Engineering Hydrology

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Lecture – 54

Hydrograph Analysis-UH

Hello all, welcome back. In the previous two lectures, we were discussing about hydrologic system for the purpose of hydrologic analysis. We have discussed about general hydrologic system model, which is considered as a linear model. So, if you are analyzing the hydrologic system, considering it as a linear system, we need to have an understanding about linear system theory. So, that we have discussed in the previous lecture. If we are considering the hydrologic system as a linear system, then the system will be following the principles put forward by linear system theory. So, that way we have gone through two different principles, which a linear system should follow that is principle of proportionality and principle of superposition. After that we have gone through three different input functions and the corresponding response function that is the impulse input, step input and the pulse input.

What is meant by these three inputs we have studied, after that the corresponding outputs or the responses from the system that is the impulse response function, step response function and also the pulse response function these we have discussed in detail. We also understood the relationships between these three response functions.

Today, let us move on to the topic of hydrograph analysis in which we are going to consider hydrologic system as a linear system. So, definitely in this analysis, we will be following linear system theory, that is why we have gone through the basics of linear system theory in the previous lecture.

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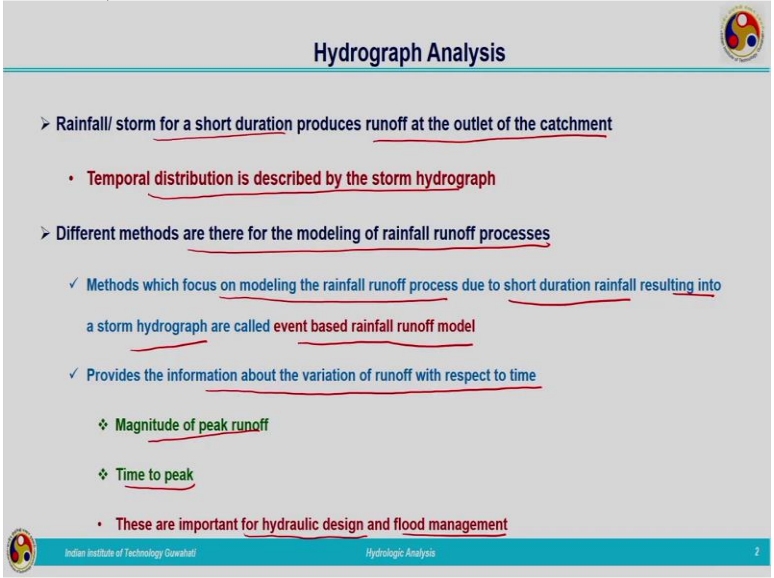

Now, let us start with today's lecture. So, we know when rainfall or storm for a short duration occurs on a catchment, it produces a runoff at the outlet of the catchment. So, we are going to consider a storm which is occurred for a certain time duration, we are not talking about the total amount of rainfall, we are going to consider a storm which is having a particular duration. If the rainfall intensity is more than that of the infiltration rate, and it prolongs for some time definitely there will be a runoff taking place at the outlet of the catchment. So, here when we are discussing about the rainfall, we are going to consider rainfall having certain duration. So, definitely it will be producing a runoff at the outlet and the temporal distribution of the runoff we have studied by means of storm hydrograph. In the previous module, we have discussed about storm hydrograph in which runoff of the streamflow is plotted against time that is known as the storm hydrograph.

Different components of the hydrograph also we have covered in that lecture. So, temporal distribution of the runoff or streamflow is represented by means of storm hydrograph. Different ways of estimating direct runoff we have seen, in all those cases either the runoff depth or the runoff volume we have calculated. In those cases, we were not representing the time distribution of the streamflow or runoff. But in the case of storm hydrograph we are considering the time distribution of runoff that is very much important when we were planning about some hydrologic project. So, different methods are there for modeling rainfall runoff processes, some of the methods focused on modeling the rainfall runoff process due to short duration rainfall resulting into a storm hydrograph that is known as event-based rainfall runoff model, that is we are going to consider a rainfall event, that event will be of severe event, depending on the severity of the storm, we will be choosing a particular rainfall event and based on that we will be understanding the impact of that particular event on the water resources system. So, in such cases we are studying the runoff which is produced due to this storm. So, a particular event is chosen and the impact of that is studied. So, those type of studies are termed as event-based rainfall runoff models. Especially in the case of flooding related studies, we need to look into event-based rainfall runoff models. In such cases we will be choosing a particular rainfall event which is having a certain duration which may be a severe event that event will be chosen for modeling the runoff. So, such modeling studies are termed as event-based rainfall runoff model. This provides the information about the variation of runoff with respect to time. Variation of runoff with respect to time means we can get from the beginning of the storm till the time entire catchment contributes water to the outlet point we will get the results related to runoff. So, we can understand the magnitude of peak runoff, we can understand the time to peak all these matters a lot whenever we are going to study a particular flood event. So, in such cases we will be choosing an event rainfall event which is having certain duration and event-based rainfall runoff modeling will be carried out to understand the peak runoff and also time to peak. These are very important for hydraulic design and flood management. If you are planning for certain flood management strategies, we need to have the idea about time to peak flood and also magnitude of the peak runoff. Based on that for different areas different types of flood management strategies need to be proposed. So, for that we need to have an accurate rainfall runoff model based on events, we will be going for choosing event-based rainfall runoff models in such cases.

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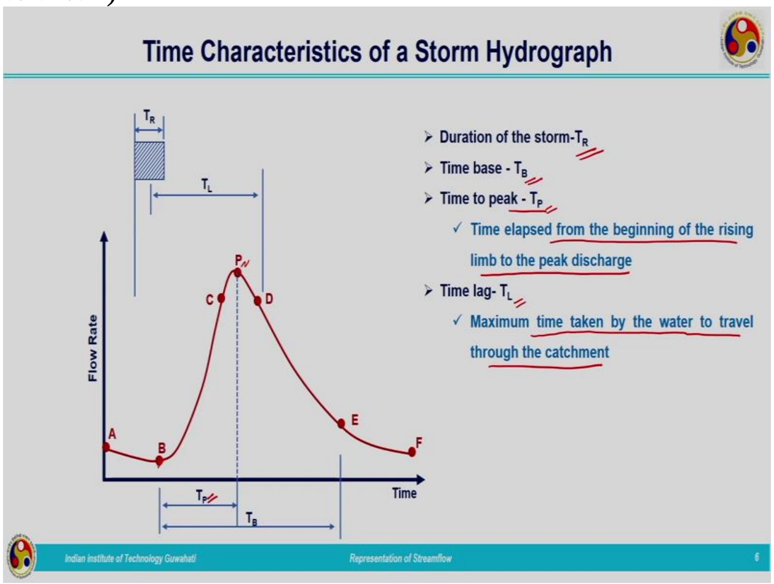

We were discussing about the time to peak runoff and the magnitude of peak runoff. So, we need to have some idea about time characteristics of storm hydrograph. So, for that we are first considering a rainfall event. The event is chosen in such a way that it is an isolated event which is having a certain duration. Rainfall will be occurring for long time, continuously it is occurring. So, entire period what is the rainfall we are not looking into we are choosing certain, event rainfall event or storm event for a particular duration. A simple event which is having a uniform magnitude is shown here, this is representing a rainfall hyetograph which is having a duration of T_R because of this rainfall, which is having a duration T_R there will be a runoff at the outlet. So, that can be obtained by means of some streamflow measurement that can be plotted as a storm hydrograph. So, duration of the storm which we are considering this T_R and this is the storm hydrograph. This figure we have already seen before while explaining about the characteristics of storm hydrograph.

So, here the same hydrograph is used for the explanation of time characteristics of storm hydrograph. This is a smooth curve. Actually, what is this hydrograph? Hydrograph is the curve representing the time distribution of runoff at the outlet of the catchment. The flow contributed by the catchment at the outlet is measured and plotted. So, depending on the type of the catchment, the outflow which is occurring at the outlet of the catchment will be different. It may not be always a smooth curve as shown in this figure. It will be having certain fluctuations present because different areas will be contributing runoff at different times. So, after certain time of the occurrence of the rainfall majority of the areas will be contributing water at the outlet point. So, because of that the hydrograph will not be a smooth curve certain fluctuation will be present there. But for understanding purpose we can consider a smooth hydrograph like this. So, in this we have studied different components AB and EF represents the baseflow recession, that is AB is the part of the hydrograph which is the contribution coming from the baseflow, it is not due to the rainfall. So, that is the contribution from the baseflow and that is represented by AB. When the hydrograph is rising that is representing the rising curve where the contribution from the storm has started. So, here BC is the rising curve and CPD is the crest. Crest represents the part of the flow or during that time majority of the catchment starts contributing to the runoff and it consists of the peak also. Peak of the hydrograph is also present in this particular area. After that what will happen, when it reaches the point D, point D is representing the point of inflection which is corresponding to the maximum storage, all the storage components are satisfied. After that the contribution from runoff to the channel or the overland flow might have ceased and withdrawal from the storage components will be taking place and that is the beginning of the recession curve and once it reaches E entire runoff component is stopped and EF represents the contribution from the baseflow. So, this is the storm hydrograph which we have seen in the previous module.

So, here we are going to understand the time characteristics of the storm hydrograph. So, T_R is the duration of the storm which is caused runoff at the outlet because of that storm event how much is the runoff produced along with the baseflow is plotted over here as a storm hydrograph. So, this is the time base of the hydrograph. Time base means, we know there is some contribution coming from the baseflow, groundwater contribution to the stream, that we are deducting and the remaining hydrograph which we are obtaining will be having a time base that is represented by the time base T_B of the hydrograph, that is from where the runoff starts and runoff ends within that time that base period of the hydrograph is the time base.

So, next is the time to peak, time to peak is nothing but the time elapse between the peak runoff and the beginning of the runoff. This point B is representing the beginning of the runoff and the time base between the beginning of the runoff to the peak runoff, peak of the hydrograph is representing time to peak. T_P is the time elapsed between the beginning of the runoff to the peak runoff, that is the time elapsed from the beginning of the rising limb to the peak discharge, that is what we have marked over here.

Next is the time lag, time lag is the maximum time taken by the water to travel through the catchment. So, we have studied about time of concentration, it is the time taken by the water droplet to travel from the remotest point to the outlet point. So, it is similar to that of time of concentration, it is not exactly the time of concentration. So, it is the maximum time taken by water to travel to reach the outlet of the catchment. Actually, this is calculated based on the time elapsed between the centroid of the hyetograph to the centroid of the storm hydrograph. But it is not that easy to find out the centroid of the storm hydrograph. Then what we will be doing? We will be finding out the peak of runoff when it is occurring that time minus the centroidal time of the hyetograph. So, this time will be determined by considering the centroid of the hyetograph and the point where all the catchment contributes water at the outlet. That is the point of inflection D. All the storage components will be satisfied at that time, it represents the maximum storage that is the point of inflection. So, we will find out the time elapsed between the centroid of the hyetograph and the point of inflection. So, this is represented by T_L time lag. Again, I am repeating it is the time elapsed between this centroid of the hyetograph and the centroid of the storm hydrograph. Since it is difficult to determine the centroid of the storm hydrograph we will consider the point of inflection where all the storage components are satisfied, that point is representing the maximum storage and the time elapsed between the point of inflection and the centroid of the hyetograph is considered and that represents the time lag. So, these are the four important characteristics related to time whenever we talk about storm hydrograph. First one is the duration of the storm T_R, second one is time base, the time represented by the base of the direct runoff hydrograph. Time to peak T_P and time lag T_L. So, you should carefully understand the difference between all these T_R is not an issue it is the duration of the storm and time base is also very clear, time to peak is the time from the beginning of the recession limb to the peak runoff. Then slightly complicated definition is related to time lag, it is nothing but the time elapsed between the centroid of the effective rainfall hyetograph to the point of inflection. For that you need to understand point of inflection carefully. Point of inflection is representing the time at which the maximum storage just reached or all the storage components are satisfied within the catchment. After that what will happen, the contribution from overland flow will be seized and withdrawal of water from storage components will be taking place.

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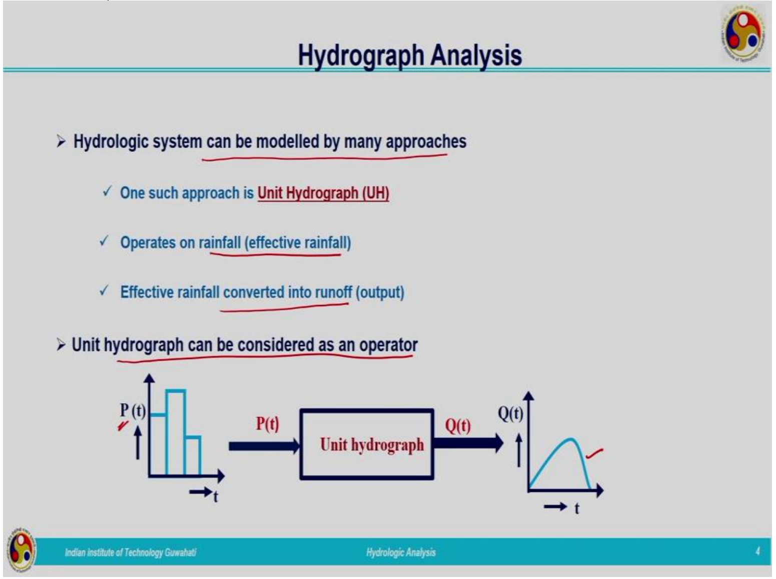

Now, let us move on to hydrograph analysis. Hydrologic analysis we will be doing by making use of the principles of hydrograph. Mainly I am focusing on the hydrograph analysis. Hydrologic system can be modeled by means of many approaches. So, many different techniques are there for modeling a hydrologic system. Out of that unit hydrograph approach is one method. So, here in this module, we will be discussing about the unit hydrograph approach which can be used for rainfall runoff modeling.

In this, the rainfall that is we will be considering the effective rainfall, effective rainfall is the rainfall which is obtained after deducting the initial abstractions and the infiltration which is contributing towards the runoff or the overland flow that is the effective rainfall. That we will be extracting from the total rainfall. That will be acted on the watershed and it will get translated to runoff at the outlet of the catchment. That is termed as the direct runoff, that is effective rainfall gets translated to direct runoff at the outlet of the catchment. So, unit hydrograph can be considered as an operator, that is we have seen in the previous lecture that if you are considering a system there is a transfer function which translates the input to the output. So, that transfer function in this case is the unit hydrograph. It is the operator. We are having the effective rainfall this *P(t)* is representing the effective rainfall after deducting the abstractions which is acted on the catchment. Here the transfer function is the unit hydrograph, it will be converting the input *P(t)* to *Q(t)*. The effective rainfall is converted to direct runoff hydrograph. *Q(t)* is representing the direct runoff hydrograph. So, now, let us look into unit hydrograph what is meant by unit hydrograph.

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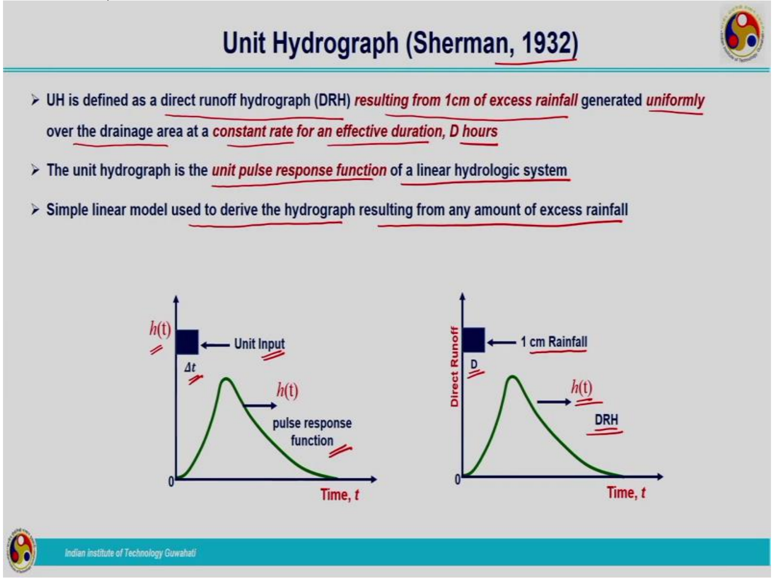

The principle of unit hydrograph is proposed by Sherman in the year of 1932. This is a very simple model which is working based on the linear system theory which produces the direct runoff at the outlet of the catchment by making use of linear system principles more or less accurately. Even though the catchment is not behaving as a linear system, we are assuming that the catchment can be considered as a linear system, because we know the processes which are taking place within a catchment is not linear, very complex, very dynamic which has to be represented by means of nonlinear equations, but here the main assumption which we are making is system behaves as a linear system. First let us start with the definition of unit hydrograph. Unit hydrograph is defined as a direct runoff of hydrograph resulting from 1 centimeter of excess rainfall generated uniformly over the drainage area at a constant rate for an effective duration *D* hour. So, this is the definition of the unit hydrograph. Unit hydrograph is that direct runoff hydrograph produced from a 1-centimeter rainfall which is occurring uniformly over the catchment or the drainage area for an effective duration or for a specific duration D hour. What do you understand by this definition? That is the catchment is experiencing 1-centimeter rainfall, the duration of the rainfall is considered as *D* hours. For *D* hours it can be 1 hour, 2 hours, 3 hours anyway whatever it is. So, for *D* hours we are having a uniform rainfall having a depth 1 centimeter which is acted upon the catchment uniformly, entire catchment is experiencing 1-centimeter rainfall for a duration of *D* hours and the runoff produced by this rainfall, that is D hour 1-centimeter rainfall is producing a runoff at the outlet of the catchment that is what is termed as the unit hydrograph. That runoff which is produced at the outlet of the catchment is the direct runoff. That direct runoff hydrograph produced due to 1 centimeter of rainfall for *D* hours which is uniformly experienced by the catchment.

In the previous lecture, when we were discussing about different inputs to a linear system, we have seen three different inputs: that is impulse input, pulse input, step input. Impulse input was the input which is acted upon the system instantaneously and the step input was the input which is applied on the system in which the rate changes from 0 to 1 at time *t* is equal to 0 and it continues indefinitely. The third one was the pulse input; unit pulse input is defined as the input which is acted on the system for a duration of Δt. Can you compare this 1-centimeter rainfall for *D* hours with that pulse input? There in that case, 1 unit of input whatever be the system whether it is hydrologic system or any other system, 1 unit of input for a specific duration Δt was acted upon the linear system, which is producing an output which is termed as unit pulse response function. Here also the DRH which is produced due to 1 centimeter of effective rainfall uniformly acted upon the catchment for a specific duration of *D* hours, these two can be compared to each other. So, this unit hydrograph is the unit pulse response function of a linear hydrologic system. In the general way, we have discussed the unit pulse input is producing unit pulse response function. Here our system is the hydrologic system, so, this unit hydrograph is nothing but unit pulse response function of a linear hydrologic system. So, this is a simple model used to derive hydrograph resulting from any amount of excess rainfall. Since this is developed based on the linear system theory, we can make use of principle of proportionality or principle of superposition for finding out the hydrograph from any amount of rainfall. We can schematically visualize that. So, this is the figure which we have seen while explaining about the pulse response function, we were having a unit input, pulse input for a duration of Δt. The response produced was represented by *h(t)* that is nothing but the pulse response function. Here you can compare it with the unit hydrograph concept that is we are having 1-centimeter rainfall for a duration of *D* hours which is uniformly applied over the drainage area for a duration of *D* hours, 1-centimeter rainfall for a duration of *D* hours uniformly applied over the catchment or the drainage area. So, same way here we can consider for *D* hour duration, 1 centimeter of rainfall it can be considered as a pulse input and that will be producing an output. Here in this case, it is the direct runoff because we are considering the effective rainfall of 1 centimeter for a duration of *D* hours. So, it will be definitely producing the direct runoff at the outlet. So, that is represented by our DRH which is represented by *h(t)*. This green curve is representing the direct runoff hydrograph. So, this is exactly same as that of the pulse response function which we have seen by explaining the linear system theory. So, for understanding this, we have gone through the linear system theory in detail in the previous lecture. Now, we need to understand the assumptions made in the hydrograph theory.

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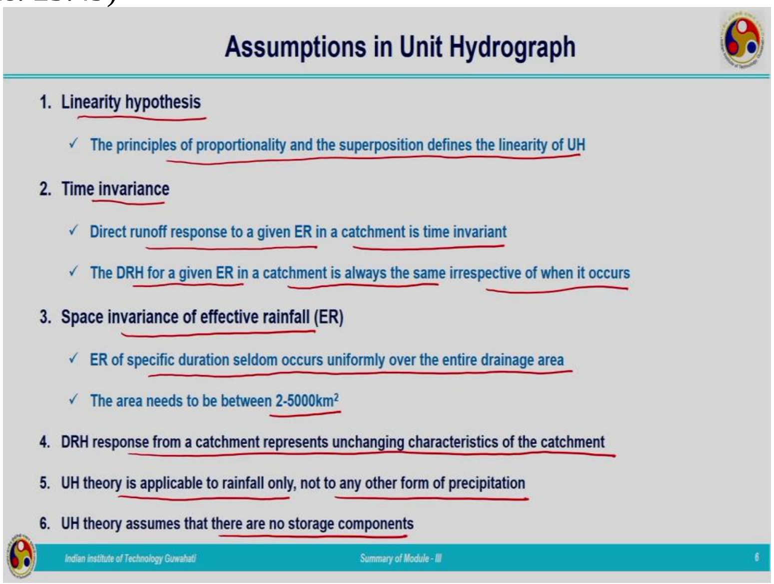

First one is linearity hypothesis. Catchment if we are assuming it as a linear system, it should behave as a linear system actually it is not linear. For example, if you are having so many storage components present in the catchment, then system cannot behave as a linear system because initially the storage components have to be satisfied after that only runoff will be produced at the outlet. So, if you are assuming the processes to behave as linearly or the system as a linear system, then it will not happen, it will not be similar to that of the actual hydrologic system, it is not representing the complex dynamic process which is taking place in the actual hydrologic system. So, this is an important assumption, which is different from the reality. Since the linearity hypothesis is assumed, the principles of proportionality and superposition defines the linearity of the unit hydrograph.

Second one is the time invariance. Time invariance means direct runoff response to a given effective rainfall in a catchment is time invariant. What does it mean? what is meant by this time invariance? That is the direct runoff hydrograph for a given effective rainfall in a catchment is always the same irrespective of when it occurs. We are having a unit hydrograph produced from 1-centimeter effective rainfall which is having a duration of D hours, by making use of that unit hydrograph we are producing the direct runoff for a certain input of rainfall, that direct runoff hydrograph is the same all throughout the season. It is not going to change irrespective of the occurrence of the storm any time the storm is occurring, if you are making use of 2-centimeter storm, 3-centimeter storm, it can occur any time, there is no change observed in the direct runoff hydrograph.

Next is the space in variance of effective rainfall, that is we have assumed that the effective rainfall is uniformly applied on the drainage basin, that is also an ideal condition. In a catchment everywhere uniformly one rainfall is occurring is not the actual practice, this is an assumption for development of unit hydrograph. Effective rainfall of specific duration seldom occurs uniformly over the entire drainage area. So, for this there are certain restrictions related to the area, the area should be between 2 to 5000 kilometers square, the area should not be beyond 5000-kilometer square. Even 5000 kilometers square is a very large area for this type of assumption to be made. Ideally, we cannot assume that the rainfall is uniformly acting on the catchment.

Now, the next assumption is DRH response from a catchment represents unchanging characteristics of the catchment. Once a unit hydrograph is developed for a particular catchment, later on we are making use of that unit hydrograph for the development of direct runoff hydrograph, we are not taking into account of the changes which are taken place in the catchment. Hydrograph is having the influence of catchment characteristics, while explaining the factors influencing hydrograph we have seen one important factor is the catchment characteristics, there may be some urbanization taken place, there may be some construction of reservoir, or some other hydraulic structure might have constructed, some storage components might have created. So, all these will be affecting the unit hydrograph. So, without updating the unit hydrograph if we are using that for the same catchment, it is not representing the changing characteristics which has taken place in the catchment. So, we need to update the unit hydrograph in order to incorporate the changes taken place in the catchment.

Unit hydrograph theory is applicable to rainfall only not only any other form of precipitation This is a limitation, unit hydrograph theory is applicable to rainfall. Different types of precipitation we have studied, but this method is applicable to rainfall only. It is not applicable to snow or any other form of precipitation and it assumes that there are no storage components. This I have already explained while explaining the linearity hypothesis. For linearity hypothesis need to be accurate, there should not be any storage components present. Storage components are present in the catchments means that needs to be satisfied initially before starting the runoff. So, here we are assuming the effective rainfall runoff relationship to be linear. So, if the catchment is having so many storage components, it will be against the assumption of linearity principle. So, these assumptions should be very clear to you, that is first one is the linearity hypothesis, second one is time invariance then comes the space invariance of effective rainfall and other limitations and assumptions we have seen here in this slide. So, these assumptions and approximations behind this unit hydrograph theory is very important. This should be understood very carefully before applying it to a particular rainfall runoff modeling.

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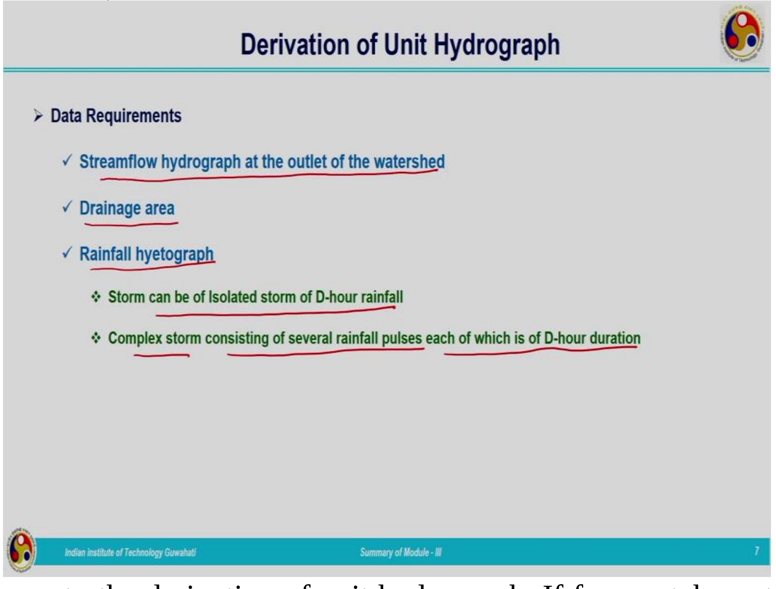

Now, let us move on to the derivation of unit hydrograph. If for a catchment unit hydrograph is available to you, you can carry out the event-based rainfall runoff modeling. So, first we need to derive the unit hydrograph for a particular catchment. So, what are the data requirements for that? That is, we need to have the streamflow hydrograph at the outlet of the watershed, then drainage area, then rainfall hyetograph and storm can be of isolated storm of *D* hour duration, if we are considering an isolated storm of *D* hour duration there should not be any rainfall before this *D* hour rainfall and after this *D* hour rainfall. For a duration of *D* hours, we are having a uniform rainfall that we are considering as the effective rainfall and in that case, there should not be any rainfall before and after this that is the isolated storm of *D* hours.

Second type is complex storm consisting of several rainfall pulses, each of which is of *D* hour durations. Considering a *D* hour isolated rainfall is very difficult. So, what we can do, we can consider a complex storm also, but this complex storm should be selected in such a way that it is consisting of different pulses having *D* hour duration without any gap. So, it should be continuous event and each pulse can be considered for *D* hour duration. So, this much of data can be utilized for the derivation of unit hydrograph. First let us see the derivation of unit hydrograph based on isolated storm of *D* hours.

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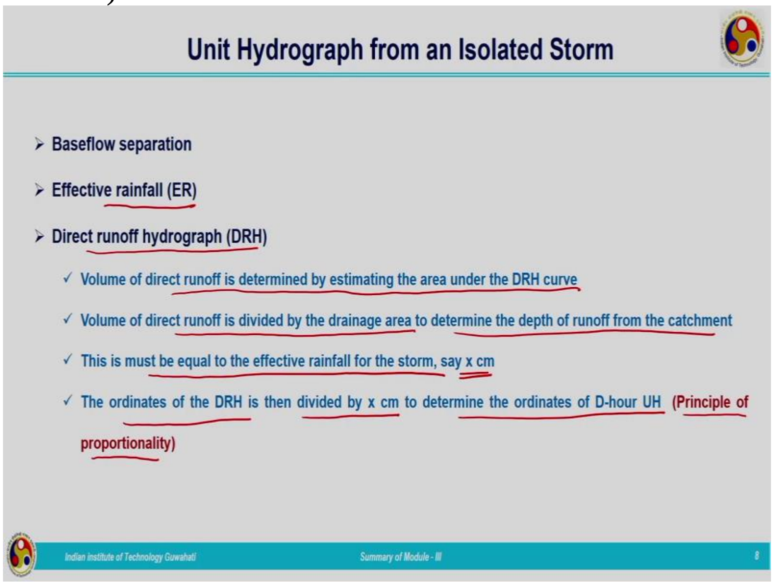

When we are deriving the unit hydrograph baseflow separation we need to carry out, because the storm hydrograph which is produced at the outlet of the catchment is inclusive of the baseflow. But here we are going to study rainfall runoff process i.e., because of certain effective rainfall, certain direct runoff produced. So, if you are making use of the storm hydrograph it will not serve the purpose for that we need to separate the baseflow because that contribution is not coming from the rainfall it is coming from the groundwater.

So, first step is that after data collection is done, from the storm hydrograph we need to separate the baseflow. Then we need to determine the effective rainfall. Effective rainfall of *D* hour duration needs to be found out, because we will be having a series of rainfall events, from that effective rainfall of *D* hour duration which is uniformly occurred over the catchment, it is difficult to find out, still we can approximate even if the time difference is slightly different. Then, we will assume that that has been acted on the catchment for a *D* hour duration. So, once the baseflow separation is over, we will get the direct runoff hydrograph, that is the resulting hydrograph after deducting the baseflow from the storm hydrograph is the direct runoff hydrograph. The volume of direct runoff is determined by estimating the area under the direct runoff hydrograph curve. We will be estimating the volume of direct runoff from the curve it is obtained, that is we will be calculating the area under the direct runoff hydrograph that will be representing the volume of direct runoff and volume of direct runoff is divided by the drainage area to determine the depth of runoff from the catchment. From the direct runoff hydrograph, we have determined the volume of direct runoff. This volume of direct runoff divided by the catchment area will be giving you the depth of direct runoff. This must be equal to the effective rainfall for the storm. For example, we can assume it as x centimeter, that is we have determined the depth of direct runoff as x centimeter, by dividing the volume of direct runoff by the catchment area, we will be getting the depth of direct runoff, that depth of direct runoff we are representing by means of x centimeter.

So, once we get this effective rainfall, we can compare it with the effective rainfall data which we have collected, it should match each other. So, after determining the effective rainfall, the ordinates of the DRH is divided by this effective rainfall to determine the ordinates of *D* hour unit hydrograph. So, we have determined the depth of direct runoff based on the previous step. Area under the direct runoff hydrograph is calculated divided by the catchment area taken, that is giving you the direct runoff depth. Once this direct runoff depth is obtained, we will be dividing each ordinate of direct runoff hydrograph with this direct runoff depth. Which principle we are utilizing here? It is based on the principle of proportionality, principle of proportionality based on linear system theory we are utilizing here to get the ordinates of unit hydrograph from the ordinates of direct runoff hydrograph. So, direct runoff hydrograph ordinates have been divided by the effective rainfall depth. That effective rainfall depth how we are determining? Either effective rainfall data or the rainfall hyetograph will be given to you, or from the rainfall hyetograph after deducting the initial abstractions or by means of φ-index method you can determine the effective rainfall. This is the method utilized for deriving the unit hydrograph from an isolated storm. So, we need to solve some problems related to it.

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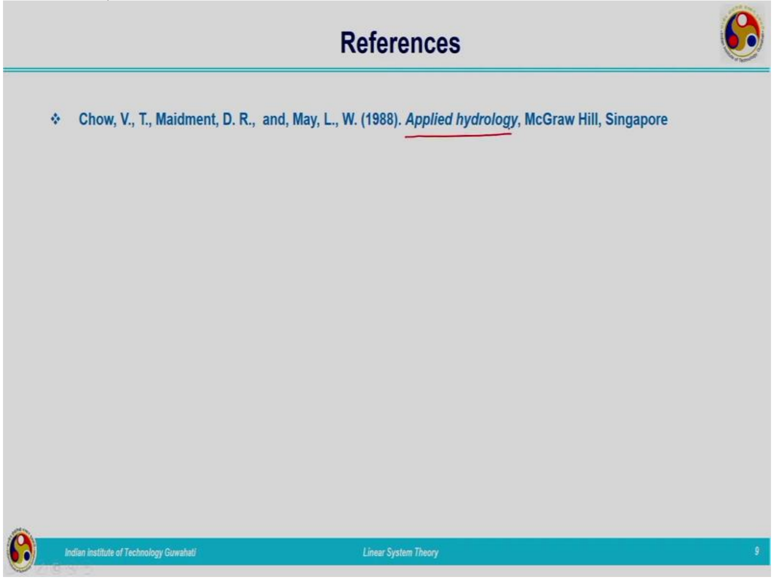

The reference related to this topic is applied hydrology textbook by Van Te Chow and others. Here I am winding up this lecture. Thank you.