Watershed Management
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Module No. # 4
Lecture No. # 18
Subsurface and Groundwater Flows

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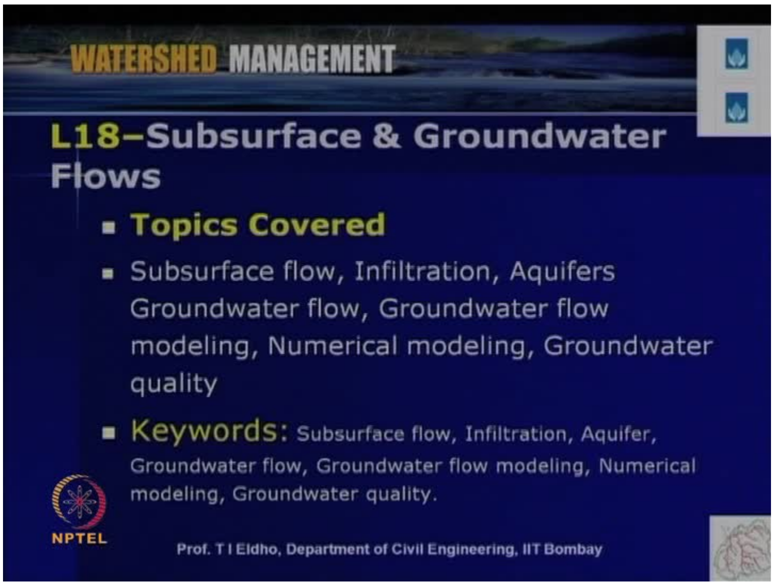

Namaste and welcome back to the video course on watershed management. In module number 4, lecture number 18, today we will discuss subsurface and groundwater flows. So, some of the important topics which will be discuss today include - Subsurface flow, Infiltration, Aquifers, Groundwater flow, Groundwater flow modeling, Numerical modeling and ground water quality.

So, some of the important keywords are - Subsurface flow, Infiltration, Aquifer, Ground water flow, Ground water flow modeling, Numerical modeling, Groundwater quality. So, as we discussed earlier in some of my earlier lectures, so as we discuss about the water resource in a watershed, so related to watershed management, so we have to see the total availability of the water. So, as far as water is concerned, water can be either surface water or ground water.

So, in any of the watersheds ground water is a major resource as water, so that we have to say utilize it properly; we have to plan it properly; we have to understand its behavior within the watershed, and then also we have to, while we use the ground water, we have to replenish the ground water through the various schemes like rain water harvestings, artificial recharge and other ways.

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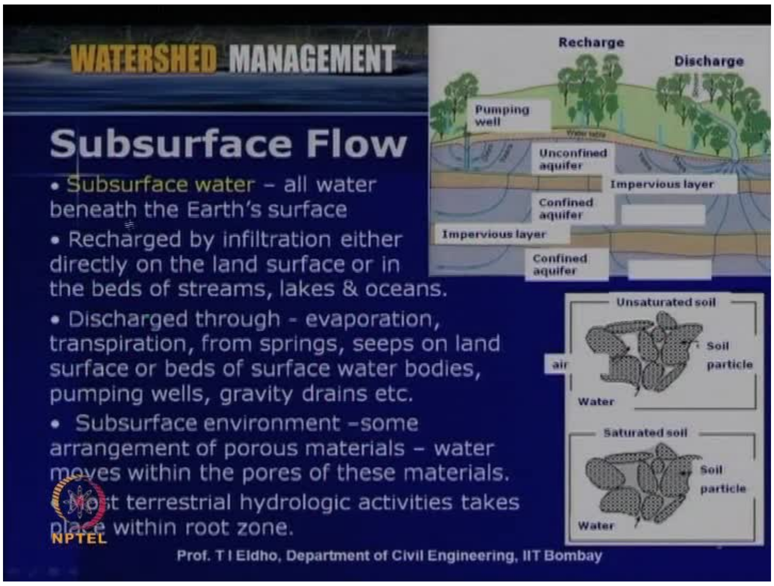

So, within this context, today we will discuss the important aspects of ground water flow and it is modeling within the perspective of watershed management. So, as we have already seen the groundwater is a part of subsurface flow. So, subsurface water is the all water beneath the earth's surface.

So, we can see that whenever rainfall takes place, there is the infiltration takes place and then water will be percolated down, and that movement, so all water beneath the air surface, we can call it as subsurface water.

So, the water will be is recharged by infiltration either directly on the land surface or in the beds of streams, lakes and oceans. So, you can see in this figure, so when the rainfall takes place, the recharge is taking place with respect to the infiltration and then also say from the surface water resources like lakes, then rivers and oceans also the water is infiltrated down to the subsurface and that becomes the subsurface water.

And then, as far as the subsurface water discharge is concerned, it is discharged through evaporation, transpiration and then from springs, seeps on land surface or beds of surface water bodies, and then, we can get this water through pumping wells, gravity drains, etcetera.

So, as far as subsurface water is concerned, there is say the water recharge taking place with respect to rainfall or with respect to the movement of water from the surface water sources like lakes, rivers, ponds or ocean. That is the recharge taking place to the subsurface as subsurface water, and a discharge is concerned, the water which we are taking through pumping wells or water coming out as springs or say the gravity drains which we give; so, that way, the discharge is taking place.

So, as far as subsurface environment is concerned, you can see that some of the, so this depends, this subsurface flow, the subsurface water movement depends upon the porous material; so, water moves within the pores the soil. So, you can see that if this is the soil media, so within the soil media lot of pores will be there. So, water will be moving through this say the pores and that water is coming as the subsurface water.

So, most of the terrestrial hydrological activities takes place within a few feet’s from the surface of the earth or within the roots zone. You can see that whatever is happening is that say water is recharging and then, so it is a, the, immediately it is going through the soil and then it will be reaching the aquifer system or the water table. It can be, say aquifer can be confined or unconfined in nature. So, generally, it will be initially within the unconfined layers, and then, say most of these activities will be taking place within the root zone, and then, further this ground water may percolate down deep. So, the deeper portion also can takes place.

So then, say as far as subsurface water is concerned, say what we discuss now is, say within the context of soil water. So, this soil water - we can divide into three parts. So, say how the water is available within the subsurface or within the soil.

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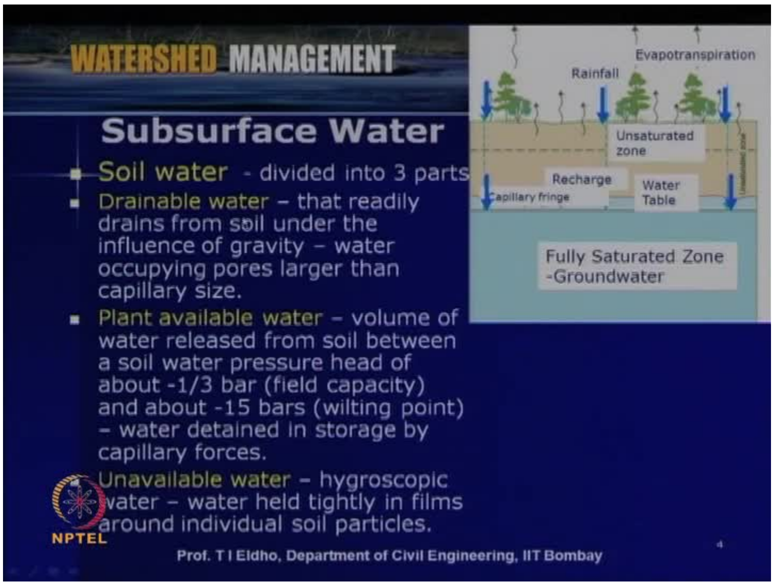

So, accordingly, we can classify into three types – so, first one is the drainable water. So, that is the water that readily drains from soil under the influence of gravity and water occupying pores larger than capillary size. So, that way, that will be drained out. So, that is say with respect to the recharge and then what is available, say within the subsoil or the subsurface. That kind of water is called a drainable water.

Then second class is so called plant available water. So, plant available water is the volume of water released from soil between a soil water pressure head of about minus 1 by 3 bar, which is so called generally called field capacity, and about minus 15 bars which is so called wilting point. So, this water is at general detained in storage by capillary forces.

So, you can see that when this water is infiltrating down, so we can generally classify the water available in subsurface or in the soil as fully saturated, which is generally called as groundwater, and then, there will be a capillary fringe like this and then there will be unsaturated zone, where the water will be available within the soil which is not fully saturated.

So, that way, then the water which is generally available to the plant; I mean between the field capacity and the wilting point. That is so called plant available water, and third one is say the water still exists in the soil. That is so called unavailable water which we cannot drain or which we cannot, which will not be available to the plants. So, that is so called hydroscopic water.

So, water held tightly in films around individual soil particles. So, that is will not be available to the plants or even it will not be possible to drain. So, that way, the water, subsurface water - we can classify into drainable water, plant available water and the unavailable water.

So, as we discussed earlier, say within the hydrologic processes, then say with respect to the rainfall to run off various processes are there like infiltration, then evaporation, evapo transpiration, interception, like that various processes will be there. So, what is available as water subsurface water or ground water is coming from the infiltration of the water which is coming from the rainfall.

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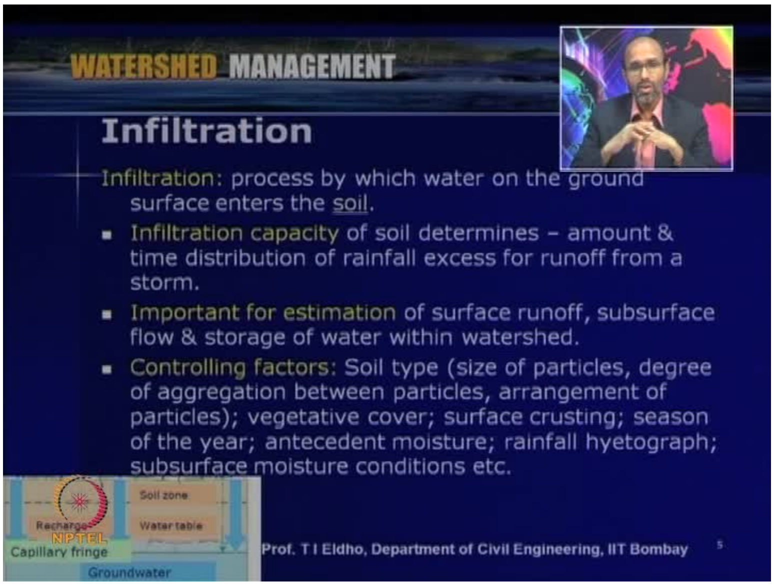

So, this infiltration process is a very important as far as groundwater or subsurface water is concerned. So, the, about the infiltration we discussed already earlier. So, again, say as subsurface water we will have a brief discussion further. So, infiltration is the process by which water on the ground surface enters the soil, as we already seen earlier. Then the infiltration capacity of soil determines how much water is infiltrated down and then how much is the time distribution of rainfall excess for runoff from a storm.

So, accordingly, the infiltration capacities varies and say it is a very important to estimate the infiltration, with, within the context of surface runoff and then the availability of water as far as the subsurface water is also concerned.

So, subsurface flow and storage of water within the watershed depends upon the infiltration. So, as we have discussed, in a, in one of the earlier lecture, the controlling factors, say that control the infiltrations or the soil type like size of particles, then degree of aggregation between particles, arrangements of particle, then what kind of vegetative cover is there, then surface crusting, then season of the year, then say what is the soil moisture level available within the soil or so called antecedent moisture, then rainfall hyetograph subsurface moisture conditions, etcetera. So, we had a detailed discussion on infiltration in one of the earlier lectures. So, we will not be discuss further on infiltration.

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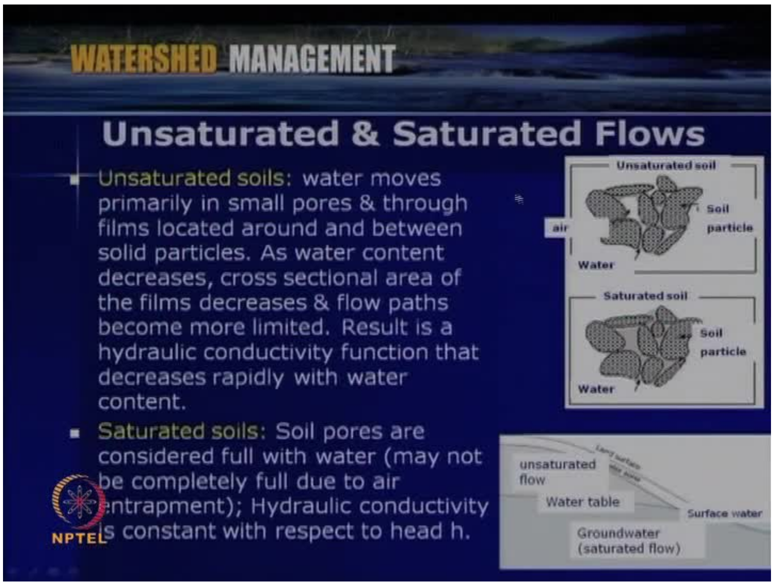

So, now, we will further discuss about the ground water, say within the contest of the subsurface water and ground water flow. So, as we discussed just in the previous slide, so water is, the water available within the soil we can classify into unsaturated and saturated. So, the flows within the soil can be unsaturated flow or saturated flow. As you can see here, say, the, once the water is infiltrated down, so here, the, we can classify unsaturated soil and saturated soil.

So, unsaturated soil means the water moves primarily in small pores and through films located around and between solid particles. As water content decreases, cross sectional area of the films decreases and flow paths become more limited. So, this result in hydraulic conductivity function that decreases rapidly with water content.

So, this unsaturated flow or unsaturated soil is a very important as far as especially as far as the water availability to plants are concerned, and then saturated soil or saturated flow is related to the soil pores are considered full with water. So, it may not be completely full due to air entrapment within the soil, but say wherever we consider, the hydraulic conductivity will be constant with respect to the head h as far as saturated flow is concerned or saturated soil is concerned.

So, here, you can see that as shown in this figure, so say once the water is infiltrating down, this is the unsaturated flow region, and here, this is the so called a water table; then this is the ground water or the saturated flow. So, so, that way, now this so called unsaturated flow that depends upon how much is infiltration, how the infiltration process taking place, and then, say how much is the, what kind of soil is that accordingly the water availability within the unsaturated zone and water movement through the saturated overflow condition takes place.

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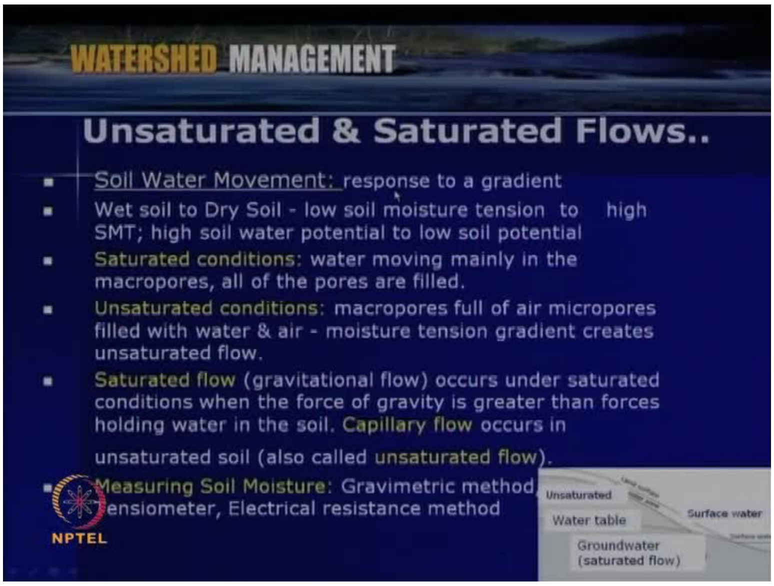

So, as far as the soil water movement is concerned, so this is the response to a gradient generally. So, depends upon how much is the pressure or how much is the gradient, accordingly the soil water movement takes place. Say for example, if the soil is fully wet, so wet soil to dry soil, so generally low soil moisture tension to high soil moisture tension and high soil water potential to low soil potential when we consider wet soil to dry soil.

And when we say that the soil is fully saturated or saturated condition means water is moving mainly in the macro pores so that all of the pores are filled with water. Then the unsaturated flow is concerned, unsaturated conditions are concerned, the macro pores are full of air micro pores filled with water and air. So, the moisture tension gradient creates the unsaturated flow.

And then very similarly the saturated flow is concerned, it is we can also call saturated flow as gravitational flow. So, this occurs under saturated conditions when the force of gravity is greater than forces holding water in the soil. So, from capillary flow onwards the saturated flow starts. So, capillary flow occurs in unsaturated soil. So, here, this is the unsaturated soil and just below there is a capillary fringe is there and then below is the saturated flow.

So, we can measure this, this, say this, the soil content, the water content in the soil. So, the measurement of soil moisture various methodologies are available like a gravimetric method, then tensiometer, then electrical resistance method, etcetera, number of methodologies are available. So, using these techniques, we can identify how much moisture content is there within the soil. So, anyway, we will not be discuss further on this aspects. Now, we will go to the saturated flow conditions or the groundwater flow.

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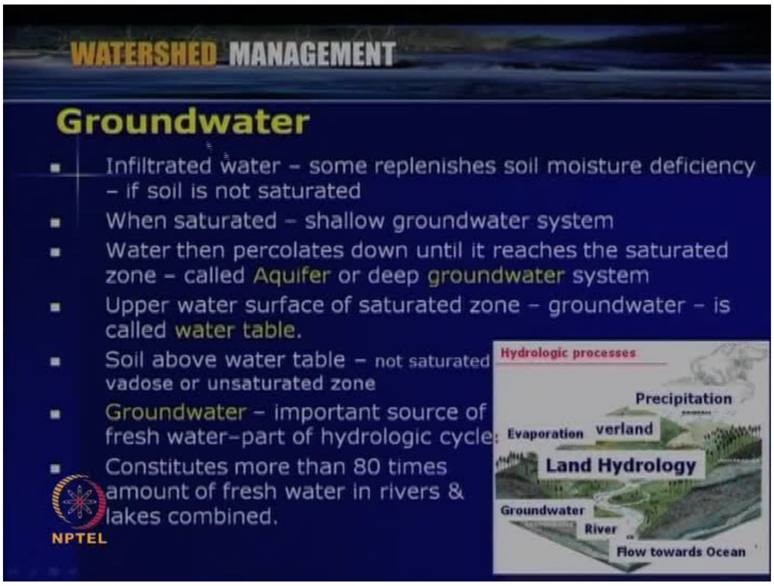

So, the groundwater flow is, say fully saturated flow condition. So, infiltrated water, say some replenishes soil moisture deficiency if soil is not saturated, and when the soil is fully saturated, then we are having the shallow groundwater system. So, as you can see within the hydrologic processes, so you can see that with respect to rainfall, the water is infiltrating down, and then, where the shallow groundwater system is web after the saturation, we are having the shallow groundwater system.

So then, water then percolates down until it reaches the saturated zone called aquifer or deep groundwater system. So, here, once it is say fully saturated and then water is further percolating down to the aquifer system. So, the upper water surface of saturated zone is called generally a water table. So, when we consider an unconfined aquifer, we are having the, say the unsaturated zone, then the capillary fringe zone and then the saturated zone. So, that saturated zone, that say the surface is so called a water table.

So then, say as we can see that say here, say for example, this is the water table and this is the unsaturated zone and this is further, the, to the saturated flow condition. So, as we can see that as I mentioned earlier, groundwater is one of the important source of water for the humanity, for say domestic and all types of uses.

So, it is an important part of the hydrologic cycle, so we cannot separate the groundwater flow with respect to the runoff or the surface water. So, say out of the available fresh water resources, the major source is the ground water. So, an estimate says that the ground water constitute more than 80 times amount of fresh water in rivers and lakes combined. So, you can see so the importance of groundwater.

So, groundwater is one of the most important say resource - water resource - available for humanity. So, only difficulty is that the deeply percolated water - it is a very difficult to pump out, but say in most of the places, we can, the, whatever the especially shallow water or the somewhat deep zone water we can say pump it out and then use accordingly.

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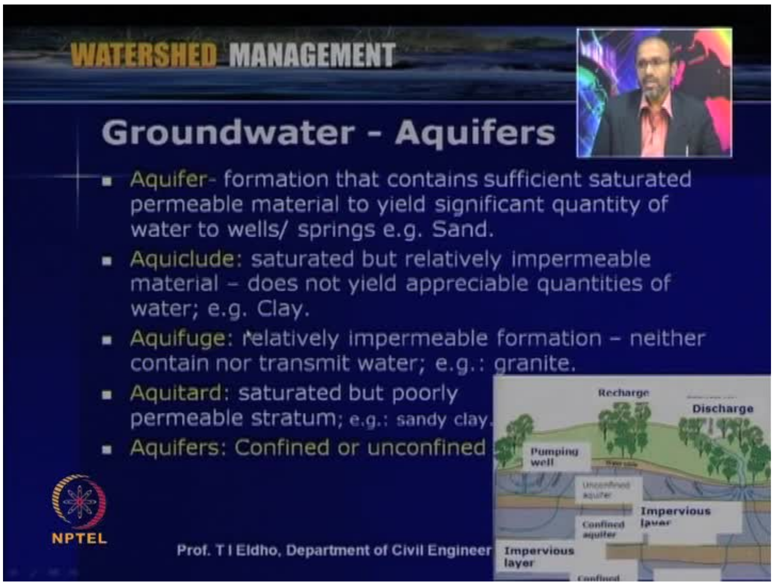

So, groundwater is one of the important source of water. So, as we, as we discussed say once the water is percolating down, we are the, water through the saturated zone once it is reaching the aquifer system or where the water is stored or water is moving through the soil. So, that formation is so called aquifer.

So, accordingly, now let us see the different types of classifications as far as the aquifers are concerned. So, here, in this slides, the classification of aquifers are given. So, aquifer as I mentioned, it is a formation that contains sufficient saturated permeable material to yield a significant quantity of water to wells or springs. So, this is the definition of aquifer. So, say for example, if a sand formation where significant amount of water is holding within the soil and that can be drained say by using wells or it will coming through springs; so, that is so called a aquifer.

Then say there is classification like a aquiclude. Aquiclude is a saturated but relatively impermeable material and it does not yield appreciable quantities of water. Say for example, clay formation, so clay formation once it is saturated contains so much of water but we cannot drain the water easily; so, it is relatively impermeable material; so, we cannot drain the water. So, that is that kind of formations soil formation is called aquiclude, and then, aquifuge. Aquifuge is a relatively impermeable formation it neither contains nor transmits water. Say for example, granite formation, so that is so called aquifuge.

Then aquitard; aquitard is a saturated but poorly permeable stratum, so like sand clay mix or sandy clay. So, that is, that kind of formation is called an aquitard. So, that way, when we look the groundwater as a source is available mainly from aquifer or aquitard, and then, say other formations even the water is available, we cannot get the substantial amount of water.

So then, aquifers again further can be classified into confined or unconfined. So, you can see that say an unconfined aquifer means say water is say infiltrating down and this is the water table as shown in this figure, and then, there is a impermeable layer below. So, there is a water table over a free surface as you can see here in this figure.

So, that kind of formation is so called unconfined aquifer, and then, confined aquifer means the formations or the aquifer between which is confined between two layers. We can see that here this is 1 layer of impermeable form layer and this is another layer of impervious layer. So, the confined aquifer is this soil, this material, where considered amount of water is there and which is also moves with respect to gradient.

So, that formation is so called a confined aquifer. So, generally, the aquifers can be classified into either confined aquifer or unconfined aquifer. So, that depends upon the hydrological conditions of the particular area. So, now, let us further discuss what the important characteristics are as far as the aquifers are concerned. So, we have seen that the rainwater or the precipitated water is say infiltrating down, and then, that is further percolating down to the aquifer system.

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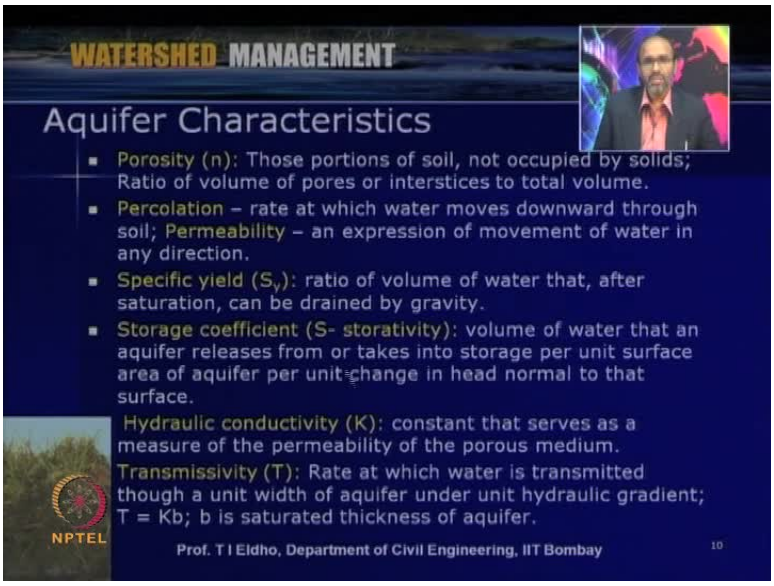

So, the water movement within the subsurface or within the soil depends upon various parameters like porosity, specifically yield storage coefficient, hydraulic conductivity, etcetera. So, let us see some of these important definitions as given in this slide.

So, first one is porosity. So, those portions of soil not occupied by solids, so, that is say the meaning of porosity. So, generally the porosity is expressed as ratio of volume of pores or interstices to total volume. So, that is the porosity; so, you can see that in this soil medium, say large number pores you can see. So, porosity is the ratio of volume of pores to pores or interstices to total volume.

Then further percolation means rate at which water moves downward through the soil. So, once it the water is infiltrated down, so what is the rate at which the water is moving. So, that is so called percolation, and then, another important term is so called permeability. Permeability is an expression of movement of water in any direction. So, percolation is generally we mention as downward movement, but permeability means it can be in lateral directions also. So, that is, the, so, permeability an expression of movement of water in any direction, and then, as far as the aquifer is concerned, say the terms like a specific yield. Specific yield especially we mention for unconfined aquifers. So, it is the ratio of volume of water that after saturation can be drained by gravity. So, that is the definition of specific yield.

And then storage coefficient or generally call it as storativity. So, storativity is the volume of water that an aquifer releases from or takes into storage per unit surface area of aquifer or per unit change in head normal to that surface. So, generally we mention the storage coefficient for confined aquifers or sometimes we mention for a unconfined aquifer also depending upon the way which is mentioned within specified equations.

Then another important term is so called hydraulic conductivity. So, hydraulic conductivity which is generally mentioned as the symbol is K. So, this is a constant that serves as a measure of the permeability of the porous medium. So, how much water can move through the soil medium, say from one location to another location. So, it is that K represents or a hydraulic conductivity represent the measure of the permeability of soil media or porous media.

So, accordingly, the, the, the movement takes place within the soil media, and the, it is unit is the velocity, the unit of velocity like meter per day or meter per second like that. Then another term is called transmissivity of the of the aquifer media. So, transmissivity is the rate at which water is transmitted through a unit width of aquifer under unit hydraulic gradient. So, generally transmissivity is equal to hydraulic conductivity multiplied by b - where b is the saturated thickness of aquifer.

So, these are some of the important terms which we will be using as far as the subsurface flow or groundwater flow is concerned. We have seen what is subsurface water or groundwater and what is aquifer and what are it is important characteristics. So, now, let us discuss what are the governing laws as far as the groundwater flow or groundwater movement is concerned. So, one important say governing law was proposed by Darcy in nineteenth century.

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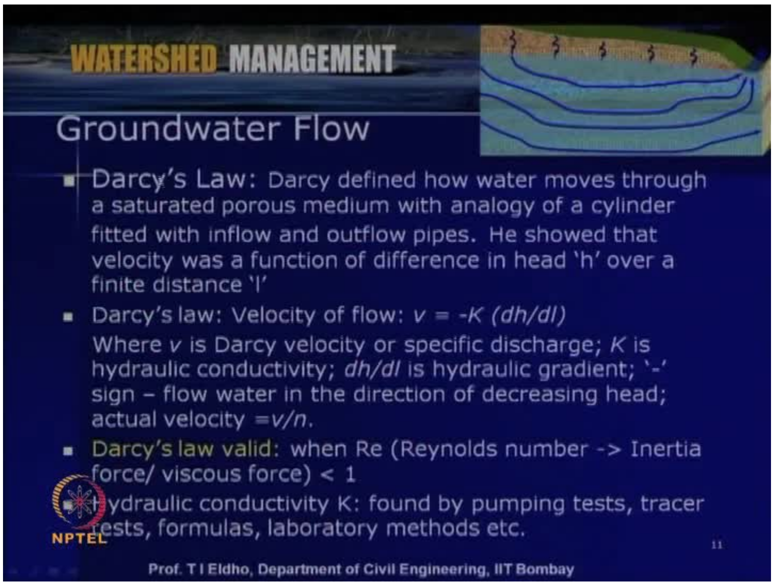

Darcy is a French engineer. Darcy was a French engineer who conducted large number of experiments in nineteenth century and put forward certain laws called as Darcy's law. So, Darcy defined how water moves through a saturated porous media with analogy of a cylinder fitted with inflow and outflow pipes. Darcy showed that velocity was a function of difference in head h over a finite distance l.

So, if we consider the, say for example, if this is the soil media, so between say one location to another location within the flow direction, say what is the head difference and what is the distance between those two points accordingly he proposed the Darcy's law.

So, Darcy's law is say velocity of flow v is equal to minus k d h by d l - where v is so called darcy's velocity or specific discharge and K is the hydraulic conductivity and this dh by dl is the hydraulic gradient. So, here, in this equation, minus sign indicates the flow of water is in the direction of decreasing head, and once we find the Darcy's velocity, we can find the actual velocity by dividing Darcy's velocity divide by the porosity.

So, this Darcy's law is one of the most important law as far as groundwater is concerned, and based upon that only all the further theories on groundwater flow movement and transport process were put forward later time.

So, Darcy's law is very important. So, generally the Darcy's law combined with mass balance or the conservation of mass. We derive the governing equations as far as the groundwater flow is concerned. So, that we will be discussing later, and as per this Darcy's law, generally, the flow should be very low Reynolds's number or laminar flow condition.

So, Reynolds's number which is the ratio of inertial force to viscous force. Generally, this law is valid when Reynolds's number is less than one but still it may be valid within the range of, say even Reynolds's number up to 10.

So, now, say this hydraulic conductivity which we have seen one of the most important parameter as far as the porous media is concerned. We can find the hydraulic conductivity by various experiments like pumping tests within the aquifer or tracer test or say depending upon the soil media we can use formulas, and then also based upon laboratory methods; we can determine the hydraulic conductivity. So, now, let us further discuss say how the ground water flow is moving within the porous media and then what way we can quantify or what way we can model this ground water flow movement. So, let us see in the coming slides.

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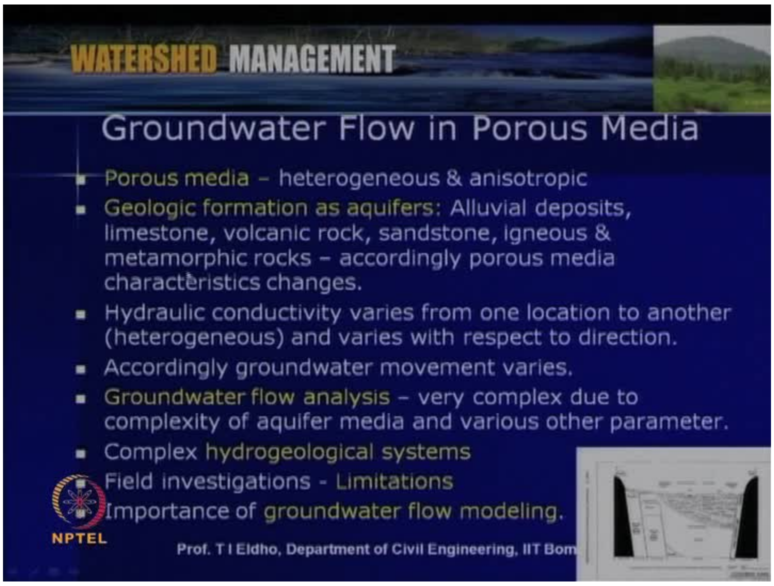

So, as I mentioned earlier also, as far as soil or the porous media is concerned, it is very heterogeneous and then the it is properties like the porosity or the hydraulic conductivity is varying drastically from one location to the another location and from one direction to another direction. So, the soil media or porous media is totally heterogeneous and anisotropic. So, anisotropic means the parameters are varying with respect to direction; heterogeneous means the parameters are varying from one location to another location.

So, due to this, say generally it is very difficult to say get the correct value of this hydraulic conductivity or porosity. So, generally, we use some approximations depending upon say some pumping test or some of the field test. We determine some values and then we do through a calibration process. We identify the hydraulic conductivity and other parameters as far as the aquifer concerned.

So, as I mentioned earlier also say as far as the soil is concerned, say or the aquifer is concerned various types of soils forms the aquifer system like a aluminum deposit, limestone, volcanic, rock, sandstone, igneous and metamorphic rocks. So, accordingly, since all these varieties taking place say and sometimes say one variety or most of the time a mixture of this varieties. So, that way, the post medious characteristics drastically changes from one location to another location.

So, that is why we got the porous media is heterogeneous, and then from, say the vertical direction or lateral direction also this parameters are changing. So, that is why we call this porous media as anisotropy. So, accordingly, say when we discuss about the groundwater flow movement, so due to the heterogeneity or due to the anisotropy, the movement rate also the groundwater movement rate also varies. So, that way, when we discuss about the groundwater flow analysis, so the process is very complex due to the complexity of the porous media and then various other parameters.

So, most of the time when we are looking for groundwater quantity or quality investigations, say the we have to deal with very complex hydrogeological systems. So, you can see that as in as shown in this figure, say there are number of layers of material, different types of materials as far as porous media is concerned.

So, that way, it is very difficult process or very complex to say study the groundwater flow movement or the groundwater quality analysis. So, that also is clear from this figure also where watershed is concerned, the parameters are changing from one location to another location.

We have the limitations as far as the field investigations are concerned. So, we cannot say generally field investigation means through bore holes or bore wells we have to get the data. So, that is also not so easy since we cannot have so many bore wells or bore holes say as far as a watershed is concerned.

So, generally say few through the data available, through, through some of the bore wells or bore holes we get the data and then we average as far as the various parameters are concerned. So, that way, groundwater flow modeling, the computer based modelings are the only solutions as far as the groundwater flow investigations or groundwater quantity investigations or quality investigations.

So, now, another issue, the, other than the groundwater quantity another important issue is the quality of the available ground water. So, when we discuss about the water resource plans within a watershed, the watershed management plans say water resource is concerned. So, the available water should be the not only the quantity but quality also should be good for various uses like the domestic uses or the agricultural uses.

So, groundwater quality is a major issue. So, earlier times say, with the, there was a thinking that the groundwater is a good quality and we can directly utilize, but due to the industrial revolution or say over use of fertilizers and other things for the agriculture. Now, last few decades it has been identified that groundwater is also very much amenable to pollution and many locations groundwater pollution have been identified.

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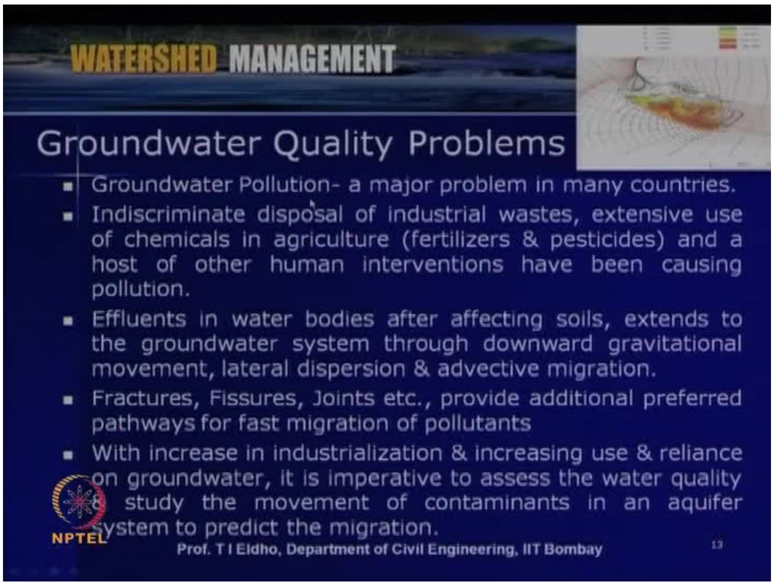

So, ground water pollution has become a major problem in many countries. So, the reasons are - indiscriminate disposal of industrial wastes, extensive use of chemicals in agriculture like fertilizers and pesticides, and a host of other human interventions are causing the groundwater pollutions.

So, effluents in water bodies after affecting soils, so, if say the untreated effluents or to say treated effluent to certain extent have putting into the in the river or lakes. So, this water will be percolating down to the groundwater system through downward gravitational movement, lateral dispersion and advective migration.

So, that way, you can see that like in this figure, so this groundwater pollution takes place and that it will be further moving, and further the fractures, fissures, joints, etcetera, what are there in groundwater or the aquifer system provide additional prefer pathways for fast migration of pollutants. So, with increase in industrialization and increasing use and reliance on groundwater, it is very important to assess the water quality and study the movement of contaminants in an aquifer system to predict the migration.

So it is not only the issue of groundwater quantity or the quantity of the water available as ground water, but quality is very important. So, after identifying that many locations, groundwater is polluted. So, we now you have to understand how the pollution is taking place and what extent the pollution has been taken place and then what kind of remedial activities can be done. So, that is nowadays a major question.

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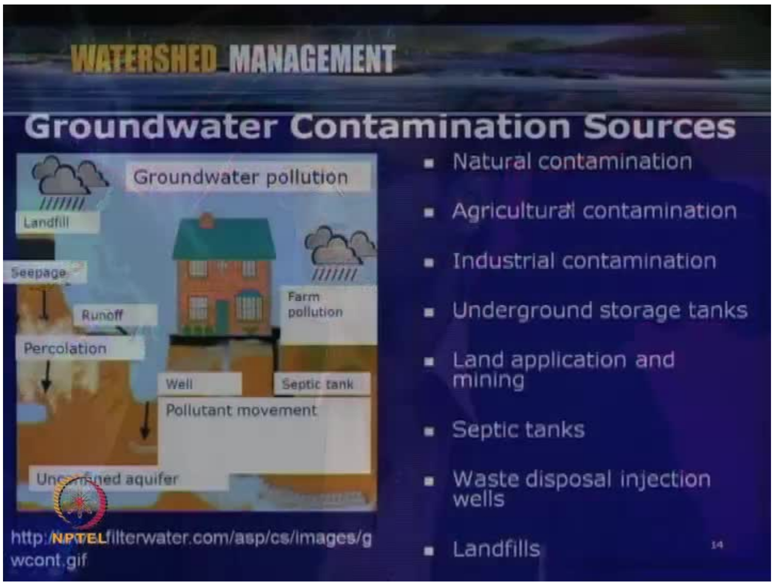

So, as far as groundwater contamination is concerned, as I mentioned earlier some of the important sources are mentioned here. So, groundwater pollution can be from natural contamination like sea water intrusion or fluoride or arsenic contamination which is taking place in many locations, and then, the pollution or contamination can be agriculture contamination by the use of fertilizers, say fertilizers, pesticides, etcetera.

Then industrial contamination that means the effluent liquid waste or solid waste which is putting as land fill and that is further say the Leichardt is seeping down, so, that kind of industrial contamination. Then underground storage tanks like in many countries, the, like a petroleum products and other say liquid forms are kept in underground. So, there is always possibility of leakage from these tanks; so, that can be the underground storage tanks.

Then land application and mining. So, what kind of say the fertilizer applications or what kind of ah solid wastes are kept on the land. So, that will percolating within with respect to rainfall this pollutants will be percolating down, and then, another source is mining. So, you can see that many areas are different types of mines are there. So, mining is another important source of ground water pollution.

And then, say the septic tanks. Say most of the houses or many locations the septic tanks will be there, and even if it is scientifically constructed, there is possibility of leakages, so that septic tanks can be another source of pollution.

Then waste disposal in injection wells. So, many areas say the liquid ways or solid ways keep it in the there is some soil media or very deep rocks. So, that can be a source of pollution, and as I mentioned, landfill is another source of pollution, where if it is not properly or scientifically constructed landfill, then Leichardt will be percolating down to the to the aquifer system.

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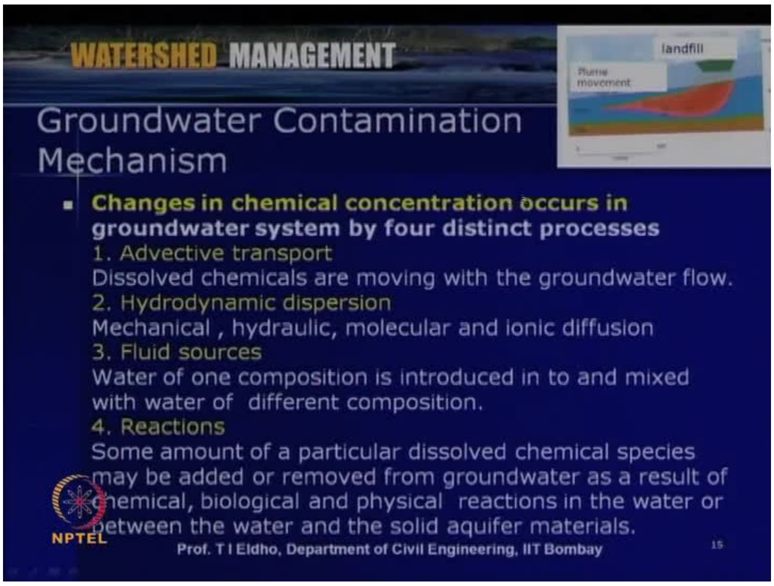

So, these are some of the important groundwater contamination sources .So then, as far as once the groundwater is contaminated, so or the or the pollutant is introduce to the subsurface or to the aquifer itself. So, there are number of processes taking place so that this plume will be or the contamination will be further spreading. So, the changes in chemical concentration or the contamination depends on four distinct processes like advective transport.

So, here, the dissolved chemicals are moving with the ground water flow. So, you can see that already groundwater flow is there, and then, with that flow, this contaminant plume is also taken within the flow. So, that is so called advective transport. And then second one is hydrodynamic dispersion. So, since the, so the soil media is porous and then as far as the various way of movement within the soil the plume movement or the contamination movement.

So, hydrodynamic dispersion is another important process. So, this can include mechanical dispersion, hydraulic dispersion molecular and ionic diffusion, and then, another source, another concern the groundwater pollution mechanism is fluid sources.

So, water on one composition is introduced to and mixed with water of different composition. Then that that is the groundwater contamination mechanism like what is happening sea water intrusion, and then, reactions, say some amount of a particular dissolved chemical species may be added or removed from groundwater as a result of chemical, biological and physical reaction in the water or between the water and the solid aquifer materials.

So, like that, the groundwater contamination various mechanisms are there. So, when we study about the groundwater pollution, we have to study this various mechanism, and then accordingly, we have to investigate how the contamination is further spending.

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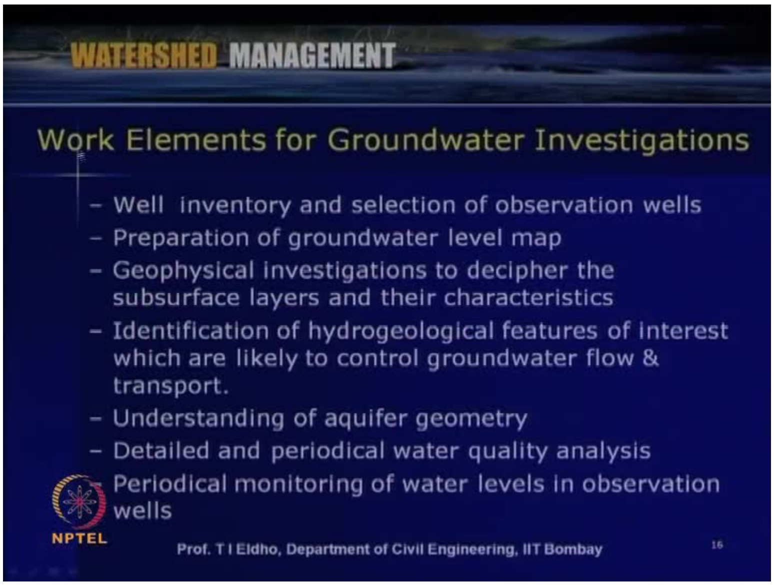

So, now, say let us go to the groundwater flow or groundwater quality modeling. So, before that, so, let us further summarize what are the important work elements as far as groundwater investigations are concerned. So, here I have listed. When we go for groundwater investigations, we have to go systematically. So, the work elements are well inventory and selection of observation wells, then preparation of groundwater level map for the particular watershed or particular area concerned.

Then, geophysical investigations: to decipher the subsurface layers and their characteristics. Then identification of hydrogeological features of interest which are likely to control groundwater flow and transport, then understanding of aquifer geometry, then detailed and periodical water quality analysis, then periodical monitoring of water levels, in, in observation wells.

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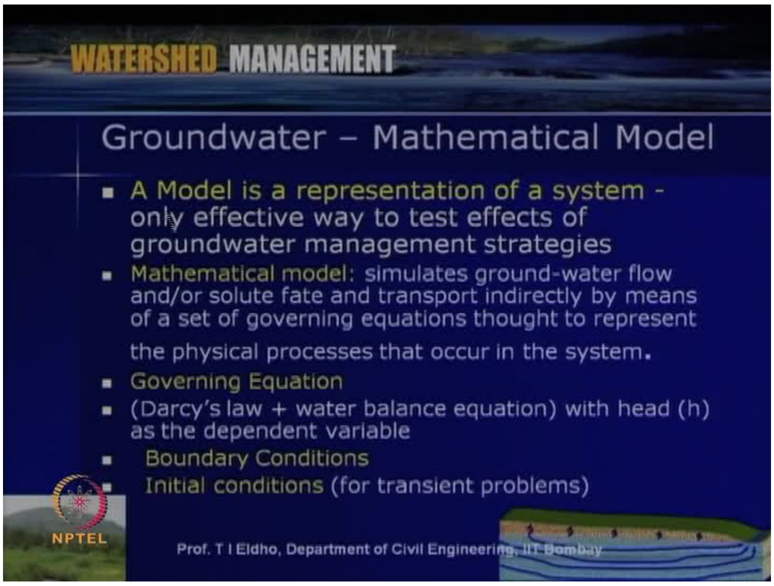

So, when we discuss about the groundwater, say investigations within a watershed, we have to go systematically. So, either water quantity investigations or quality investigations, we have to study systematically as we are discussed in the work element. So, various things we have to study systematically and then come up with the investigation report.

So, now, as I mentioned, say we cannot have so much of field investigations to assess how much ground water is available or how the groundwater quality varies. So, most of the time, we have to depend upon mathematical models. So, now, let us see some details about the mathematical models as far as groundwater is concerned.

So, a model as I mentioned earlier is a representation of a system; that means here the groundwater system. So, only effective way to test effects of groundwater management strategies through modeling. So, due to especially surface water is concerned, we can say directly see what is happening, but groundwater is as we can see that only observation is possible through the wells or the bore holes. So, that way, it is always better to go for mathematical modeling or mathematical modeling is the only way out as far as groundwater investigations are concerned.

So, mathematical model simulates a groundwater flow and, or, solute fate and transport indirectly by means of a set of governing equations thought to represent the physical process that occur in the system. So, that is the mathematical model within the context of groundwater. Then the governing equations - we can identify governing equations are generally derived from Darcy's law and water balance equation with head as the mainly as the dependent variable.

And then, of course, we have to define the boundary conditions, say if this is the aquifer system, we have to identify what is the head available here or the flux, say for example, if this is an impermeable medium, water cannot percolate down further. So, that is an impermeable where the flux can be assumed as 0.

So, the boundary condition can be the direct boundary conditions or dirichlet boundary conditions and then Neumann boundary conditions or in terms of flux, and then, when we are going to transient analysis like within an aquifer system, when we are pumping water, there the head will be continuously varying with respect to time. So, that is so called transient analysis. So, there we have to start with some initial conditions what is at time t is equal to 0, how the head is distributed or how the contamination is spread through the throughout aquifer.

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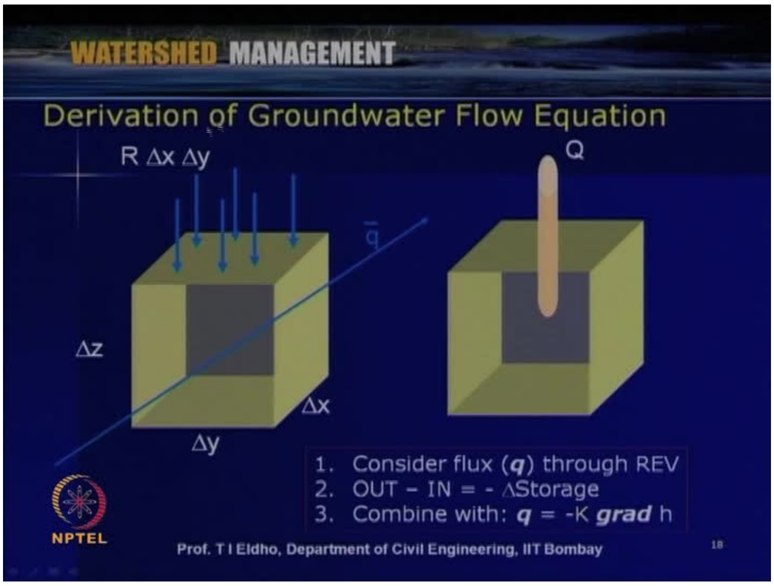

So, based upon that only, we will be doing further the mathematical modeling. So, that way by using the Darcy's law or and the conservation of mass or water balance, we can derive the groundwater flow equation. So, as shown in this slide, the derivation of groundwater flow equation is - we can do by considering a representative elementary volume R E V. So, delta X by delta Y divided by delta Z. So, if you consider flux through the R E V representative elementary volume.

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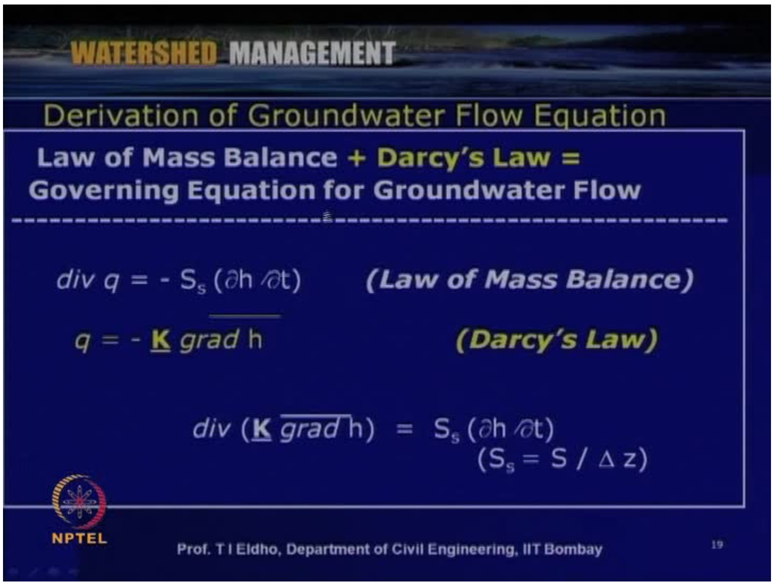

So, what is coming out minus what is in is equal to the change in storage, and then, this we can combine with the Darcy's law. So, that way, we can derive the groundwater flow equation. So, the derivation of groundwater flow equation is based upon the mass balance and the Darcy's law. So, here, this is the say representation as far as Darcy's law and then law of mass balance with respect to this.

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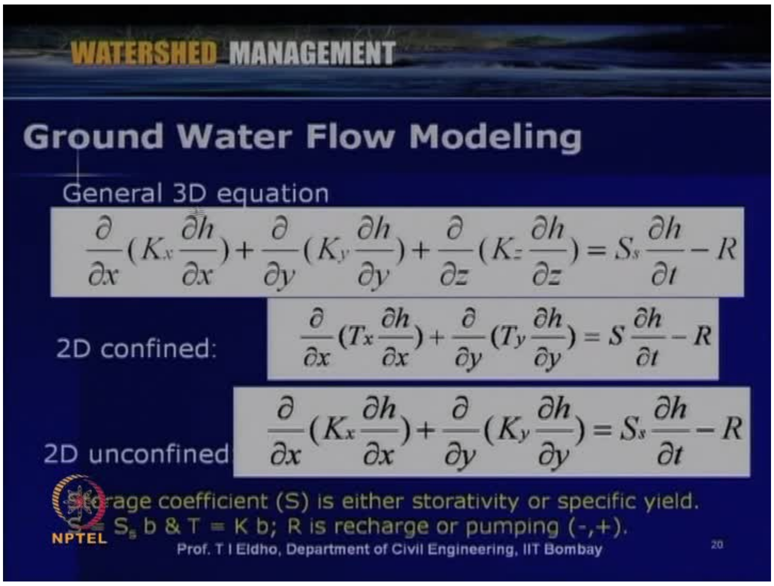

So, finally, using both, we get the divergence K gradient h is equal to S del h by del t. This equation we can obtain which is the governing groundwater flow equation. So, in a better mathematical form, here I have written the groundwater flow equations generally in 3D form.

Say for example, confined, unconfined aquifer, so del by del x of K x del h by del x plus del by del y K y del h by del y plus del by del z of K z del h by del z is equal to S s into del h by del t minus R - where this R is the recharge of pumping, so, minus for recharge and plus for pumping. So, S s is the say specific yield or specific storage coefficient as given here, and for confined aquifer, we can represent the equation like this, and in 2D, the same equation can be mentioned like this.

So, of course, depending upon like various recharge or pumping terms or other sources coming to the aquifer system, this equation can some more times will be there or some changes will be there; otherwise, general equations are in this form.

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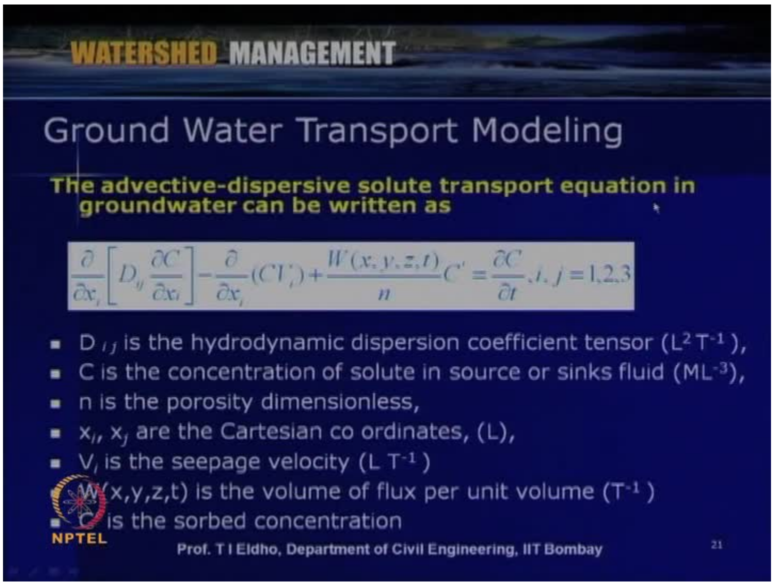

And then as far as ground water quality is concerned, we have to say study the transport process taking place as far as the aquifer is concerned. So, very similar way, we can derive the groundwater transport equation by using the fix slope. So, here, the advective dispersive solute transport equation in groundwater, we can write here. I am not going to derivation here, the equation is written here.

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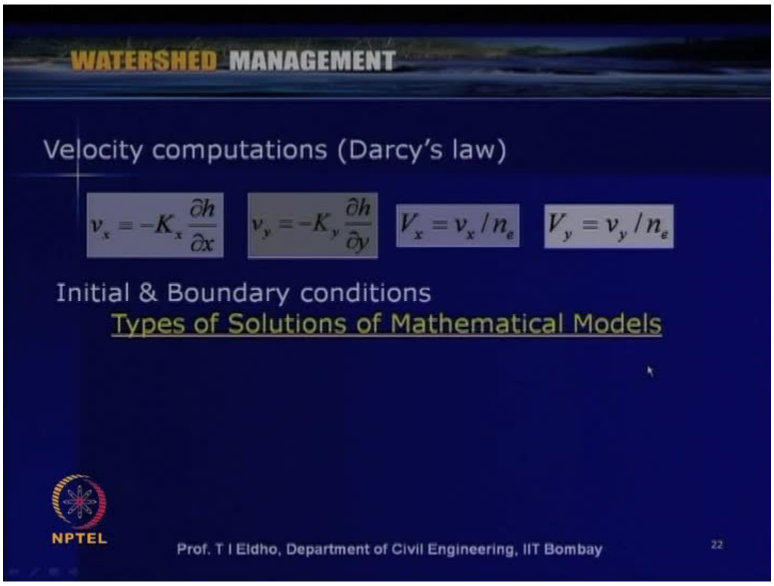

So, it is del by del x of D i j del C by del x minus del by del x i C V i plus W by n into C dash is equal to del C by del t - so, where D is the hydrodynamic dispersion coefficient tensor; C is a concentration of solute in source or sinks fluid; n is the porosity dimensions, and x i x j are Cartesian coordinates; V i is the seepage velocity obtained by solving the groundwater flow equation and then V is obtained by using the Darcy's law and W is the volume of flux per unit volume and C dash is the sorbed concentration. This equation is also concerned different forms are available depending upon various kinds of transport processes but a general form is written here.

So, as I mentioned, so here, once the groundwater flow equations are solved, we get the head variation, and then using the head variation by using the Darcy's law, we can obtain the velocity in X Y Z direction, and then, from that velocity components, we can utilize within the transport equation, and then also we have to specify the initial and boundary conditions. As I mentioned initial condition for, flow will be, flow equation will be, that is, say if the head variation within the aquifer system, that will be initial condition, and boundary condition flow for flow equation will be either head prescribed or flux prescribed in terms of dirichlet boundary condition and the Neumann boundary condition, and as far as the transport equations are concerned, initial condition can be the variation of concentration at the starting on the time step, and the boundary condition can be in terms of the knowledge of concentration at particular boundaries or it is a gradient of the concentration.

So, this, this constitute, so once we define the boundary of the aquifer system and then we identify whether it is confined aquifer or unconfined aquifer, and correspondingly, we can take the equation for the confined aquifer unconfined aquifer and then we can use the transport equation.

So, the modeling can be either in two dimensions or three dimensions or sometimes in one dimension, and then, say we can also use the Darcy's law with respect to calculate the velocity components. So, that constitute the mathematical model as far as the groundwater flow is concerned, and then, say the solutions of this mathematical models, say we can go for say for simple problems like some hypothetical or a small type of problem where not complexities are there.

Analytical solutions are possible say simple steady state groundwater flow in homogeneous isotropic medium. We can go for analytical solution, but as far as field problems are concerned, analytical solutions are not at all available not at all possible.

So, we have to go for only for numerical solutions. So, numerical solutions as I discussed in the previous lecture, so various numerical techniques are use to transform this partial differential equations, the second order partial differential equations and the equations are transformed into algebraic form by using techniques like finite difference method, finite element method, boundary element method or finite volume method, etcetera. So, in the last lecture, we discussed the methodologies like a say finite element method and finite difference method. Also nowadays method called analytical element method is also available for the solution of groundwater flow and the transport equation.

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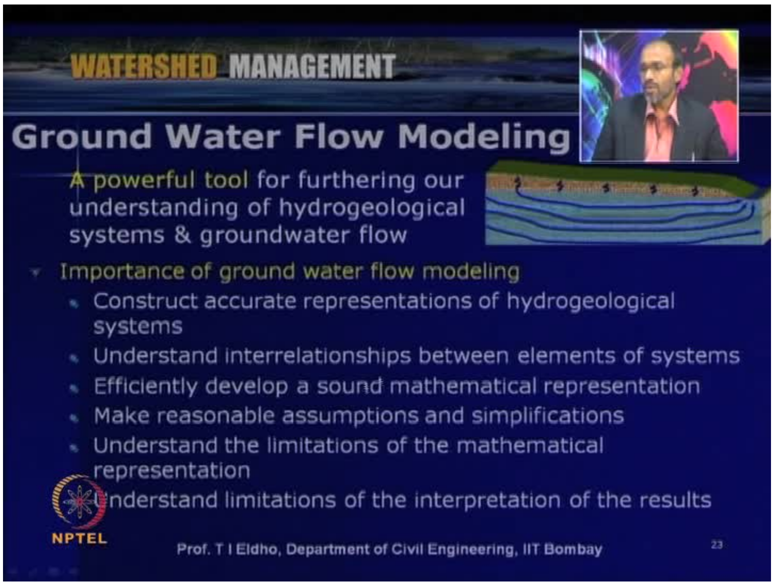

So, now, say before discussing little bit further about the groundwater, the numerical techniques, so groundwater flow modeling is very important as I mentioned. So, this groundwater flow modeling is a powerful tool for furthering our understanding of hydro geological systems and groundwater flow and transport. So, that is what we are discussing.

So, the importance of groundwater flow modeling include construct accurate representations of hydro geological systems and understand the interrelationships between elements of systems and efficiently develop a sound mathematical representations as we have already seen in the previous slides. Then make reasonable assumptions and simplifications like a whether two-dimensional modeling, three -

dimensional modeling or one-dimensional modeling, transient modeling or steady state modeling, then understand the limitations of the mathematical representations.

So, we have derived these equations and then we are going for numerical modeling based upon number of assumptions. So, that are our limitations as far as the groundwater flow modeling is concerned. Then understand the limitations of the interpretations of the results. So, why, since the data availability and it is accuracy is a very much varies with respect to groundwater flow investigation. So, that way, getting 100 percent accuracy in groundwater flow modeling is impossible to us.

So, what way, the how much is, how, what kind of assumptions we put and then what kind of limitations are there. Accordingly, the model results will be the accuracy of the model results depends either for flow or transport is concerned.

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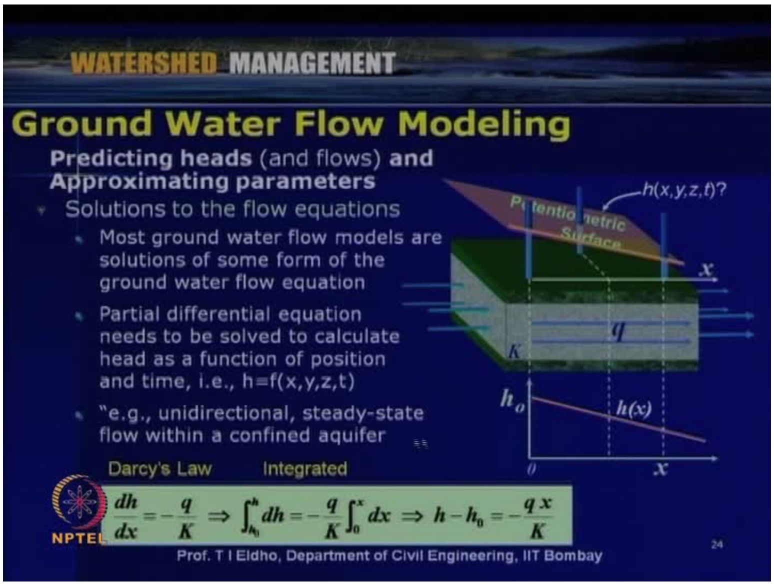

So, now, say for example, here before discussing the numerical technique like finite difference or finite element, so here, say for example, for simple flow, say like a we can even simply derive analytical equation, like say if you consider the Darcy's law, say for flow movement from one location to another location. If it is flow is homogeneous isotropic, then, the, we can simply derive equation like this.

So, solutions, say for simple problems, we can derive the analytical solutions, but most of the field problems, this kinds of analytical solutions will known be valid. So, this, for this flow, says isotropic homogeneous media, we can say the said variation is actually linear variation which is obtained by this equation.

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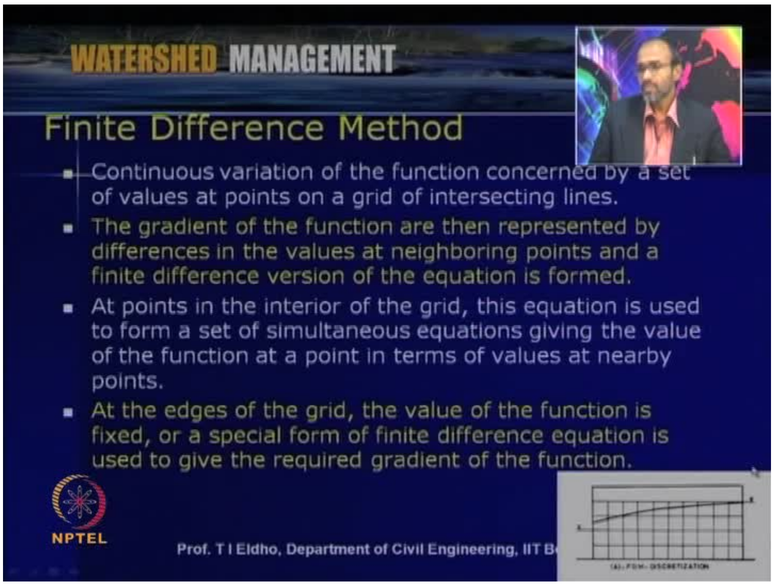

So, that way, we have to go for finite difference method or finite element method or other numerical tools. So, finite difference method and finite element method, we discussed in the last lecture. So, further, say as I mentioned in the earlier lecture finite difference method gives the continuous variation of the function concerned by a set of values at points on a grid of intersecting lines as shown here.

So, the gradient or the functions are then represented by the differences in the values of neighboring points, and a finite difference version of the equations is formed. At points in the interior of the grid the equation is used to form a set of simultaneous equations giving the value of the function at a point in terms of values at nearby points.

At the edges of the grid, the value of function is fixed or a special form of the finite difference equation is used. So, as we discussed in the previous lecture, so this finite difference can be implicit or explicit, we can have forward, backward or central finite differences. So, according to the formulation which we are doing, so, we can have this various schemes and then we can transform the either the groundwater flow equation or groundwater transport equation using the finite difference method.

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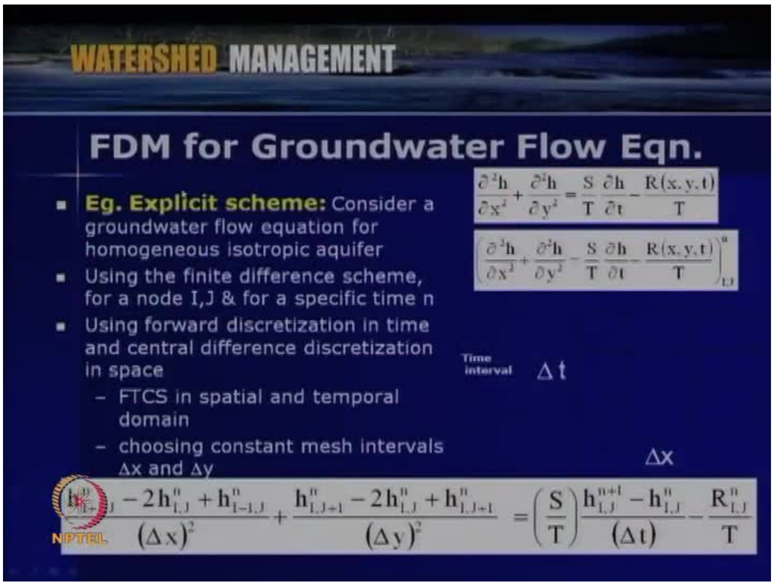

Say for example, in this slide, say the finite difference explicit scheme for the ground water flow equation is given. So, if this is our groundwater flow equation, two dimension for, say for example for confined flow. So, in explicit scheme using the finite difference schemes for a node I J, so this is I J node for a specific time n using forward discretization time and central difference discretization space, we can derive this system of equation.

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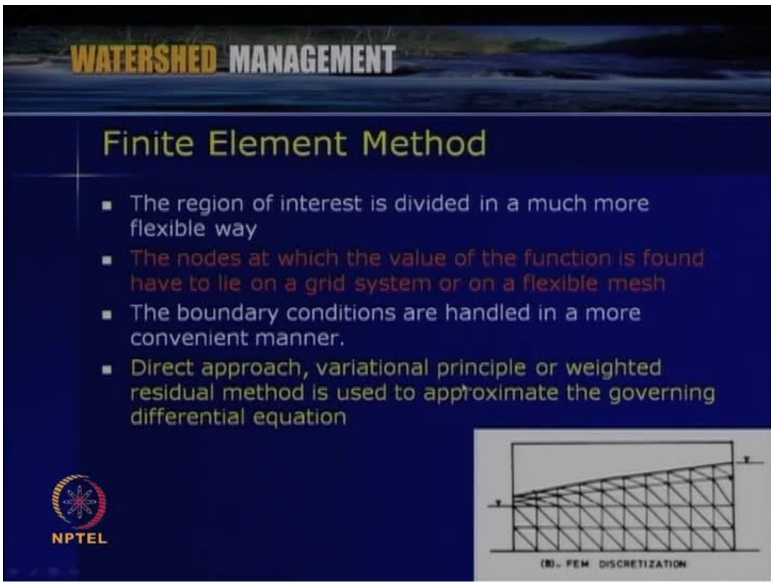

So, these details are available in test books like introduction to groundwater modeling is in finite difference and finite element method by Wang and Anderson and say Jacobier groundwater flow, Jacobier (( )) is a porous media by Jacobi er, etcetera. So, this books gives all this details. So, due to lack of time for this, this only groundwater flow only one lecture is dedicated. So, that way, not much time is there. So, that way, I am not going to the details of these methodologies.

But finite difference in explicit scheme, we can obtain like a stone in the slide. So then, finite element method is another method as we have discussed in the previous slide, previous lecture. So, the region of interest is divided in a much more flexible way. The nodes at which the value of the function is found have to lie on a grid system or on a flexible mesh as we can see here.

Then either like a triangular elements, rectangular elements in two dimensions or correspondingly prism elements or tetrahedral in three dimension we can use. So, various schemes are there; direct approach, variational principle or weighted residual method, etcetera. So, that way also this governing equation like the groundwater flow equation or transport equation, we can transform and then we can have the system of equation all by system of equations.

Then we can apply the boundary initial conditions and boundary conditions and solve those system of equation either iteratively or direct methods to get first the head variations, and then, using the head variations, we can get the velocity variation using the Darcy’s law, and then, if you want to say identify how the transport mechanism, then we solve the transport equation also, very similar way using finite element method or finite difference method.

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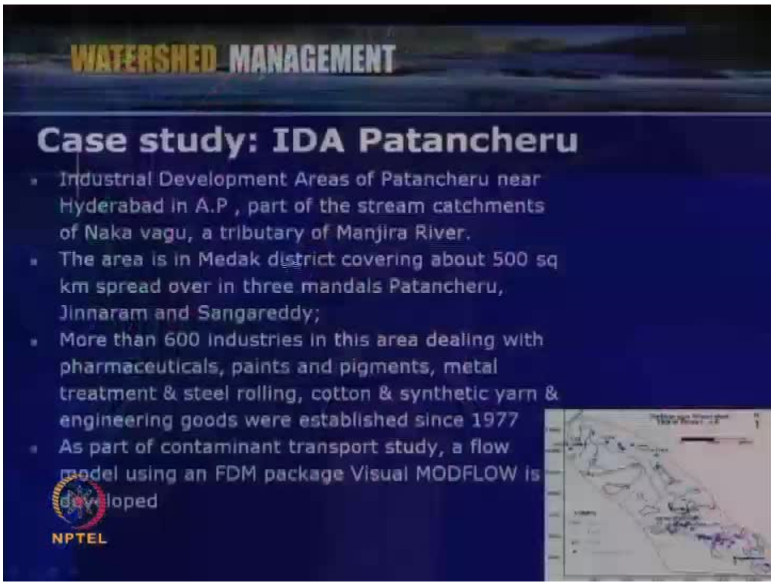

So, before closing this lecture, let us go through one case study. So, the case study here is the I D A patancheru. So, here, industrial development area in patancheru near Hyderabad, the area is in medak district and the area is about 500 square kilometer.

So, this is the aquifer region and it is spread in 3 mandals. More than 600 industries in this area dealing with pharmaceuticals paints and pigments, etcetera, where established in 1977. Since 1977 and then say in eighties, say there was no in, when it was the industries were established, there was no say effluent treatment plans. So, these industries directly put these effluents to the nearby streams. So, that way, this has becoming major problem. In this area, groundwater pollution has been a major problem.

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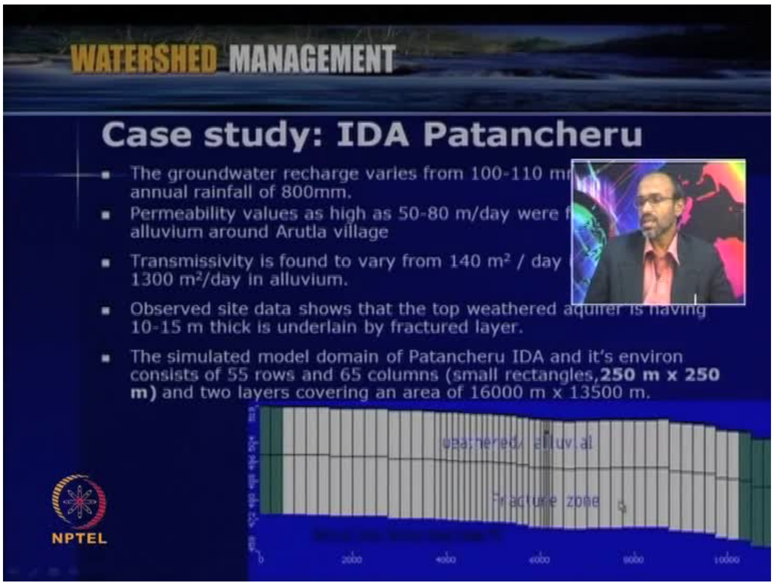

So, as a part of this groundwater flow transport mechanism and groundwater quality modeling, here we have developed a model using visual mudflow. So, I will briefly discuss about that. So, here, in this area, the groundwater recharge varies from hundred to hundred and ten mm per year for an annual rainfall of 800mm.

Permeability values vary from 50 to 80 meter per day and a transmissivity varies from 140 to 1300 meter square per day and observed site data shows that the top weathered aquifer is having 10 to 15 meter thick underlain by fractured layer.

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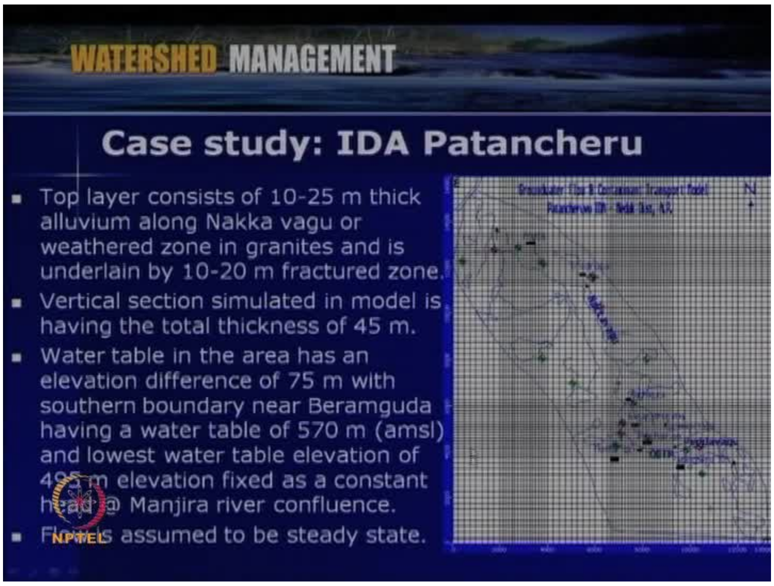

So, simulated model domain is about consists fifty five rows sixty five columns and with 250 meter approximately by 250 meter grid and two layers. You can see here two layers and this is the grid which we have generated using the visual mudflow.

So, the modflow is based upon the finite difference scheme and this is the boundary. So, now, this cells will be inactive cells and only the cells within this boundary will be the active cells. So, top layer of 10 to 25 thick meter alluvium nakka ver of nakka vagu or weathered zone is granites and is underlain by 10 to 20 meter fractured zone.

Vertical section simulated in model is having the total thickness of 45 meter and water table in the area has an elevation difference of 75 meter. So, with southern boundary near this location is about 517 meter above means sea level, and here, it is about 495 meter.

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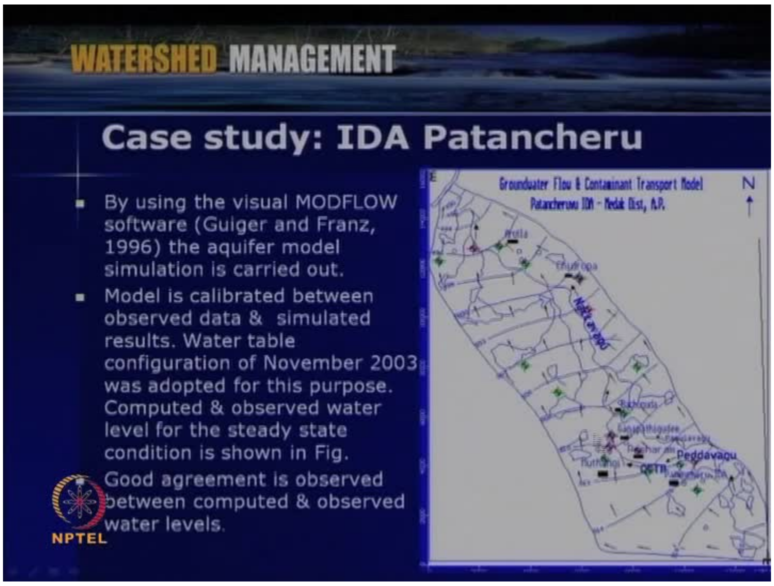

Say as far as analysis is concerned, main issue was here the transport modeling. So, that way, we conducted a steady state analysis. So, this using the mudflow, as I mentioned modflow is a finite difference based package developed by McDonald and harbaugh. So, the aquifer model simulation is carried out. So, model is calibrated between observed data and simulated results. So, water table configuration of November 2003 was adopted for this purpose.

So, computed and observed water level for the steady state condition is shown here. So, this is the variation of the, so once the model is run, modflow is run, we obtain the head variation from here to here and that is this contour line shows and then also we can calculate how the velocity variation taking place. So, you can see that this arrow mark shows the velocity variation within the aquifer system.

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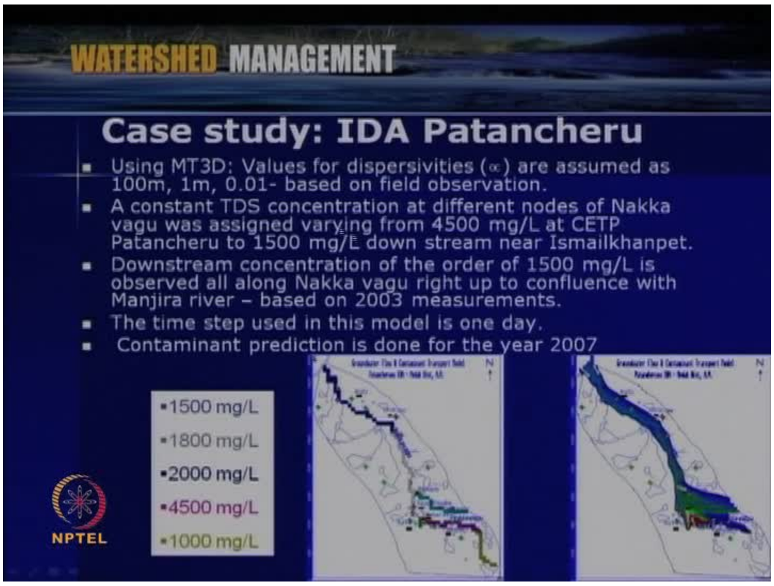

So, using this mudflow, good agreement is observed between computed and observed water levels for the aquifer system, and then, we run another model called mass transport in three dimension. That is also finite difference based model by assuming dispersivity values 100 meter, 1 meter, 0.01 - based on field observation.

A constant TDS concentration at different nodes of nakka vagu which is this here and varying from 4500 milligram per liter to 1500 milligram per liter has been used. So, the main pollution was on the source. So, this is the initial contamination at 2003, and then, we run the model to find out how the spreading will takes place in 2007 and further.

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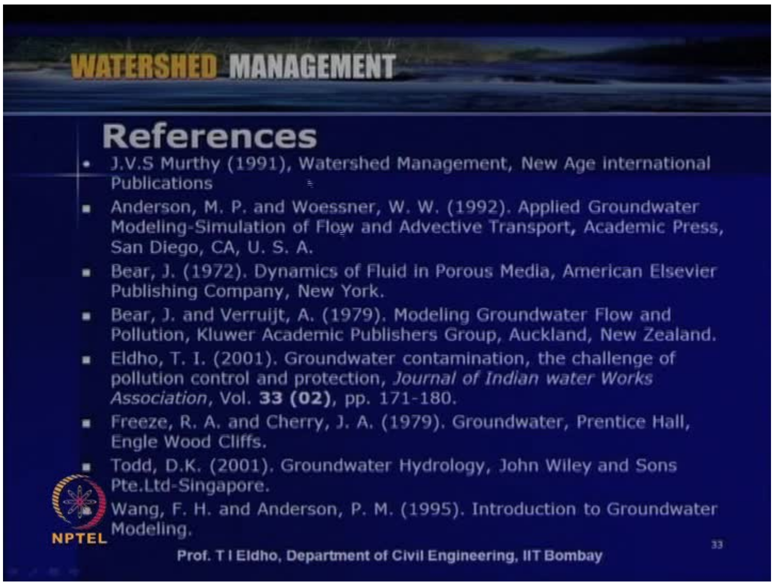

So, 2003 measured data was available. So, based upon that, we run the model to identify how the contamination spreading in 2007. So, this shows the variation. So, like this, say by using the mathematical or numerical model like a modflow or m t 3D, we can assess the groundwater say flow condition or the quantity based modeling and the transport modeling how the contamination spreading is taking place.

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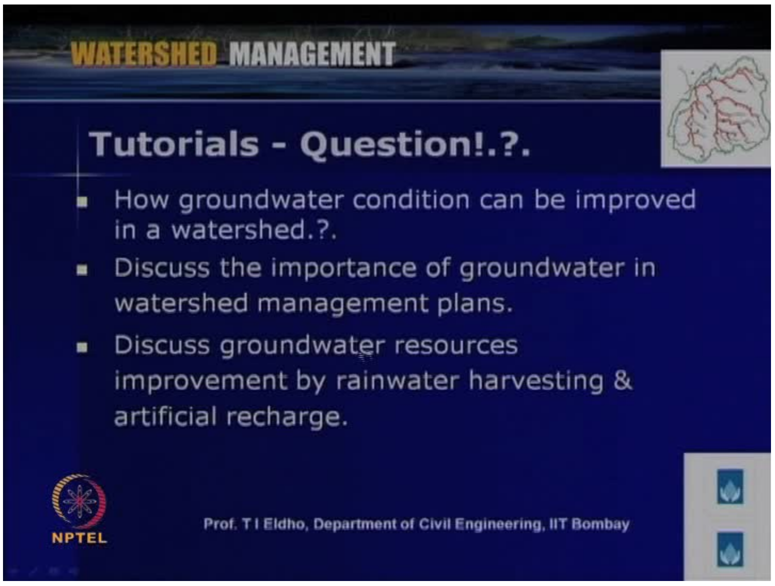

So, that way, we can model using, the ground, the groundwater flow model using finite difference finite element method or other kinds of numerical techniques. So, for this today's lecture, some of the important references are listed here, and then, before closing the lecture, some tutorial questions – so, how groundwater condition can be improved in a watershed? Discuss the importance of groundwater in watershed management plans. Discuss groundwater resources improvement by rainwater harvesting and artificial recharge. So, these questions can be answered based upon today's lecture and some of the previous lectures on rainwater harvesting and artificial recharge.

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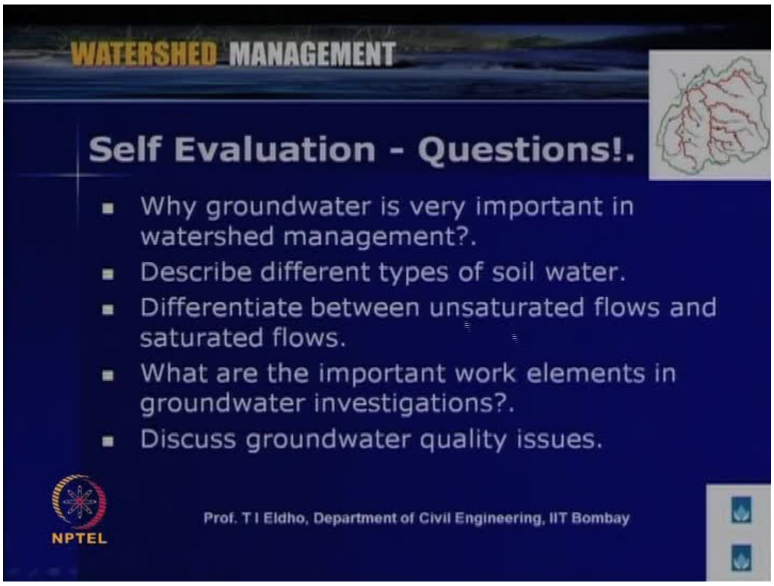

Then some self evaluation questions - why groundwater is very important in watershed management? Describe different types of soil water. Differentiate between unsaturated flows and saturated flows. What are the important work elements in groundwater investigations? Discuss ground water quality issues. So, these, all these related answers you can obtain from today's lecture.

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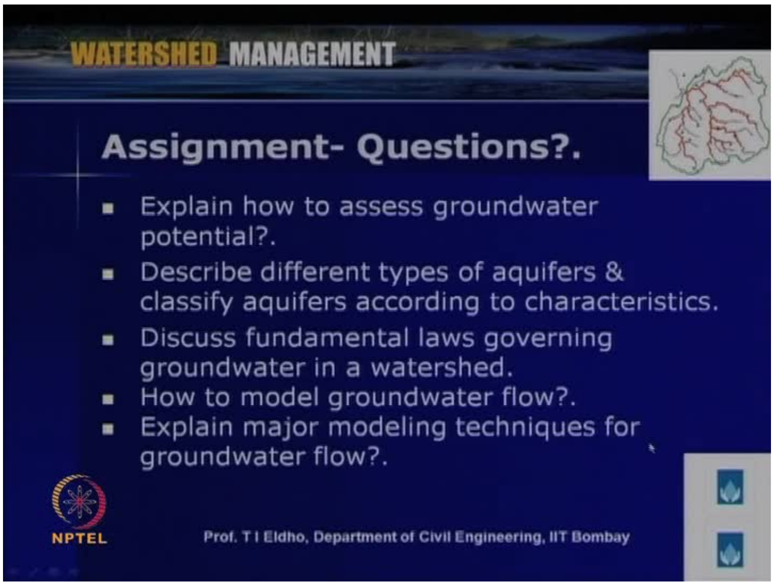

And then, some assignment questions - explain how to assess groundwater potential? Describe different types of aquifer and classify aquifer according to characteristics. Discuss fundamental laws governing groundwater in a watershed. How to model groundwater flow? Explain major modeling techniques for groundwater flow. So, these questions are also can be answered by going through today's lecture

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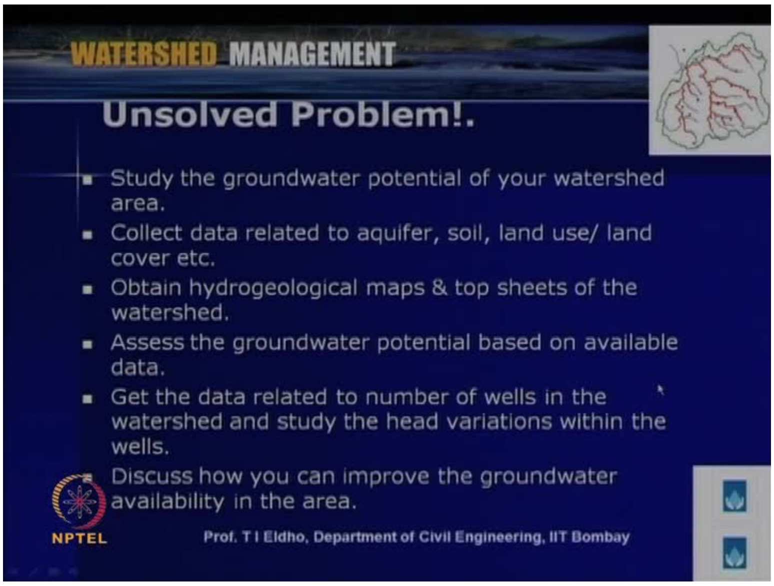

And finally, as an unsolved problem, say study the groundwater potential of your watershed area. Collect data related to aquifer soil, land use, land cover, etcetera. Obtain hydro geological maps and top of sheets. Assess the groundwater potential based on available data. Get the data related to number of wells in the watershed and study the head variations within the wells discuss. How you can improve the groundwater availability in the area in terms of rainwater harvesting or artificial recharge?

So, today what we discussed is the groundwater flow or subsurface flow conditions. So, we have seen various aspects of groundwater flow and groundwater flow modeling. So, we have, say here only one lecture is given for ground water flow so only the introductory aspects only we could discuss today. So, those who are interested in this, you can refer to some other text books given in the reference lists. Thank you very much.