Watershed Management
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Module No. # 08
Lecture No. # 33
Flood Routing

Welcome back to the video course on watershed management in module number eight on storm water and flood management in lecture number thirty three today we will discuss about the flood routing.

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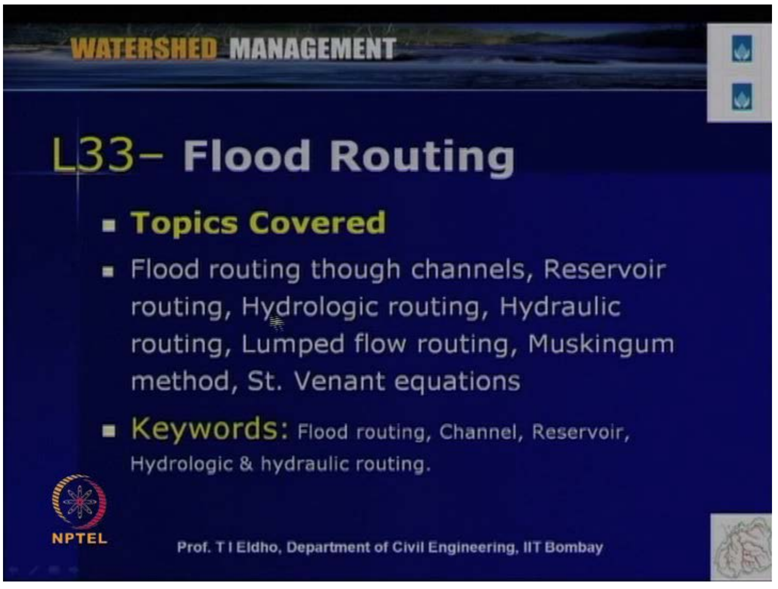

So, some of the important topics covered in today's lecture include flood routing through channels, reservoir routing, hydrologic routing, hydraulic routing, lumped flow routing, Muskingum method, Saint Venant equations. So, some of the keywords for today's lecture are flood routing, Channel, Reservoir, Hydrologic and hydraulic routing.

So, we were discussing about the flood problems; say on a watershed basis we have seen what will be happening. Say, with respect to the rain water runoff processes and then with respect to channel flooding and then with respect to the over land flow conditions, urban flow, flood management, urban drainage system, all these details we are discussing in this module in the last 2 lectures. So, in today's lecture we will be mainly focusing on the flood routing; so let us first look into what is flood routing.

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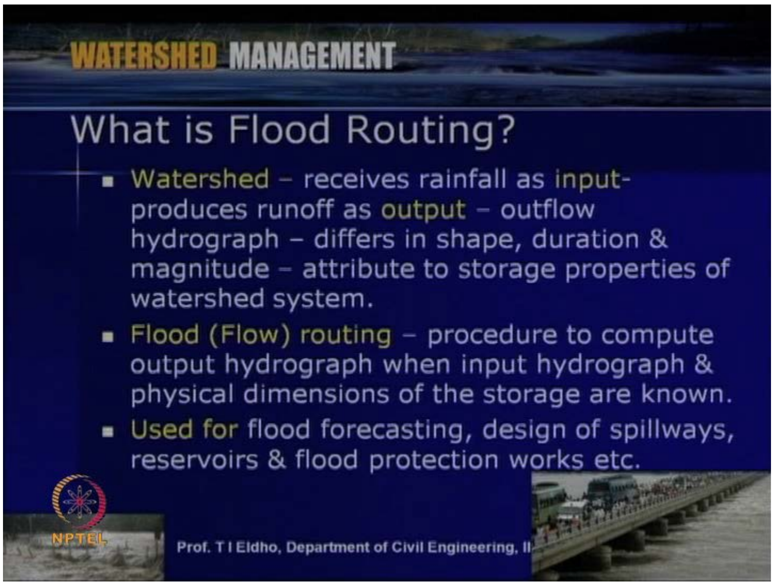

As we discussed, when we look into on a watershed basis say, watershed receives the rainfall as inputs and then say through various hydrologic processes, say this input of rainfall is transformed into runoff, so that is the output. So, that way as we discussed in some of earlier lectures, we can try to get the discharge or the product at particular location with respect to time or the discharge versus time that is so-called hydrograph we can get.

So, as we can see that when this rain water runoff process taking place and then the runoff hydrograph will be coming from various locations through various channels to a main channel or through various drains to a main channel and then this will be say, these hydrographs or the flow will be merged. Then, the flow depth will be increasing or the discharge will be increasing the main channel which we consider. So, as we can see as far as a watershed based say flow routing is concerned, we can see that the hydrograph differs in shape duration and magnitude.

So, as the flow is keep on coming from various locations and then merging into the main channel, there will be the shape and duration and magnitude will be keep on changing. So, this attribute to the storage properties of watershed system, what is the storage properties within the watershed? Or, what is the storage property within a channel?

Accordingly, the things will be changing; I mean, the hydrograph say the pattern will be changing, its peak will be changing, or time to peak will be changing, or its shape will be changing.

So, within this context let us look what is flood routing or Flow routing. Flood routing or Flow routing means it is the procedure to compute output hydrograph when input hydrograph and physical dimensions of the storage are known. Say for example, if you consider a river like this, the flow will be keep coming from various locations through as over land flow or say as inflow to a particular location and then say we can see that this hydrograph say if you consider any location with respect to time the discharge versus time we can see that this the shape and other properties will be changing.

So, the flood routing or Flow routing means this is a procedure to compute say the output hydrograph at any location with respect to time for the given input hydrograph and then what will be the physical dimensions and storage properties of this river channel or the over land flow or the watershed so like that So, flood routing means it is a the process of say what say we know what is the inflow coming and then say at various locations, at particular location we are identifying what will be the outflow I mean, the discharge versus time the hydrograph we are identifying.

So, this depends upon what is the inflow coming to the system when we consider say between 2 sections and then, what will be the channel properties or the storage properties of the channel or the river or the watershed which we are considering so this procedure is so-called the flood routing or Flow routing. So, this flood routing or Flow routing is very important in many of the hydraulic calculations since, when we are going for flood predictions flood warning system, we have to calculate how this outflow hydrograph at particular location with respect to even in inflow hydrographs and then also when we are going for design of various hydraulic structures, we should know this outflow hydrograph.

Flood routing or Flow routing is a very important procedure in hydraulics engineering and of course, within the context of watershed management also this is very important since, we have to identify how this outflow hydrograph will be changing with respect to the storage system between 2 structures or 2 sections of a channel or a river with respect to the inflow hydrograph.

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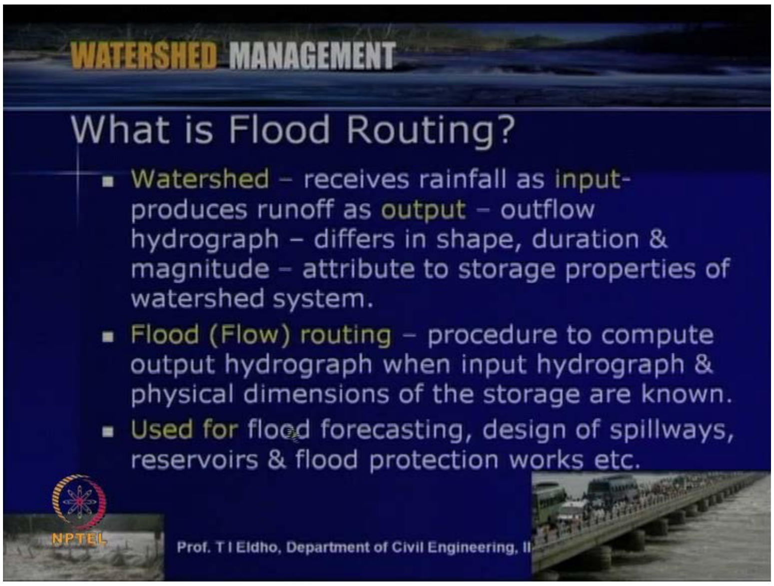

So, this flood routing is used for flood forecasting. As I mentioned, it is very important we have to identify the flood routing to see how the flood will be taking place or flood forecasting; then design of spillways. If you consider reservoir or a say hydraulic structure say like, while designing we should know how this… for given inflow, how will be the out flow flood routing required? Then also for various flood protection works we should know say, how this outflow hydrograph is changing or how. What is the pattern?

So, that way flood routing is very important in watershed management say, to identify say whether there will be any flooding problems or t while designing various structures in a river or in a channel, we need to say identify how the flood is proceeding or we have to go for flood routing. Now, let us look what are the important motivations for this flood routing. Flood routing as we identify for the given inflow conditions say at particular location, we want to know how the outflow condition is taking place or outflow hydrograph or outflow hydrograph, so we should identify. Why we should go for this?

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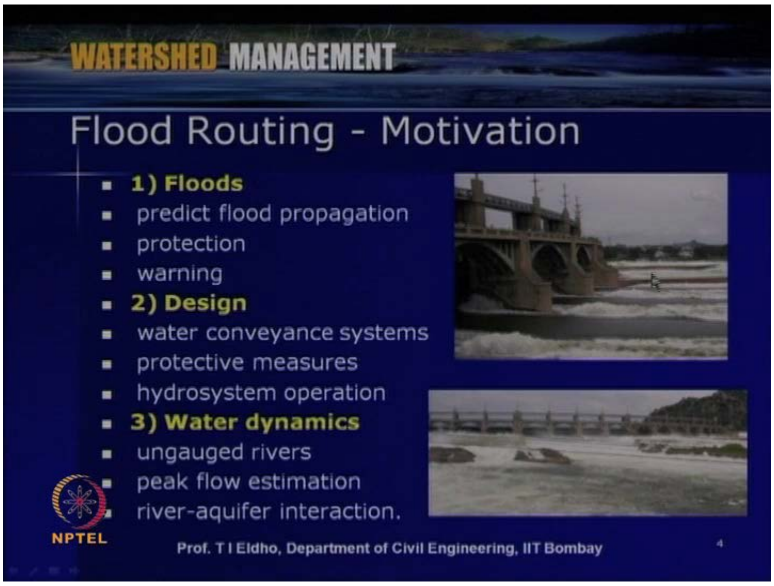

As we have already seen we say, for various flood flow conditions like flood forecasting or hydraulic structure design we need some of the important motivations I have listed here. Say, when we consider the floods we should know the say we have to predict the flood propagation.

So, as you can see in these photographs how the flood is moving from one location to another location - that is so-called flood propagation. Then, if you want to take some protection measures with respect to the flooding, we should know and then say, to go for flood warning, we should know how this flood movement or flow movement takes place. So, that process is the flood routing; flood routing is very important as far as the floods are concerned with respect to prediction of floods or flood warning system or to go for protection from the flooding like that and then it is very important to do flood routing to for the design of various structures like a water conveyance systems say, like a channels canals or what kind of a conveyance system.

We should know for the given inflows say how the outflow will be at particular locations. So, water conveyance system design then protective measures like a if you are going to construct a flood protection say embankments or the protection bars. Then, we should know how this flood outflow hydrograph so that way flood routing is very important. Then hydro system operations say while operating a reservoir system, we should know say we should go for reservoir routing and then we should know how the water level is going to rise within the reservoir system; so for the hydro system operation we should do this flood routing.

Third one is as the water dynamics so say some of the many of the rivers will be ungauged. So, we should know how the flow can propagate or flood can propagate for ungauged rivers; then peak flow estimation; so many of the times we should know what will be the peak of flow or the hydrograph with respect to given rainfall conditions or with respect to given releases from a reservoir. So, peak flow estimation is very important and also sometimes when we deal with river aquifer interaction say whenever the water level rises in the river or say the flow will be taking place from the river to the aquifer system and when the water level resides or going down within river system then the aquifer will be recharging to the river.

So, for these kinds of calculation also we should go for flood routing; so that way flood routing is very important as far as say, when we consider various hydrologic or hydraulic phenomena like floods design of various hydraulic structures, water dynamics, etcetera.

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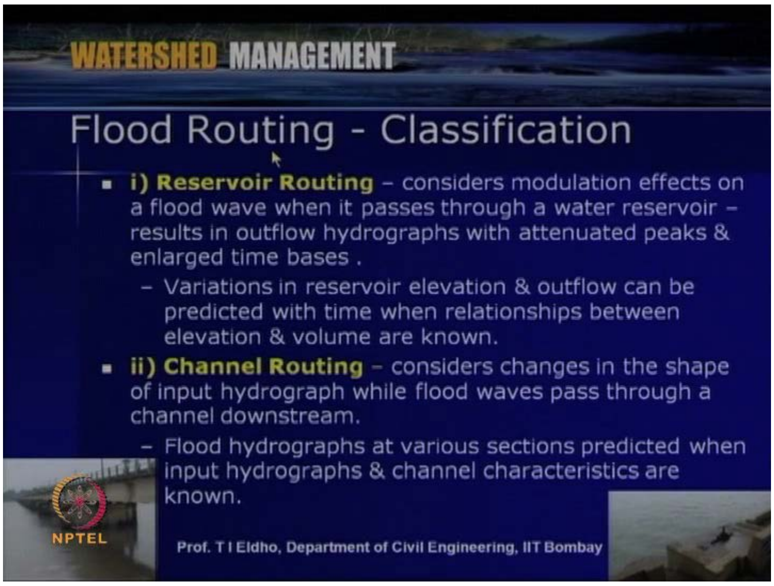

Now, let us see say when we discuss about flood routing say we can classify the flood routing mainly into 2. One is the reservoir routing second one is the channel routing.

So, say as I mentioned say when say as far as reservoir when there is a dam and then there will be reservoir so that to the reservoir what will be flow will be keep on coming in the upstream section say from various channels and then we should know how the depth of flow is changing. So, that is so-called reservoir routing and as far as channel or rivers or canals are concerned, for the given inflow condition say on downstream sites we should identify how the outflow or how the discharge of the flow depth variations, that way, we can classify the flood routing into reservoir routing and channel routing. So, as I already mentioned reservoir routing considers modulation effects on a flood wave when it passes through a water reservoir results in outflow hydrograph with attenuated peaks and enlarged time basis. That way say as far as a reservoir is concerned, with respect to given inflow conditions how the flow depth variation taking place and with respect to the space and time that we will be identifying through reservoir routing.

Variation in reservoir elevation and outflow can be predicted with time when relationships between elevation and volume are known. As far as reservoir is concerned, we if you know the, at various flow that conditions what will be the volume and within the reservoir. Then, we can easily identify say how much is the outflow or how much storage is there; how much is the possible outflow from the reservoir system; so that way reservoir routing is very important. The second one is channel routing; so, channel routing considers changes in the shape of input hydrograph while flood waves pass through a channel downstream.

So, whatever inflow is taking place from upstream side and then there will be storages and then various changes taking place within the river or channel section. So, channel routing means we are considering say on the downstream side say, what will be the hydrograph or what will be the flow depth or what will be the discharge. Flood hydrographs at various sections predicted when input hydrographs and channel characteristics are known. So, here the reservoir characteristics or channel characteristics are important since, accordingly there will be some storage will be taking place within the reservoir or within the channel. That way when we go for reservoir routing or channel routing we should know the channel characteristics and the reservoir characteristics for these kinds of routing.

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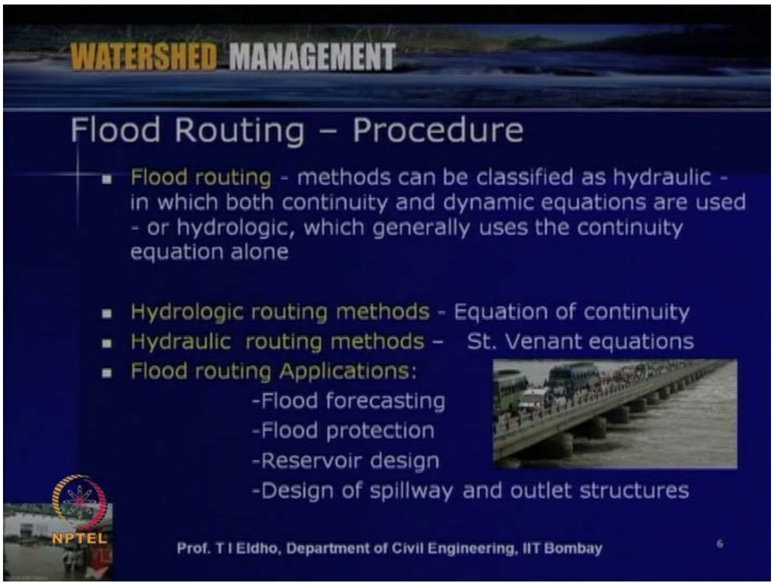

So, that way we can classify the flood routing into reservoir routing and channel routing. Now, when we consider say flood routing, we have to systematically say consider the inflow and then the various channel properties or reservoir properties and that way flood routing we have to go systematically.

So, flood routing methods we can classify into hydraulic routing in which generally both continuity and dynamic equations are considered so hydraulic routing means with respect to channel with respect to time and space; how the flow depth or how the discharge will be varying?

So, generally we will be solving the continuity equation which is based upon the conservation of mass and the dynamic equations so-called Saint Venant's equation generally by considering the conservation of momentum. Then that is how with respect to the hydraulic routing with respect to channel or hydraulic routing which generally uses the continuity equation alone. So, that way the flood routing can be hydrologic routing methods generally which we consider the conservation of mass or equation of continuity. then hydraulic routing methods generally which we consider the conservation of mass or continuity equation and the conservation of momentum or the so-called momentum equation which are say we call as Saint Venant's equations.

So, that way we can we have to systematically consider the system within a control volume approach generally, either with respect to the continuity equation or the continuity equation and the momentum equation so with respect to the hydraulic routing or the hydrologic routing. So, as we mentioned these kinds of routing is very important as far as flood forecasting, flood protection reservoir design or design of spill way and various outlet structures. So, that way say either hydrologic routing or hydraulic routing we have to do as far as while design and planning of say various say structures or say, when we go for watershed management the this routing either hydraulic routing or hydrologic routing are essential.

So, now say as flood routing when we consider we have seen that we are trying to identify how the flow depth is varying or discharge is varying with respect to given inflow conditions and to the storage conditions of the channel or the reservoir. So, that way the flood routing say as we discussed it is a technique of determining the flood hydrograph at a section of a river or a channel by utilizing the data of flood flow of at one or more upstream sections.

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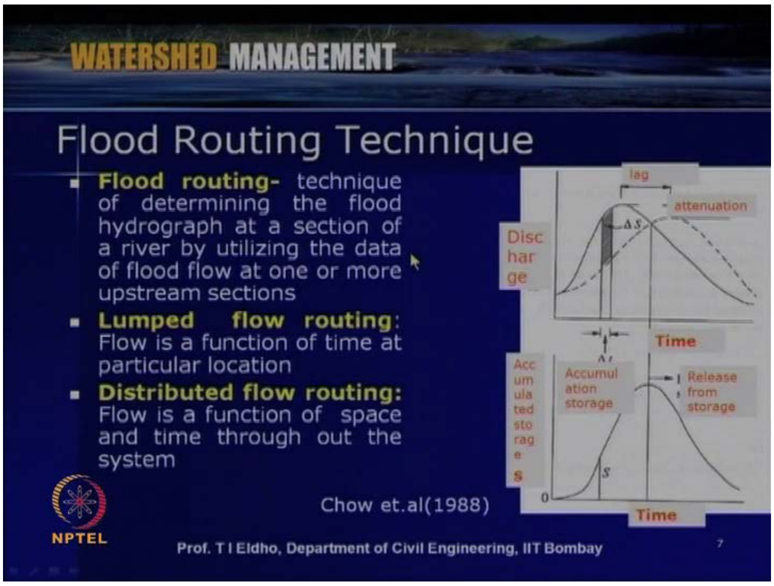

You can see that here this is the hydrograph discharge versus time so, if this is the inflow hydrograph coming and then say you can see that attenuation and various changes, this can be the outflow hydrograph so similarly say there can be storage taking place within the river or the reservoir then you can see that say as far as the reservoir is concerned release from storage then accumulation storage; so that way we can identify with respect to the hydrograph.

So that way when we deal with the flood routing we can have 2 types of flow routing: or flood routing one is lumped flow routing and second one is the distributed flow routing. Lumped flow routing: here, flow is a function of time only at particular location. So, the special aspects we are not considering but with respect to time, that is the lumped flow routing and then distributed flow routing is concerned, flow is a function of space and time throughout the system.

So, that way we have to see the channel section and then slope and various conditions weather it is channel routing or river routing or as far as a reservoir is concerned, we should know the aerial extends and then with respect to the depth conditions, how the volume changes so that way we should know that also. So, that way flood routing can be either lumped flow routing or distributed flow routing.

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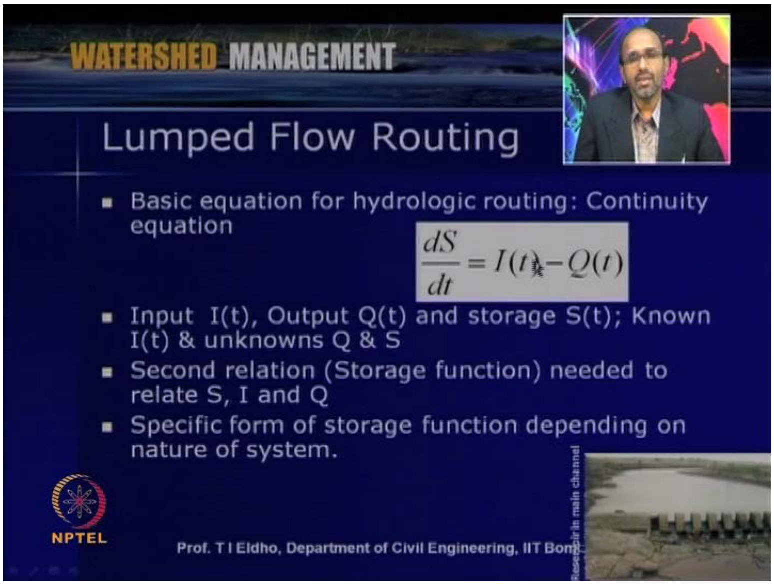

As I mentioned, when we deal with the lumped flow routing so generally we will be going for the solution of continuity equation so that we can express as the rate of change of storage is equal to inflow minus outflow or input minus output. So, here input or inflow is as a function of time and then outflow or output is a function of again time; so, that inflow minus outflow that gives the change in storage; so here S is the storage. If you know the inflow then the unknowns also are the outflow and storage for Q and S.

So that way, other than this continuity equation like the change in storage is equal to inflow minus outflow. So, we should have some second relationship as a storage function this is needed to relate this storage inflow and outflow.

So, that way we will be dealing with lumped flow routing so specific form of storage functions say like a say, when we deal with the reservoir then reservoir capacity with respect to the depth variation within the reservoir or with respect to channel, how the as a either linear or non-linear variations with respect to the storage function so that we can get specific form of storage function depending upon the nature of the system. Either a channel or river or a reservoir we have to get so that way, the lumped flow routing is mainly based upon this continuity equation.

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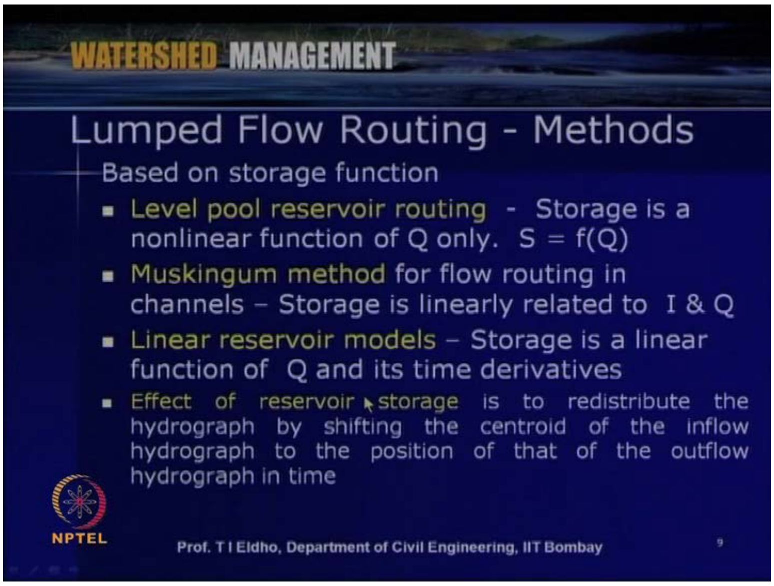

So, lumped flow routing some of the methods as I mentioned one equation is the continuity equation and then the other relationship which we need to identify how the storage is varying or how the discharge or the outflow is varying. So, some of the important relationships which we can get is like level pool reservoir routing where storage is a non-linear function of the outflow only. So, like the storage say if you consider for example a reservoir storage will be a function of the outflow so S is equal to f Q and then say for example, in channel routing say using Muskingum method which is one of the commonly used method.

So, here flow routing in channels so the storage we can relate linearly; so, linear relate inflow to the outflow, there can be inflow to outflow we can say relate linearly. So, that is say which is generally Muskingum method which we will be discussing in detail later. Then also say, like other type of relationships like linear reservoir models where storage is a linear function of the outflow and its time derivatives; then the effect of storage.

So, that way we can relate to redistribute the hydrograph by shifting the centroid of the inflow hydrograph to the position of that of the outflow hydrograph in time. So, like that depending upon the conditions are the non-relationship. In the lumped flow routing the main equation is the conservation of mass or continuity equation which gives the change in storage is equal to inflow minus outflow. Then the second relationship say there are 2 unknowns one is storage and second one is the outflow. So, we should have 2 relationships: one is the continuity equation; second is say like the relationship which I mentioned, like the level pool reservoir routing where storage is a function of the outflow.

Then, Muskingum method where storage is linear related with respect to inflow and outflow and then linear reservoir models where the storage is a linear function of outflow and time derivatives. So, like that we can connect and get another relationship and then we can solve for the outflow or the storage depending upon the condition; that way, this lumped flow routing we can consider say in 2 methods.

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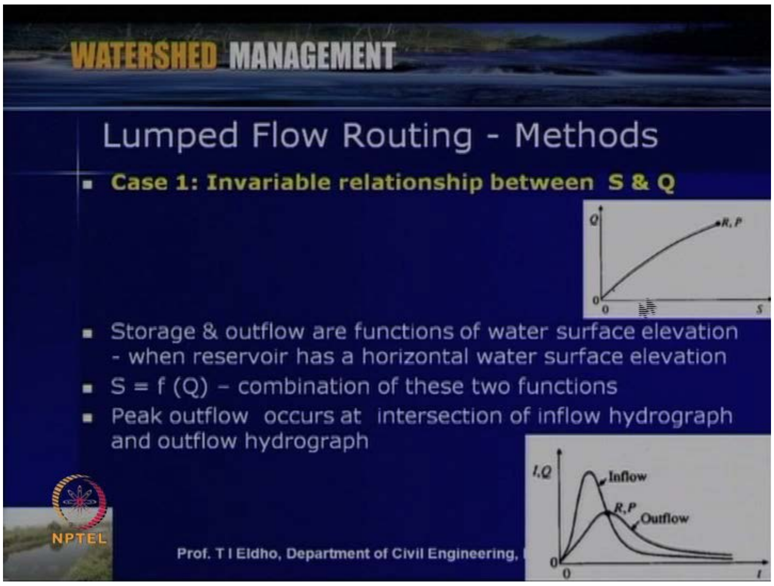

So, first method is case 1: we consider as invariable relationship between the storage and outflow S and Q. Here, there is, it is invariable relationship so like storage versus outflow Q versus s we can put like this and based upon that we can get a relationship. Second relationship storage and outflow are functions of water surface elevation when reservoir has a horizontal water surface elevation; so S can be written as a function of Q or combination of these two functions. So, then as we can see the peak flow occurs at intersection of inflow hydrograph and outflow hydrograph.

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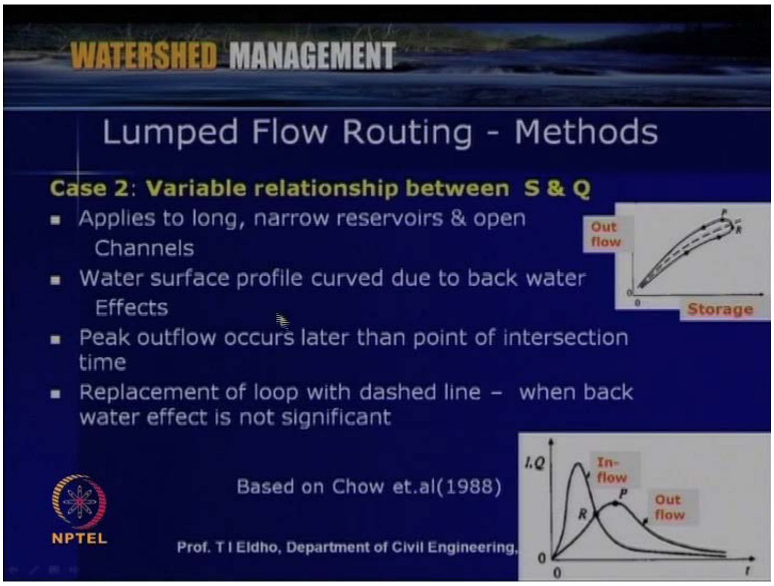

So, say if this is the outflow hydrograph, this is the inflow hydrograph. So, here with respect to the peak flow, we can identify the outflow; this is peak outflow. we can identify and then this is case one we consider the invariable relationship between the storage and the outflow. The second case is where we can have variable relationship between the storage and outflow; so this applies to long narrow reservoirs and open channels. So, depending upon the conditions weather the channel is narrow and the reservoir is also narrow or long so there we can apply this variable relationship between storage and outflow

So, here the outflow is y axis, storage is this x axis; then we can see that this is not considered as a single line as we considered in the last slide. But, here this will be varying like this; so there is a variable relationship so the water surface profile is curved due to the back water effects.

So, there is possibility of back water effects; that way, the back the water surface profile may be curved; one peak outflow occurs later than point of intersection. So, you can see that, if this is the inflow then the peak flow you can see that is a later stage than the point of intersection between inflow hydrograph and outflow hydrograph. This would be the location of peak outflow; so replacement of loop with the dash lines so as we mentioned the outflow and storage it is a loop like this.

So, we can consider we can replace this loop with respect to a dash line then, back water effect is not significant; that way also we can consider. In the case 2, we consider the variable relationship between storage and the outflow. That is about the lumped say, flow routing. Now, we will be discussing in detail about the reservoir routing and the channel routing with respect to some of the important techniques which we generally use as far as the flood routing or flow routing…

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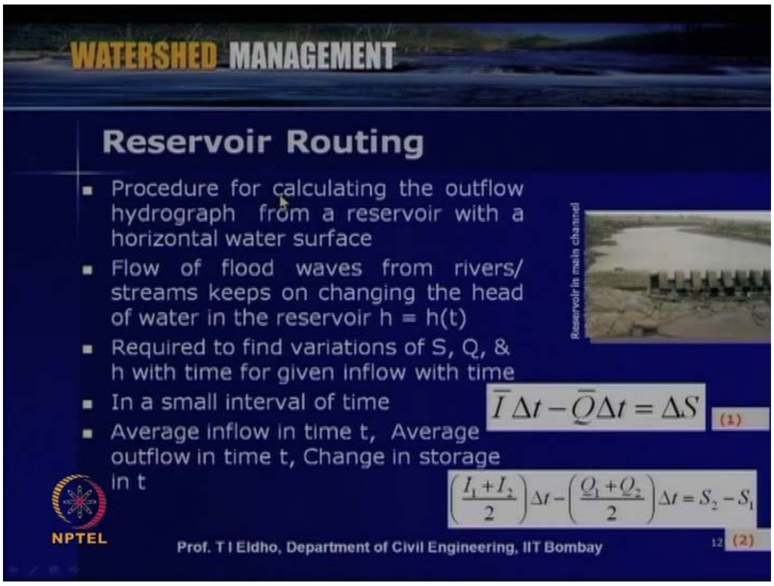

Now, let us look into first into the reservoir routing; so reservoir routing as we discussed it is the procedure for calculating the outflow hydrograph from a reservoir with a horizontal water surface. So, if this is a reservoir, this is a procedure for calculating the outflow hydrograph; so flow of flood waves from rivers streams keeps on changing the head of water in the reservoir the head in the reservoir is a function of time.

Since, flow is keep on coming in the upstream, so that way this is a function of time and so we are required to find variations of the storage within the reservoir outflow and this depth of flow within the reservoir or depth, flow depth within the reservoir for given inflow with time. So, the problem in reservoir routing is that we know the inflow what is coming to the reservoir then we know the reservoir characteristics. So, we have to identify what will be the storage within the reservoir and then what is the outflow possible from the reservoir and then say the depth of flow or the water depth available within the reservoir. If you consider a small time interval so here again, if you use the continuity equation, we can write the inflow into delta t minus outflow Q into delta t is equal to change in storage delta s equation number 1. So, if you consider small time interval say for example, few minutes then we can write inflow into delta t minus outflow into delta t is equal to change in storage delta S.

If you consider the… as far as inflow is concerned, if you consider say, an average with respect to time so that we can write I 1 plus I 2 say, if I 1 is the say the flow at time t 1 and I 2 is the inflow at time t 2 so if the delta t is t 2 minus t 2. Then we can write I 1 plus I 2 divided by 2 into delta t minus similarly the outflow is Q 1 at time t 1 and outflow is Q 2 at time t 2. So, Q 1 plus Q 2 divided by 2 into change in time delta t so that will be change in storage S 2 minus S 1. So, this average inflow we consider here in time t and average outflow in time t and then the change in storage t. That way we can re-write this equation and then we go for reservoir routing.

So, now when we deal with the reservoir routing say we should have some important data with respect to the various characteristics of the reservoir. Then, we should also know the inflow pattern coming to the reservoir say accordingly only we should be able to say predict the outflow conditions or the storage variations within the reservoir.

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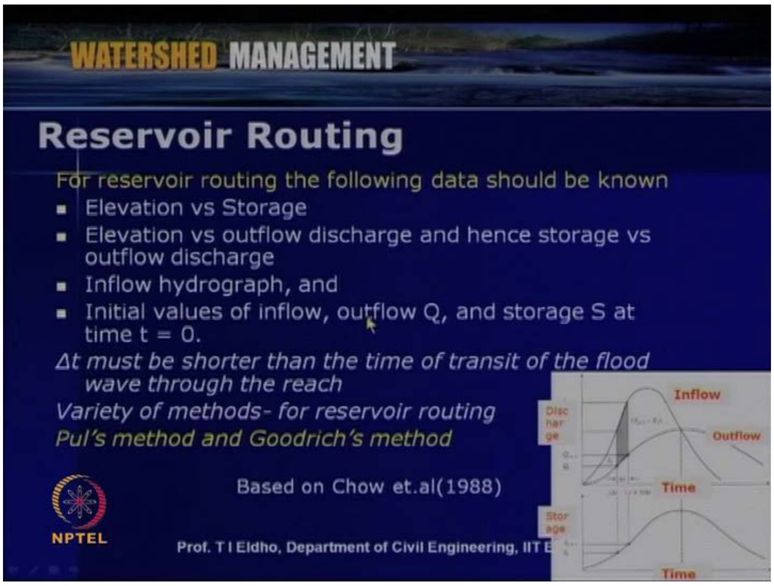

So, let us look at some of the important data required as far as reservoir routing, data like elevation versus storage. So, when the water level in the reservoir raises how much storage is available so elevation versus storage then elevation versus outflow discharge and hence storage versus outflow discharge so that data also needed. Then we should know how much inflow is coming to the reservoir so that inflow hydrograph should be known and then we should also know initial values of inflow initial values of outflow and then what is initial storage S at time t is equal to 0. So, if the time - starting time is t is equal to 0 and at the time, since this is a time dependent problem at that time, what is the inflow, what is the outflow and what is the storage? So, based upon that only we will be going for the prediction as far as the next time step is considered.

So, here as I mentioned when we go for reservoir routing the time step delta t must be shorter than the time of transit of the flood wave through the reach which we consider say now within the reservoir reach. So, varieties of methods say you can see as far as reservoir routing mainly based upon this continuity equation. Variety of methods we can see in the literature, like Wendy Chow et.al, have given in their test book.

So, some of the two important methods which are generally used we will discuss briefly for reservoir routing one is the Pul's method and second one is the Goodrich's method so these are 2 important methods which generally used as far as reservoir routing is concerned. So, as I mentioned, what we are trying to do? We know the inflow; we want to identify how is the outflow or the storage with respect to time; so that is what we are trying to solve in reservoir routing.

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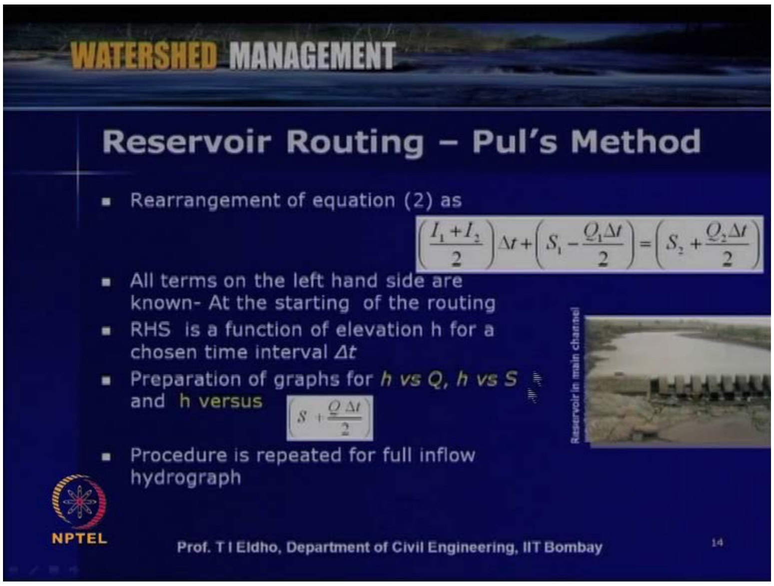

So, now let us look into these two methods Pul's method and the Goodrich's method. Now, in a reservoir routing using Pul's method, we have earlier seen the continuity equation as given here so this equation number 2 we will be re-writing as like this I 1 plus I 2 by 2 into delta t plus S 1 minus Q 1 into delta t divided by 2 is equal to S 2 plus Q 2 into delta t and divide by 2.

So, here we can see that if you consider this equation which is obtained from equation 2 which is the continuity equation here, all times on the left hand side are known at the starting of the routing so all these terms are known so what are the unknowns are this S 2 and Q 2. So, right hand side is a function of elevation for a chosen time in Delta t. now, we can prepare graphs say which can give say the that means the flow depth or the depth of water in the reservoir versus the Outflow h versus Q and h versus storage and then we can also get h versus S plus Q into delta t by 2.

So, this way we can prepare graphs with respect to various given conditions and then from that we can try to get this for the given time with respect to the given time, we can identify what is the possible storage and then with respect to given time; we can also identify how much is the outflow which can takes place.

This procedure is repeated for full inflow hydrograph so we can accordingly we can prepare curves and then based upon that curves we can easily identify for the given inflow what is the possible outflow and then what will be the possible storage.

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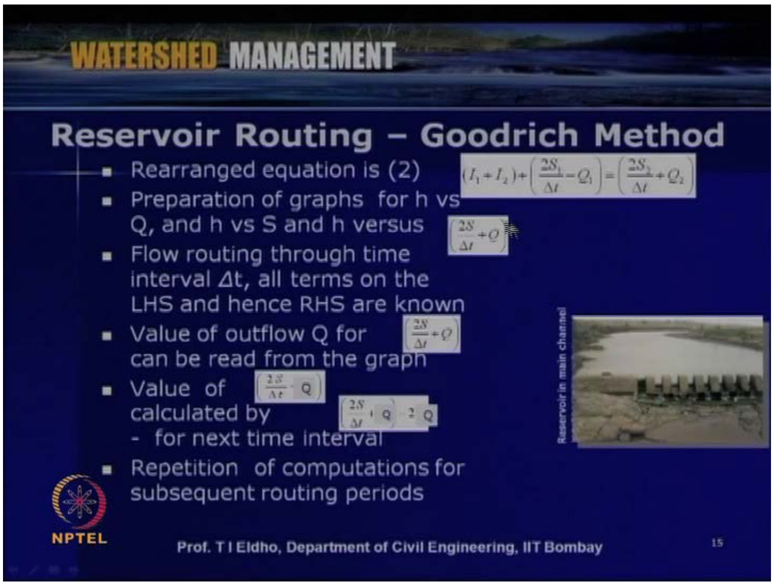

Through these graphs like h versus Q h versus S and h versus S plus Q 1 delta t by 2; so this is so-called Pul's method. Then the second method is so-called a Goodrich method; so here again the continuity equation number 2 this equation we will be re-writing in another form here in Goodrich method. So, here I 1 plus I 2 plus 2 S 1 by delta t minus Q 1 is equal to 2 S 2 by delta t plus Q 2 so where I 1 I 2 are the inflows with respect to time t 1 and t 2 and S 1 S 2 are the storage with respect to time t 1 and t 2 given Q 2 are the outflow with respect to time t 1 and t 2. So, now we prepare graphs for h versus Q and h versus S and h versus 2 S delta t by plus Q so as in the previous step here we prepare graphs h versus Q h versus S and h versus 2 S delta t plus Q.

So, flow routing through time interval delta t or terms on the left hand side and hence say left hand side is not from that we can get for what is there for the right-hand side. Value of outflow Q for say with respect to 2 S delta t by Q can be read from the graph so we can prepare the graph from that say for this 2 S by delta t plus Q for the value of outflow say we can the outflow can be obtained.

So, value of 2 S plus delta t minus Q is calculated by so I mean, for the next time step time we calculate by means of say 2 S by delta t plus Q we will deduct 2 times Q for next time interval so that this again we for the next time interval this is repeated. The procedure repeated so we get the left hand side and based upon that we can obtain the right-hand side from this graphs.

So, repetition of the computations for subsequent routing periods we can continue and then when we can identify what will be the storage or the what will be the outflow for the given inflow conditions so this is so-called Goodrich's method. So, that way when we deal with the Muskingum when we deal with the reservoir routing 2 important methods: one is Pul's method and the second one is Goodrich method.

So, this is mainly we prepare graphs for various conditions and from that we can identify what will be the outflow conditions or the storage possibilities. So, that is about the reservoir routing so there are number of other techniques available in literature but say due to lack of time we will not be going through all these techniques so here we consider only 2 techniques with respect to Pul's method and the Goodrich method.

So, now we will discuss the channel routing; as channel routing is concerned, we will be discussing one lumped approach and then another one is the distributed approach so-called a solution of Saint Venant's equations. So, first let us look into the Muskingum's method which is again a lumped approach.

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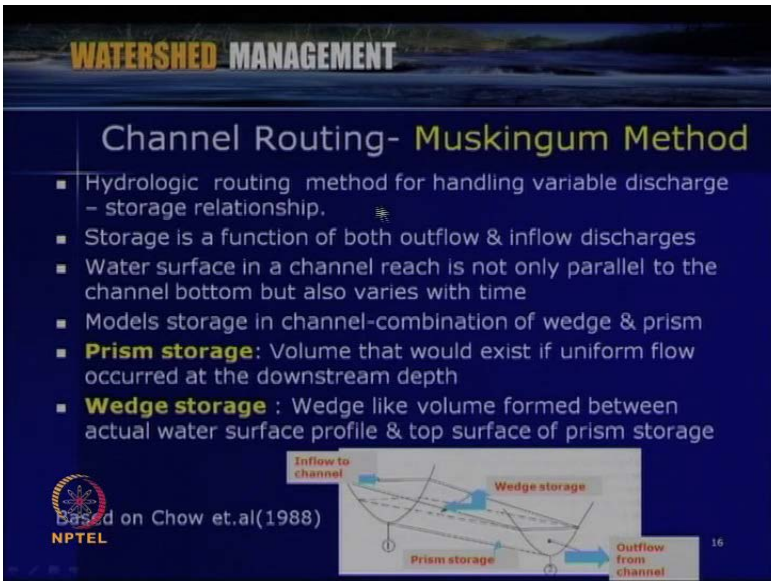

Here as you can see the Hydrologic routing method so this is a hydrological routing method for handling variable discharge and storage relationship so that is the essence of the Muskingum method so this is a Hydrologic routing so based upon the continuity equation. So, storage here is a function of both outflow and inflow discharge so as we have seen in for reservoir routing so this is mainly for channel routing. So, here again the outflow is a function of say or storage is a function of outflow and inflow characteristics for inflow discharges. So, water surface in a channel reach is not only parallel to the channel bottom but also varies with time. Based upon these assumptions say model storage in a channel is a combination of wedge and prism.

So, as you can see in this figure the bottom one we considered as a prism and then above that there is a wedge. This is with respect to the uniform flow condition is a prism storage and then above this is a wedge storage; which will be the flow depth will be keep on changing so this is the wedge storage so this a model storage we consider as wedge and prism storage. Prism storage is the volume that would exist if uniform flow occurred at the downstream depth as I mentioned here and the wedge storage wedge is like volume formed between actual water surface profile and top surface of the prism storage. So, this wedge storage is due to the change in depth between two reaches; so prism storage is with respect to the uniform flow conditions.

So, this is the inflow to the channel; here is the outflow from the channel and here we consider 2 sections so this is the prism storage and this one is the wedge storage. Now, in Muskingum method, we consider say this continuity equation say with respect to the change in storage.

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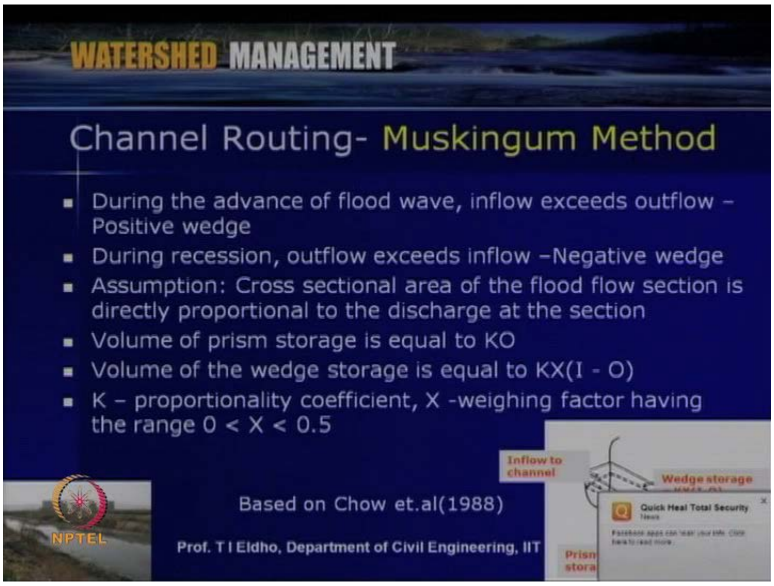

During the advance of flood, wave inflow exceeds outflow. So, whenever the flood is advancing the inflow will be more; inflow will be exceeding the outflow. So, we say that the there is a positive wedge during the recession when flow is say the depth is reducing with respect to inflow and then, during recession outflow exceeds inflow so there is a negative wedge. Also, some of the assumptions like a cross section area of flow section is directly proportional to the discharge at the section. Based upon this assumption only, this Muskingum's method is working. That way when we consider this assumption, we can put volume of prism storage is equal to K into O; where here, O is the outflow so volume of the wedge storage is equal to K into X into I minus O where I is the inflow O is the outflow and K is the proportionality co-efficient depending upon the channel characteristics and then, X is a weighing factor generally, that varies from 0 to 0.5.

Here, this is the channel inflow and this is the outflow and prism storage we can consider as this the proportionality coefficient K multiplied by the outflow K into O and then wedge storage is K into X into I minus O where X is a weighing factor which varies from 0 to 0.5. So, these entire details are given in this textbook by Chow and others of 1988.

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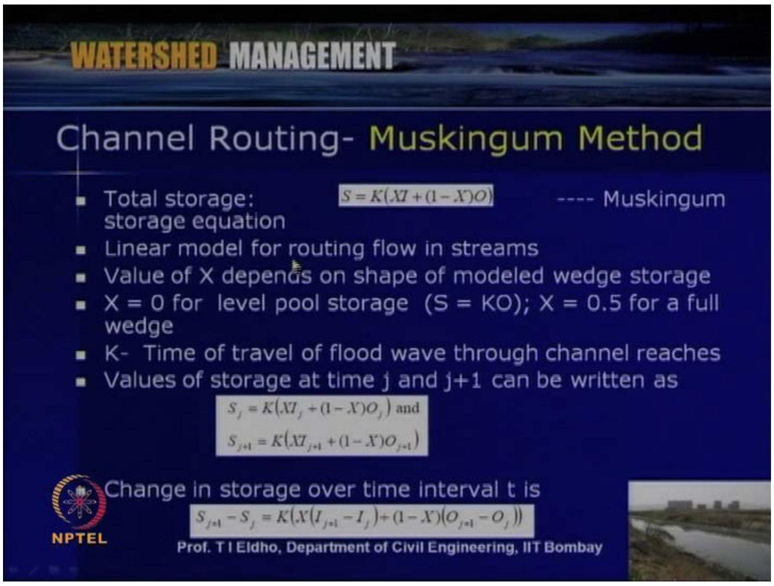

So, then say we can write the total storage with respect to the wedge storage and prism storage. Total storage is equal to S is equal to K into X I plus 1 minus X into O so this equation is called the Muskingum storage equation. Now, here we consider a linear model for routing flow in the streams so that way value of X depends upon the shape of modeled wedge storage. So, X is equal to 0 for level pool storage so that we have to consider only S is equal to K into O and X is equal to 0.5 for a full wedge so that way we can consider say with respect to say the last figure like this.

Now, as I mentioned here, K is the time of travel of flood wave through channel reaches and values of storage at time if you consider j and j plus 1. We can re-write this Muskingum equation as follows: S j S subscript j is equal to K into X into I j I subscript j plus 1 minus X into O subscript j and S at j plus 1 time we can write K into X I j plus 1 plus 1 minus X into O j plus 1.

So, at two time intervals j and j plus 1, we can re-write the Muskingum equation in this fashion. Now, the storage change in storage between these two time steps will be the difference between this j plus 1 j time step. So, S j plus 1 minus S j is equal to K into X into I j plus 1 minus I j plus 1 minus X into O j plus 1 minus O j. So, this is the change in storage when we consider the Muskingum method.

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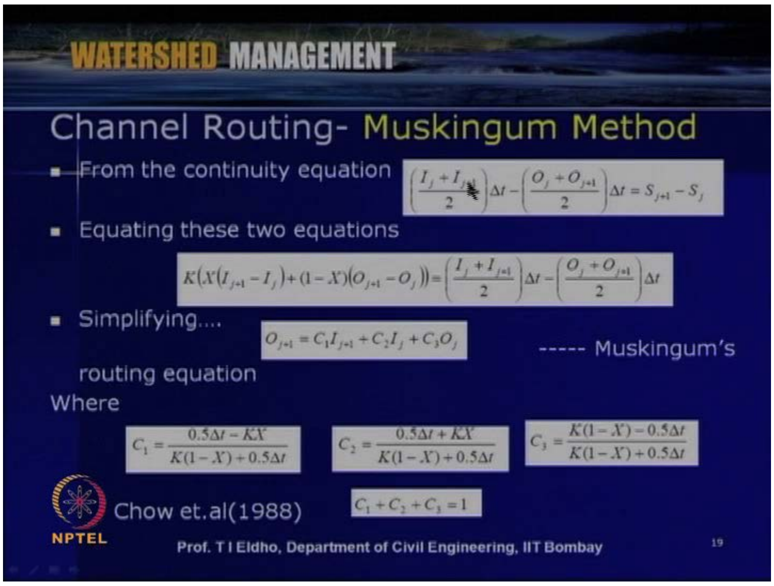

Now, we have considered the area of the continuity equation so continuity equation is inflow minus outflow is equal to change in storage so that, we can write with respect to jth j plus 1; time table we can write I j plus j plus 1 divided by 2 into delta t minus O j plus O j plus 1 divided by 2 into delta t is equal to S j plus 1 minus S j. So, we can equate this equation and then we can equate with respect to this continuity equation so we when we equate these 2 equations say we finally get the equation like this.

Now, this is our final equation as far as Muskingum channel routing method is concerned. This we can simplify as O j plus 1 is equal to C 1 into I j plus 1 plus C 2 I j plus C 3 O j. so, this is the Muskingum routing equation where this the C 1 is equal to 0.5 delta t minus K X divided by K into 1 minus X plus 0.5 delta t and then C 2 is equal to 0.5 delta t plus K into X divided by K into 1 minus X plus 0.5 delta t and C 3 is equal to k into 1 minus x minus 0.5 delta t divided by K into 1 minus X plus 0.5 delta t and the C 1 C 2 C 3 coefficients.

So, summation of this should be equal to 1 C 1 plus C 2 plus C 3 equal to 1 as explained in the textbook of Chow and others; that way we can derive this Muskingum routing equation.

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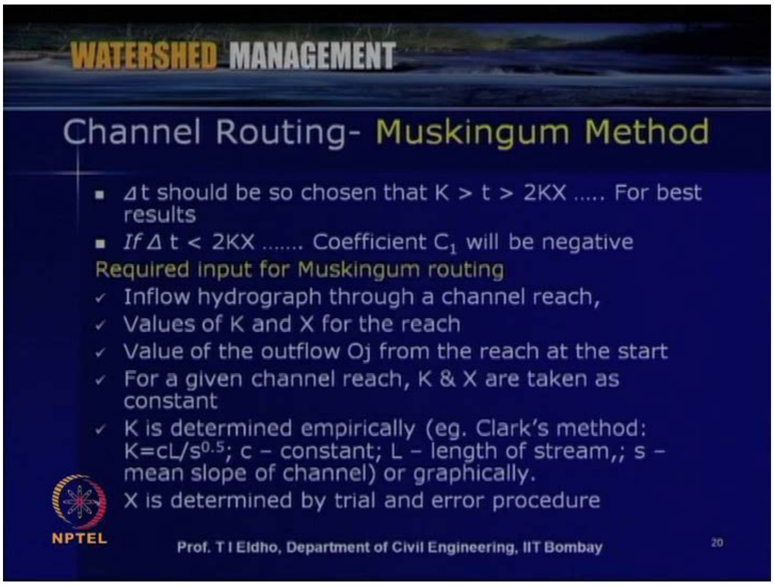

So, here say when we consider the time step in Muskingum method, it should be such a way that delta t should be chosen such a way that K should be greater than t should be greater than 2 times KX for best results. Through various case studies these are shown and if, delta t is less than 2 KX then, coefficient C 1 will become negative; so that way some restrictions of the methodology are there. Now, this Muskingum method is - Muskingum routing method - is one of the commonly used routing method as far as channel's routing or river routing is concerned. Some of the important data required as far as the Muskingum routing method is concerned, like inflow hydrograph through a channel reach that should be known then values of K and X for the reach. So, the coefficient K and X we can determine through either some empirical relationships or through trial and error approach as per the X.

So, that way we can determine; these values should be known for the given channel reach then value of the outflow O j from the reach at the starting time. Based upon that only we proceed outflow at j plus 1 time step. So, for a given channel reach K and X are taken as constant and then K is determined empirically.

So, as far as I mentioned this K we can determine empirically like Clark's method where it is defined as K is equal c into L divided by S 2 the power 0.5 where c is a constant, L is the length of stream and S is mean slope of the channel. Or, this also K can be also determined for given inflow outflow condition. We can do the, plot a graph and from that graph also we can determine this K.

Generally, X is determined by trial and error procedure for the given channel reach. So that way, once we know K and X and then systematically with respect to inflow and say at the initial time step the outflow is known, for the other time steps we can find the this the outflow and the storage using the Muskingum method. So, this method is one of the commonly used methods for channel routing and the systematic procedure is there.

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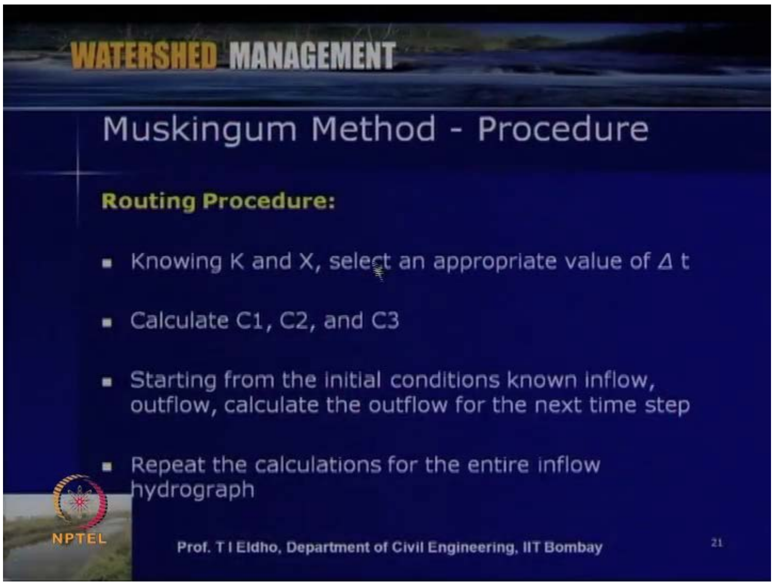

The routing procedure here I have put in the slide; so, knowing K and X this coefficients we can select an appropriate value of delta t. The time step we can choose then we can calculate C1, C2 and C3. So like here this C1 C2 C3 using K X delta t we can identify what will be C1, C2 and C3. Then, staring from the initial conditions known inflow outflow we can calculate the outflow for the next time step.

So, we can repeat the calculation for the entire inflow hydrograph; so that way with respect to time we can identify how the outflow Hydrograph will be varying. That way we can do the flood routing using the Muskingum method. So, you can see that this also a lumped approach as far as channel routing is concerned.

So, now before closing today’s lecture we will discuss the flood routing say, flood routing as I mentioned, it can be a distributed approach or lumped approach. So, we have already seen the lumped approach reservoir based upon the continuity equation and then the lumped approach for the channel routing or river routing; we have seen the Muskingum method. So, these are all say we have not considered spatial variations; these are all so-called lumped approach.

Now, say in the distributor approach we have to generally solved the governing equations; say it is based upon the physics of the problem. So, we have to say, obtain the governing equations. Either 1 dimension, 2 dimension, 3 dimension, depending upon the conditions. Generally, say river routing or channel routing is concerned, most of time we rely upon 1 dimensional modeling. So, we will be having the continuity equation: one continuity equation and one moment equation. Based upon that say, for the given channel conditions non characteristics of the channel or river and the inflow condition, we can identify how the flow depth or how the discharge is varying with respect to space and time. This is the essence of flood routing in the distributed approach. Generally, we use so-called Saint Venant's equations. Regarding Saint Venant's equations we have discussed earlier in some of the lectures earlier.

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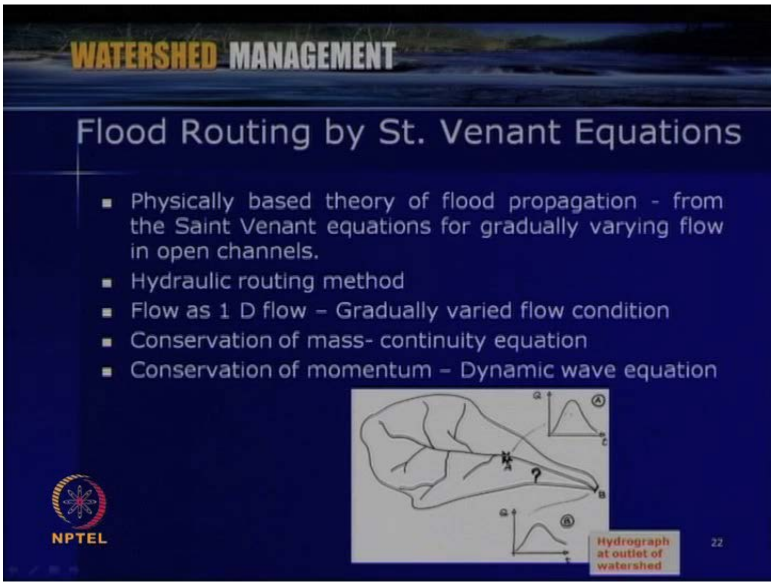

This is as I mentioned, this is a physically based theory of flood propagation. So, from the Saint Venant's equation say for gradually varying, this is generally used for gradually varying flow in open channels; so this is so-called hydraulic routing method.

Here, you can see that if this is the watershed which we consider, what we do? We know the inflow coming through these channels and then from various the sub watersheds or from various drainage systems of the small streams like this, what will be the flow coming inflow coming to the main channel?

This here in this figure, this is the main channel; so this inflow we know at various locations. Our main question is what will be the outflow or the flood hydrograph or the discharge versus time at particular location like; here at this location or at the outlet of the watershed.

Generally, for these kinds of problem we consider flow as 1 dimensional flow and then the assumption is gradually varied flow condition. So, generally say we consider the hydrostatic pressure distribution condition and also we consider the flow is as incompressible like that some of the important assumptions. So, here we consider the conservation of mass the continuity equation and conservation of momentum; the dynamic wave equation so that is so-called Saint Venant's equation.

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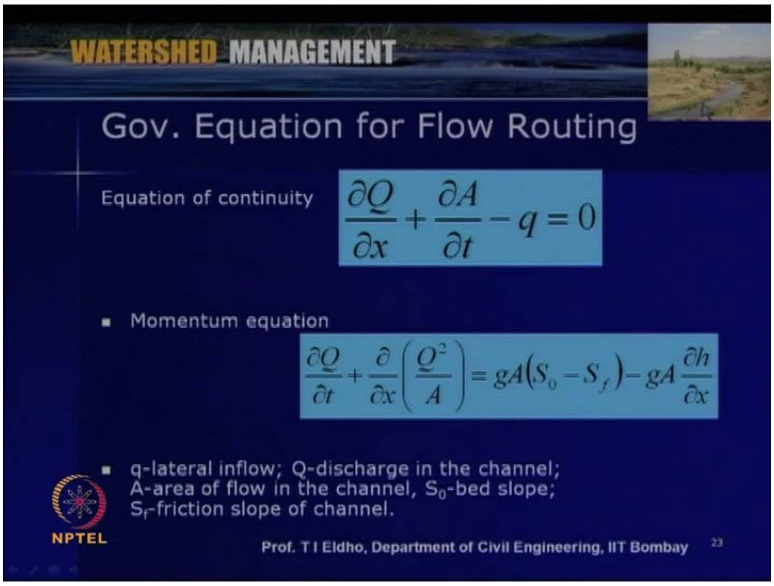

This equation we have already discussed earlier; the governing equation for flood flow routing or flood routing is the equation of continuity given as del Q by del x plus del A by del t minus Q is equal to 0; where Q is the discharge at any location and A is the cross section of the flow and then t is time x is the distance and small q is the inflow coming from say the from over lands say or the latter inflow coming to the channel. Then the second equation is so-called momentum equation; so momentum equation is del Q by del t plus del A by del x of Q square by A is equal to g into A into S 0 minus S f minus g into A into del h by del x. So, h is the flow depth and A is the flow cross sectional area g is the acceleration due to gravity S 0 is the bed slope of the channel S f is the energy slope so this energy slope which is generally find using Manning's equation.

So, that way we have to say in 1 dimension we have to solve these 2 equations so that we can identify what is the discharge or what is the flow variation with respect to space and time; so that way, this is a distributed model. Whatever the equation which we consider here these are so-called dynamic wave equations or the full form of the Saint Venant's equations.

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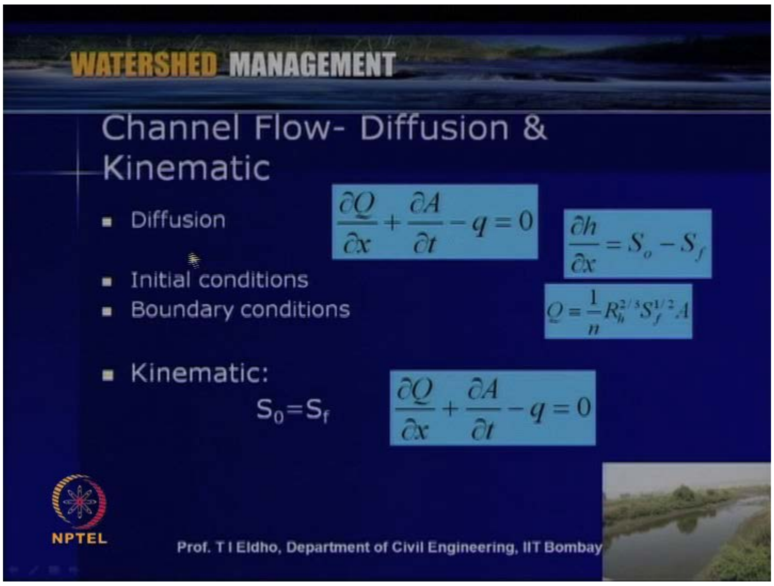

There in literature we can see two kinds of approximations; one is so-called diffusion wave approximation and second one is so-called kinematic wave approximation. In both of these approximations, the continuity equation is same. So, the same continuity equation is used and in diffusion wave approach here, dynamic moment equation we consider only like this where del h by del x is equal to S 0 minus S f. Whereas, S 0 is the bed slope S f is the energy slope which we can identify by using the Manning's equation.

So, to solve this system the diffusion equation, appropriate initial boundary conditions to be applied and then kinematic wave form is further simple; simplification of this model the continuity equation is same equation.

But here say if the slope is not drastically varying we can write S 0 is equal to S f or energy slope is equal to that slope so kinematic wave form we will be solving the continuity equation and this putting the energy slope is equal to the bed slope so this is one simplified form.

So, that way we can either solve the dynamic waveform or the diffusion wave form or the kinematic waveform depending upon the requirement or depending upon the problem with appropriate initial condition like what will be the initial flow depth or the discharge and then boundary conditions the upstream boundary what is the condition or downstream boundary what is the condition. So, accordingly with respect to these governing equations, initial conditions and the boundary conditions we can solve the system equations. So, that we can do the flood routing or flow routing so that the output will be say we know the discharge or flow depth for the given conditions at any location of the river or the channel.

As we discussed earlier, as far as solution is concerned for this governing equations say, in the distributor model or the Saint Venant’s equation the say generally, either we can go for analytical methods or computational method. So, as I mentioned earlier these analytical methods are very difficult to get only for simplified governing equations or boundary conditions and geometry. We can have some very simple analytical solutions but this is not applicable for most of the field flow.

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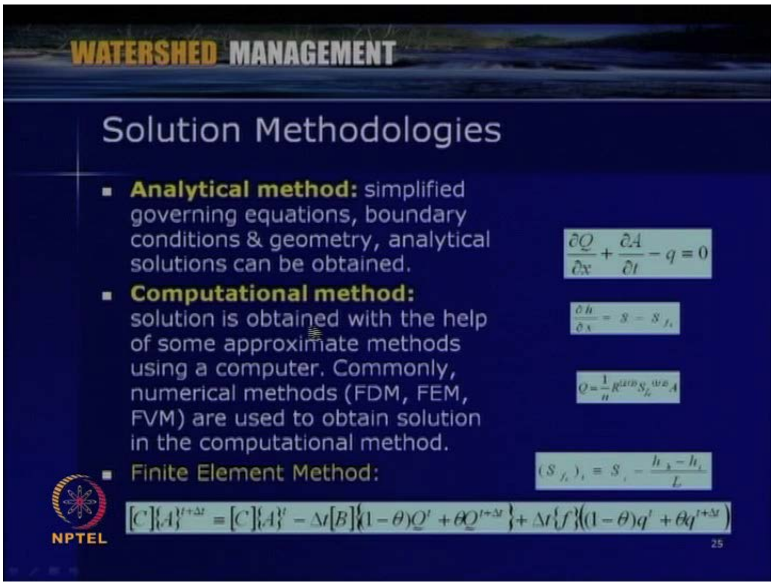

So, that way this equation say either in dynamic waveform or the diffusion waveform or the kinematic waveform we have to solve using the numerical techniques. So, here in computational methods solution is obtained with the help of some approximate methods using computer. So, commonly used in numerical techniques like finite deference method finite element method or finite volume method are used to obtain the solution in the computational method.

So, this we have already discussed earlier so we are not go into details so say for example in finite element method if you want to solve this diffusion waveform of the equation we can consider the channel to be say constitute of number of linear line elements and then we can consider the element properties and then say for example using Galerkin approach we can approximate this continuity equation and the final form of the equation by considering the an implicit form time variation final form of the equation can be written like this.

So, here in the finite element formulation for the given condition say, we can solve this boundary condition. We can solve this system of equations to get the unknowns of flow depth or the discharge under given condition.

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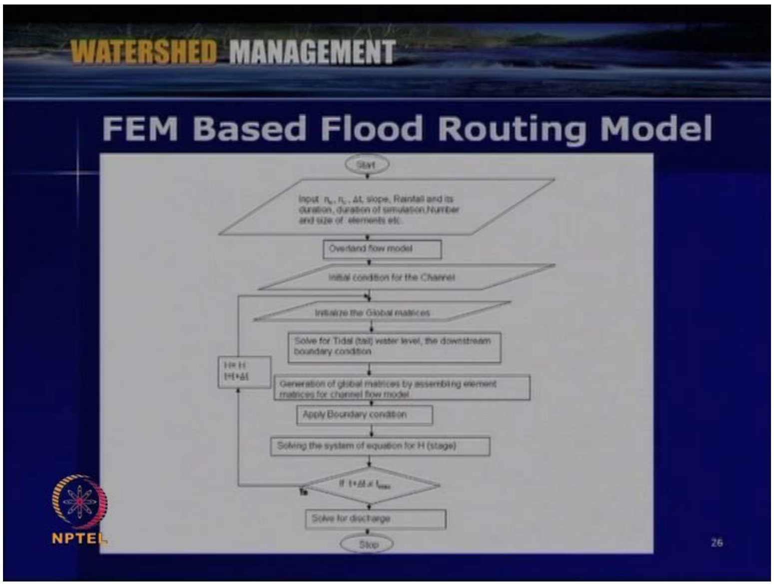

So, that way we can go for…. so we have developed some flood routing model for as far as channels are concerned, with respect to the power land flow and then say for example, tidal boundary conditions urban watershed basis. So, these kinds of flood routing or flow routing, the essence is inflow conditions are known from lateral flow or the beginning of the channel and then we want to identify how the flood or the outflow is taking place; so output will be in terms of discharge or the depth of flow.

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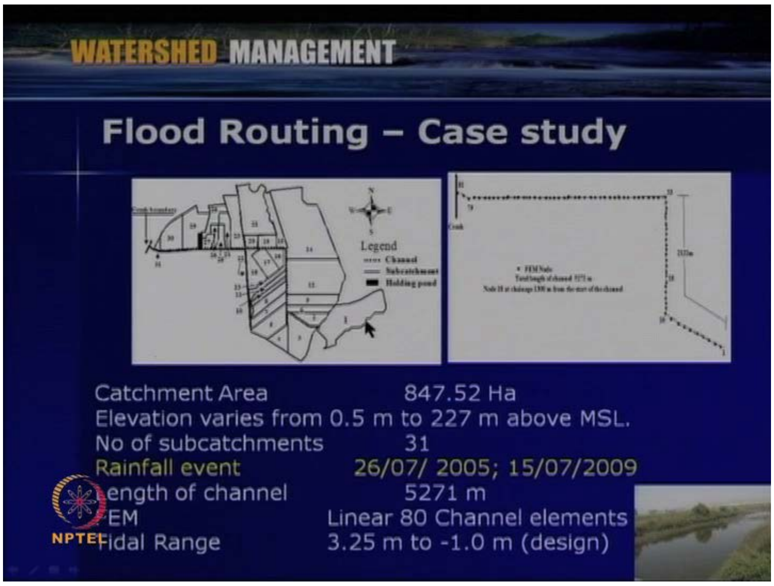

Before closing today's lecture we will just briefly go through one case study. The case study is a catchment called Kalamboli watershed - urban watershed in Navi-Mumbai, near Mumbai. So, this is the watershed; there is a main channel through which the drainage taking place. The question here is, how the flood routing is to be done through this channel? Catchment area is about 8 point 47 square kilometers elevation varies from 0.5 meter to 227 meter above the MSL.

Here, this through this channel the flow is reaching to the creek or the sea. So, here we consider say lumped model approach as far as the power line flow by considering the continuity equation. So, we saw about 31 sub catchment to get the overland flow come into these channels at various locations and length of the channel is about 5.271 kilometer and here we used finite element method as we discussed earlier. So, about 80 channel elements are shown here, is taken and here the tidal boundary condition is there at this location which varies from 3.25 meter to minus 1 meter depending upon the spring tide or neap tide or the tidal variation - daily tidal variation - at this outlet of the channel.

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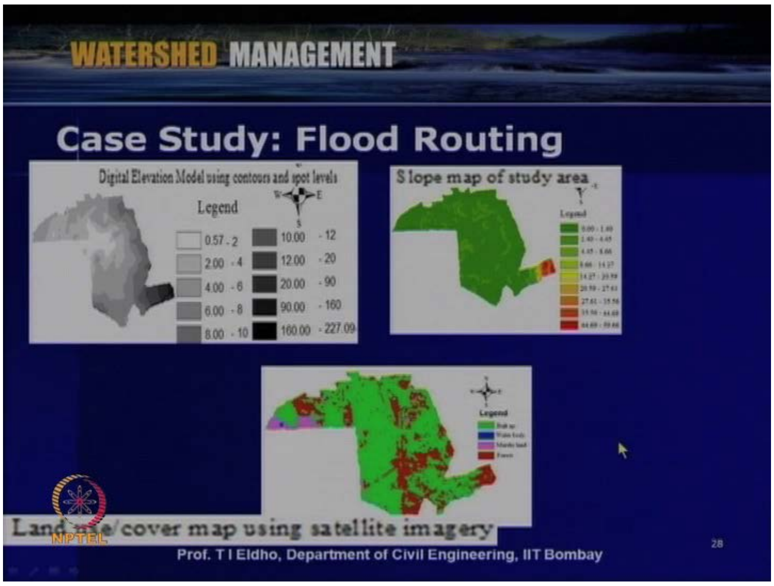

So, here we used an integrated approach of remote sensing GIES. We prepare the digital elevation map; then, slope map and then land use land cover map as shown in this figure – figures. Then, say this is a rainfall which we simulated this to identify the flood routing.

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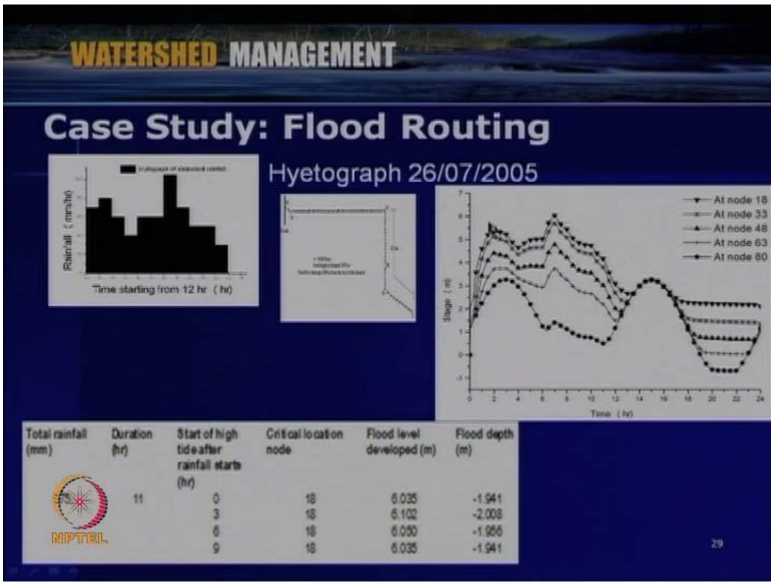

So, for 26 July 2005 the rainfall was about 670 m for duration of 12 hours 675 m. So, say using the model which we develop so we routed this flow so at various locations of the channel like node number 18. Here, node number 33 here node number 48 node number

63 node number 80. So, like that the time versus state of outflow is for the Hydrograph is shown here so from this we can identify how the flooding is taking place we can see that say for example for this problem some location here there is some flooding flood depth is shown with respect to the bank elevation.

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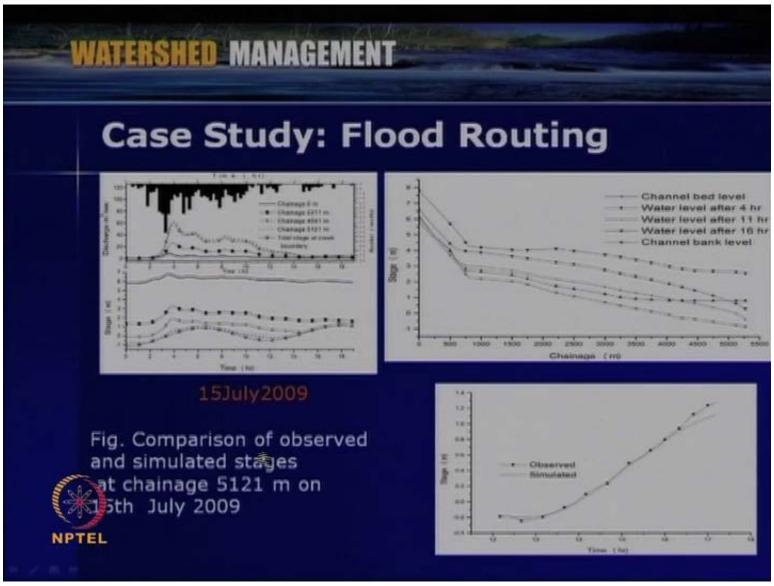

So, then again this for this area the model was run again for another rainfall of 15 July 2009. So, the rainfall pattern is shown here and then the channel the stage variation with respect to the chain age from beginning to the creek end is shown here. So, we can see that this is the channel dam level so there is no flooding and here we did some measurement with respect to the flow depth with respect to time so that is we have compared our model results with observed and simulated.

So, that way what I want to say here is this the flow routing or flood routing is very important in the flood assessment or flood control warning systems for urban watershed or agricultural watershed so that way flood routing is very important.

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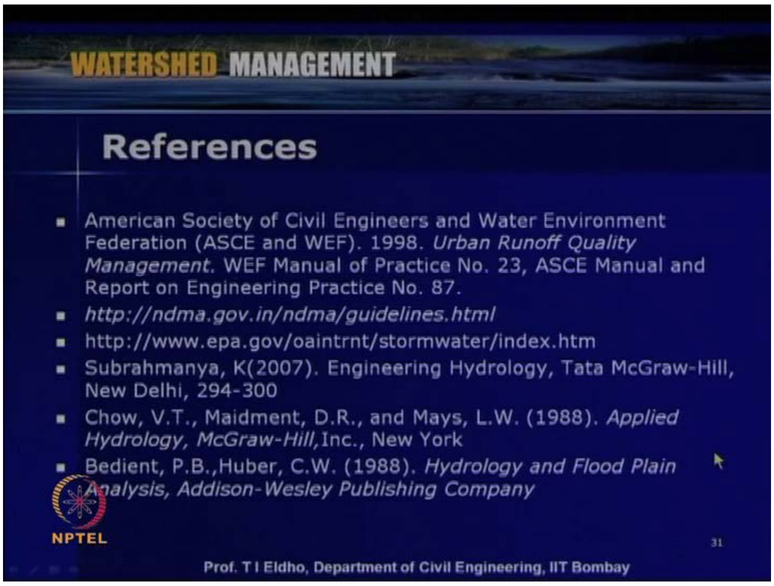

So, some of the important references especially this chow and others applied Hydrology which is some of this aspects are used in today's lecture.

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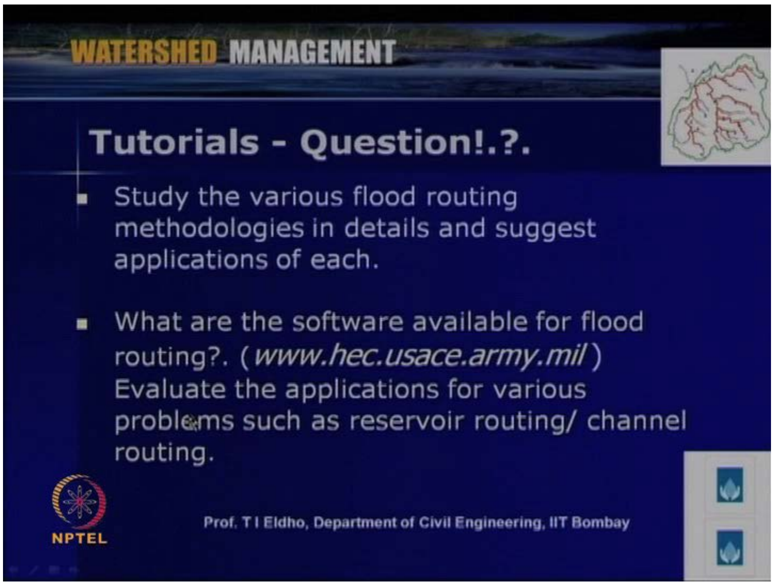

So, before closing today's lecture some of the questions like tutorial questions study the various flood routing methodologies in details and suggest applications of each then, what are the software available for flood routing. So, for example, hec usace all these details are available in this website evaluate the applications for various problems such as reservoir routing or the channel routing.

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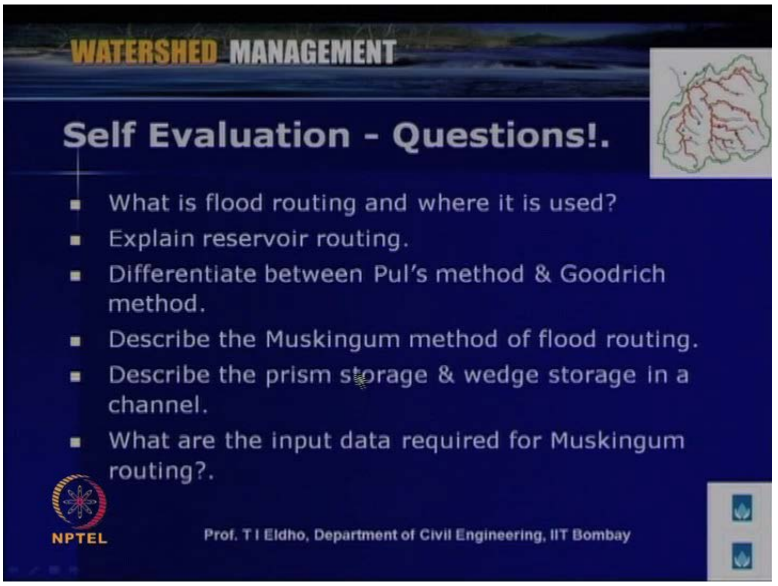

So, then few self-evaluation questions what is flood routing and where it is used explain reservoir routing differentiate between Pul's method and Goodrich method. Describe the Muskingum method of flood routing describe the prism storage and wedge storage in a channel. What are the input data required for Muskingum routing and then the assignment questions.

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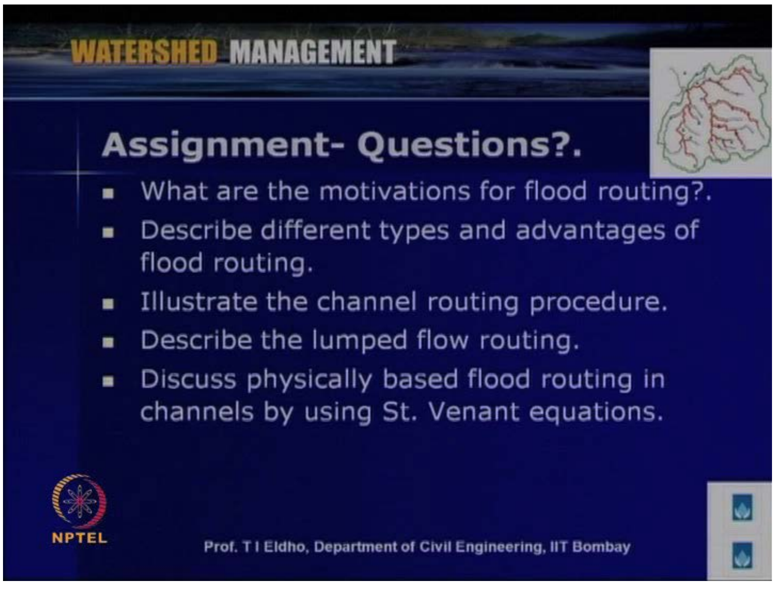

What are the motivations for flood routing? Describe the different types and advantage of flood routing illustrate the channel routing procedure and describe the lumped flow routing. Discuss physically based flood routing in channels by using the Saint Venant's equation. All these questions you can answer by going through today's lecture. so, today what we are discussing was about the flow routing or flood routing in channels and reservoir and say on a watershed basis also flood routing is or flow routing is very important say in the watershed management; thank you.