Watershed Management
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Module No. # 04
Lecture No. # 16
Hydrologic Modeling

Namaste and welcome back to the video course on watershed management in module number 4 - watershed modeling. Today, lecture number 16, we will discuss hydrologic modeling. So, some of the important topics covered in today's lecture include rainfall runoff modeling, runoff process, physical modeling, distributed model.

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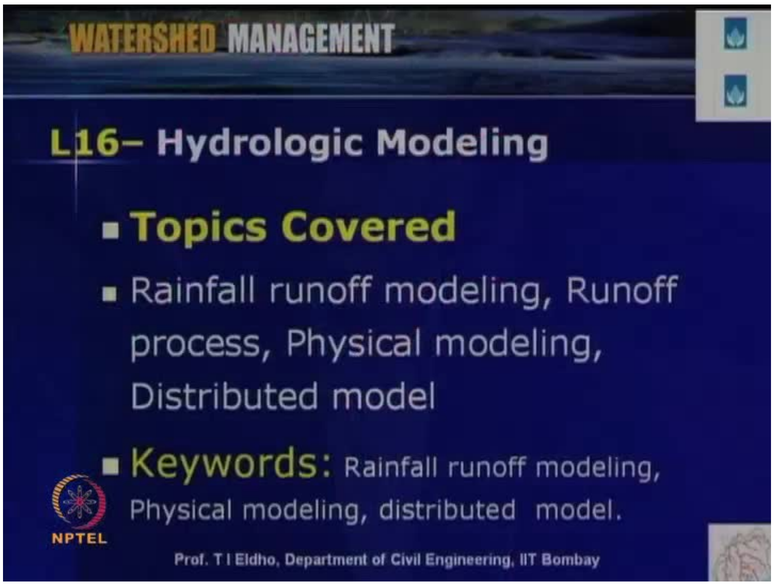

Then some of the important key words for today's lecture include rainfall runoff modeling, physical modeling and distributed modeling.

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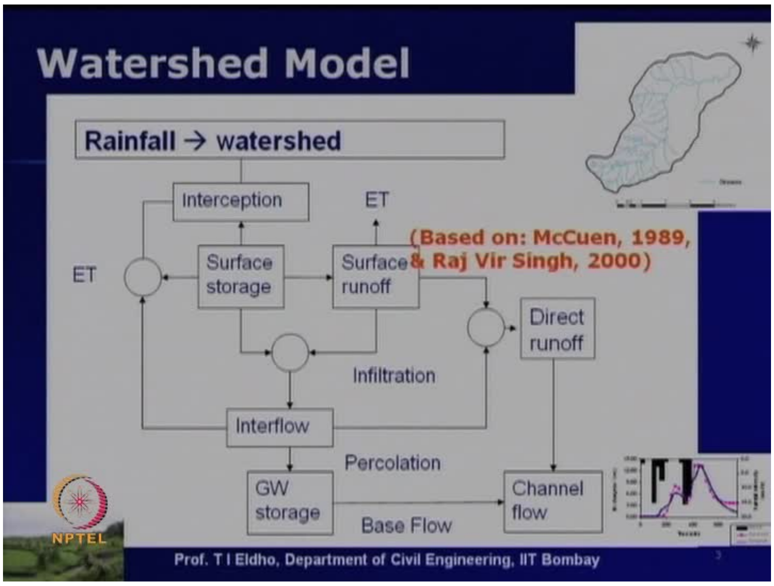

So, as we discussed earlier, when we deal with the water as resources for a watershed, we have to see the various processes what is happening for the transformation from rainfall to runoff, for the precipitation to runoff.

So, we have already seen that various hydrological processes will be there between this transformation from precipitation to runoff. Some of the important hydraulic processes which we have already seen earlier is the interception by the vegetation, and then evapotranspiration, then surface storage or depression storage, then the infiltration, then interflow percolation, and then, surface runoff, and finally, coming back to the direct run off. Then all these direct runoff from the overland flow runoff, it will be joined to the channel for example, this is the watershed then you can see that from various small channels finally, a big stream for the watershed and the runoff will be taking place through the channel to the outlet of the watershed (Refer Slide Time: 01 14).

So, here also we may have to include the ground water storage, ground water processes. So, mainly the surface water processes and the ground water process and surface water processes, we can classify into the overland flow component and the channel flow component.

Then, when we are looking for the hydrologic modeling we have to assess for the given rainfall condition how much will be the runoff at any location of the watershed; either the distributed way or as a lumped way at the outlet of the watershed.

Generally, at the outlet of the watershed we will be describing as in terms of a hydrograph, where the hydrograph is the discharge versus time. So, you can see that if this one is the given rainfall millimeter per hour, and then, correspondingly we can identify how much will be the runoff as the hydrograph discharge versus time, at the outlet of the watershed or in the case of distributed model at any location of the watershed.

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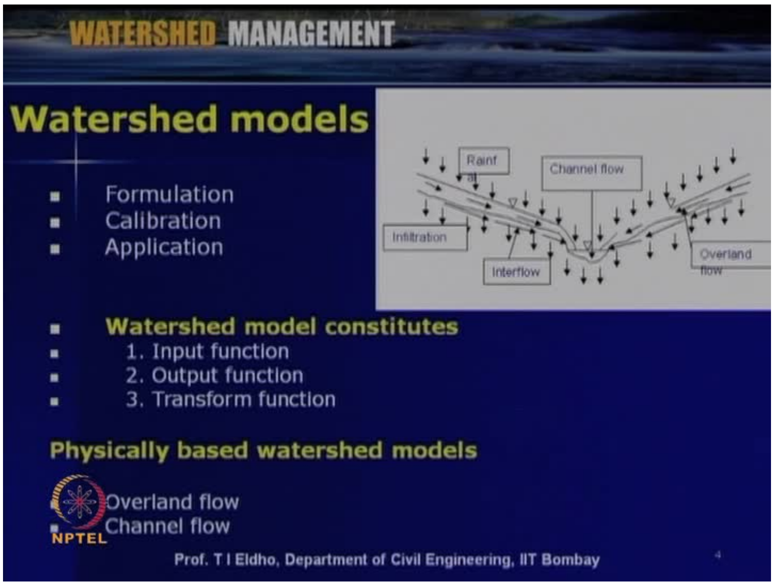

So, that way as we discussed earlier we have various components as far as within the transformation from the rainfall to runoff. We have already seen how to construct a watershed model in the previous lectures. First we have to develop a conceptual model for the watershed including watershed delineation and the consideration of various parameters. Then we have to formulate the model so it can be either lumped model or the black box model or the distributed model, so that aspect also we have seen in the last lecture. Then once the model is formulated we have to develop the corresponding model as a computer model or otherwise an analytical model.

Then, for the given problem, for the given area, we have to calibrate various parameters. As far as the watershed is concerned and then for the given conditions for the given intensity of rainfall or for given the event based rainfall conditions, either for event based simulation or continuous simulation, we can do as far as the rainfall to runoff modeling as a watershed model is concerned.

So, in all these aspects as we have already discussed there is an input function. So, input function is mainly the rainfall as far as the watershed is concerned and then output function is the runoff. So, runoff taking place at the outlet or at any location of a watershed and the transformation function is the third one and that is mainly the various hydrological processes taking place between the rainfall to runoff. As we already discussed, so as far as surface runoff is concerned, when the rainfall is taking place we can classify as far as runoff rainfall runoff is concerned, we can classify as the surface runoff into overland flow and the channel flow.

After the losses or the or the transformations taking place, then we can see that the overland flow, the on the overland flow the runoff starts and then through small channel it will be coming to the main channel and then, the channel flow is taking place. So, when we say that when we are going to model in watershed as far as rainfall runoff is concerned, we have to consider various processes as so-called transformation taking place and then we have to also consider the down water flow components if it is there. Then, as far as surface flow is concerned, the model for the overland flow and the channel flow.

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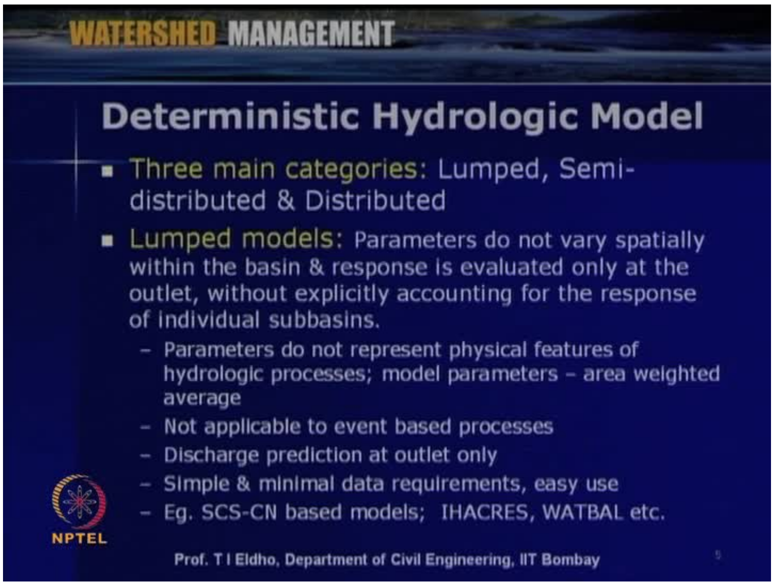

So, both should be combined together to get the runoff at any location of the watershed or the outlet of the watershed. Now, we will see more aspects as far as the hydrologic modeling is concerned. We have seen the various classifications of the different types of models and different kinds of concept-wise we have seen in the last lecture.

Now, in today's lecture we will be discussing about the deterministic hydrologic modeling. Here, depending upon the parameter considered for the watershed we can classify into 3 main categories. So, first one is the lumped model, second one is a semi-distributed model and the distributed model.

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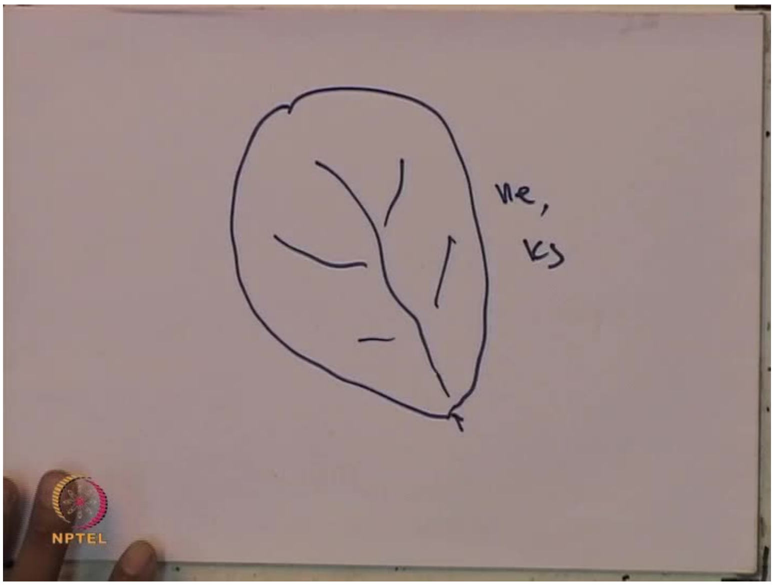

This classification is mainly based upon how we consider the various parameters; first one is the lumped model. So, lumped model is concerned, when we are discussing a particular watershed like this. This is our watershed which we are considering, so we can see that here as far as the watershed is concerned we have to see the various parameters are concerned here. Say, like the porosity or various other parameters like ne or the saturated hydraulic conductivity like that various parameter will be lumping for the total watershed as a single parameter. So, that process is called lumped model, so when we are discussing for the given rainfall condition for the area is concerned there will be one value for the total watershed.

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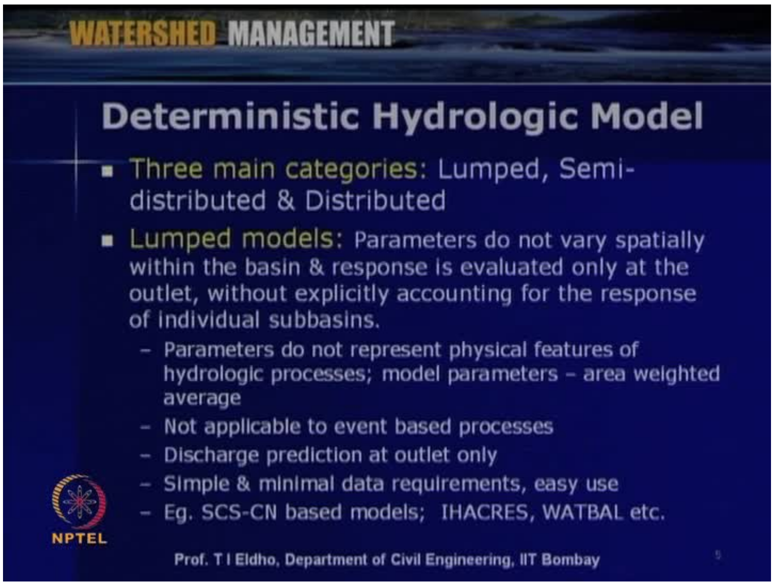

That is so-called a lumped model. In the lumped model we consider the parameters which are not varying, specially within the basin and response is evaluated only at the outlet. So, the parameters the variation we are not considering but the parameters lumped for the total watershed as a single parameter. Then this is without explicitly accounting for the response of individual sub-basins. So, you can see that so here you can see that there are various sub-basins; we can consider for this watershed this may be different sub-basin for the considered watershed. Here, we are not considering the variations as far as these sub-basins are concerned. But, here the parameters we lump for the total watershed. So, here the parameters do not represent physical features of the hydrologic processes.

Model parameters are the parameters which are area weighted; so it is an average, for the various parameters for sub-basins are known. We consider the average of those parameters and then we lump for the total watershed; so that way, when we are doing these kinds of,… when you are using the lumped models. It is difficult to cope up with the event based rainfall to runoff modeling but, we can do continuous simulation for a daily basis or weekly basis or a monthly basis. What is happening, since most of the parameters here are lumped?

Generally, when we use lumped models, the discharge prediction is only at the outlet and so that way, we may not be able to identify what is really happening with respect to spatially or with respect to time. What are the various hydrologic processes? How these processes are varying we may not be able to identify when we use the lumped models. But, of course, these lumped models have got a number of advantages. As I have listed here, these models are very simple and then minimal data requirements and then easy to use. Since the parameters are lumped, an average parameter we are taking; so that way the modeling is very simple and data requirement is very less. In the model development and running and getting results are much easier but of course, some of the disadvantages like these lumped models we know, truly represents the various hydrological processes taking place within the watershed.

So, that way we may not be able to capture what is happening with respect to the rainfall to runoff various things happening. And, then how the runoff is distributed throughout the watershed? All those things we may not be able to capture as far as the lumped models are concerned. So, there are number of lumped models available.

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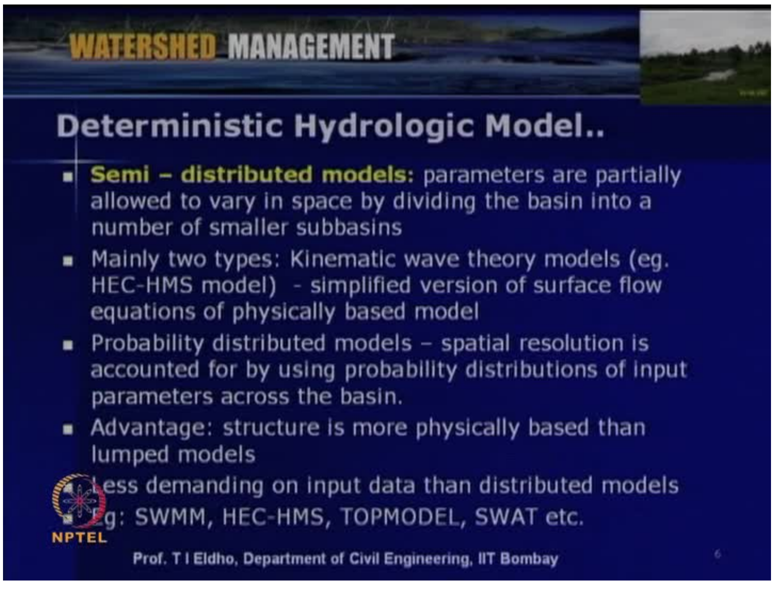

We already discussed in the last lecture about the soil conservation curve number based model. So, that is one of the commonly used lumped model for watershed modeling. Then, other software like IHACRES; IHACRES then water balance models, etcetera. So, these are some of the lumped models commonly used in practice. So, that is one category of model; we have already seen the advantages and limitations of lumped models.

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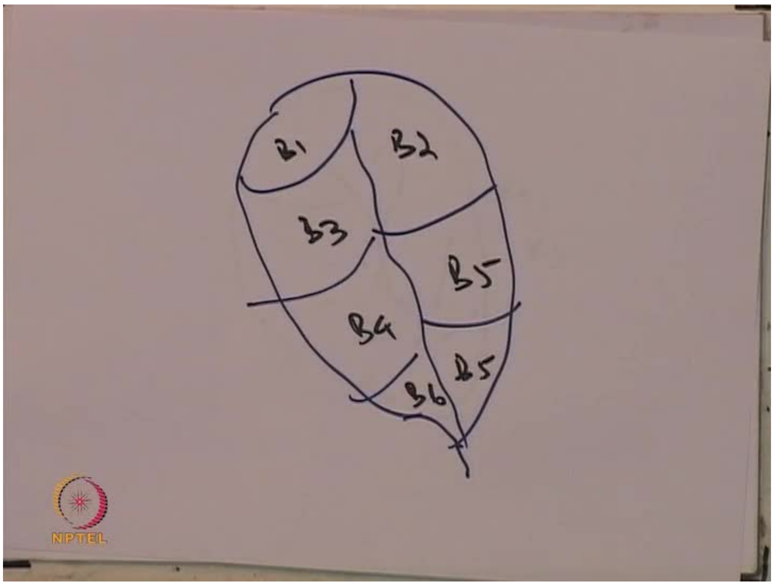

Now, if you want to identify what is truly happening within a watershed, we have to go for either semi-distributed models or fully distributed models. In the case of semi distributed models, the parameters are partially allowed to vary in space by dividing the basin into number of small sub-basins; so here you can see that if this is our watershed which we consider, then we can say if this is channel.

Then, various sub-basins we can identify for the watershed. So, this is a basin 1, 2, 3, 4, like that. So, various sub-basins depending upon the for example, the land use, land cover, so like that. We can classify various sub-basins for the given watershed and for each sub-basins we can identify the various parameters which are, we are, directly dealing with for that particular model. So, that sub-basin-wise actually, it is lumped or we are taking the weighted average. That way actually, to certain extent the various parameters variation will be represented within the watershed but, not full extent like a fully distributed model. Here, the parameters are partially allowed to vary in space by dividing the basin to number of smaller sub-basin as shown in this figure (Refer Slide Time: 12:20) and there are mainly two types of semi-distributed models.

So, here the kinematic wave theory based models like example: is HECHMS models and then simplified version of surface flow equations. These are all actually simplified version of surface flow equation. So, physically based model there are semi distributed models are concerned.

There can be two types of models: one is actually, it is distributed from the distributed flow model based upon the Saint-Venant’s equations. That is so-called kinematic wave theory based model. Here, the important parameters in this kinematic wave theory models we obtained from the,… we take it for the sub-basins and then we do the modeling.

Second categories so-called probability distributed models; probability distributed model the spatial resolution is accounted for by using the probability distribution of input parameters across the basic. So, here instead of say for the given sub-basin also or for the watershed also, we can identify how the parameters are varying according to some probability distribution like, a normal distribution or any kind of probability distribution which is suitable for that parameter and then we can take that distribution. So, when we use that kind of modeling that is so-called probability distributed models, here probability distributed models, some of the advantages like, its structure is more physically based than lumped model.

So, then here the less demanding on input better than distributed model; so, here the parameters compared to a fully distributed model. For the semi distributed model the parameters the variation is considered so that, some of the important features of the watershed are captured.

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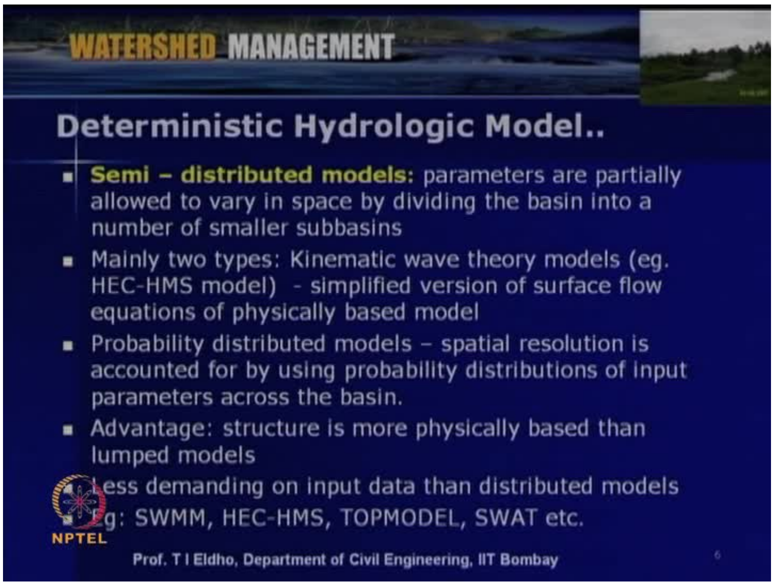

So, here less demanding on input data than distributed models, some of the advantages are like the features are somewhat represented and these parameters are not fully like compared to fully distributed model. Here it is not the complete variation is taken care but sub-basin ways variation is taken care. So, there are number of semi-distributed model available literature like a SWMM model, storm water management model then, HEC hydraulic engineering center hydraulic model, simulation HECHMS model. Then, top model and then soil water assessment tool SWAT model. All these are somewhat semi-distributed models. Here we can see that we consider for example SWAT model, we consider the hydrologic response unit and for each response unit we take the weighted average parameters.

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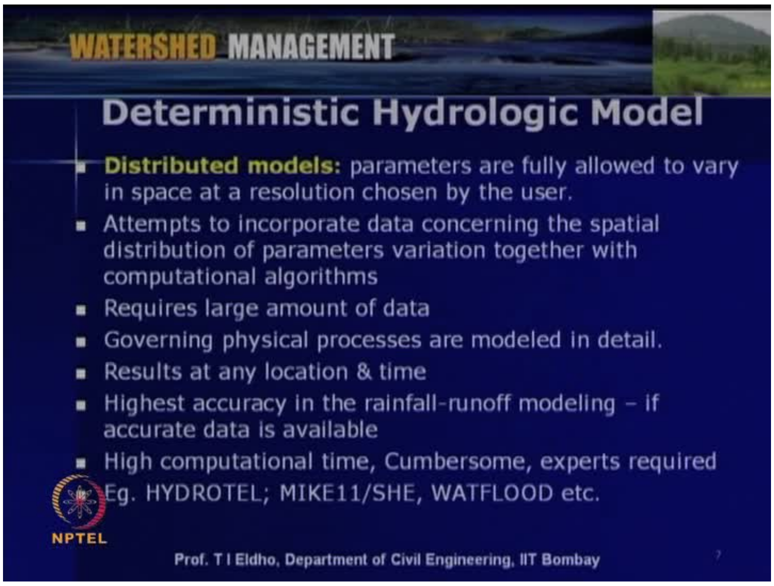

Then accordingly, the modeling is done so that, category of modeling is called a semi-distributed model and then the next category models are called distributed models. So, here the parameters are fully allowed to vary in space at a resolution chosen by the user. Here, the parameters are varying according to the realities or how much data we can collect for the watershed. Accordingly, the parameters variation can be taken care and then we attempt to incorporate data concerning the spatial distribution of parameters variation together with computational algorithms.

So, even this variation we can represent in terms of like some algorithms or some equations for example, infiltration is concerned. So, for that how the variation is taking place with respect to soil or with respect to the depth of soil. Like that we can have various computational algorithms and so actually, these are truly the physical models which is are representing the complete features of the watershed. But, some of the disadvantage of these kinds of modeling include and requires large amount of data. We need to capture the entire variations of the various parameters within the watershed either through field investigations or through some that kind of equations. Then, some advantages include the governing physical processes, are modeled in detail; so all the aspects we can capture and then results at any location and at anytime when we are dealing time depending modeling, the spatial variation we can obtain from rainfall runoff. So, how much is the runoff at particular location or what is the depth of flow or how the discharge variation is taking place? So, location and time base we can identify and then if all the data are available in an accurate way, I mean, the data is accurate then the results will be also accurate. So, highest accuracy in rainfall runoff modeling is possible but, most of the time this is a big question mark; since, most of the time as far as a watershed is concerned many of the parameters are varying drastically from one location to another location.

Accordingly, it is very difficult to get all these parameter variations and then to get the accurate data. As far as the parameters are concerned, it is not so easy; so that way the accuracy of the model results will not be set to the expected levels. So, there will be lot of variation. Since the data input is not accurate then obviously, results will not be also accurate and then some other limitations like high computational time. When we are going to run such models we need to run the computer for long time and then the modeling will be cumbersome. Then that kind of models only experts can do; so that means those who know how the modeling is done. And then, most of the time we have to go for numerical modeling like a final difference or final terminal modeling; so the experts only can easily do these kinds of modeling.

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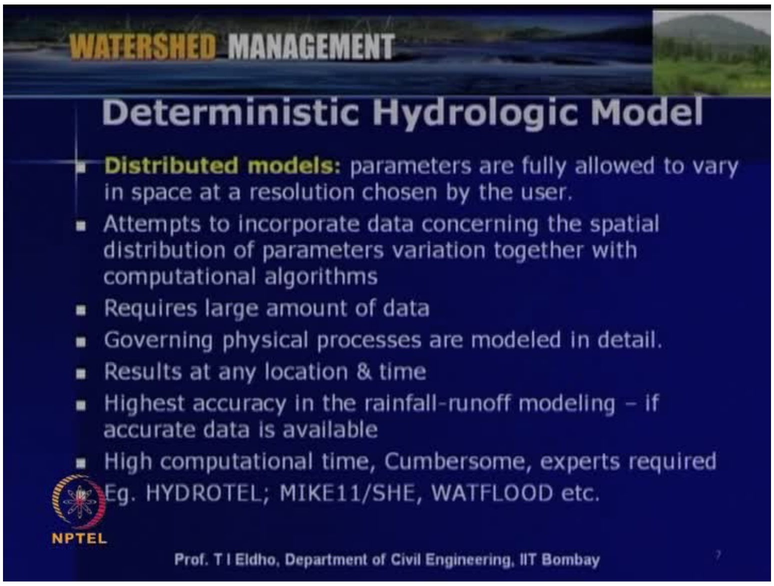

Some of the available software included like hydrotel modeling mike11 or mikeshe models; then watflood model, etcetera. So, these are all physically based model where we solved the Saint-Venant's equations or the governing equations by considering the conservation of mass or continuity equation and then momentum equations. Then, we use a numerical tool like finite difference method or finite element methods and then we develop this model by considering the various hydraulic processes like infiltration, evapotranspiration, interception, interflow, groundwater flow component, etcetera.

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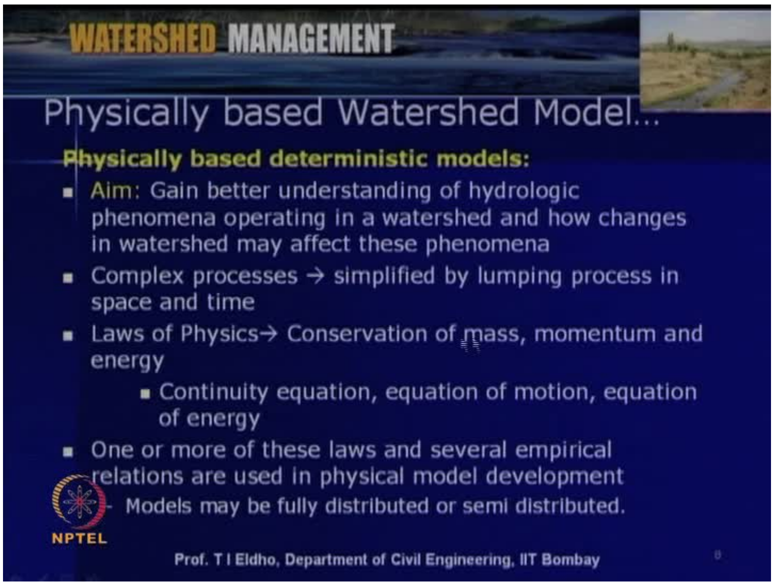

Then we make this model; so as you can see so much of data is required to get accurate results for these kinds of models. Now, we have come back to the physically based watershed model, based upon the governing equations and within a based upon a system approach. So, the main aim in physically based deterministic modeling is to gain better understanding of hydrologic phenomena operating in a watershed and how changes in watershed may affect these phenomena. So, this is what we are trying to do as far as watershed modeling is concerned.

We want to understand the hydrologic phenomena operating and then if any changes are proposed like, we constructing a check dam at particular location or we are going for water harvesting measures. Then, what will happen? So, that way, that is our aim. As we can see that all the variations or all the topography or the topological features or geological features of the watershed is concerned, is so complex. Accordingly, this modeling is also very complex. So, only thing is that we can using certain assumptions we can, may go for a 1 dimensional, 2 dimensional modeling. Or, we can lump various parameters or processes with respect to space and time and then we can simplify the models.

Most of the physically based deterministic models generally, follow the loss of physics. So, that means mainly in these kinds of models according to the poor mechanics theories we use conservation of mass conservation of momentum and conservation of energy principles. Out of this generally, we use conservation of mass and conservation of momentum. So, conservation of mass, corresponding continuity equation and conservation momentum, corresponding equation of motion and then equation of energy or Bernoulli’s theorem we can utilize. One or more of these laws and several empirical relations are used in physical model development. Generally, as far as the modeling is concerned, we use these governing equations. But, to deal with various hydrological processes between the transformation functions like a evaporation, evapotranspiration then intersection, then infiltration, etcetera. So, various hydrologic processes are to be considered.

So, that way we may have to combine various empirical relations with this physical model or the models based upon the laws of physics. Finally, as we have seen in the previous slides, these kinds of models may be fully distributed if all the parameters variations are considered in a better way as far as the watershed is concerned.

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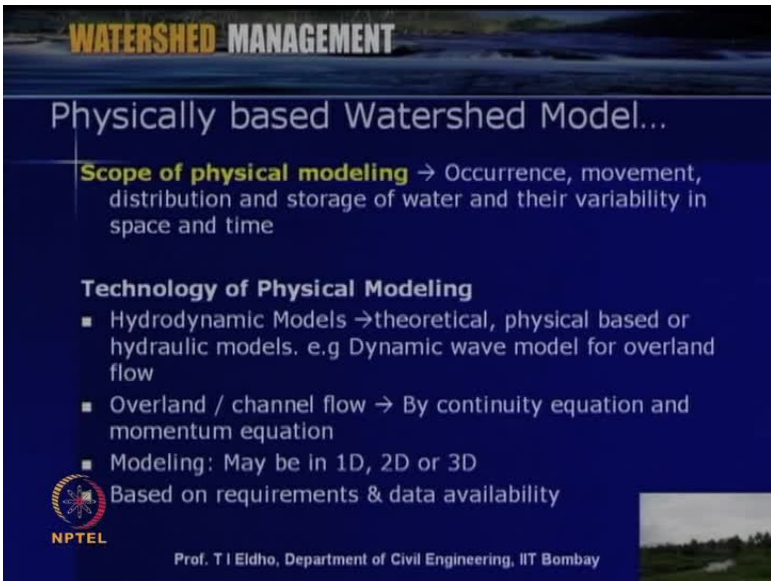

Or it may be semi-distributed models depending upon the way which we consider the parameter distribution or parameter variations within the watershed. As I mentioned so the scope of physical modeling is, we want to identify what is happening. For example, rainfall to runoff: so that means, occurrence, moments distribution and storage of water and their variability in space and time. So, that is what we are trying to do as far as any hydrologic modeling is concerned. So, rainfall occurrence and then how the runoff movement is taking place and how it is distributed and then what kind of storage is taking place in between so all those things we are checking we are studying or we are analyzing with respect to space and time.

Then the,… as far as the technology of physical modeling is concerned, as we have already seen, we are solving these governing equations. These governing equations are partial differential equations then single order but it is a non-linear type of equations so we have to go for a numerical modeling.

These hydrodynamics models we have developed based upon these governing equations and so, these are all physical based or hydraulic models. So, like a dynamic wave model for overland flow, then as we have seen, we can consider the overland and channel separately. Overland flow and channel flow by continuity equation and the momentum equation: as far as modeling is concerned, even though the physical phenomenon is 3 dimension nature depending upon the problem which we are solving we can make into either a 1 dimensional or 2 dimensional approach depending upon the problem. So, depending upon the requirements for which we are trying to develop the model and then the data availability we can go for 1 dimensional model or 2 dimensional model or in certain cases it is quite cumbersome.

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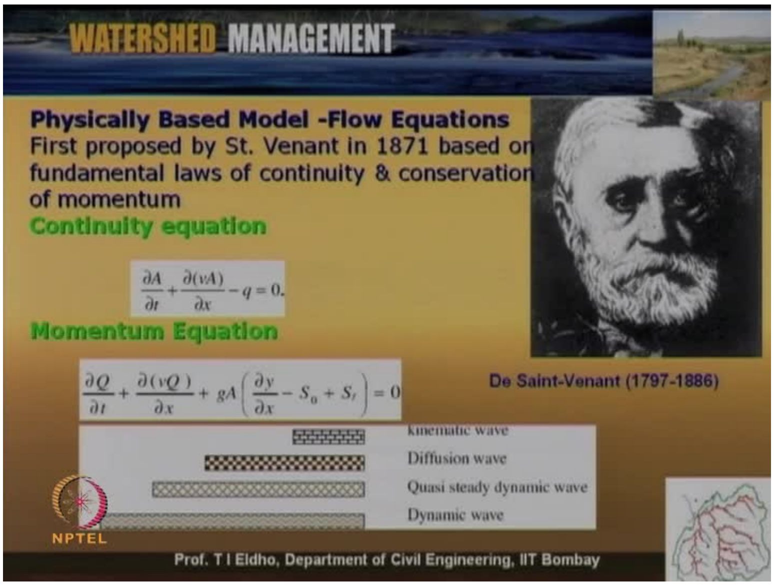

But 3 dimensional models also sometimes we may do as far as the watershed modeling is concerned. Now, we will come back to the governing equations; what are the governing equations like? As we have already seen, the laws of physics like conservation of mass and momentum, we are utilizing as far as the physically based model development is concerned.

Actually, these governing equations were derived in the 19th century itself by Saint-Venant. Here, we will not discuss the derivation of these equations. Derivations of the equations in standard fluid mechanics or watershed based books we can see the derivations. So, here we have discussed only the governing equations; here Saint-Venant in 1871 derived this equation based upon the fundamental laws of continuity and conservation of momentum. So, the continuity equation we can write as del A by del t plus del v A del x minus q is equal to 0, where A is the area which we consider and v is the flow velocity and q is the, for example, any inflow or some abstraction taking place within that particular system is concerned.

Then this is the continuity equation and then momentum equation; we consider del Q by del t plus del v Q by del x plus g A into del y by del x minus S 0 plus S f is equal to 0. So, this is the momentum equation so here Q is the discharge at any particular location which we consider then v is the flow velocity; then g is acceleration due to gravity A is the area cross section or the flow of the section which we consider y is the depth of flow S 0 is the bed slope S f is the energy slope. Now, these are the fundamental equations so-called Saint-Venant's equations a continuity equation momentum equations so when we solve this so these equations you can see that this is presently it is given in 1 dimension

So if this is the watershed which we consider, if the main channel and then various overland is concerned, we can consider as various strips or various plains joining to the main channel and then it can be also considered overland flow; also can be considered 1 dimensional and the channel flow also can be considered as 1 dimensional. When we are solving these both equations completely like the continuity and momentum equation then, that kind of models are called dynamic wave modeling. So, this is the entire both equations are considered then we call it as dynamic wave and then when we are not considering the time dependent term in the momentum equation this term del Q by del t then that kind of models are called Quasi study dynamic wave models. But, of course, this will be solved with the continuity equation and then, when we are considering when we are neglecting these two terms, only up to these terms are considered in the as the momentum equation is concerned (Refer Slide Time: 28:35).

Then we call that kind of model diffusion wave model, this term in this equation and plus the continuity equation, that is so-called diffusion wave modeling and the kinematic wave model - a continuity equation and we consider this bed slope is equal to energy slope so that kind of models are called kinematic wave model.

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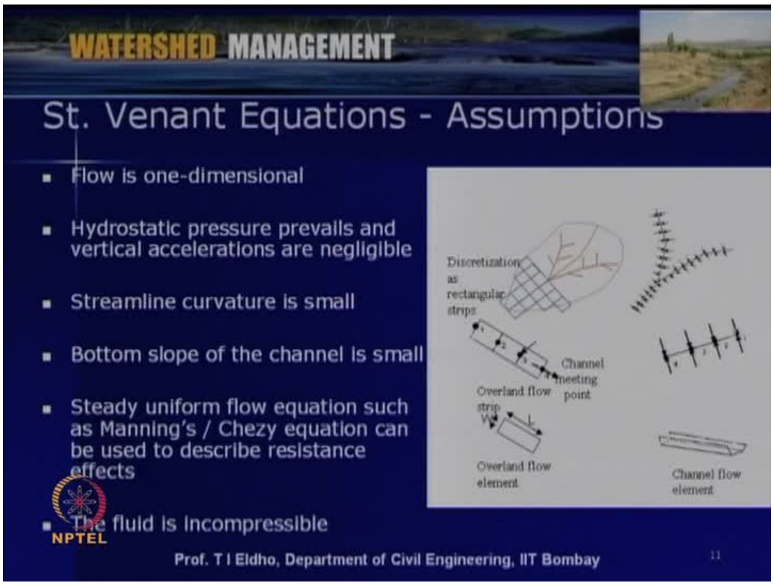

So, these physically based models we can classify into dynamic wave model Quasi steady dynamic wave model or diffusion wave model and the kinematic wave models this Saint-Venant's - the equations divided by Saint-Venant's are based upon certain assumptions; the assumptions I have listed here. In this modeling in the governing equations are based upon that the flow; is 1 dimensional then hydrostatic pressure prevails and vertical accelerations are negligible then stream line curvature is small bottom slope of the channel is small.

Steady uniform flow equation such as Manning's or Chezy's equation can be used to describe the resistance effects or the frictional effects. Then, the fluid is incompressible; so these equations are based upon these assumptions. So, the governing equation as I mentioned in the previous slides, are 1 dimension nature as we can see that here if this is the main channel for the watershed.

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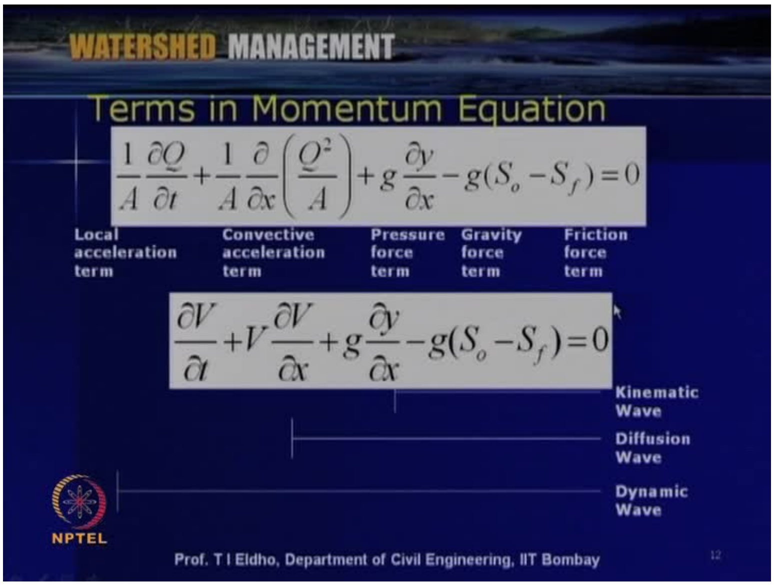

Then you can see that we consider as 1 dimensional flow and then the overland flow is concerned, we consider strip flow joining the main channels as 1 dimension. If you critically analyze the Saint-Venant's equations, we can see that different forms of this equations especially, momentum equations we can write in different forms. Say, either in terms of velocity only or in terms of discharge only as shown in these two equations. So, if you critically analyze this equation you can see that this term 1 by A del Q by del t or del V by del t this is so-called local acceleration term and then this term which is V into del V by del x or 1 by A del by del x of Q square by A; this is so-called convective acceleration term.

Then this term is so-called pressure force term and then we are having the gravity force term. So, here this S f is the frictional force term; as I mentioned, we can have a kinematic wave form or diffusion wave form or dynamic wave form and if it steady state we can have steady dynamic wave form also by neglecting the variations of this del V by del t or this term. Local acceleration term can be neglected.

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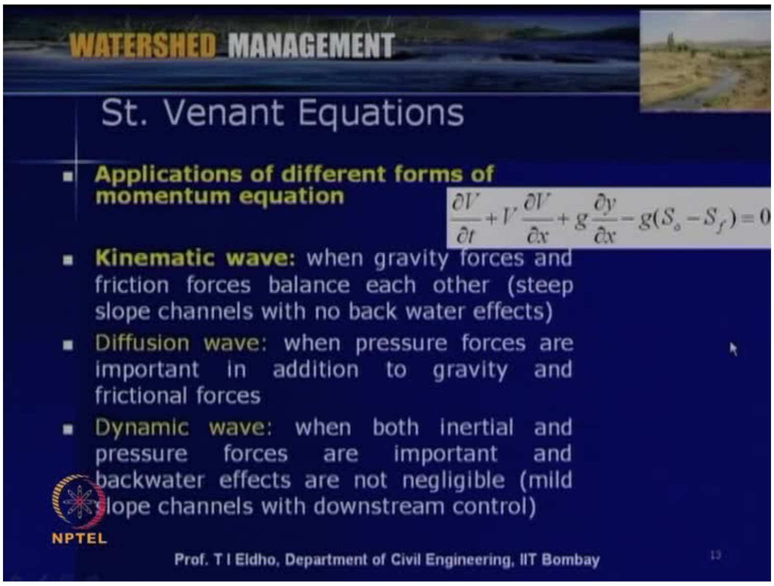

Now, the Saint-Venant's equations are concerned as I mentioned, we can have various forms like a kinematic wave form or diffusion wave form or dynamic wave form. So, when the gravity forces when the kinematic wave is the perform when gravity forces and friction force forces balance each other like for example, steep slope channels with no back water effects, so then that kind of modeling is called a kinematic wave model and diffusion wave model we can use when pressure forces are important in addition to gravity and frictional forces. So, that kind of model is diffusion wave; then dynamic wave is when both inertial and pressure forces are important and back water effects are not negligible like mild slope channels and downstream control with downstream control; so that way we may have to use the dynamic wave model.

So, depending upon the problem we can choose either the full dynamic wave form like the full Saint-Venant's equations or we can go for the diffusion wave form; depending upon the condition the channel condition or depending upon the problem or we can go for the kinematic waveform.

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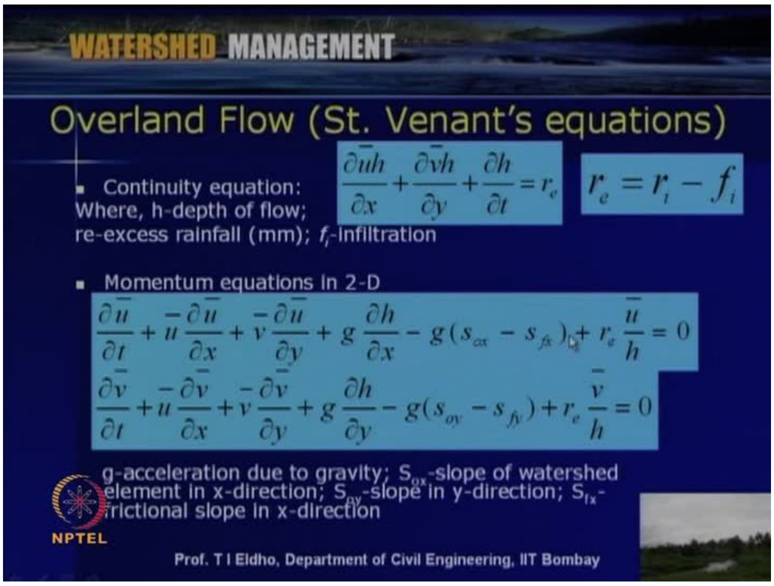

Accordingly, we can choose the model; so what we have discussed is the Saint-Venant's equations in its general form. As I mentioned, we are having the continuity equation based upon the conservation of mass and then equation of motion based upon the conservation of momentum. So as far as these equations are concerned, we can write either in 2 dimensions or 1 dimension; most of the time either 2-D or 1-D equations will be utilized. So, these equations different forms like conservative form or non conservative form, different forms we can write depending upon the way which we consider.

Now, we will consider this Saint-Venant's equations for the overland flow and channel flow separately; since when we go for watershed model as I mentioned, we may have to consider the variation or the from the rainfall runoff with respect to the overland flow and the channel flow. So, now let us see how we go for overland flow. The Saint-Venant's equation continuity equation in 2 dimension we can write in this form, where del by del x of u bar h plus del by del y of w bar h plus del by del t of h is equal to r e where r e is the rainfall excess so if r i is the rainfall then and f i is the infiltration and taking place so r e we can get. The excess rainfall so this will be equal to r e; so where u bar and v bar the velocity in x and y direction h is the depth of flow and x and y are the dimensions in x direction y direction and t is the time.

So, then correspondingly as far as overland flow is concerned, the momentum equation 2 dimension we can write in this form: del u bar by del t plus u bar by into del u by del x plus v bar del u by del y plus g del h by del x minus g into S o x minus S f x plus r e into u bar by h is equal to 0; so here similarly we can write for the y component. So, u bar v bar the velocity in x and y directions S o x and S o y are bed slope in x and y direction and S f x and S f y the energy slope in x and y direction r e is the excess rainfall so this way as far as overland flow.

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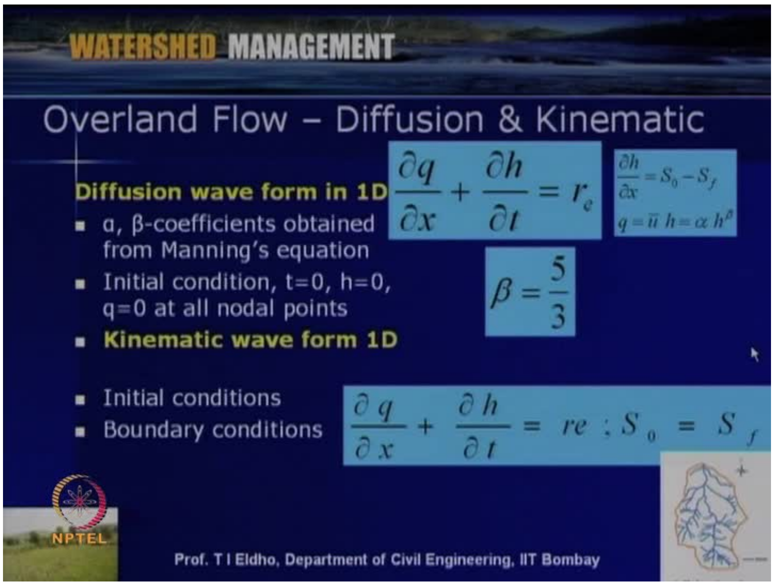

Generally, overland flow we can consider as 2 dimension and but sometimes we can also approximate as 1 dimension depending upon the way we are modeling; but, most of the time channel flow we can consider as 1 dimension flow; so these are the governing equations as far as the overland flow is concerned. Now, we have already seen now the equations what we have seen is the dynamic wave form of the Saint-Venant's equation. So that, depending upon the condition we can simplify into diffusion waveform or kinematic wave form. The diffusion wave form is shown here; so here the continuity equation will be del q by del x plus del h by del t is equal to r e where q is the discharge per unit width and r e is the rainfall excess.

So, this we can write with respect to the diffusion wave, the momentum equation will be written as del h by del x is equal to S 0 minus S f where q is equal to u bar into h u bar is the velocity in x direction and that is, can be written as alpha into h to the power beta where alpha beta coefficients obtained from Manning's equation. Beta can be written as 5 by 3 depending upon which wave consider then kinematic wave form. We can write as del q by del x the continuity equation and the momentum equation continuity equation saying del q by del x plus del h by del t is equal to r e and the momentum equation is just bed slope is equal to energy slope.

For the dynamic wave form or the diffusion wave form or the kinematic wave form, now the governing equations we have seen and now, to solve these equations we have to put appropriate initial and boundary conditions. So, initial conditions, if you are going for time dependent modeling initial conditions are required. Initial conditions can be either we can assume the depth of flow throughout the watershed. We can assume as 0 or the discharge can be assumed as 0 and then we can apply the boundary conditions. So, boundary conditions can be, we know the upstream of the watershed like the ridge we can assume the flow depth or the flow as equal to 0. The downstream condition we can put the gradient of del h by del x or these kinds of gradient we can keep it as 0 or other type of boundary conditions Dirichlet boundary conditions or the Neumann boundary conditions can be applied. So, this either dynamic wave form or diffusion wave form or the kinematic wave form as far as the overland flow is concerned, we can solve these governing equations by using a numerical technique.

You can see that the governing equations partial differential equations; we have to go for numerical solutions as far as the solution is concerned, like a finite difference method or finite terminal method. So, we have to solve these governing equations and apply the suitable initial and boundary conditions for the concerned watershed and then we can develop the model to obtain the runoff at the particular locations for the watershed is concerned. Here, like many other losses like evapotranspiration or the infiltration all these losses we can account as far as the rainfall excess calculation is concerned; so accordingly we can deal with the model.

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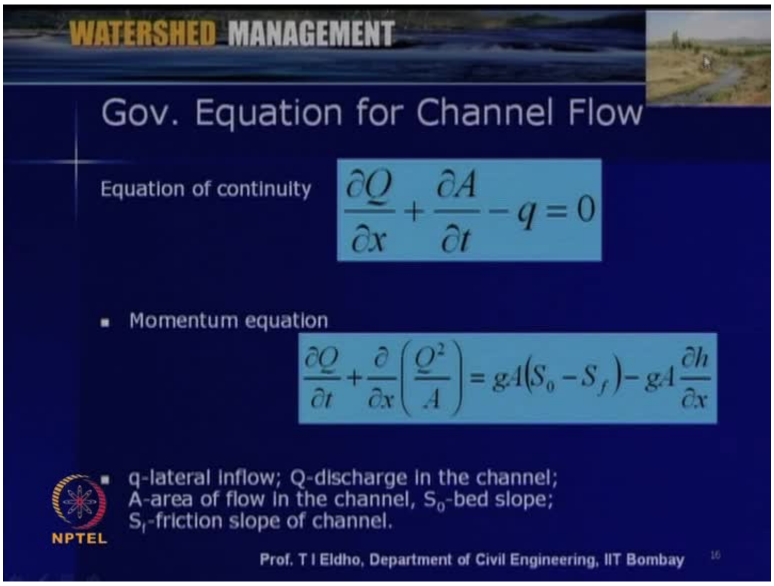

So, now so that is about the overland flow. Now, coming back to the channel flow, the other component is the channel flow. So, this overland flow will be joining to the channel at the particular locations. so you can see that if this is the watershed and then if this is your main channel, so then the when the rainfall takes place the runoff will be coming from the channel overland and will be joining to the channel and then we have to route the flow through the channel depending upon the wave changes taking place with respect to the overland flow component. Here, the governing equations are the Saint-Venant's equation but we can write slightly in a different way. The equation of continuity is del Q by del x plus del A by del t minus q is equal to 0, where Q is the discharge in the channel, A is the area flow in the channel and q is the lateral inflow coming to the channel as overland flow.

The momentum equation can be written as del Q by del t plus del 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, this as I mentioned, this momentum equation different forms we can have; so one particular form is mentioned here.

So, here this energy slope S f we can use Manning's equation or Chezy's equation to get those values and then we can solve this equation. Simultaneously, so that with respect to the overland flow from various locations we can route the flow and then identify what will be the discharge versus time at any particular location of the channel or the outlet of the watershed. So, that way the channel flow equations are solved. Here, also we need to go for numerical techniques like a finite difference or finite element modeling to solve these equations and then use the appropriate initial and boundary conditions. So, here also initial conditions like depth of flow in the channel or the discharge through the channel can be initial conditions at the beginning and then the boundary conditions can be at the outlet or at the beginning of the channel. What should be the flow coming? Or, if the channel is starting at the beginning of the watershed then that can be 0 depth.

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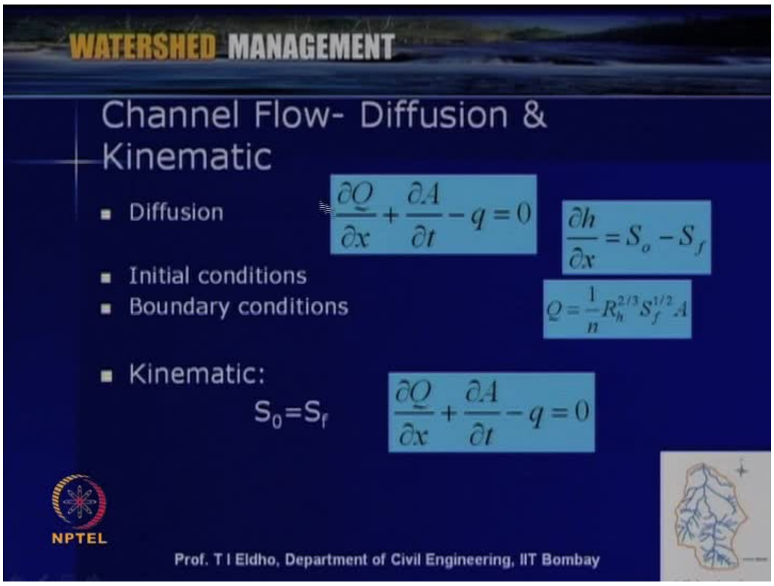

Then now similar to overland flow here also channel flow is also concerned, we can have the diffusion wave model and kinematic wave model. So, in diffusion wave model the governing equation is del Q by del x plus del A by del t minus Q is equal to 0 the continuity equation and the momentum equation is the simplified as del h by del x is equal to S 0 minus S f. So, this S f we can use the Manning’s equation or other Chezy’s equation and then in kinematic approach the continuity equation is same and then we assume the energy slope is equal to bed slope. Here also, we apply the initial conditions and the boundary conditions to identify how the flow pattern is taking place.

How the discharge versus time or depth versus time? We can identify by solving this system of equations; by using numerical techniques. So, either dynamic wave form or the diffusion wave form or the kinematic wave form; we have seen the governing equations and now using this governing equation, using particular numerical models and we can solve the system of equations. Then apply the boundary conditions initial conditions and boundary conditions and then the output will be the depth of flow or the discharge at any location of the channel. Now, we have seen the overland flow and the channel flow. If you want to identify the runoff process taking place within the watershed then we have to couple this overland flow model and channel flow model and then we have to see the coupled we have to run the coupled model. By applying suitable boundary conditions for the watershed, these numerical modeling issues we will discuss in the next lecture and then the coupling aspect also.

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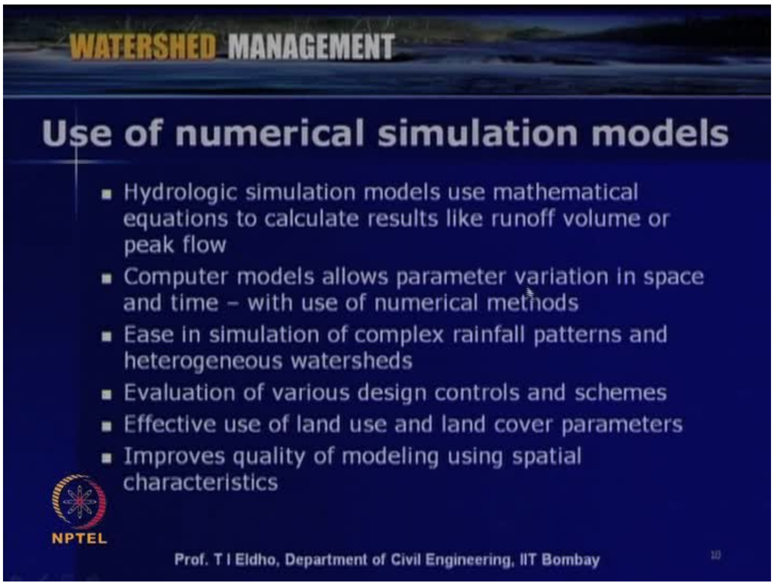

Now, the use of numerical simulation models: as I mentioned, this governing equation we have to solve using numerical techniques. So, hydrologic simulation models use mathematical equations as we have seen in the previous slides to calculate the results like runoff volume or the peak flow. Then, computer models allow parameters variation in space and time with use of numerical methods. So, like finite difference, finite element or method of characteristics or finite volume methods. Then, the ease in simulation of complex rainfall pattern and heterogeneous watershed depending upon what kind of either semi distributed or distributed or what kind of numerical approach we use. Then, evaluation of various design controls and schemes; like, if there are various hydraulic structures how to deal with those structures and how to deal with the various parameters variations like that?

Then effective use of land use and land cover parameters. so for the given watershed the land use land cover will be varying. So, then accordingly, the for example, Manning’s reference coefficient will be varying in the overland flow modeling or various parameters like ferocity saturated hydrologic conductivity, etcetera, will vary so that we can identify and then the spatial characteristics variation if we can take care.

Then we can have better quality or better models for the runoff model for the given rainfall conditions. Now, before closing this lecture let us see some of the classifications of the models. So, like we have seen now the modeling is based upon the Saint-Venant’s equation or its variations.

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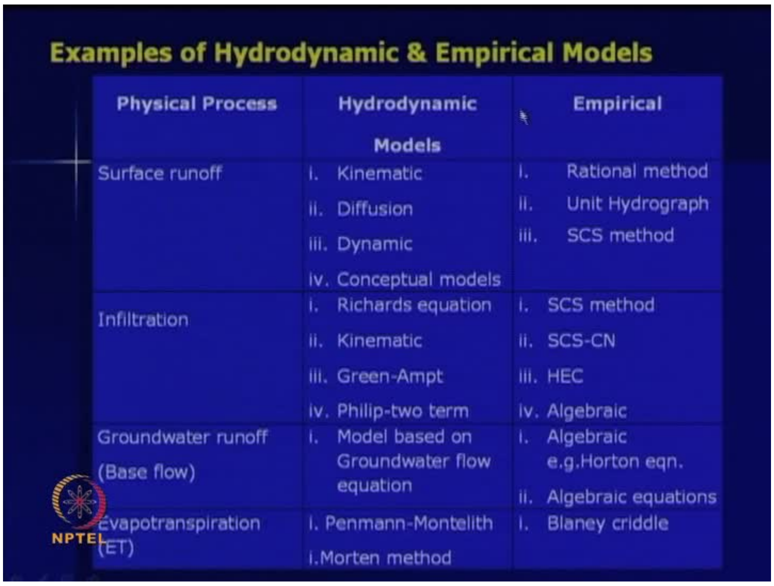

Some of the examples hydrodynamic and empirical models I have listed here. So, the physical processes are listed here then the hydrodynamic models and some of the empirical models for example, if we are dealing with surface runoff we can have the dynamic wave model or the its variations like diffusion wave model or kinematic wave model. Then simple conceptual models like mass balance approach models. So, various models are there some of the important models are only listed here and then empirical equations like rational method or unit hydrograph method, or lumped model like SCS method we can have it.

Then infiltration is concerned we can have various forms of the infiltration empirical equations or the solution to Richards equations or Green-Ampt equation or Philip-two term equations or simplified form of kinematic form. Then the empirical types infiltration models like a SCS method we can also calculate based upon SCS-CN or some kinds of algebraic variations or HEC models.

Then groundwater variation is concerned like base flow; then model based upon ground water flow equations which we will be discussing in coming lectures and then algebraic equations like Horton equation based upon that or evapotranspiration's like as we have already seen, various equations we can utilize like a Penman-Monetelith equation or Morten method or Blaney Criddle method like that.

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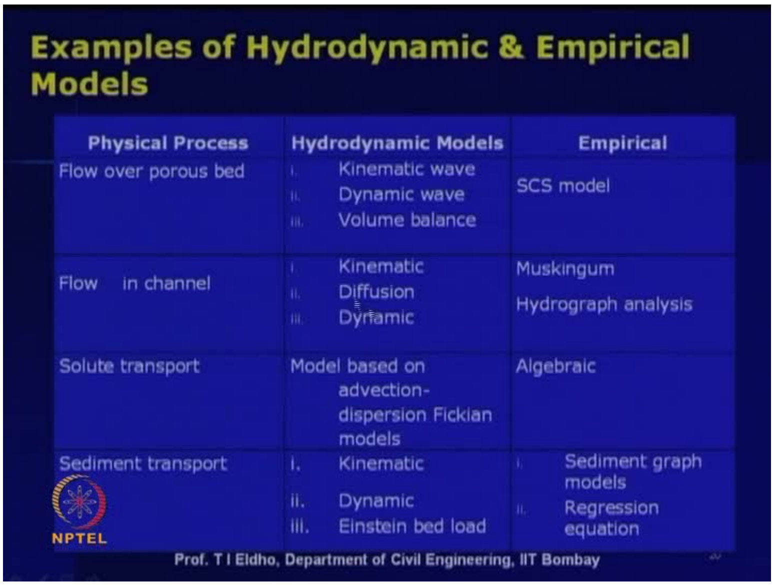

Then flow over porous bed is concerned we can either go for kinematic wave dynamic wave or volume balance models, or then empirical like SCS model, then flow in channel is concerned, as we discussed kinematic diffusion or dynamic hydrodynamic models or Muskingum method or hydrograph analysis. Then, the solute transport is concerned within the watershed model based upon advection-dispersion or Fickian models. We can have, so these issues also we discuss later; or we can have some algebraic type of modeling. Then, sediment transport is concerned we can go for diffusion - dynamic or kinematic or Einstein bed load based equations or Sediment graph models or Regression equations.

So, like that if we go through the hydrologic literature large number of models we can see; may be some of the authors mentioned may be 1000’s of models have been developed for the last few decades depending upon the conditions depending upon the assumptions or various variation like 1-D, 2-D or 3 dimensions or how many parameters we consider or what kind of hydrologic process are concerned.

So, accordingly we can see that there are number of hydrodynamic and empirical models available in literature. You can choose particular model depending upon your requirement your objectives and then we can solve the particular problem as per the objectives.

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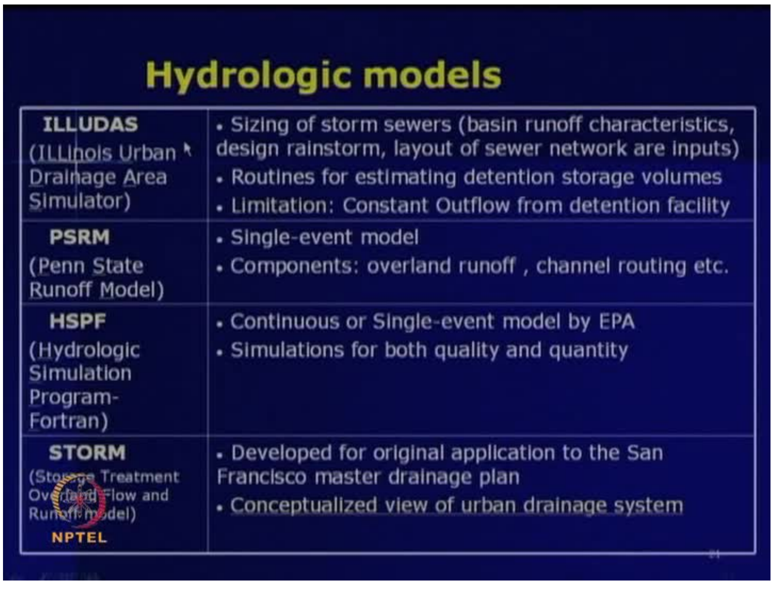

Now, coming back to the hydrologic models we can see in literature number of hydrologic models. I mean the software type software models, computer models developed for specific purposes. Large number of models is available; very few of these important models I have put here in these two slides. So, first one is so-called ILLUDAS model - Illinois urban drainage area simulator. This is used for sizing of storm sewers like routines for estimating detention storage volumes; so limitations like constant outflow from detention facility, then PSRM models like Penn state runoff models. This is single event model and the components like overland runoff channel routing, etcetera are considered. Then, HSPF model like hydrologic simulation program FORTRAN. This is either it can be continuous or single event based or simulation for both quality and water quality and quantity can be considered.

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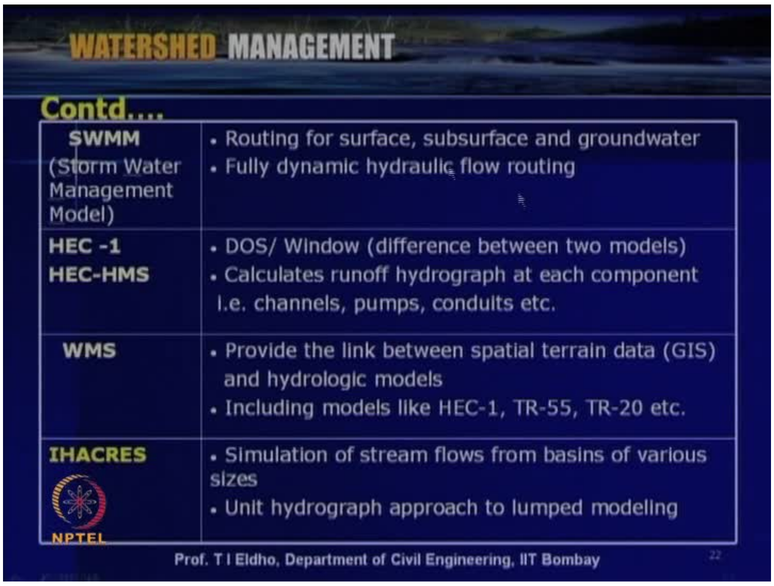

Then storm model: like developed for original application to the San Francisco master drainage plan. So, this is based upon conceptualized view of urban drainage systems and then we can have a SWMM model storm water management model. There are routings for surface subsurface or groundwater components. Then this can fully dynamic hydraulic flow routing then, we can have HEC series or HECHMS models. So, it can be either DOS based or windows, based then these models can be used to calculate runoff hydrograph at each component like channels. Then, various locations, etcetera; then WMS watershed modeling system... these provide the link to various available model using the GIS package and hydrologic models so including like HECTR-55 TR-20 there are links to this various model in the watershed modeling systems.

Then IHACRES: this is a particular model simulation of stream flow from basins of various sizes unit hydrograph approach to lumped modeling. So, if you go through the hydrologic literature, you can see number of models like this. As I mentioned, depending upon the requirement, depending upon the objectives, you can choose particular model or you can develop your model also depending upon your requirement.

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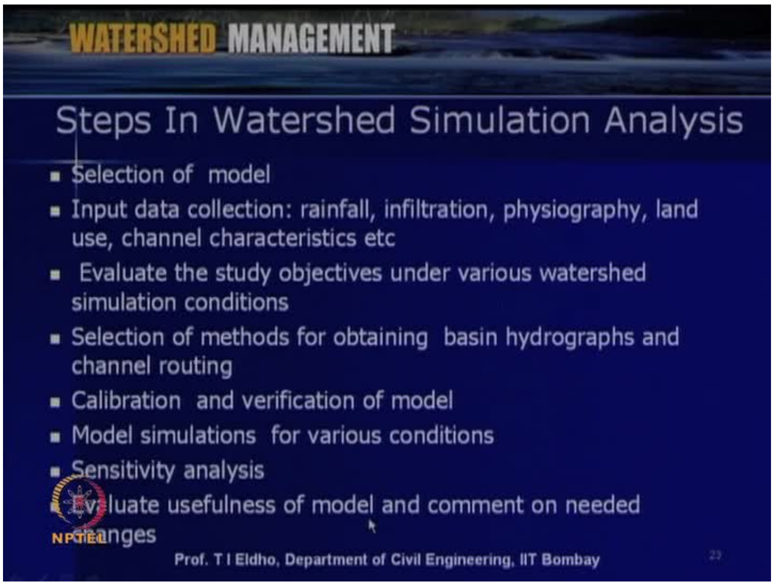

So, now finally, what are the important steps in watershed simulation analysis? When we are going for watershed simulation and the steps include, so first we can choose the model depending upon the objectives or the requirement and data availability, then we have to collect the data input data collection: like rainfall infiltration, physiography, land use channel characteristics, etcetera. Then we can evaluate the study objectives under various watershed simulation conditions. So, we can see various scenarios and then accordingly, we can simulate then selection of methods for obtaining basin hydrographs and channel routing as far as hydrology is concerned for the given rainfall condition or the given intensity of the possible rainfall how the system will be behaving.

Then we have to do calibration and verification of the models as we discussed earlier; then model simulation for various conditions for example, if a dam is built of this particular height what will happen? How much is the storage possible? so like that various conditions we can simulate and then various parameter sensitivity also we can carry out.

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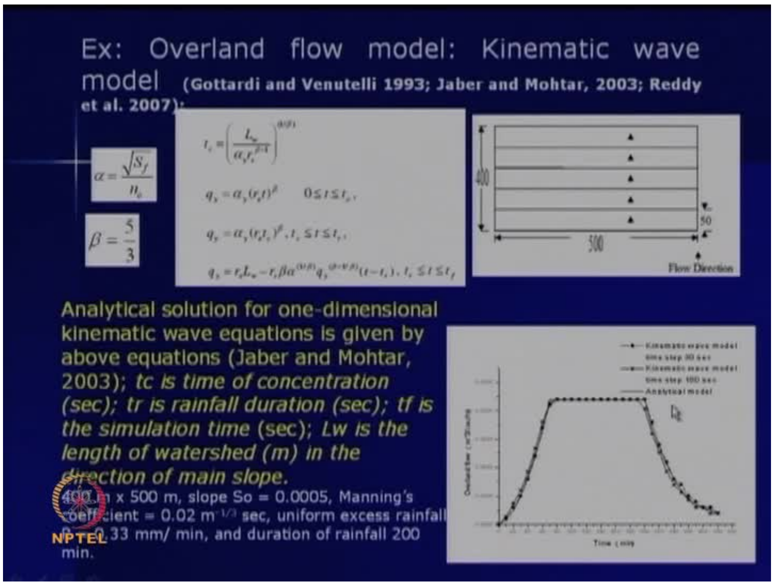

Then we can evaluate the usefulness of model and then comment on the needed changes. As far as the watershed modeling is concerned, these are some of the important steps in watershed simulation analysis. Now, before closing this lecture, here two examples: one is distributed model based upon the kinematic wave approach; so here the kinematic equations we have already seen. Here, we consider an area of this for overland flow 400 meter by 500 meter size area, then slope S 0 is given as 0.0005; Manning's coefficient is 0.02 and we apply uniform excess rainfall r is equal to 0.33 mm per minute and duration is 200 minutes. So this is the area we consider; we have to identify, how much is the runoff taking place with respect to time for this overland area. For this actually, Jaber and Mohtar in their paper in 2003 have given they have given the analytical solutions so the solution is given by this equation.

So, I am not going the details of this equation; so this q represent the discharge of flow per unit width and so then alpha and beta, some of the coefficient and here tc is the time of concentration, tr is the rainfall duration, tf is the simulation time. And, this also we have done - the overland flow simulation by using finite element model which we will be discussing in the next lecture. So, we run the model and then we simulated by using the kinematic wave approach and then its corresponding analytical solution; also you can see here with respect to time how the discharge variation is given here.

This line represents the analytical solution and then the kinematic wave model results for 2 time stamp; one is 30 second and another one is 80 second. We can see that there is a good match for the analytical solution of the kinematic wave model but, we can see that this analytical solution we can apply only for very simple cases like this. But, for a field case we cannot have these kinds of analytical solution but, since we developed a model based upon finite element method for the solution of the kinematic wave approach, we used this analytical solution for verification of the developed model. So, the corresponding finite element formulation we will be discussing in the next lecture.

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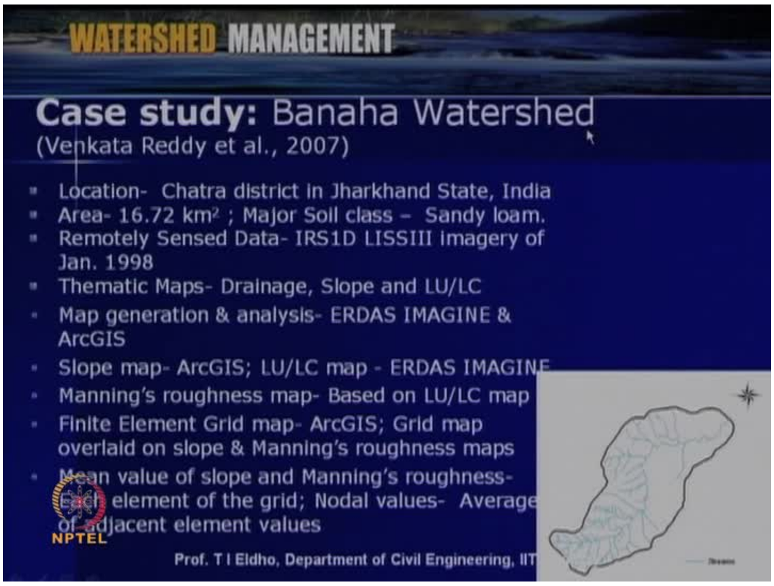

Then, another application to a case study area called Banaha watershed. As I mentioned in a civil department IIT Bombay, we have developed some watershed models based upon the kinematic wave approach and diffusion wave approach using the finite element method. So, that models we have applied for watershed called Banaha watershed. The modeling details we will discuss in the next lecture but, here my purpose is to discuss the variation, the physically based model application to identify how the runoff is taking place for the given rainfall condition.

So here the watershed is located in Chatra district in Jharkhand state and area is 16.72 square kilometer and major soil class is sandy loam and here we use a remote sensing data and GIS is used for drainage slope and LULC maps. Then, Manning's roughness all these details we obtained from the using the arc GIS and so, mean value of slope and

Manning's roughness for each grid is assigned and then accordingly the variation is taken.

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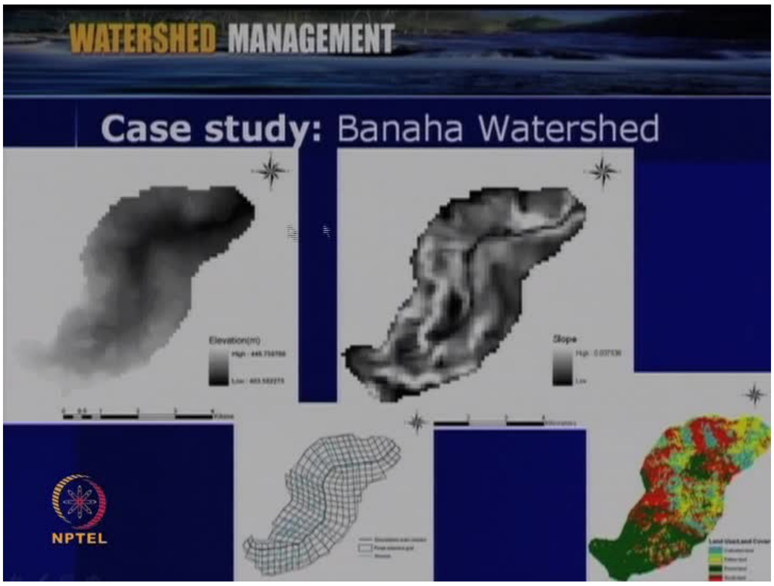

So this is the watershed and this is the main channel; this is the outlet of the channel; so, this shows actually we developed a digital elevation model for this watershed and this is showing the elevation variation for the watershed. So, here this is the variation with respect to the watershed. Then here, this shows the slope variation and this shows the land use variation for the watershed. So, this is the grid which we utilized using the finite element method this is this is the 1 dimensional modeling approach.

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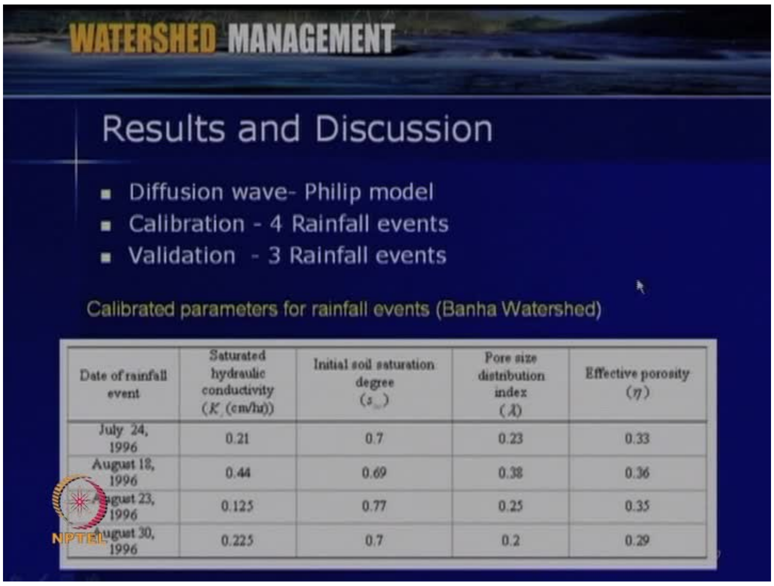

Date of rainfall event	Saturated hydraulic conductivity (K_s (cm/hr))	Initial soil saturation degree (s_{ini})	Pore size distribution index (λ)	Effective porosity (η)
July 24, 1996	0.21	0.7	0.23	0.33
August 18, 1996	0.44	0.69	0.38	0.36
August 23, 1996	0.125	0.77	0.25	0.35
August 30, 1996	0.225	0.7	0.2	0.29

These are different strips which is joining the outlet of the channel. This is the main channel for the watershed; so here we used a diffusion wave approach for the overland flow and channel flow modeling then a Philip model is used for the infiltration so here we did not the we consider only the event based model so that way evapotranspiration effects were not considered.

Only the infiltration effect was considered; so as we discussed we have done number of calibrations and then validations and especially, for infiltration models various parameters like saturated hydraulic conductivity, initial soil saturation, porous distribution, pore size distribution, effective porosity all these identified for the given data sets and then we calibrated the model and we obtained these parameters.

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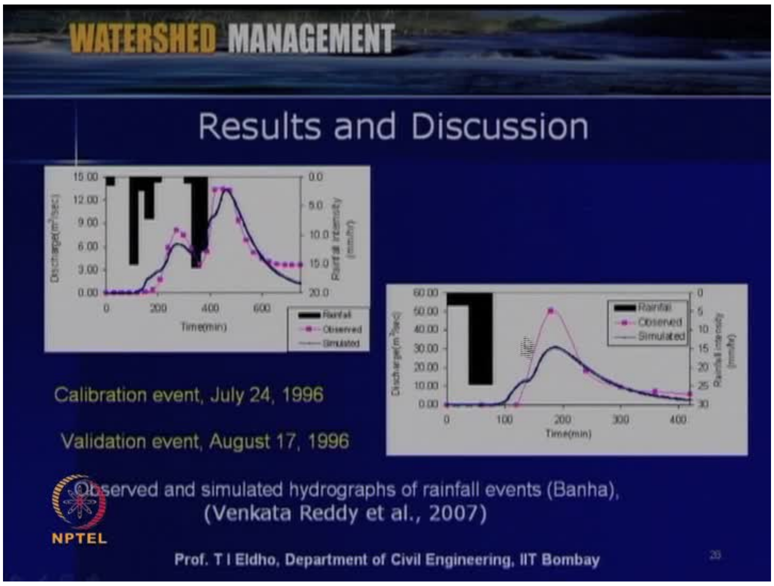

Then validation and calibration details I have shown here for example; particular event of July 24 1996 this is the rainfall pattern and at the outlet of the watershed. We have simulated the runoff discharge versus time and then we compared with some of the observed data for calibration and then this is called validation event.

So even though there is some variation with respect to observed and simulated but, in physically based model these kinds of variations. We expect since we are not able to capture the entire variation of the data like input data especially the infiltration data is very difficult to obtain.

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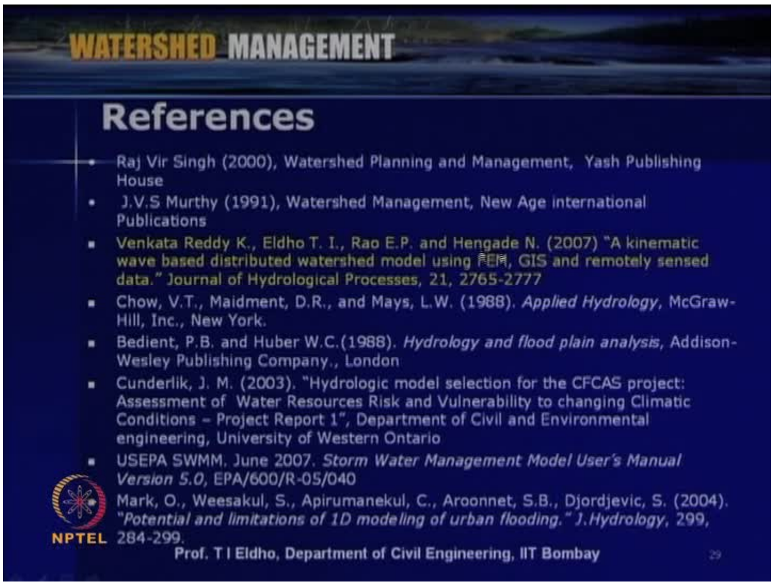

So that way; some of the parameters we started with the literature values and then we tried to calibrate and those parameters were used for the modeling. Now, these are some of the important references which were used in today's lecture; so like this paper which you published in the hydrological process.

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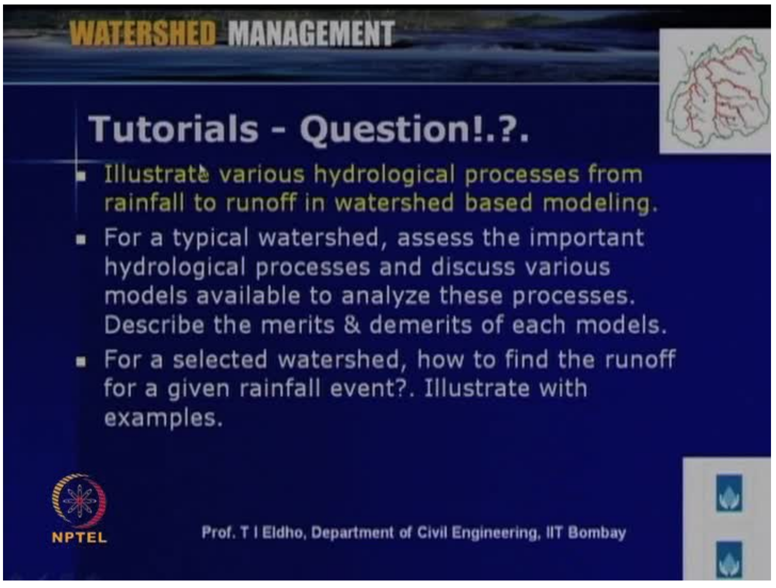

This is the case study; is based upon this paper then some of the tutorial assignment and self-evaluation questions. So tutorial question is, illustrate the various hydrologic processes from rainfall to runoff in watershed based modeling for a typical watershed assess the important hydrological processes and discuss various models available to analyze these processes.

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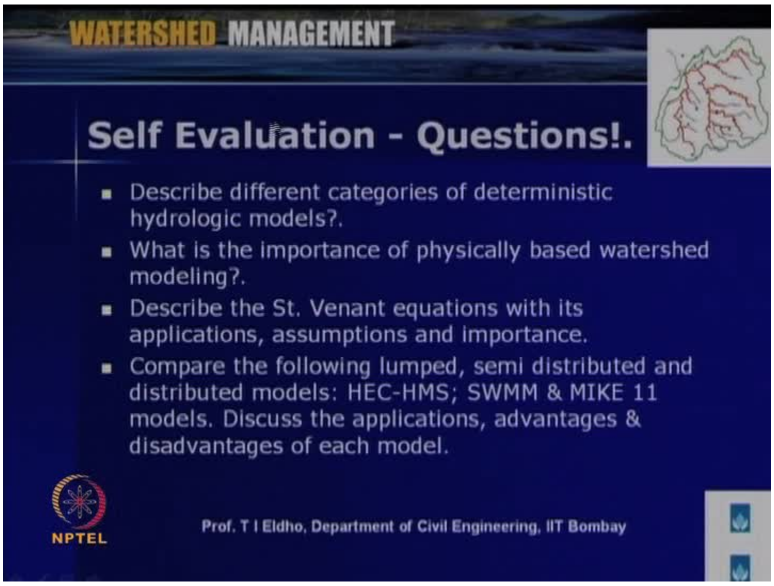

Describe the merits and demerits of each models for a selected watershed how to find the runoff for a given rainfall event illustrate with examples so these details are based upon today's lecture so you can easily get the solution then self-evaluation questions describe different categories of deterministic hydrologic models.

What is the importance of physically based watershed modeling and describe the Saint-Venant's equations with its applications assumptions and importance compared the following lumped semi distributed and distributed models HEC-HMS SWMM MIKE-11 models.

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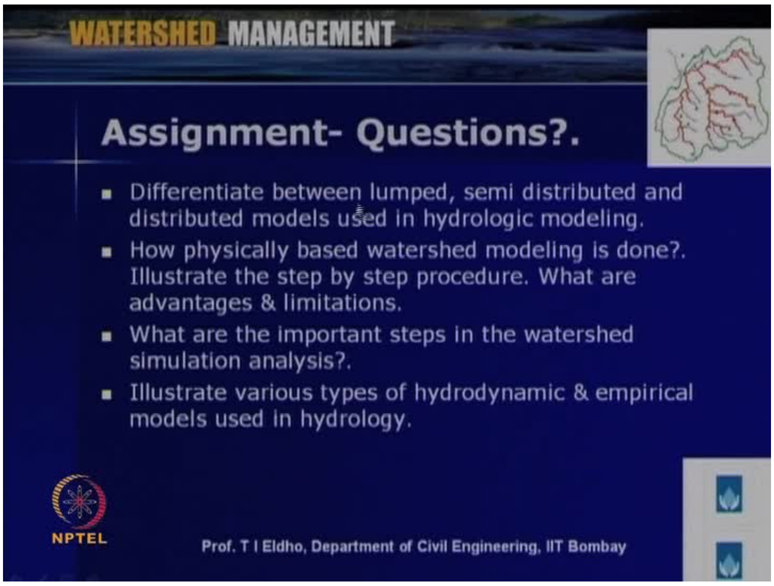

Discuss the applications advantages/disadvantages of each model; few assignment questions differentiate between lumped semi-distributed and distributed models used in hydrologic modeling and how physically based watershed modeling is done.

Illustrate the step by step procedure; what are the advantages and limitations? What are the important steps in the watershed simulation analysis illustrate various types of hydrodynamic and empirical models used in hydrology.

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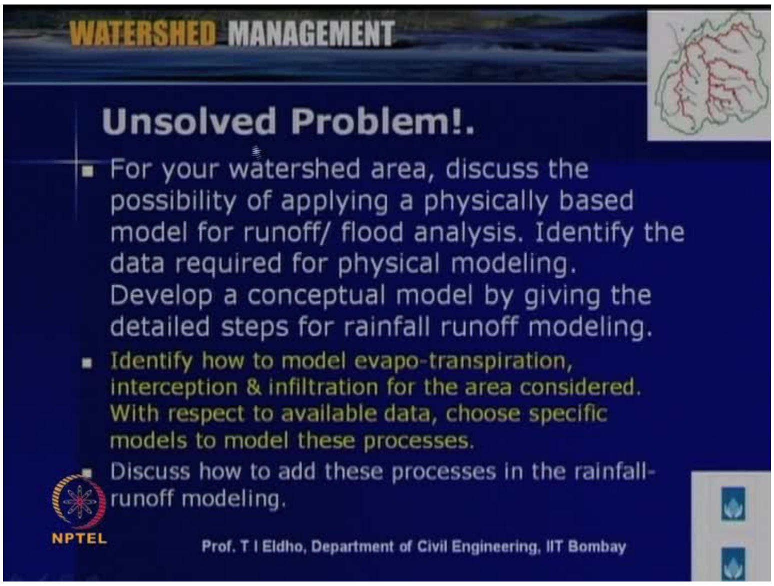

So, all these questions you can answer based upon today's lecture finally one unsolved problem for your watershed area discuss the possibility of applying a physically based model for a runoff or flood analysis identify the data required for physical modeling develop a conceptual model by giving the detailed steps for rainfall runoff modeling. Then identify how to model evapotranspiration interception infiltration for the area considered with respect to available data. Choose specific models to model these processes; discuss how to add these processes in the rainfall runoff modeling. Based upon today's lecture and the previous lectures, you can easily do this unsolved problem.

So, now, today we discussed the hydrologic modeling based upon the physically based approach now in the next lecture. We will discuss some of the numerical tools. How to solve these kinds of Saint-Venant's equations or its variations and then we will discuss some more case studies; thank you.