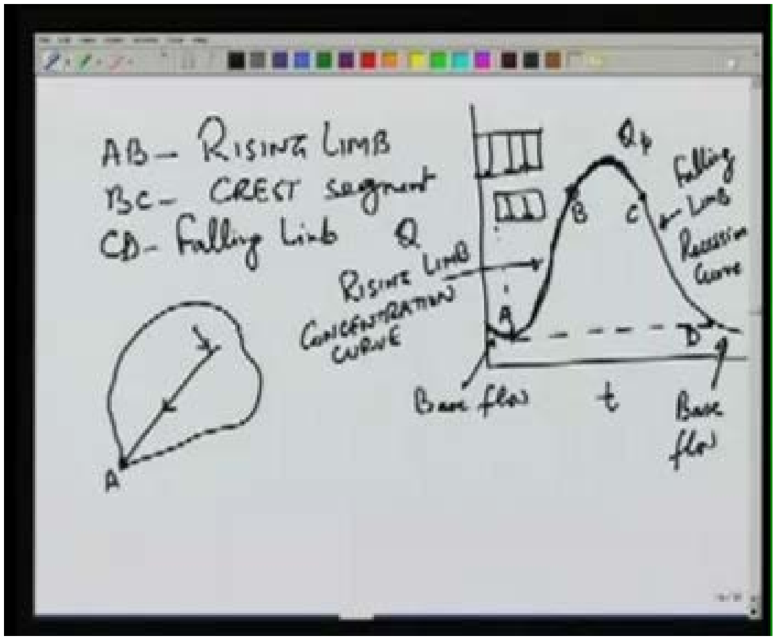

The portion from B to C includes the peak, so this BC is typically called crest segment. So AB is the rising limb, BC is the crest segment and then from C to a point D is the falling limb. The point D typically will be a point, where there will be flow. So after D we will have only base flow and there is no direct runoff beyond the point D. One method of separating the base flow is we join A and D. So the curve ABCD would be the direct runoff hydrograph DRH and also it is conventional to show not the total rainfall here, so instead of showing total rainfall, we would show only the effective rainfall and the effective rainfall would look like this. So effectively the rainfall starts at the point A because before that we say that whatever rain has occurred is not going as runoff, it is satisfying the infiltration and portion requirement of the basin and if there is some depression storage, it will satisfy the initial abstraction requirements. From the point A, the effective rain starts, it stops somewhere and the peak will occur after the stoppage of the rain, because when the rain stops, the areas which are removed from the point A, it would take some time for that water to reach the point A and therefore the runoff will continue to increase even after stoppage of rain. So let us now look at some of the methods which are used to separate the base flow.

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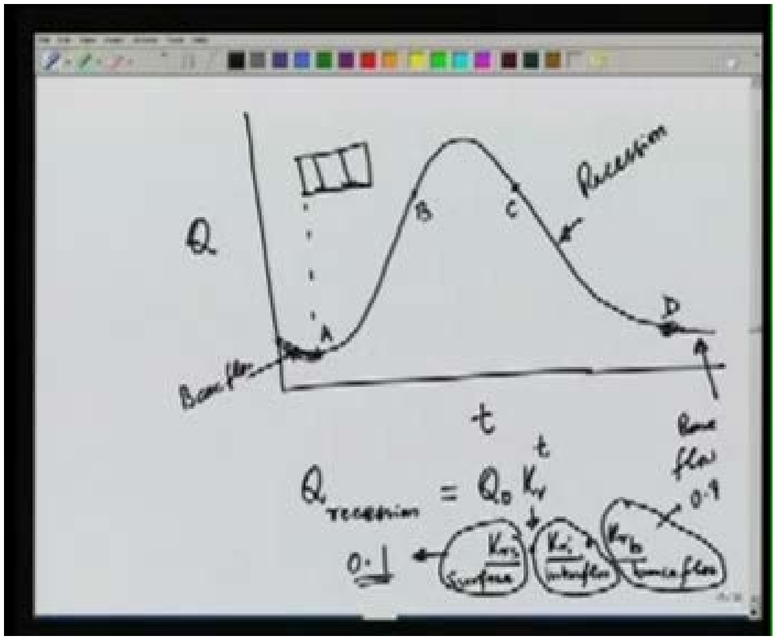

So this is the effective rainfall, point A is easy to spot because point A is the point from which the hydrograph starts rising that means our rainfall has started contributing. So let us see how to spot various points on this. We have already seen that point A it is very easy, because this is the point at which the hydrograph is starting to rise. B and C we do not need but I will just mark here, these are the points of inflection which denote change from concave to convex or in other words, the slope of this curve ah dq/dt will reach a maximum here. If you look at the slope of this curve at point A, it would be 0 at the peak. Also the slope of this curve is 0 in between the slope, is increasing. It will reach a maximum at point B and then it will start to decrease and become 0 at the peak. Point C also we do not need for base flow separation but I will show it here. The point D here is the one where we see the direct runoff has ended and beyond that we have only base flow. So before this we have base flow and beyond D also we have base flow.

The region from C to D is recession that denotes the falling or decrease in the flow with time now. This part C to D is not affected by storm characteristics because storm has already stopped. C to D denotes the decrease in channel storage or some other small depressions which may be draining. This recession limb is generally affected by three different parameters and what we say is that Q during recession is typically given by a power Q0 kr to the power t where Kr is dependant on three different kinds of factors, Krs, Kri and Krb which are for the surface stream interflow and base flow, surface interflow base flow. K denotes how fast the stream or the surface is, the discharge from the surface stream will decay, how fast the interflow is decaying and how fast the base flow is decaying. In most the basins, inter flow component may not be very large and typically Kri can be taken as one. Krs denotes how fast the water is coming out of storage from the channel and as we have seen earlier, it depends on the channel slope. If channel slope is large water will come out of it faster and base flow it depends on how the ground water contribution is decreasing. There are some typical values which are generally used for these coefficients. So Krs is typically taken as 0.1 and Krb is typically taken as 0.9, so this decreases very slowly. This decreases at a quite faster rate so this tells you about the recession length. Point D is the point at which we say that the direct runoff has ended and base flow has started ah typically whatever is the base flow at the start of the hydrograph we can use a similar pattern here or we can plot this curve on a log or semi log scale and see where the curve departs from ah this equation Q 0 Krt. So we will look at some methods which do the base flow separation.

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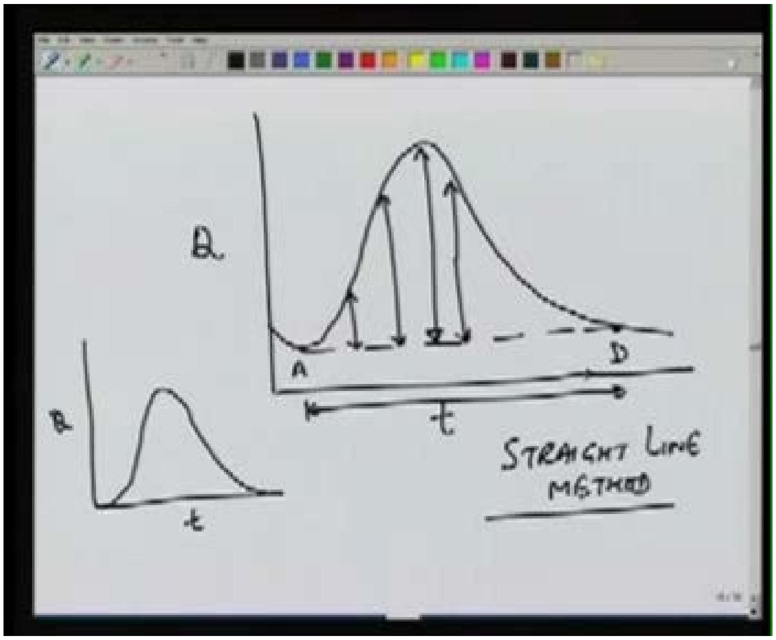

The easiest method is to join A and D with a straight line. Suppose this is the hydrograph, we say that the base flow is given by this line joining A and D and whatever area is above this line, will give the direct runoff ordinate at that time and then we can plot this direct runoff hydrograph separately, which will have a peak equal to this value and a time base which is equal to AD. Time base of course will remain same for all the methods, because we have already fixed the points A and D.

This method which is known as the straight line method is the simplest. But there are some drawbacks to this method. One is, some people say that the base flow does not remain constant throughout this period. Once this storm occurs, the ground water level will also go up and the base flow should increase. So there are different methods which can be used to improve on this.

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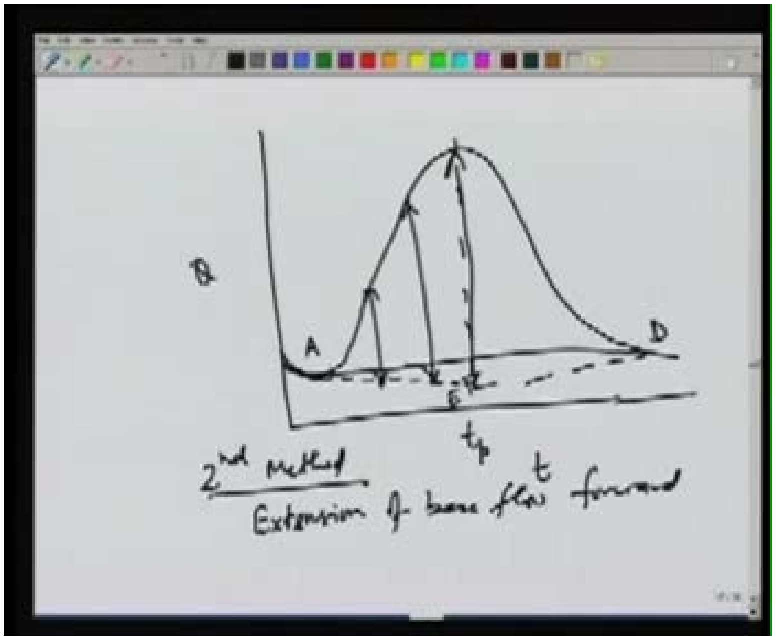

One of the methods which have been used is extending the curve on the rising limb or before the rising limb. So if you have this point A and D and this is the time of the peak, let us call this t_p then we assume that the base flow will continue to decrease beyond A till the peak of the hydrograph is reached. Let us call this point C. We have already used C, so let us call this point E and join E and D. So A E D will represent the base flow contribution and then the ordinate above this, can be taken as direct runoff. So you can see that compared to the previous straight line method which used to join A and D, this method typically gives a higher peak. So in this what we have done is extension of base flow forward from A. So this is method two in which we extend base flow forward. So from A we have extended it till the peak and then join A and D with a straight line.

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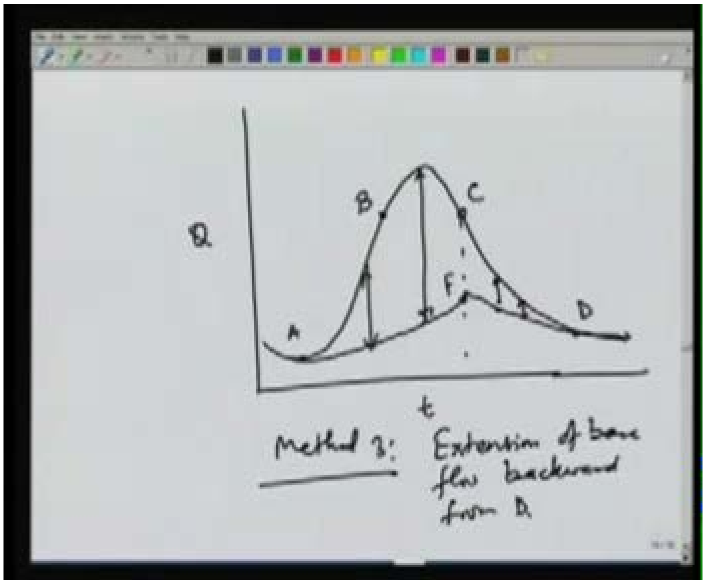

The third method is the one in which we extend the base flow backwards from D. So again let us draw the hydrograph. Find out the points A and D, these B and C are the points of inflection. So what we do in this method is extension of base flow backward from D. So we extend the base flow component, so this is going at a curve like this, so we extend it till we reach the point of inflection and then we use another smooth curve to join. Let us call this point F, so A F D will now give the base flow component and the peak. This case turns out to be smaller and these are the direct runoff components at various points. So these are the methods which can separate the base flow from the total runoff in order to give us a direct runoff hydrograph or DRH.

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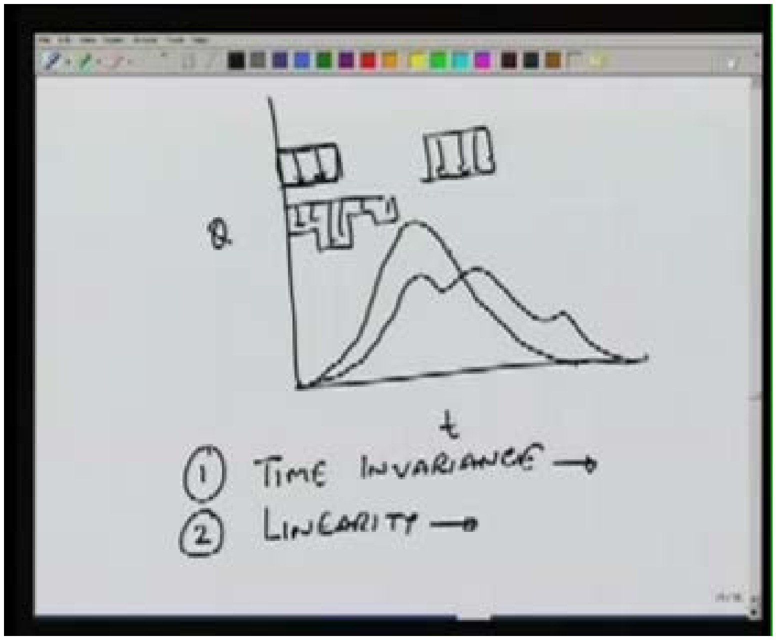

So the DRH will start from 0 because the base flow is separated, it will reach a peak and will again come back to 0 because again the base flow is separated. So there is only direct runoff component after this point. Beyond this we have base flow in the river but we are not showing it and the corresponding hydrograph can be shown like this. So this is a very simple description of the hydrograph for uniform rain occurring over the catchment. If the rain is not uniform sometimes the hydrograph may look like this (Refer Slide Time: 49:34). In that case the hydrograph may have a very different shape, it may go like this.

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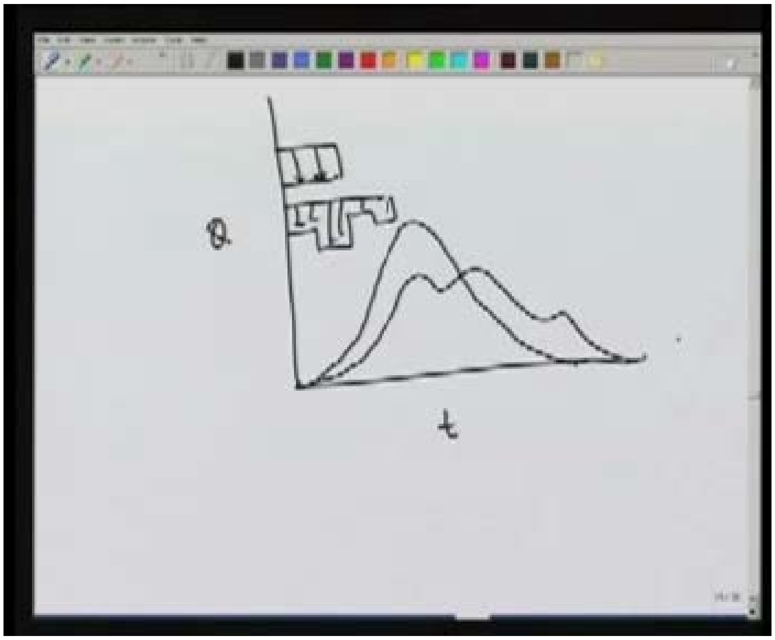

So for a complex storm in which various intensities of rain occur for different times, the shape of the hydrograph will be very different. But if we assume, there are two assumptions. If we make them then it makes the analysis much easier and those assumptions are called time invariance and linearity. In general rainfall runoff relationship is very complex. If we have two different catchments, the same rainfall will cause two different or very different hydrographs or for the same catchment if we have two different kinds of rainfalls they will also cause very different hydrographs. Sometimes even for the same catchment and same rainfall we may get different hydrographs. It depends on what the starting initial condition is. For example if the soil is very dry, rainfall occurs. Lot of it will go into infiltration and runoff will be smaller. For the same rainfall if the soil is wet initially, for example if there is a rain before that day, soil will be wet. So if the soil is wet there will be more runoff, so not even catchment to catchment but even from event to event one rainfall to other rainfall event, the hydrograph will be different. So it is very difficult to theoretically analyze this unless we make some assumptions. So these two assumptions, time invariance and linearity help us in analyzing the hydrograph and to estimate what would be the runoff for a very complex rain. So time invariance means that with time the hydrographs are not changed. If the same rainfall occurs no matter whether it is occurring at time t equal to 0, like this or if it is occurring at time t equal to 3 days, it will produce identical hydrograph of course it has to be shifted.

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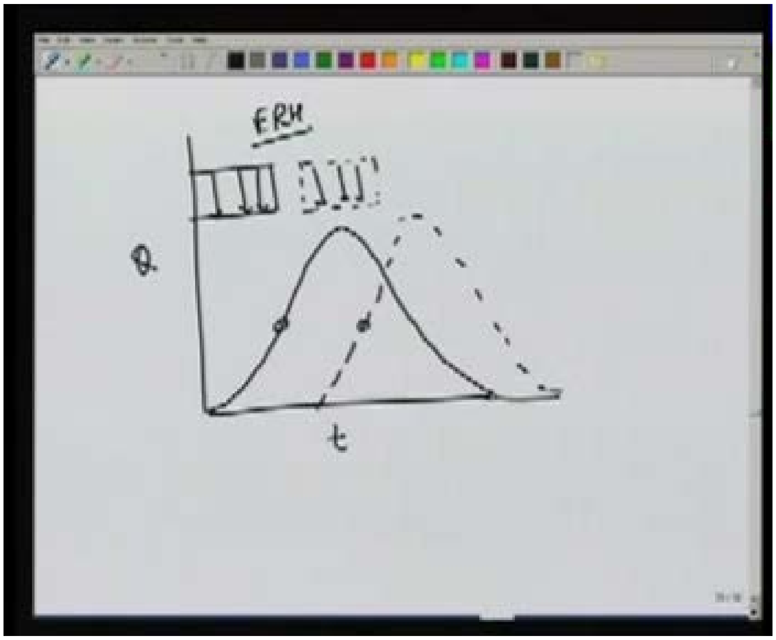

So let us look at t versus Q. So if there is rain occurring here and we are generating the hydrograph, direct runoff hydrograph like this and suppose we have another rain occurring let us say starting from this point, same intensity, same duration then the hydrograph for the second rainfall event, second storm would be exactly same as the first one. Only the base will be shifted like this. So these two hydrographs will be the same if the effective rainfall hydrographs ERH is same. So that is the principle of time invariance, no matter where in time, the effective rainfall occurs it will produce an identical hydrograph.

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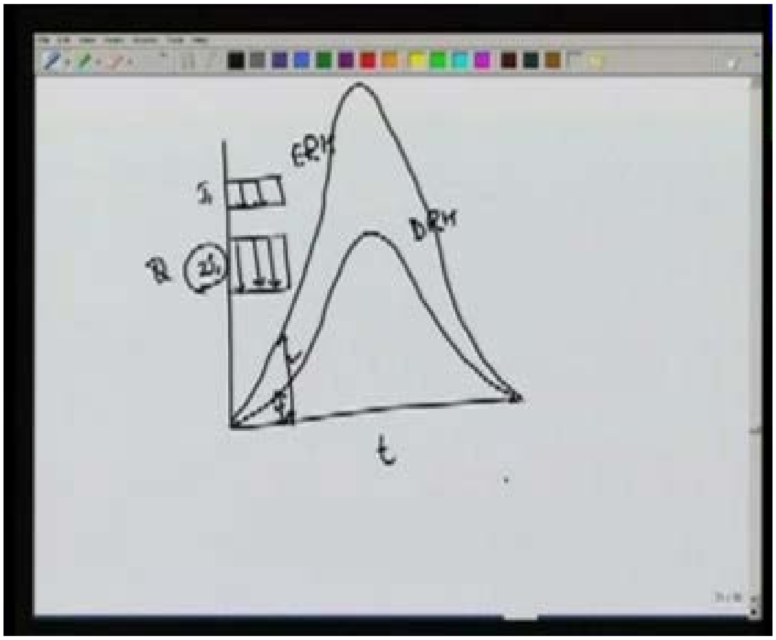

The second principle which we have is the principle of linearity which says that if some ERH causes a DRH, this DRH direct runoff hydrograph is for this effective rainfall hydrograph. If the same durational rain occurs with a larger intensity, suppose this is intensity I_1 and there is another one let us say within these $2I_1$. The principle of linearity says that the ordinate of direct runoff hydrograph because of the second rain where the intensity is $2I_1$ will be exactly twice the ordinate of the first one. So everywhere if you take the ordinates, this ordinate will be twice this ordinate, if the rainfall intensity is twice. So the principle of linearity and time invariance help us in analyzing lots of different kinds of storm patterns in order to arrive at corresponding DRH.

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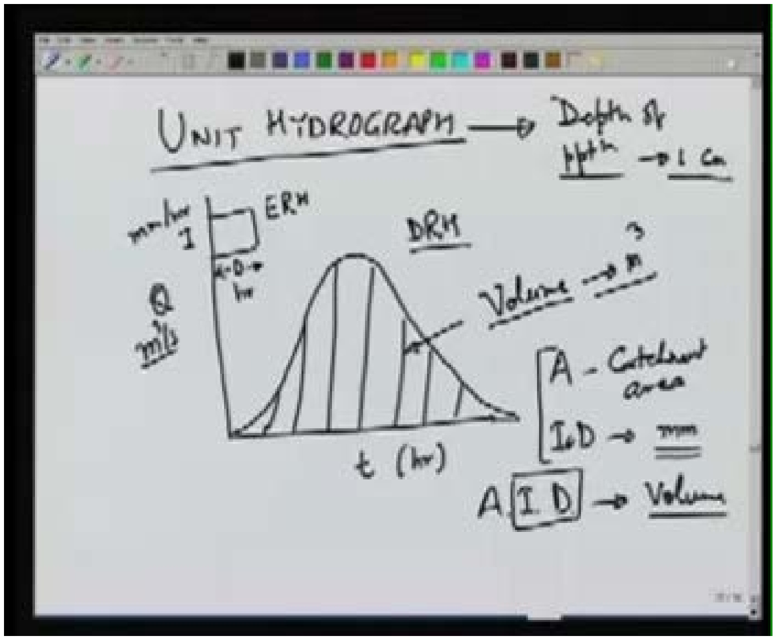

One of the most important theories which are used is known as the unit hydrograph theory. So this unit hydrograph theory creates a hydrograph for a unit rainfall and then using the principles of time invariance and linearity, it tries to estimate for any other kind of rainfall pattern, what would be the direct runoff hydrograph. So before we discuss unit hydrograph, let us look at DRH and look at the area under this curve because this will help us in finding out or deriving the unit hydrograph. This Q is in meter cube per second and t is in hours. For area of this curve would give us some volume V. If we take both of them in same unit like meter cube per second, the area will come out to be in meter cube. If they are in different units, meter cube per second and hours then we have to accordingly multiply it with a constant to get the volume in meter cube. So this volume would be let us say, we have obtained this volume in meter cube. So what does this volume indicate?

This DRH is because of some ERH which has intensity I and duration D. What we have said earlier is that this rainfall ERH is occurring uniformly over the entire catchment area. So if the catchment area is A and the rainfall intensity is I, duration is D, I into D will give us, suppose this I is in millimeter per hour and D is in hours then I in to D will give us amount of rain in millimeter units. Now this is occurring uniformly over the whole catchment area. So if we multiply A into I into D, we would get a volume and since this DRH is a result of this ERH these two volumes should be same. So this I into D is the amount of rain which is falling in terms of depth. This is the depth of rain falling over the whole catchment area and this will be different for different duration and different intensities. So when we talk about unit hydrograph we say that we normalize the depth of rain to a unit quantity. So the depth of rain should be the unit. Let us call it depth of precipitation. The unit which is used typically in India is 1 cm. In some countries depth of the precipitation is taken as 1 inch for the unit hydrograph, but we will take 1cm as the unit rainfall. So what it means is that if we have 1 cm of depth falling over the catchment in let us say D hours, then the direct runoff hydrograph which results from direct rain will be called a unit hydrograph for D hours. So let us take an example.

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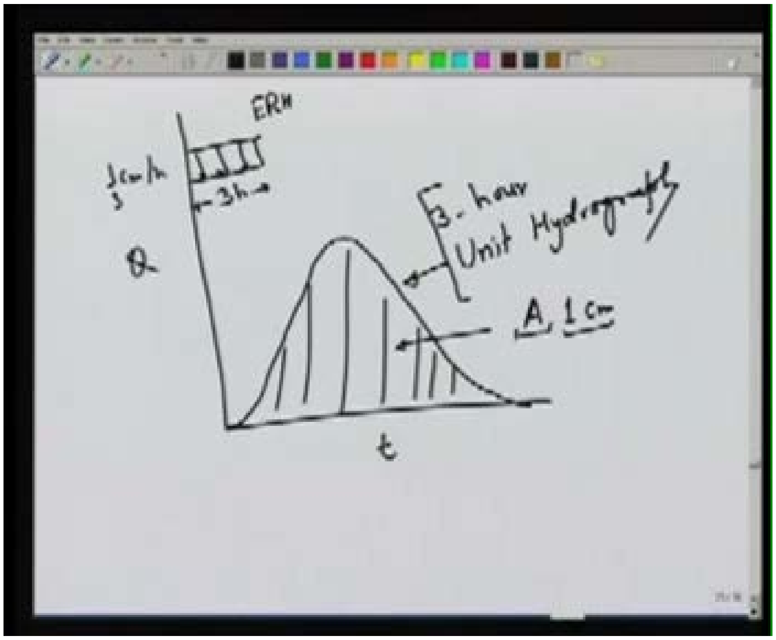

t, Q and let us say we have a rain falling for 3 hours then it’s intensity must be 1 over 3 cm per hour, so that the total depth of effective rainfall is 1 cm. Now because of this ERH whatever DRH we get, would be called a unit hydrograph. Since duration is very important, 3 hours is called as 3 hour unit hydrograph. Similarly if we have rain which is falling for 2 hours intensity will be 1 by 2 centimeter per hour and the resulting hydrograph would be called a 2 hour unit hydrograph. The area under the unit hydrograph represents A, the catchment area into 1 cm.