River Engineering
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Lecture – 03
Basic Properties of Sediment, Sediment Concentration Variation and Flow Structures in Natural Rivers

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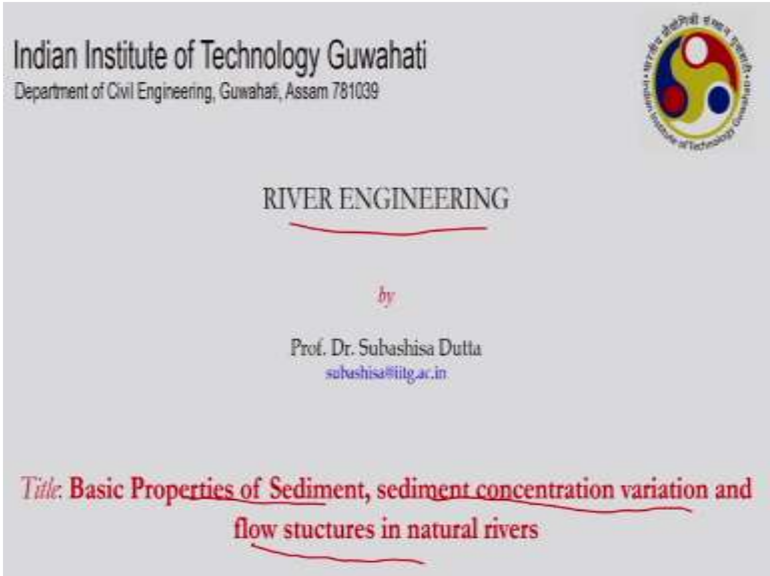

Good morning. Welcome all of you to this river engineering course and this is what the third lecture. We are going to talk about the properties of sediment, sediment concentration variations and very interesting topic, the flow structures in natural river systems.

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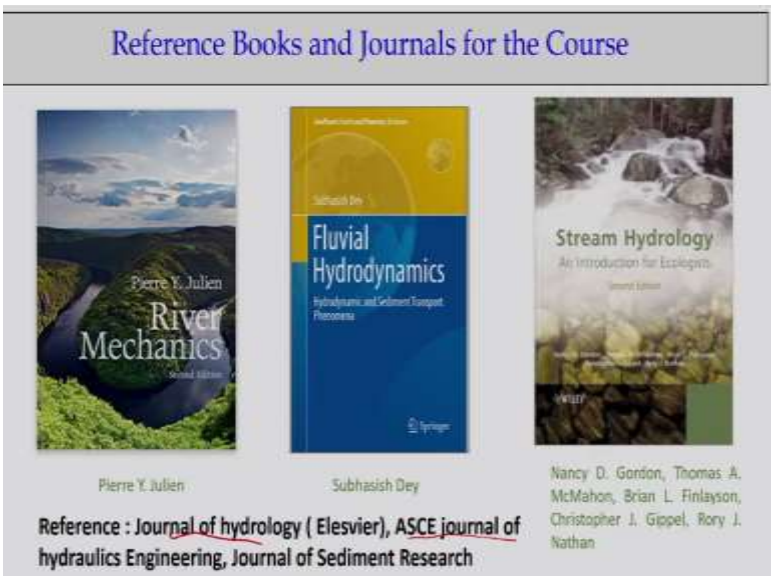

This is a combination of theoretical aspect as well as the practical aspect of the river engineering, that is what today we will discuss and as I said it earlier, we are going to follow these 3 books and, starting from River mechanics, Fluvial Hydrodynamics and the Stream hydrology as the last one is for the introduction for ecologists. You can see that these lectures will consider all the three aspects of the river mechanics, fluvial hydrodynamics and the ecological aspects.

So looking that, since it is a higher level course, we will also go through its reference journal like journal of hydrology, ASCE journal of hydraulic engineering and journal of the sediment research. The other journals we will talk about that some of the case studies from the journals also we will discuss in these lectures and really it will be the interesting lectures to show you the natural river systems as well as these theoretical, numerical expressions what we do in river mechanics.

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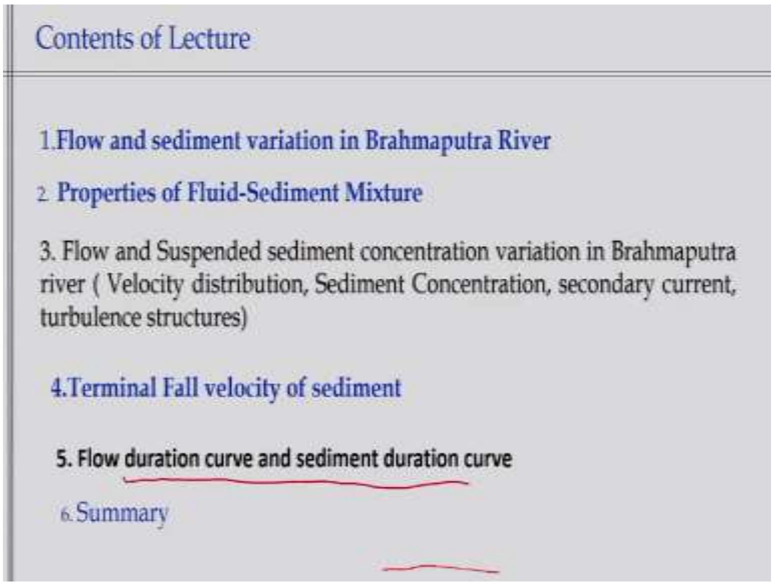

Looking that let us go for today's content what we have. Initially at the first level, I will introduce you the Brahmaputra river in very simple way and a brief variations of the flow and sediment variations in Brahmaputra river, that is what I will discuss first. Then I will talk about, again I will repeat the fluid-sediment mixture properties how we can quantify it because when you talk about the river flow, it is not only water flow, it is water and the sediment mixtures.

How to quantify that, that properties of the fluid-sediment mixtures that what we will talk about. Again, I will come back to the river scales to show it how the flow and suspended sediment concentrations varies. Then, again we will come back to if there is a sediment particle what will be the terminal velocity of the sediment particles, theoretical as well as combining with experimental things.

Then very interesting, what today we will talk about the flow duration curve and sediment curve analysis at the river scales. Then we will conclude this lecture.

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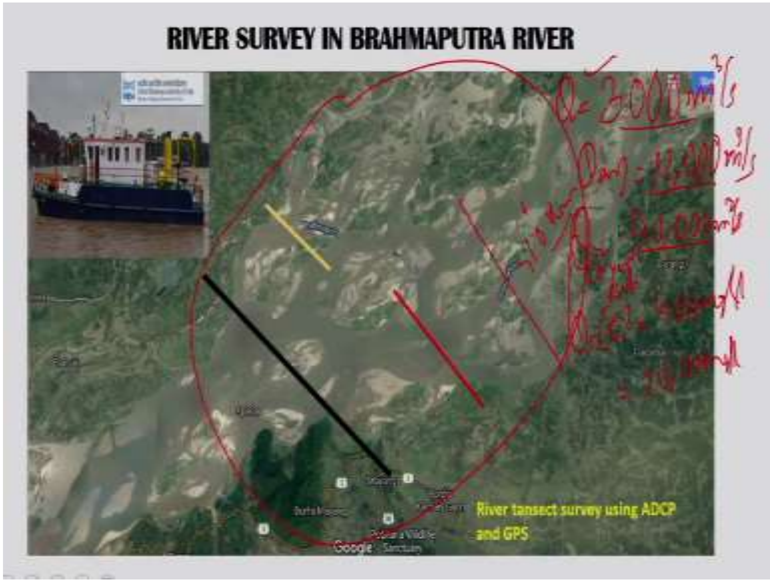

Looking that let us go for the next slides where I am showing the river survey of the Brahmaputra river. If you look at these satellite photographs, the google earth availability of the satellite data, the river width at this stretch comes about more than 10 kilometers. So you can understand what could be the width of the river? 10 kilometers that is the width of the river.

Not only that if you look at this flow variabilities, the discharge variability, how much of discharge varies in this river for a low flow? it starts about 3000 m^3/s, it is very low flow. During that of dry seasons, we will have the flow which is about 3000 m^3/s, 1 meter cube as equivalent to 1000 liters, you can understand how much of water is flowing in it.

The average flow of this river comes about 12,000 m^3/s, so much variability of flow. Average flow is 12,000 and the low flow is 3000 m^3/s and the maximum flow what is observed during a 10-year return period flood that is what comes about 40,000 m^3/s. So it is a bigger river systems. If you look at that the flow variability starts from 3000 m^3/s to average 12,000 m^3/s, then it goes to the 40,000 m^3/s.

How much of sediment it carries, if you look at that the average sediment, what in terms of sediment concentrations if I talk about it is about 400 mg/L average, but as maximum as it can go it is order of 20,000 mg/L. So if you look at this river system, so variability is there in flow and also the sediment and if you look at the river the dimensions is as I said is 10 kilometer width and this is about 30 kilometers and you can see so complex river systems.

It is confluencing, de-confluencing, forming the bars and all. So if you look at this type of river systems and we try to understand the rivers, we need to have a the knowledge on how these sediment laden water flows happens and how mechanics is developed on that and how far you have an understanding of that?, that is what the basic objective of this course to you to take it to that levels that we can understand.

So complex river systems i.e. how the morphology is changing here, how the sediment erosions are happening, depositions are happening. All this process we try to understand with our basic knowledge of fluvial hydrodynamics. We will talk about more details.

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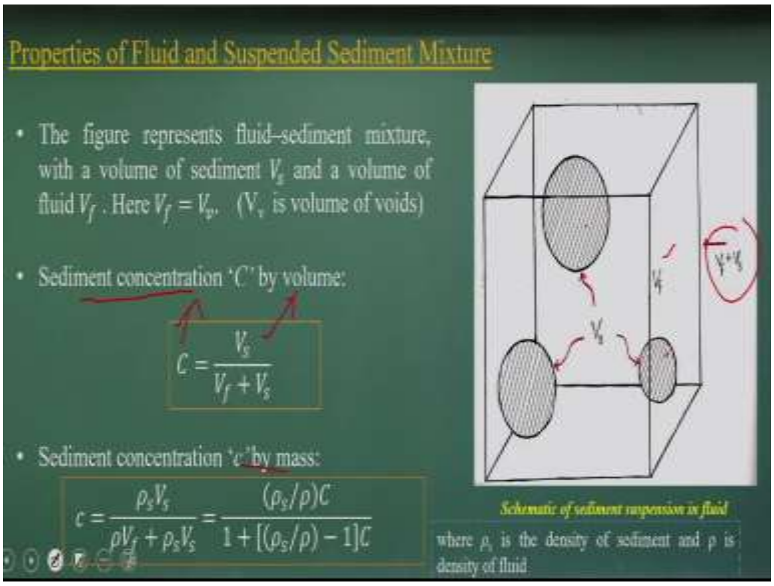

So with these variabilities that means what I talk about that the river does not mean it is water flow, it is a mixture of the fluid and the sediments. So always sediment it is there, except these very low flow periods we can see always the sediment is there and that sediment concentrations increase exponentially when we come into a larger flow order events. So you try to understand it how these fluid sediment mixtures are happening.

Like the last class I discussed it, again I am repeating it that if you talk about the sediment concentrations which is a very simple concept that if you take control volumes if you have V_s is the volume of the sediment particles V_f is volume of the fluid, the total volume of these control volumes will be $V_f + V_s$, it is very easy. The sediment concentrations by the volume will be V_s by $(V_f + V_s)$

So as this sediment V_s increases, the C will be going to increase that is very basic things. Most of the times we are not doing the volumetric levels, we do the analysis at mass conservation equations, momentum equations, energy equations. So, we always link to the mass, not with the volume. So, if I find out what is the C then the concentrations by mass which we denoted as a small c can be found.

That is what will be the mass component of the sediment particles divided by the total mass of these systems which is very easy just to multiply the particular respective density like ρ_s stands for here the density of the sediment particles, ρ stands for here the density of the water. So, you can compute what could be the sediment concentration by mass. That means if the c stands for mass, how much of mass of the sediment concentrations happens that what we do per unit volumes.

And if you substitute capital C, then you can get in terms of this. So many of the times please do not confuse it whether it is a c in terms of volume or the mass, so you can convert it. If the volume level data is given, you have to convert it to the mass level or vice versa you can do it. It is a very simple calculation we do to find out what will be the concentration.

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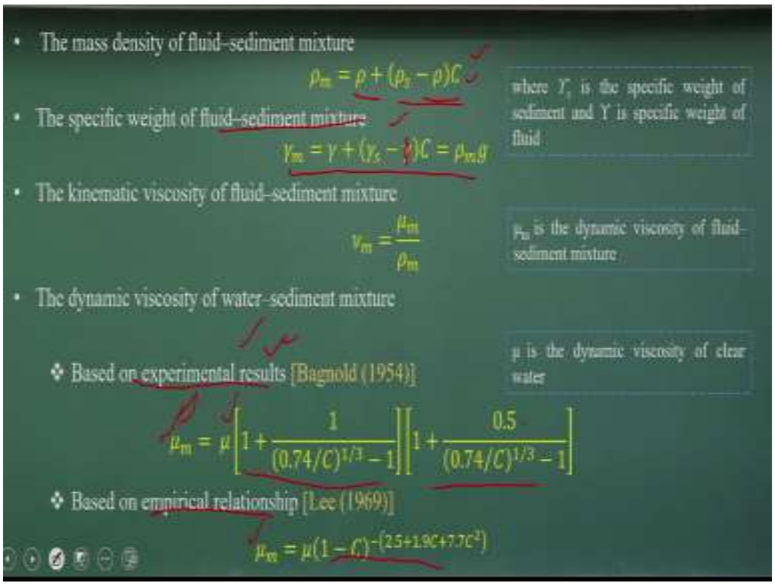

As I said it when you talk about the fluid and sediment mixtures, so what will be the density, we can find at mass per unit volume for that mixtures will be the sum of liquid part and also the sediment part, that is all. The mass is the sum of the mass of the water part and the sediment particles part that is what you can see it. The same way we can get it what will be the specific weight of the fluid and the sediment mixtures.

Again I am talking it is a fluid-sediment mixture, you try to understand that so you can have this. Now if you look at that, many of the times when you talk about the fluid mechanics, we always talk about Newton's laws of viscosities that is the Newtonian fluids. What is there it is a relationship between shear stress and the shear strain rate that is what the relationship with dynamic viscosity.

Here, because we use the fluid and sediment mixtures, the dynamic viscosity will not be exactly same as that of water dynamic viscosity. So that is what is from experimental data quite clearly establishes that the fluid and sediment mixtures will have a function of dynamic viscosities of the water and the correction factors for the sediment concentrations, C is in terms of the volumetric sediment concentration.

The fluid is mixed with the sediment particles you can just try to understand that as I increase the sediment concentration, more viscosity will come, that is what is this correction factor is standing for. These are all more than one values so that is the correction factors. If I consider the fluid-sediment mixtures if I know the C value, I can compute it what will be the dynamic viscosity of the water and the sediment mixtures which is necessary for us.

Or we can have another empirical equations also developed from experimental data which has these power functions. So, these are well documented experimental finding the relationship between the shear stress and shear strain rate assuming it is a newtonian fluid behavior, we can find out what will be the dynamic viscosity of the water and sediment mixture particles which is from the experimental data.

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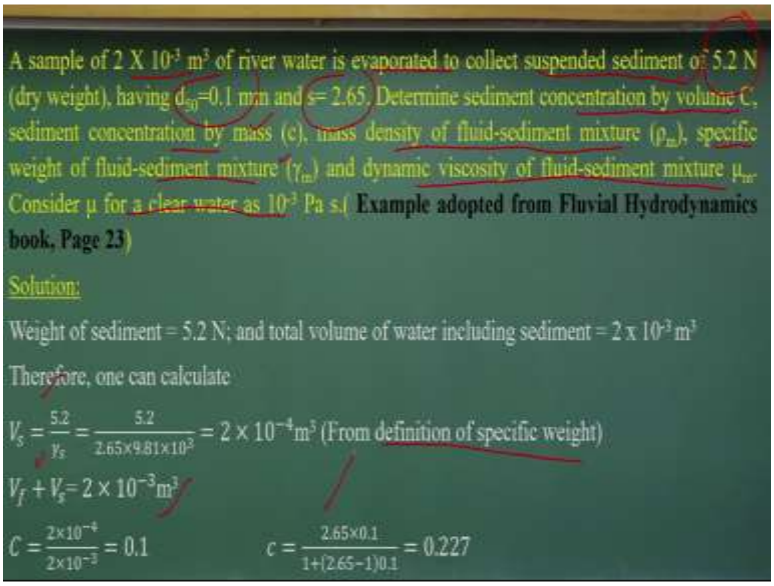

Now let me go with very simple examples to say it how we can compute it, very simple example that we consider a volume of 2 x 10^{-3} m^3 of river water evaporated it to collect the suspended sediment concentrations which will be weighed, then you have the d50 value, you have 's' specific gravity value, then you try to compute what will be the C or c value that is the sediment concentrations by volume or sediment concentrations by mass.

Then you want to find out mass density, the specific weight of this and the dynamic viscosity of the fluid-sediment mixtures and if the μ for the clear water is given. So this is a very simple problem just to apply the formulas what we discussed earlier and only the basic difference is that from the specific weight we can find out the V_s value, we know this V_f value, then we can compute this capital C and small c.

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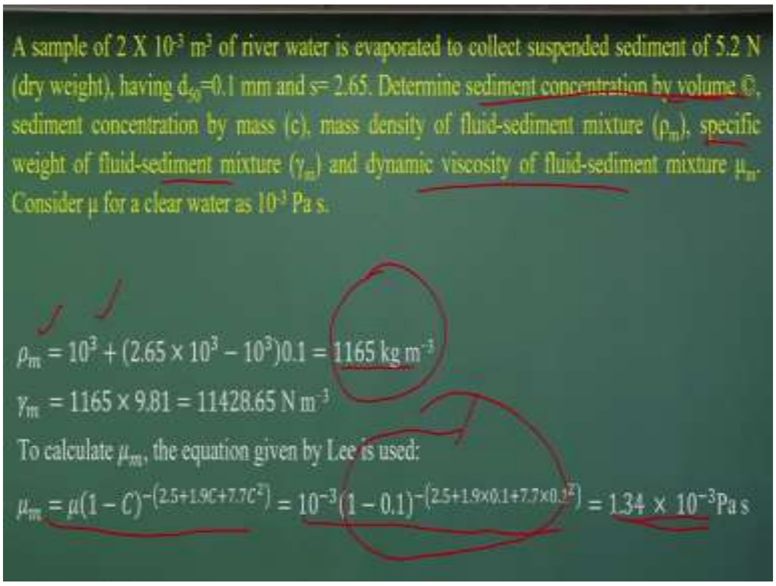

Same way if I apply it, I can get the density of fluid and sediment mixtures that is what will be much higher than as I know it the water density is 1000 kg/m^3. Because of resistance of the sediment mixtures, we have the density of this water and sediment mixtures is more than 1000 kg/m^3 which comes out to here 1165 kg/m^3. Same way you can compute what will be the dynamic viscosity.

Just substitute the c value and μ is known to us, you can see that it is more value, μ_m is more high value than the clear waters because of the presence of the sediment concentration factors. This is simple example to just to demonstrate how we can compute if we know the sediment concentration. You go to the river, collect the suspended water samples, evaporate back, weigh whatever the evaporated suspended sediment concentrations.

Then you can do this type of calculations to find out what will be the dynamic viscosity, what could be the specific weight of the sediment particles, sediment concentration by volume and mass. We can do easily. Just go to the river, collect the water samples, do the evaporations and find out what is your remaining solid particles which is the sediment particles is there, you just take the weight and find out all these the fluid sediment properties that is the basic thing.

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So now let us go for next slides, again I am coming back to the river . So Brahmaputra river if you look at that what I just have given the introduction to you. We are having a fortunate to having collaborations with this organization which is Inland Waterways Authority of India to do an extensive river surveys of this big river systems of 10 kilometer wide.

I present that data to you, which is quite interesting data to you that if you go to river like this type of river of 10 kilometer wide of the river, we cannot do a simple survey, we need to have a survey vessels equipped with global positioning systems you know about that, everywhere you have now the global positioning systems, equipped with ADCP which is acoustic Doppler current profilers for measuring the 3-dimensional velocity components.

It measures the depth, it measures the suspended sediment concentrations. More details you can browse through any of the literatures, you can see that what is the ADCP, how to use the ADCP. When you use these type of survey vessels equipped with GPS, equipped with a ADCP, equipped with echo sounders to do a survey transact of this width of more than 10 kilometers, it takes more than 5 hours , so it is not that easy job to do a survey in the river like this Brahmaputra when you have 10 kilometer river width.

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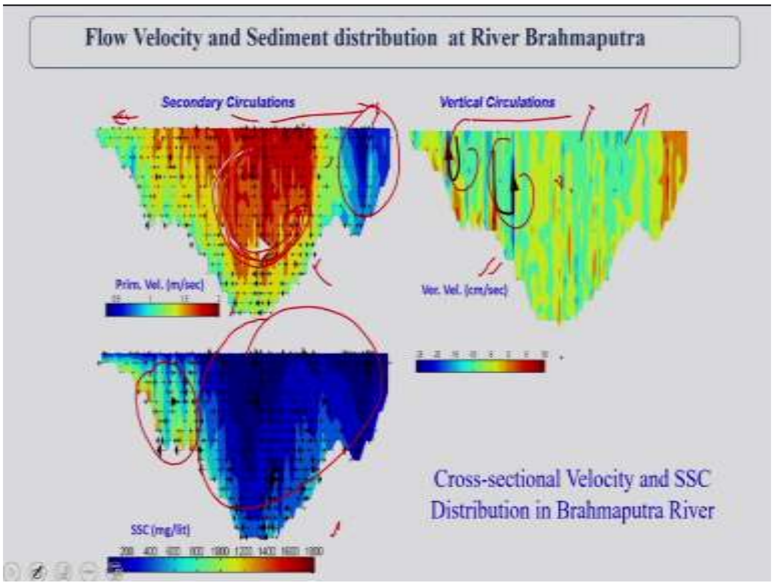

Let me present the data how complex the river is. We cannot simplify the river as we use it that is what I have to introduce to you this is the raw data what we collected from the field, it is not any generated data, this is a measured data, the field measured data of Brahmaputra river. If you look at that if I plot these 3 velocity components, one is the primary velocity component which is longitudinal direction, there is a vertical velocity component and there is a horizontal component the perpendicular to that.

This is the cross sections, this width can be something like the few kilometers and this colors are representing my different velocities. If you look at this red color zone is representing us about 2 m/s, just again I am repeating it. See if you look at the core zone, the velocity is about 2 m/s, but there are the locations where velocity is lesser than the 0.3 m/s, which is 1 ft/s.

But there are the reaches where you can have the velocity is more than 2 m/s. That means the velocity variations is there from 0.3 to 2 m/s, almost 10 times. Within these cross sections, there is a velocity difference and this is the natural river, you can see the velocity difference, what is the primary direction, but what it happens if you look at this velocity vectors what you have given at these directions.

The perpendicular to the longitudinal directions, you can see this velocity factors and from that you can see that there are large vortex formations are happening that is what you call the secondary current. You can easily see that. So when you measure this velocity using the ADCP, you can see this velocity variations in the longitudinal directions in a cross section. Similar way, there will be the velocity variations perpendicular to that.

And there are formations of the secondary currents which are large vortex structures, you can see it from this figure. If you look at the vertical directions also, we see the velocity is much lesser, the values are in cm/s, is not in m/s. Primary velocity is in m/s and secondary velocity is in cm/s. The velocities are less in vertical directions.

But interestingly, the vortex formations are there because of the velocity change gradients, due to velocity change along the cross-section. If you look at the suspended sediment concentrations which I said it earlier is 400 mg/L to 20,000 mg/L, you see that these regions the concentration on average is 300 to 400 mg/L, but there are stretches you can have a sediment concentration as high as 800 mg/L.

So you just look at the variability, just look these are original field survey data which we have, nobody has in the world these data sets. So, if you look it that way there is a variability in sediment concentration, there is a formations of the secondary current and there is the variability in a primary velocity, vertical velocity and the suspended concentration that is the reason the river is complex.

And we try to understand the river from mathematical point of view and physical concept point of view and also from conducting at the river scale experiments and that is the strength of the work we should go with.

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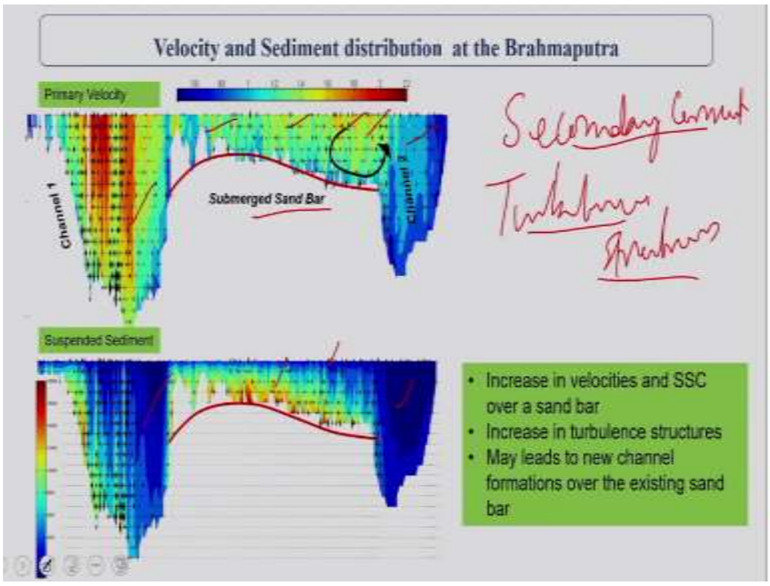

If you look at that same concept if I go for larger width, in between there could be a sandbar formations, if you look at how this primary velocity variations are there, too complex. How the secondary currents are there? How the suspended concentrations are there? All these are built up with the secondary current and large-scale turbulence structures. There are lot of turbulent structures we can see in the Brahmaputra River and a lot of secondary current formations are there.

Which carry a large flow and sediment mixtures and which varies from seasons to seasons, the day to day and the month to month, so that is the way and also varies from year to year. So that is what is the complexities comes as we change the sediment properties as we observe at the field levels that is the strength of these lectures and hope you could have enjoyed this lecture.

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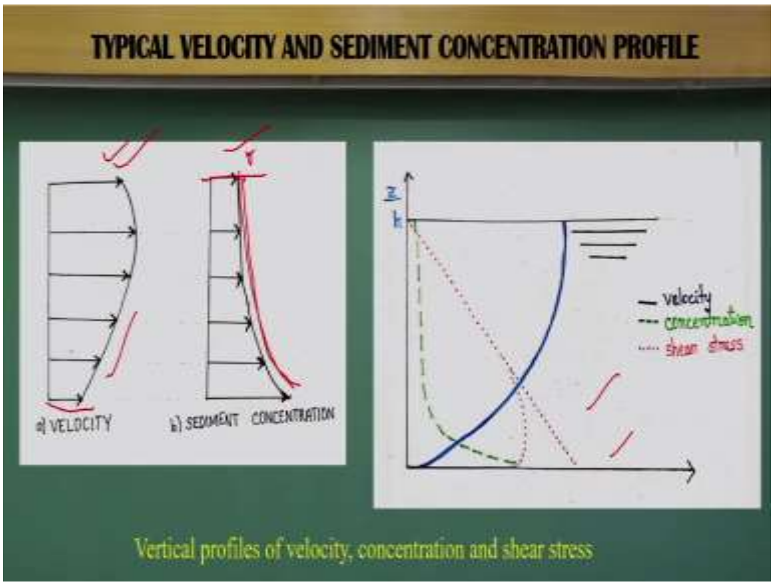

If you come to a typical velocity diagrams given in any text books of river mechanics, they say it velocity varies in logarithmic distributions and sediment concentrations of from this free surface follow the exponential decay functions, but does it happen for Brahmaputra rivers? No, that is this most of the river mechanics books they consider this variability in terms of velocity distributions, in terms of suspended sediment concentration.

One is the velocity distributions with respect to depth they assume it, it varies logarithmically from the bottom to the free surface zones. The suspended sediment concentration varies, exponential decay from the free surface to the bed, but that does not happen with complex river like Brahmaputra river, but anyway we have to learn all these text knowledge as well as our practical knowledge.

That both will combine it you to represent this river mechanics in different way that is my idea, more details we will talk about this shear stress formations and all when you go to next levels.

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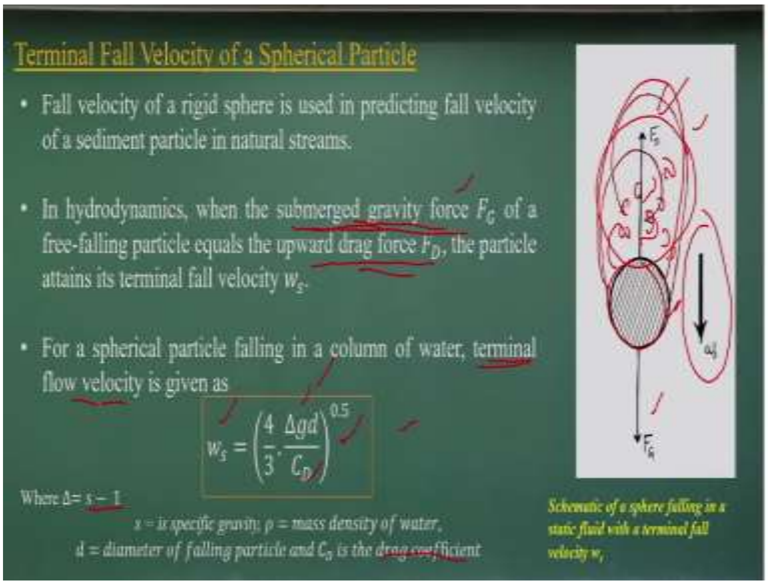

So, let us go to the next one, the terminal fall velocity of spherical particles. You know it that any particles which falls from a certain height in an atmosphere it attains the terminal velocity, beyond that the solid particle does not accelerate it, it attains a terminal velocity. That means, that is a position, like you have any particle assuming it very theoretically a spherical object which is falling in a water column or the atmospheric columns, you will see that it attains a terminal velocity.

At that regions, there will be no acceleration, velocity remains constant. When it happens when you have a submerged gravity force it equate to the upward drag force. The upward drag force and the submerged gravity force both equate each other, the net force acting on this solid particles becomes 0, there is no acceleration, it moves with a terminal velocity fall velocity which is W_s.

So we are just equating these 2 forces, the drag forces and submerged gravity forces. As you know it that when you have the particles when it goes through that it creates a lot of the vortex phenomena, the tail and vortex phenomena, any fluid mechanics books you can understand it, and these vortex phenomena are responsible for the your drag force components, whether the flow is laminar, whether it flow is turbulent.

So the drag force totally depends upon the flow Reynolds numbers, that is the concept. So if you look at that the particles which is falling in water bodies or water columns or atmospheric columns, it will have the terminal velocity. Just equating these 2 forces and rearrange the terms, you will get this one, this is very simple thing. Just look at these equations which is giving is the terminal flow velocity as a function of delta.

Delta is s – 1 that means specific gravity minus 1, d is a diameter of this spherical object, C_D is the drag coefficient. So if I know this drag coefficient. if I know this d value, we can find out what will be the falling velocity or terminal velocity of the sediment particles, how long it will take it to reach the bed materials if it is falling without any flow, it just freely suspends, how much time it takes it to reach it to bed.

That is what to compute if I know this terminal flow velocity. I know the length, if I know this velocity, I can compute how much time it takes that is very easy thing.

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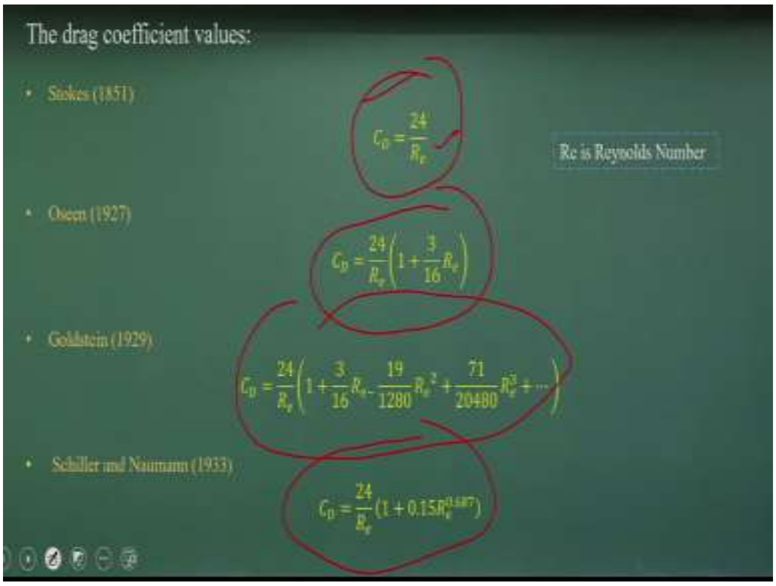

So if you look at that way mostly any textbook or any fluid mechanics textbook you follow it, the C_D is given for the spherical objects, a lot of experimental studies are done in last 3-4 decades to find out what could be the C_D values for spherical objects. For the low Reynolds numbers when the flow is laminar, the C_D is a function of the Reynolds numbers and if your flow is not laminar you can have a more complex function which are the approximations to compute the C_D.

So, if you know the C_D coefficient of drag, if you know the flow Reynolds number, you know the C_D value and you can compute what will be the falling velocity.

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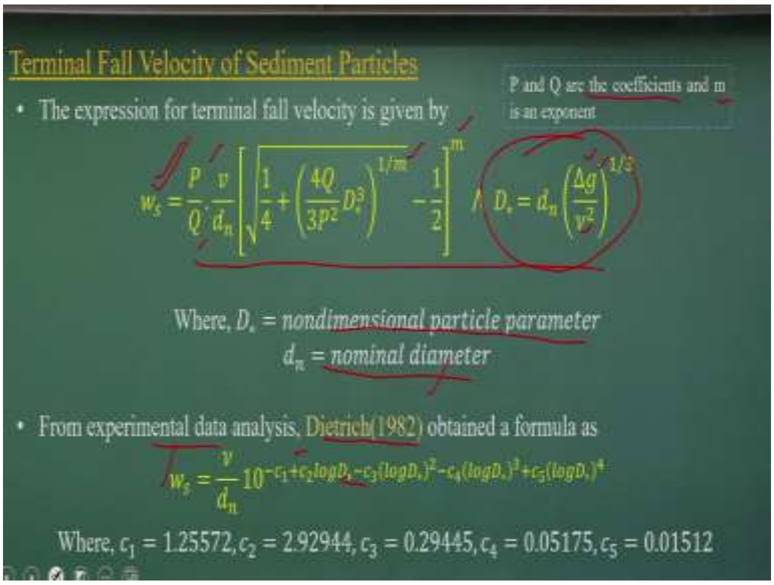

But we talk about the terminal velocity of the sediment particles. If Sediment particles are not spherical say, so for that what we need to do is apply a correction factor. The same way conducting a series of experiment it has been established with the terminal velocities with your P, Q are the coefficient, the n is the exponent value and the D_* depends upon your non-dimensional particles parameters, which does not have a dimensions, which is dn, delta you know it s – 1 value and the square of kinematic viscosity.

The d_n is stands for nominal diameter what we discussed in the previous class. So you can compute what will be the fall velocity. Similar way from experimental data if you know this D_* values and these coefficients c1, c2, c4, c5 I can also compute. These are experimental data by Dietrich (1982). There are different equations are there but more or less these results of the equations are not very much different.

They are all empirical equations and the computations of Ws does not vary muc,h that is just to have the simplifications have a range of value you will get it but not much difference.

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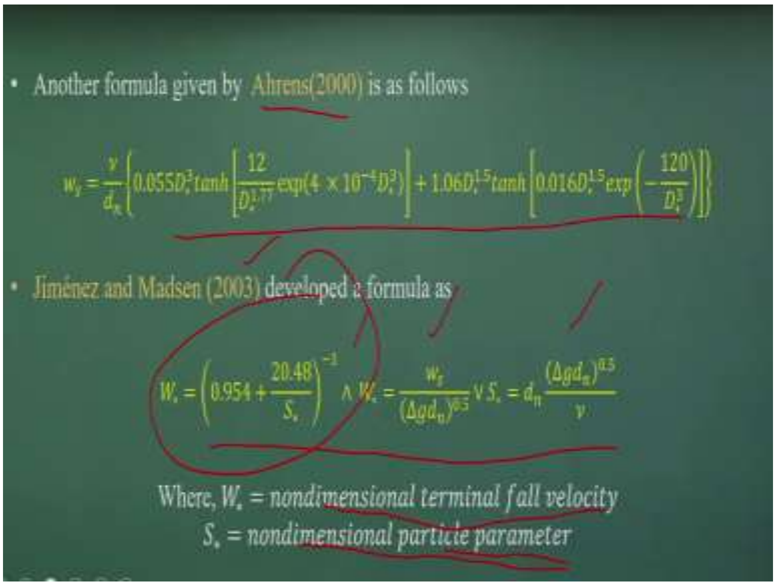

Similar way Ahrens (2000) has established more lengthy expressions to compute the W_s, in 2003 again having considering this non-dimensional particle parameters, non-dimensional terminals fall velocity is computed. So these are all more going for considering this the particle parameters that is what is developed to compute it what will be the W.

These are non-dimensional levels and that what is given it here you to compute it what will be the terminal fall velocity of sediment particles.

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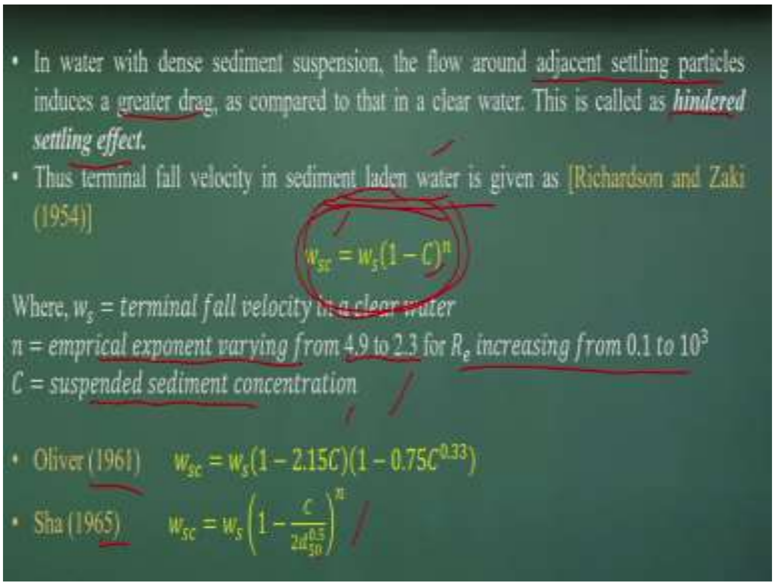

Now if you try to look that as I said it that I will have more sediment concentrations as the monsoon comes, more the flow comes, more sediment supply will come from uplands. So sediment concentrations are never be a constant, it varies. When you have a higher sediment concentrations, definitely there will be a reductions in the settling particles, more the drag force will be there.

The more the drag force will be there, more the concentration of the sediment particles that is what we defined as hindered settling effect. That is what conducting a series of experiments, it also develop that you can modify this terminal fall velocity which will be for the sediment laden water like when you have a mud flow, when you have flash flood a lot of sediment concentrations comes that time, the settling velocity, terminal velocity differs.

In this case we will consider it should consider the correction factor for the sediment concentration. More the sediment concentrations you will have less than velocity components, more the drag force will come in. That is the reason we have experimentally proven this equation

$$W_s = W_s(1 - C)^n$$

where n is empirical exponent component which vary from 4.3 to 2.3 and that is what is Reynold's number increases and C stands for suspended sediment concentrations.

And there are the empirical equations developed in 1961 and 1965 by different two functions, this is in terms of d50 and this is in terms of C only that is the empirical equations. You can have a series of equations, any of the book, probably hydrodynamics books you can see there are lot of people having done a lot of research to find out what could be the terminal velocity of sediment particles when they have a different sediment concentration.

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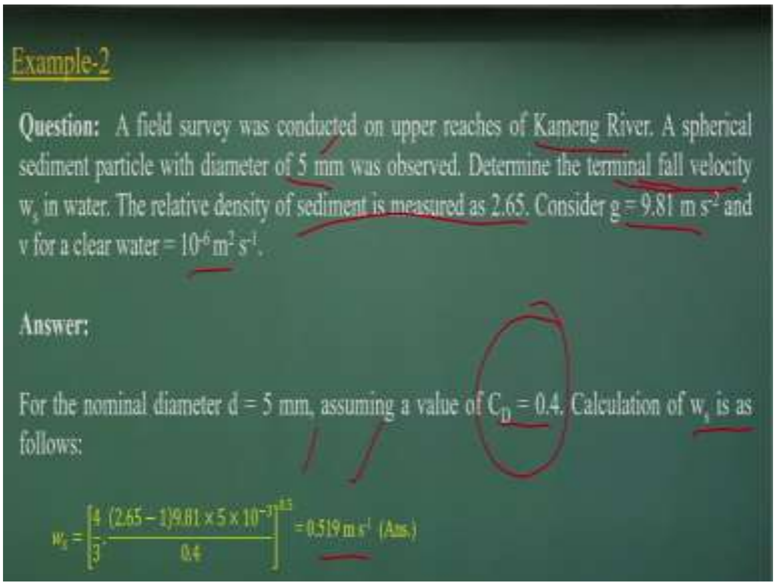

Let us have a simple example. A field survey was conducted in Kameng river, which is a tributary of Brahmaputra. The sediment particles is 5 mm and determining the fall velocities if the relative density is given, g is given to us and the kinematic viscosity. Just substitute the formulas, then you can get it what will be the W_s value. Here we have assumed the C_D value and we just compute with the formula given here.

Go to the field, collect this sediment and then you can find out what will be the sediment concentrations like particle size and then you can find out what will be terminal fall velocity.

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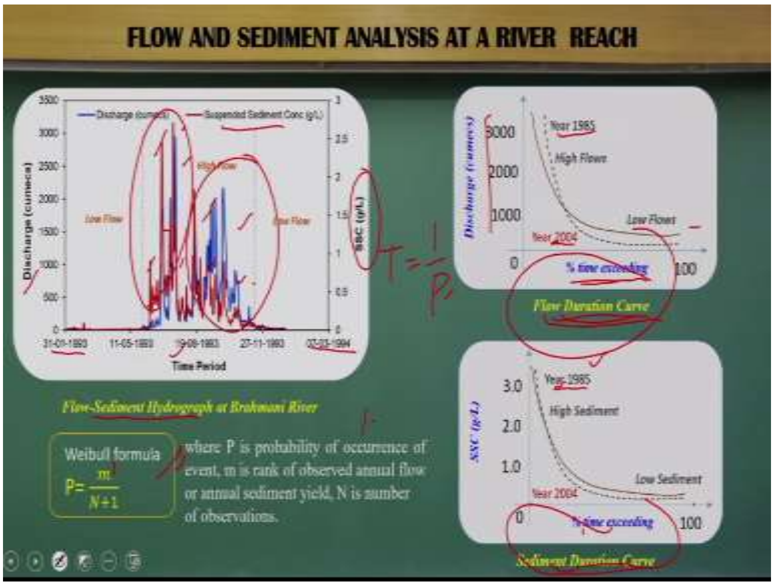

Before going to finish this lecture, let us talk about how does river flow varies, day to day, seasons to seasons, year to year. As the flow varies, sediment concentrations carried by the river also varies from day to day, year to year and month to month. That variability is there, how do you analyze that? It is very simple analysis, today I will introduce to you. First what you do is we plot a hydrographs that means a plot between discharge and the time period.

So you can plot the discharge versus time period, here the discharge in the blue color. You can see that the discharge versus time period starting from 31st January to 07 March, so just to have a period of data. It is showing that how you have a data variability is there in a year. There will be low flow zones, there will be high flow zones and you can see that the daily variations of the discharge, the flow rate, how the daily levels is varies.

The red color indicate the sediment concentration data which is called sediment hydrograph, but very interesting if you look here is that the sediment concentrations will be in gm/L here and the discharge is given in this, you can have this plot of flow sediment hydrographs. Like many of the times you go for any medical doctors you go for you go for x-ray reports.

The similar way, we look at, whenever you start any river engineering projects first we look at how the flow variability is there, how the sediment variability is there. First we draw flow hydrograph, sediment hydrograph because that what it explains to us how does it behave. Like for example if you look at this case the sediment variabilities and the flow variability they do also has a relationship.

In some period flow is there but sediment variability is not there. There are early period, so there is clear-cut the difference you can identify or you can understand the river systems if you just plot the flow hydrograph and sediment hydrograph, that is the basic things like what you call x-ray reports for any patient. We draw first the flow hydrograph and the sediment hydrographs and you try to analyze that how things are happening.

Visually first try to understand it, then we go for a simple flow durations and the sediment durations curve analysis. What we do with that? As you know from hydrology book we follow very simple probability concept that plotting point method concept where the

Probability, $P= m/ N+1$

Where N is a total number of the data set, m is ranking.

So any data set you can do descending the order, you can rank the data, so you know the m value is a rank value.

More detail you can go to any hydrology book. So you know the rank value, you know this N value, you can find the probability, the P you can get it. So if I have a 365 days of daily discharge data I can always compute this rank of the value in terms of rank value N + 1 value for a particular discharge data. So I know the P, the probability of occurrence, Then Time Period $T = 1/P$

The time of occurrence is inversely proportional to the P. So you know the probability, so you can draw percentage of time of exceeding and the discharge that is what we call flow duration curve. From the discharge data, we can plot it that it can have like this. After conducting this the flow data analysis, we can develop a full flow duration curve. Similar way, we can develop the sediment duration curve.

The sediment data can be sorted out, can be rank it, compute the probability, compute the time periods and you can have a percentage of time exceeding whose range goes vary from 0 to 100% and you have the suspended sediment concentration. Now if you try to interpret it, what it happens like for example there are 2 years, 1983 and 2004. The flow durations curve changes, it says that how the river flow is changing because of anthropogenic activities.

Because of natural availability how the year wise the flow variabilities are there. The low flow is increasing, high flow is decreasing, what is happening at the probability space that is what we can do when you have the flow duration curve analysis. Same way we can know the sediment durations curve that between these 2 year 1985 and the 2004 how the things are changing it.

So, the simple way we do the analysis, one is the flow sediment hydrograph analysis, flow durations curve analysis and the sediment durations curve analysis. More details, I think you can follow any of the books of hydrology books but in river engineering we cannot go much details as we have to go at next level in this.

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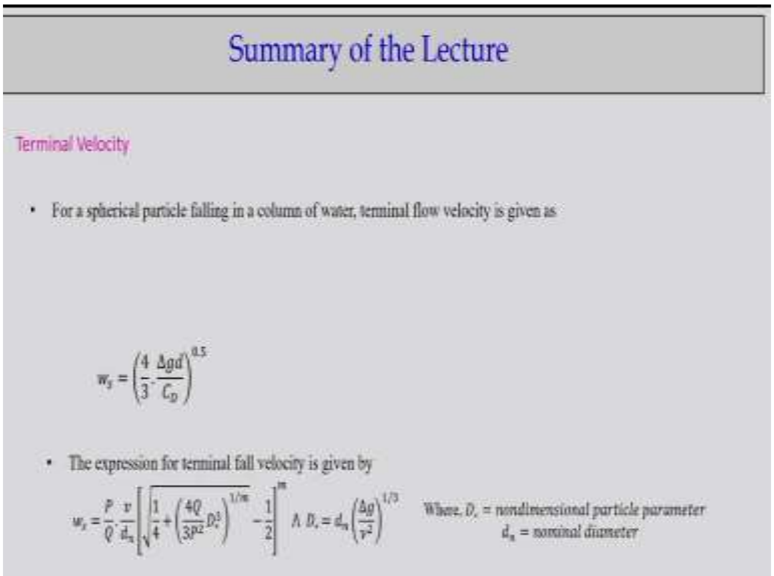

With this, let me I conclude today’s lecture starting with we discussed about the terminal velocity.

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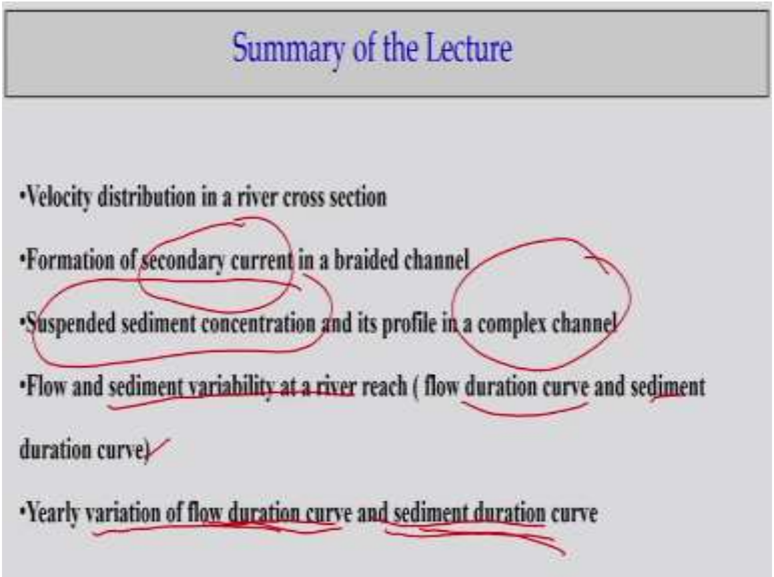

We discussed more concept just trying to revise back to you we discussed about the secondary current. Just to remember there is secondary current generation happens in the natural rivers. The suspended sediment concentrations is much more variabilities in a complex river flow, it is not that simple logarithmic or exponential decay functions. We discussed about the flow duration curve and the sediment durations curve.

We remember the flow durations curve and sedimentation curve it has a variability in a time domain as well as it has a variability in the space domain. It varies from one river gauging station to other river gauging station. It also varies from year to year. So those quantifications we should do it, try to know it what is happening to the river catchment. The sediment and the flow durations curve shows that what is the response is happening at the catchment field at that particular point.

What is happening it, whether we are doing deforestations, we are constructing lot of dam structures, any anthropogenic effect is there that is what it is reflected in flow duration curve and the sediment duration curve. That is as I said it earlier it is just an x-ray of any disease like a doctor needed, so we also follow it flow duration curve and sediment duration curve.

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With this, let me conclude this lectures and these are my Ph.D. students who have been helping me to develop some very interesting slides for you and to conclude that from I can quote from Laura Gilpin's letters that a river seems a magic thing. A magic, moving, living part of the very earth itself. So we should understand the river, it is the magic and it is enjoyable to understand the river. With this, let me conclude this lecture. Thank you.