**River Engineering**
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**Lecture – 13**
**Sediment Transport in Rivers (Part - 2)**

Welcome all of you for this class on sediment transports in rivers, as we discussed in the last class, we talk about bed load, we talk about flow resistance in alluvial rivers. Today, we will discuss more details on suspended sediment concentrations.

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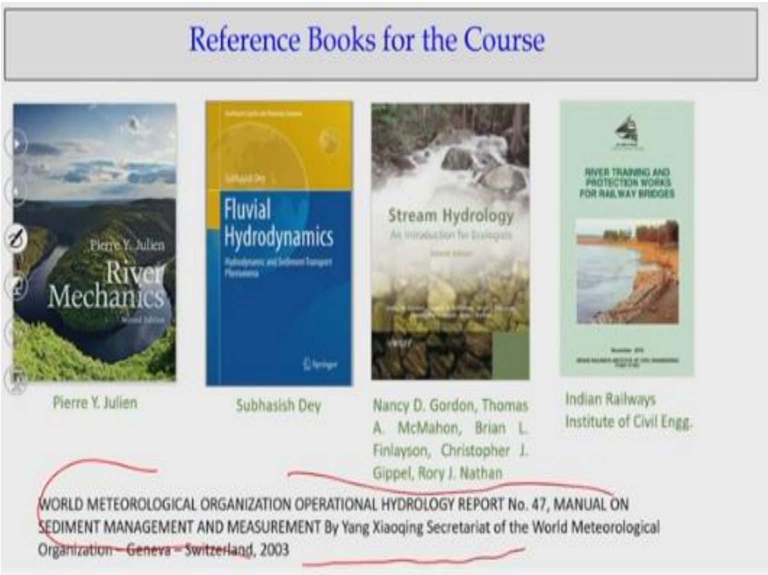


Going before that again I want to highlight you that we have been following these books, okay, these very interesting book what we have been following yet and which has summarized the sediment transports in the rivers and quite well that is the strength of this part and either river engineering the components what we are interested on sediment transport part that is what I discussing on these classes.

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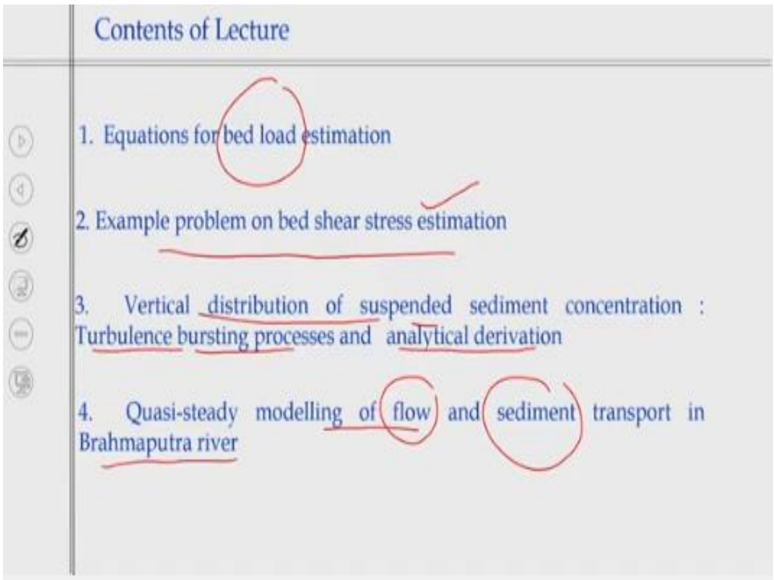


Looking that today what I will talk about what are the equations are there to estimate the bed load which is quite interesting for us, okay. What are the equations are there? There are so many types of equations are there. Then I will solve a simple example, numerical problems to estimate bed shear stress. Then, I will discuss about the vertical distributions of sediment concentrations.

That is what in any river systems which depends upon very interesting process which called turbulence bursting processes and also we will discuss about analytical derivations and then I will show it using this modelling concept of the flow and the sediment with example of flow and the sediment transport process in a very complex river like Brahmaputra, we did a quasi-steady simulations that part also I will discuss.

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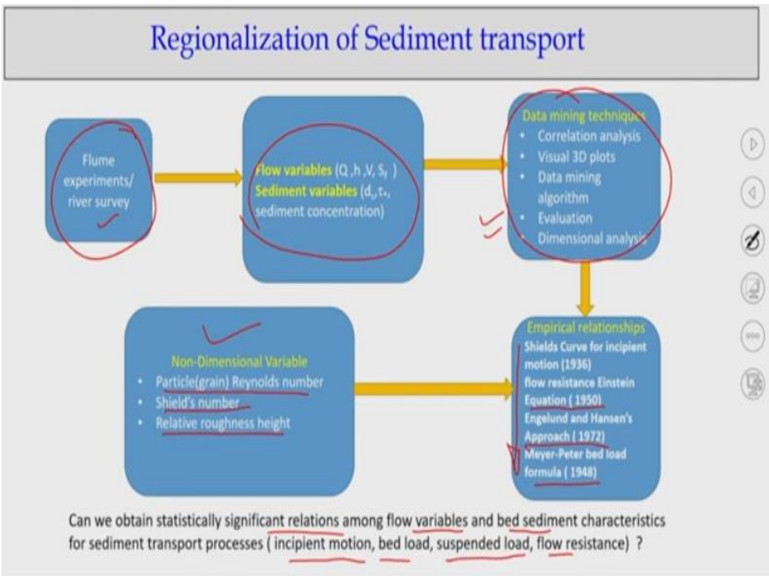

What are the equations available for bed load equations? Before that let me repeat the same slides what I have used in the last class just to repeat it, the data mining concept, the data science concept what we were talking today as a river engineers, we have used this concept almost 70 years back 1950. So, we try to write equations using 1950's for derive the equations.

How did we do it? We follow the data mining techniques, we follow the data mining techniques, we have very, lot of algorithms but basic our objective is to establish the relationship between flow variables and bed sediment properties with a bed load or incipient motions, the suspended load or the flow resistance which is very complex process as I discussed earlier.

Non dimensional variables also introduced for doing these process like the particles Reynolds numbers, Shield numbers, relative roughness height, so many non-dimensional parameters also introduced by establishing these relationships what for the bed load estimations, suspended load estimations or the total load estimations. We try to use flume experimental data, the river survey data and we identify the flow variable, the sediment variable, sediment bed stratifications.

Then, we try to establish presently we call the data mining concept but that is the data analysis techniques what was followed it almost 70 years back, just near to the Second World War. So, if you look at that this concept is well designed almost 70 years back, so I do not want to go individual equations level to explaining you, because this course is meant for river engineering's.

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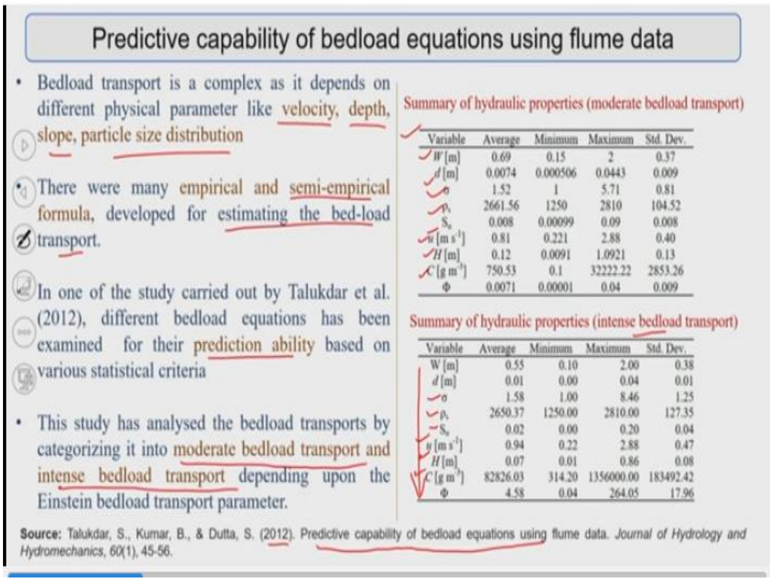

## Predictive capability of bedload equations using flume data

- Bedload transport is a complex as it depends on different physical parameter like velocity, depth, slope, particle size distribution
- There were many empirical and semi-empirical formula, developed for estimating the bed-load transport.
- In one of the study carried out by Talukdar et al. (2012), different bedload equations has been examined for their prediction ability based on various statistical criteria
- This study has analysed the bedload transports by categorizing it into moderate bedload transport and intense bedload transport depending upon the Einstein bedload transport parameter.

Summary of hydraulic properties (moderate bedload transport)

| Variable | Average | Minimum | Maximum | Std. Dev. |
|---|---|---|---|---|
| $W$ [m] | 0.69 | 0.15 | 2 | 0.37 |
| $d$ [m] | 0.0074 | 0.000506 | 0.0443 | 0.009 |
| $\sigma$ | 1.52 | 1 | 5.71 | 0.81 |
| $\rho_s$ | 2661.56 | 1250 | 2810 | 104.52 |
| $S_o$ | 0.008 | 0.00099 | 0.09 | 0.008 |
| $u$ [m s$^{-1}$] | 0.81 | 0.221 | 2.88 | 0.40 |
| $H$ [m] | 0.12 | 0.0091 | 1.0921 | 0.13 |
| $C$ [g m$^{-3}$] | 750.53 | 0.1 | 32222.22 | 2853.26 |
| $\Phi$ | 0.0071 | 0.00001 | 0.04 | 0.009 |

Summary of hydraulic properties (intense bedload transport)

| Variable | Average | Minimum | Maximum | Std. Dev. |
|---|---|---|---|---|
| W [m] | 0.55 | 0.10 | 2.00 | 0.38 |
| $d$ [m] | 0.01 | 0.00 | 0.04 | 0.01 |
| $\sigma$ | 1.58 | 1.00 | 8.46 | 1.25 |
| $\rho_s$ | 2650.37 | 1250.00 | 2810.00 | 127.35 |
| $S_o$ | 0.02 | 0.00 | 0.20 | 0.04 |
| $u$ [m s$^{-1}$] | 0.94 | 0.22 | 2.88 | 0.47 |
| $H$ [m] | 0.07 | 0.01 | 0.86 | 0.08 |
| $C$ [g m$^{-3}$] | 82826.03 | 314.20 | 1356000.00 | 183492.42 |
| $\Phi$ | 4.58 | 0.04 | 264.05 | 17.96 |

**Source:** Talukdar, S., Kumar, B., & Dutta, S. (2012). Predictive capability of bedload equations using flume data. *Journal of Hydrology and Hydromechanics*, *60*(1), 45-56.

But I want to just highlight one of the study what we did it on the predictive capability of bed load equations using the flume data, okay that is what the papers in 2012. So, if you look at these papers what we did it, we consider the flume data and we have a series of bed load equations and those equations we try to see that which equations performs well. So, flow characteristics like we consider the velocity, the flow depth, the bed slope, particle size distributions.

There were the equations are empirical equations, it does not have any basic concept with that. There are the equations are semi-empirical, so partly it is analytically derived and partly it is established as a relationship, so that is what we call the semi empirical formulas, we used to estimate the bed load transport. So, basically we try to look it in that papers, what is the predictability of the bed load equations.

And we divided in 2 part; moderate bed load transport and the intense bed load transport, we categorize into 2 groups and if you look at the summary of the hydraulic properties, the flow, width, the depth okay with this variance from 0.69 to 2 meters depth, we have the sediment concentrations, the beds to bed loads properties, velocities and H and sediment concentrations and Einstein constants.

The same way if you look in intense bed load transport also we have used the data set, which is having the flow, width, depth, sediment properties, the standard deviations, the bed slope, flow velocity, H, sediment concentrations gm/m$^3$, all we consider it to look it that how the bed load equations are having the predictive capacity for these flume data.

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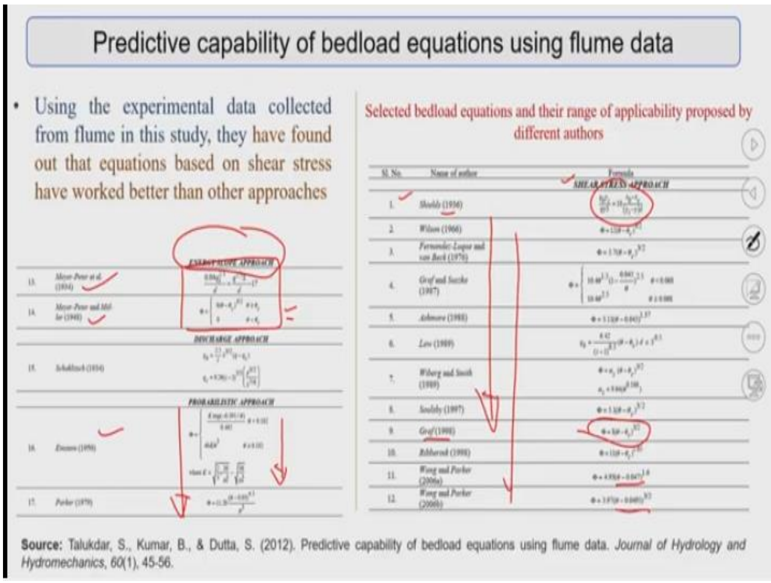


Now, if you look at that part, what are the equations are there; there are so many equations are there on bed loads. If you look at that, that is very old 1936, shield equations which has, if you look at this formulas basically, it is a shear stress based approach. The same way if you look at the methodologies based on the shear stress approaches are so many okay, there are certain assumptions like Graf 1998, it is very simple equations, it is just depend upon $\theta$ and $\theta_c$ that is the shield parameters at the critical stress.

So, based on that we can compute what will be the bed load, so same way if you look at there are different models, different empirical equations, there are lengthy expressions, there are the expressions which is having this a simple power function and there are certain assumptions is there. So, same way if you look at this energy slope approach, there are the equations is established based on energy slope approach is Meyer-Peter formulas in 1934 or Meyer-Peter Muller formula in 1948.

This still these 2 equations are widely used because it is an energy based concept and more or less if you look at that equations follows that and there are the probabilistic approach is way back in 1950 by the Einstein's, junior Einstein's established that what will be the bed load equations, if we follow the probabilistic concept what we are not going in a much detail for that but if you look at there are so many equations here as it listed the 17 equations, the 17 bed load equations are there.

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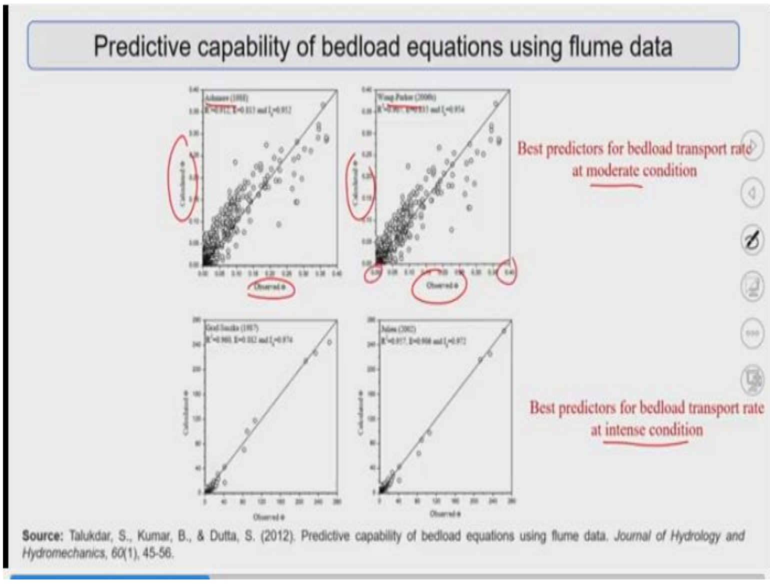


The point is coming is that which one is better predictability, what we try to do it, all these equations we implement it and try to look it for the 2 category; for moderate conditions and for the intense conditions. If you look at these moderate conditions of sediment concentrations, there are Ashmore 1988 paper, Wong and Parker 2006, the equations. So, both these if you look at the scatter plot between observed versus the calculated; really it is a quite interesting.

And that is what is as expected in a natural river systems, any equations what you develop it or any flumes you cannot have exactly the matching of the data, so you will have the spreading of the data and you can look it the mostly, it is improving in terms of $r^2$, the error components but if you look at the scatter plot for moderate conditions because the data collected it has some errors as well as the equations what is established from that period, it depends upon that concept and whether it is a validity is there.

So, looking all the uncertainty in observations and model formulations, it is expected that this type of scatter plot could be there, but we are; so similar way if you look it for intense conditions, it is quite interesting because that data is quite well spread. This is the varying from 0.00 to 0.40 and this is what is going up to 280. So, as the data spreading is there and if you look at this Julien 2002 or Graf which is 1987's, both the observed and predictabilities are quite well.

So, what I am to summarize based on these study is that instead of using one equations, try to use the 2 or 3 equations, recalculate the bed loads and you take a judgement based on that, how accurate it is and most probably, I can say that a few measurements can be included, any bed load estimations you can do a few measurements or literatures about that rivers if it is available, you can use that.

And try to validate which is appropriate bed load equations for the particular river reach what you are working on that. So that is what my experience when we working with river modelling.

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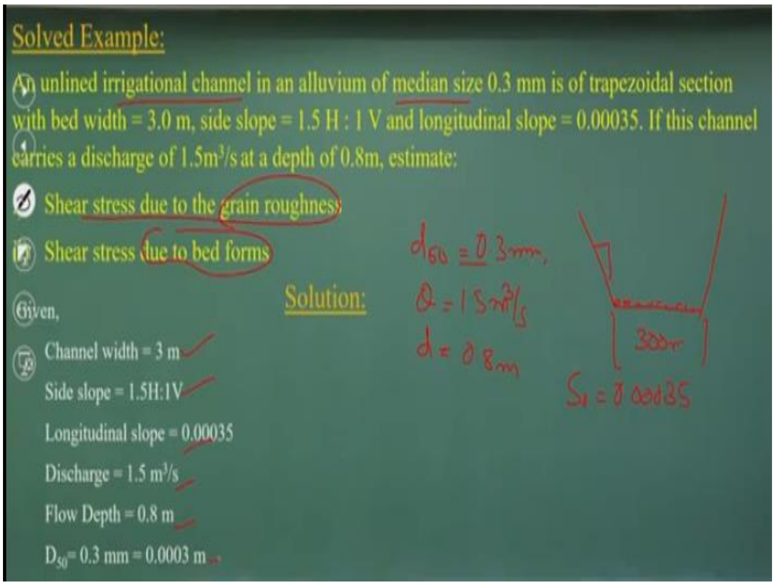


Now, if you look it coming back to an example problem, it is a very simple example problems we have given it here. The basically the problem is it is an unlined irrigational channel okay having the d50 size is 0.3 mm okay, trapezoidal correct sections okay, this quite easy problems okay and it has the dimensions here is 3 meters channel width and here you have a 1.5 horizontal to vertical slope and the longitudinal slope of this channel $S_0$ is 0.0035.

So, this is the condition, what is that? Discharge is given to us as 1.5 $m^3/s$ and the flow depth is given is as 0.8 m. So, in these alluvial channels, definitely there is a flow resistance because of bed forms and the grain resistance because of the particle size on this bed. So, this regions you will have the resistance to estimate the shear strain due to the grain roughness whatever this d50 particles that is what is giving a resistance to for us.

Also from that we also compute what will be the shear stress due to bed forms, so the bed forms are there and the grain roughnesses are there. So, we will do a simple calculations and this is the; the data is which is there, if we can look it the same data is highlighted here.

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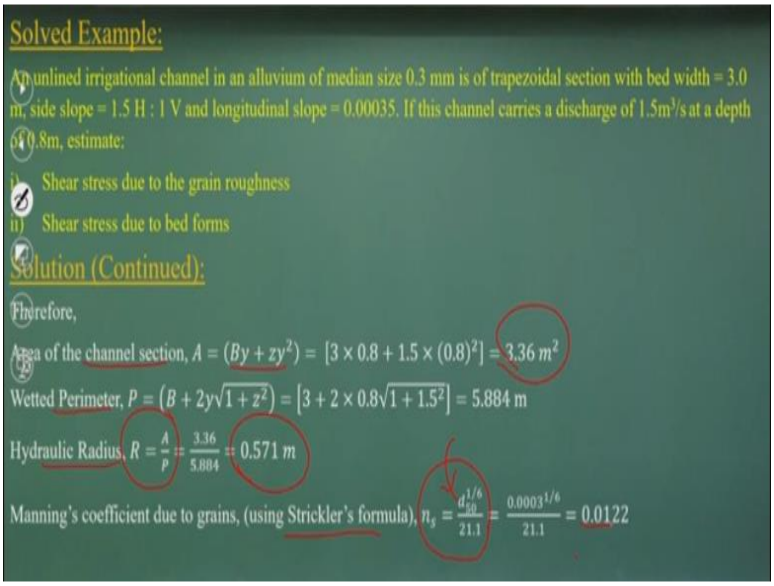


The first what we will do it that we need to compute the basic geometry properties like area of the channel cross sections, being a trapezoidal, you can compute this part which comes out to be 3.36 $m^2$. We can find out the wetted perimeters, we can find out the hydraulic radius which is a ratio between flow area and the wetted perimeters, it is comes out to be 0.571 m.

Next is coming it that grain roughness we always have a establish a relationship with the n value, Mannings n values, the roughness coefficients has an empirical relationship with d50 that is what is the empirical relationship which is called a strickler formulas. Based on that we can compute the n value which is come out to be 0.0122 that is what Manning's roughness coefficients due to the grains due to the particle size distributions of d50 values.

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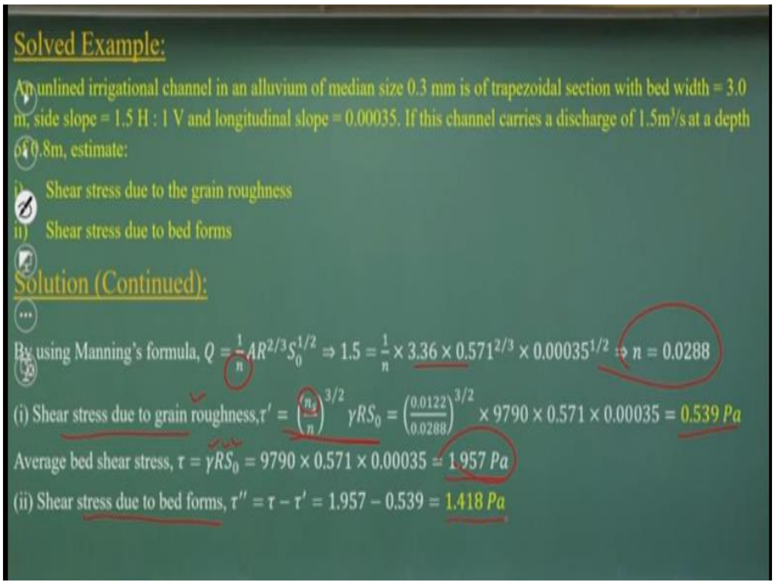

Now, since the discharge is given to us, the flow depth is given to us, hydraulic radius is known to us and the bed slope is known to us, so we can inversely, we can compute what will be the equivalent Manning's and coefficients that what we can do it. So, since all the data is given to us, so we can compute the ns value which is considered both the effect, this is a resistance due to the grain also resistance due to the bed forms.

That is what shear stress due to the grains we can establish use these equations as a proportionate with the ratio between ns, the ns is the Manning's roughness coefficient based on the stricklers equations and is total roughness what you get it, based on that if you just substitute these values, we will find out the shear stress because of the grain roughness is this part.

Since the flow all these values are given it for omega $RS_0$ which is a shear stress, so we can find out the total shear stress. So, this is the shear stress due to the grain, this is the shear stress due to total shear stress, so subtracting these 2 we should get it the shear stress due to the bed forms that is what is coming about to this part. So, they are very simple examples, numerical examples we have discussed with you.

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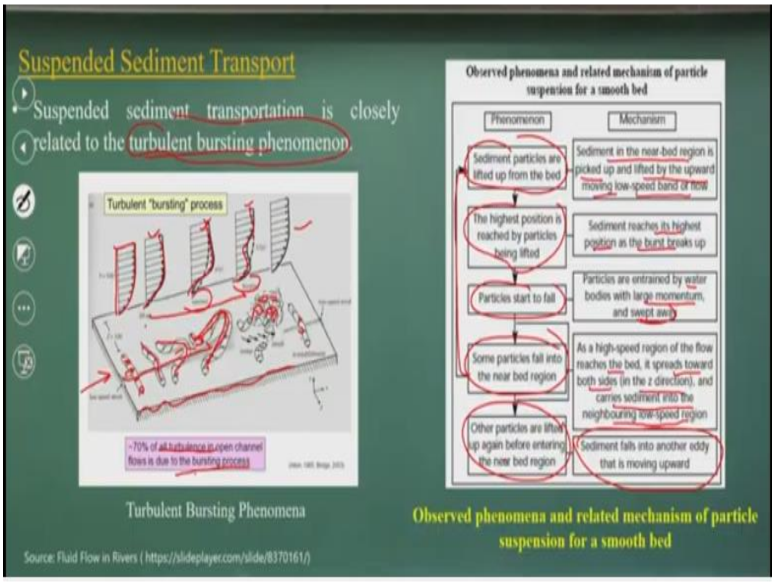


Let us come into very interesting topic on suspended sediment transport mechanisms, here I am not going details but still try to understand it suspended sediment concentrations what it happens in the river is the primarily due to the turbulent structures. So, let me have a very good understanding that what it actually happens it, like if you have the rough beds, you have some bed materials grains are there.

And if you have the bed material grains are there and when the flow is going through these you cannot see it but you can visualize that, that what will be form these the turbulence vortices like this, it is starting, a formations of very, very micro scales the turbulence eddies, the formations will vortices formations will be that, that is what slowly will grow it, further it is grow it, it is in a 3 dimensional forms with the vortex change, if you can see that what is exchanges are there.

And as is going through these surface to this, it grows it, the eddies formation grow it, then at this point the bursting happens it, at this point the bursting happens it. So, if you look at the microscope scales, this type of the process happens within the river, within the flow systems, and the very, very micro scales properties if you look at that that is what it happens in the vortices.

And these vortices after certain stage, it cannot sustain the slope, it is bursting out and these bursting process acts as, try to keep the sediment particles in the floating conditions that is what it additional momentums because of this bursting process is what it happens it, again is the follow after the bursting are. If you look at that very interestingly, if you look at the velocity distribution up to these points where you just formations of vortices are there, velocity distributions are different.

But as we go up, the lifting of that at this point the sediment particles will lift it from the bed then it will go for ejection process and the bursting process and if you just look at the velocity distributions how it is changing it like during the bursting process, the velocity distribution like this, during the ejection process velocity distribution and then in the ejection process like this, after that again velocity will come down.

So, if you look at the macro scales, the process what is happening it in a river flow in a flumes where you can really this the process of turbulence burstings, the 70% of turbulence in open channel flow because of the bursting process. These are the studies hence for what is now in this decade has been going on, so we are not going to that level of the particles levels to try to locate how the turbulence bursting phenomena is supporting the additional forces in the upward directions.

And that is what is keeping the sediment particles, the lifting of injected it and it is remain in the suspended states and if you look at how the process are happening, it is very interesting. The first phenomena the sediment particles are lifted up from the bed, the sediment particles will be lifted up from the bed that is what the sediment in a near bed regions picked up and lifted by the upward moving low speed band of the flow.

The low speed is near the bed is a very low speed that is what will happen, then the highest positions of is reached by the particles being lifted, the particles which is sediment particle is lifted up it goes to the highest positions that is what is happening. The sediment reaches its highest positions after the burst breaks up this burst is taking up the sediment particles.

Once it is bursted off that is the highest locations where the sediment can be carry by the turbulent structures up to the bursting. After that bursting happens is particles start falling, a particle entrained by the water bodies with a large momentum swept away. So that is the reasons the flow in the longitudinal directions having the large momentum and that is what help the particle to swept away.

Some particles they fell into the near bed regions, again come backs to near bed regions as the high speed regions of the flow reaches the bed, it spread to both the direction in the z direction carry sediment into neighbour low speed regions that the process can continue it is happening, it is, this is the process can continuously happening it, other particles will be lifted again before entrained to the near bed regions.

Sediment falls into another eddy and moving upwards, so if you look at the very interestingly microscopically or tracking the sediment particles how it is suspended, how it falls down, how these further eddies are generated from near bed regions to the suspended regions, how it is reaches to the maxima reaches, all its depends upon the turbulent bursting phenomenon.

This is the process what we have been added is that the same concept you can talk about how the process happens in aerosol movements in air or pollution movement in the air, so the same process is happens it. So, if you are trying to look at that when the water flow is there, there is a formations of the vortices, the turbulence vortices as it grows it, it is having the bursting phenomena and that is what is a control, how the sediment mixings are happening it so river bed and the water zones.

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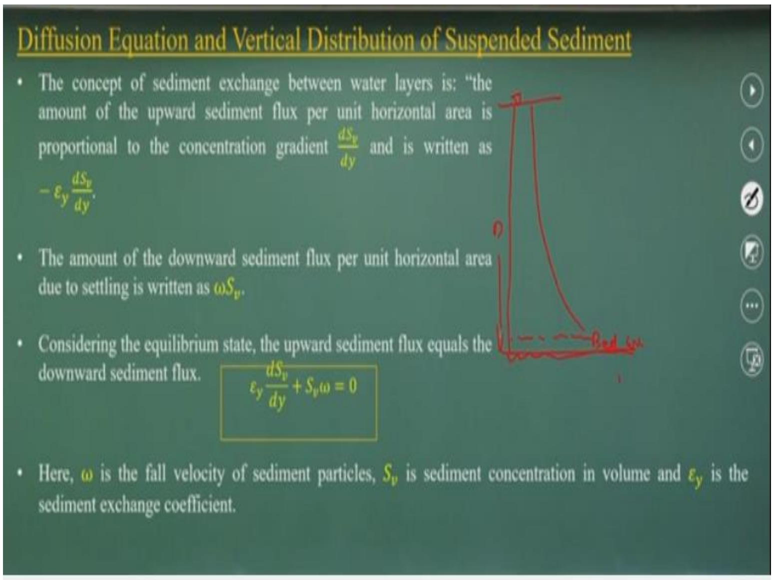


Most of the times what we look at we do not have to go into more details how it happens at the particles levels, we try to look at what could be the vertical distributions. That means we know very well as this is a bed and it is a free surface, the sediment concentrations follows like this, and this is the bed zone, this is the bed level. Sediment concentrations we look it; they will be like this.

Okay, it is highest at the bed regions and becomes exponentially decay down till to the free surface, so this is the flow length. Now, if you try to understand it we are not looking at non-equilibrium condition because we are looking it at the equilibrium conditions, where the sediment concentration profile does not change it, the vertical distributions of sediment concentration does not change it, if it is the equilibrium it is coming it.

If that is the conditions let me I take it, this z locations, this is z distance from this free surface. What will happen if there will be a sediment flux coming down and there is a sediment flux is going up, these should be equate each other, equal each other, then these profiles remains at the equilibrium condition. So, the sediment fluxes at this surface is going down and the lifting up both should be the same.

Going down it is very easy, you know the settling velocities, you can find out with the sediment concentration c, Sv, you can find out what will be the amount of sediment concentrations will fall down with a settling velocity and these because of sediment concentration gradient is there okay, Sv gradient is there. That gradients have the upward sediment flux per unit horizontal area that is what we do it is a proportional to the concentrations gradient that is we defined as a proportionally constant of epsilon y, we are going to discuss that.

So, if you look at that, this is a very basic concept what any process is happening for the diffusion equations that the flux is always proportional to the concentration gradient that is the same concept, the amount of downward sediment flux for horizontal area we can define it this. If you equate it you get a very, very simple ordinary differential equations with having $S_v$ unknown, so which we can get the analytical solutions where $S_v$ is a sediment concentrations, €y is indicating the sediment exchange coefficients that will be the different sediment components.

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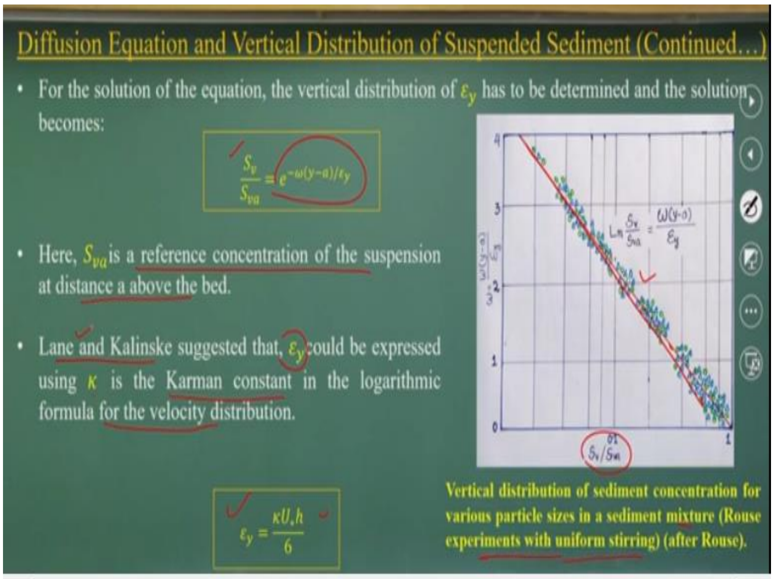


So, if you look at the next part, if you get the analytical solutions of these equations, the ordinary differential equations it is very easy, you will get an exponential decay functions. That means you know this the $S_{va}$ is a reference concentrations of the suspension sediment above the bed level and the $S_v$ value we can get it and here it is showing it how the $S_v/S_{va}$ sediment concentrations by sediment concentration at the bed level that ratio how it is depends upon your these coefficients.

And if it is a plot in logarithmic values you will get this linear relationship between them that is what it is showing it and these are all observed data. Using this, the particle size sediment mixture, the Rouse sediments experiment with a uniform strains. The Rouse did that experiment and quite establish is that the sediment concentration profiles it depends upon and we can always establish this part.

Later on that questions comes is how to create it these coefficients; the Lane and Kalinske suggested that it could be expressed as Karman constant, as a logarithmic formulas for the velocity distributions, it can define as a shear velocity, flow depth and the von Karman constants, you can define it through these ones which is major simplified the process.

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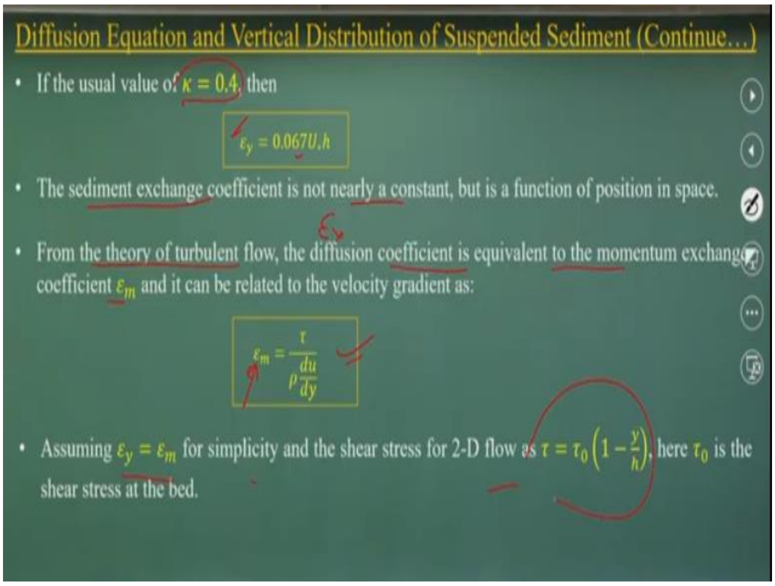


Now, if you look at this way if you substitutes von karman constant is 0.4, so you will get it this moment exchange coefficients which is not nearly a constant but is a uniform positions in a space, it is a flow depth dependent but for the turbulence flow, the diffusion coefficients is equivalent to the momentum exchange coefficients. It can be related with the diffusions coefficients.

It can be related as equivalent at the momentum exchange coefficients and newton's laws of viscosities in a turbulence gradient, if I flow it, it will be give is these equations, it is very easy equations. So that means, sediment exchange coefficients is equal to the moment exchange coefficients for the turbulent flow for simplicity and then you can also find out the shear stress distributions as a linear distributions and the $\tau_o$ is a shear stress at the bed, it is a very simple things.

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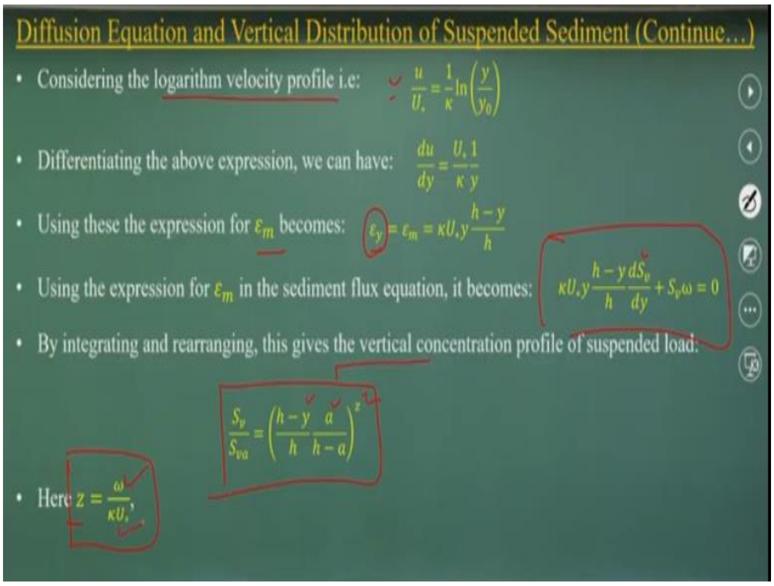


So, just substituting these values if you interestingly if you can see that we can use logarithmic velocity profiles which is earlier we have discussed lot that velocity distributions is a logarithmic and using these expressions we can always compute it for what will be the sediment exchange coefficients and also the momentum exchange coefficient in turbulence flow.

And if you look at that you can get a new equations in terms of $S_v$ and if you solve that equations is a simple equations you will get a relationship now more details in terms of flow depth, it is the y is the positions and a and the z values and the z value. Z is a non-dimensional parameters again, we are defining z is a non-dimensional parameters in terms of settling velocity and the shear velocity.

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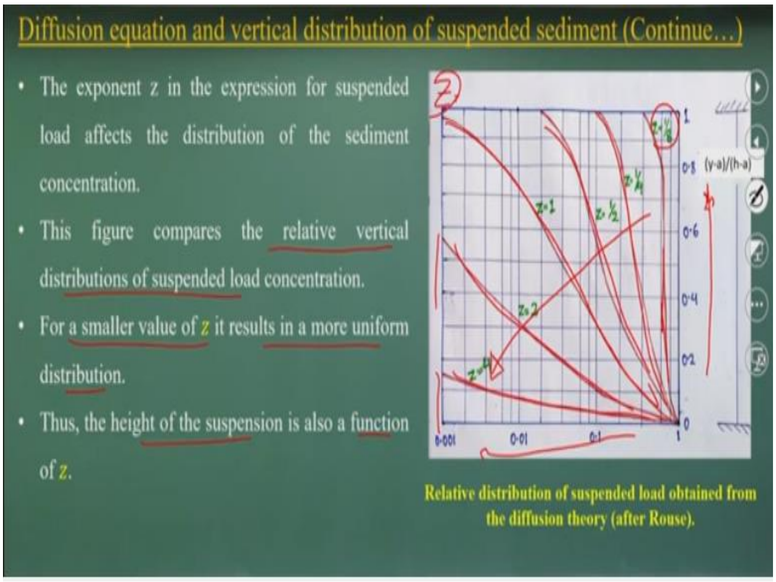

Now, if you look at the distributions pattern, which is the graphical we can get the solutions like this, for the different z value, which is a functions of von Karman constants, settling velocities and the shear velocity. The shear stress is acting on the bed which is also controls the suspended loads, so if you look at that part with a low value of z value, sediment concentration is more or less uniform.

This is the vertical directions, more or less uniform but as the z is increasing it okay, this is the just analytical solutions as z is increasing, you can see that if you look at that sediments concentrator profiles will be change it. So, it is depends upon your z value which is the ratio between settling velocities and the shear velocities. These components if you look it and it has a distributions like this, z is 1 you will have a distribution like this.

So, we can get a sediment concentration profiles how; if we know the z values, one parameter is depends upon the particle size and other parameters it depends upon the turbulent structures. So, if you look at that this figure indicates that the relative vertical distributions of the suspended load concentrations. The smaller value of the z, it results in a more uniform sediment distributions and the height of the suspension is always a functions of z value.

This is the height of suspensions if you look at okay, this height of suspensions also it depends upon how far it will be lifted, maximum that is the height of the suspensions is also function of the z. So, z is a very critical, z is indicating is that the ratio between settling velocity of the sediment particles and the shear velocities that is what represent it how the sediment concentrations vertical distributions will change it.

As we are changing the z values, which is analytical solutions that so because when z is very small, we will have a uniform sediment distributions but when z is more, you will have very less the height of suspensions and you will have a distributions like this. So, these are very interesting things, this can be used also used the same way the particles, the sand particles in the air we can concept of this also same but only this data will be the change.

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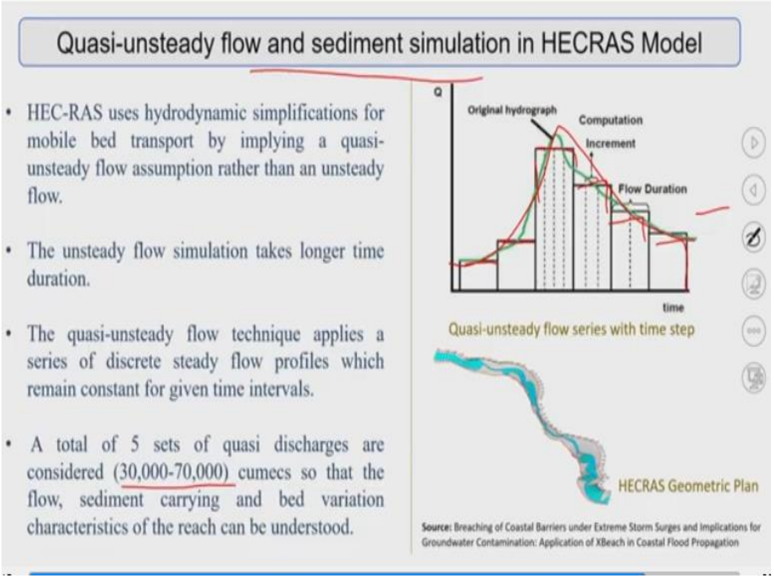


Before concluding is that one of the studies what we have recently did it for the Brahmaputra river, I want to just to share with that, that is what is Quasi unsteady flow and sediment simulations. So, quite interesting study we did it for the Brahmaputra rivers and the quasi-unsteady means in this case, we are not running total unsteady simulations but we are making a strip of steadiness like we have the hydrographs.

We are not simulating for the hydrographs, we are, a phase of the steady modelling we do it, make it a Quasi unsteady state, more detail you can refer to HECRAS technical manuals, we are not going to more details and this is the model has set up for 200 kilometre of Brahmaputra rivers with having a discharge of 30,000 to 70,000 $m^3/s$, if you look at the discharge range.

And try to look at how the sediment concentrations profile are changing it, how the bed level changes as this flow will passes through it that is quite interesting, that is the things we have to try to understand how to, how did Brahmaputra rivers behaves during the flood periods.

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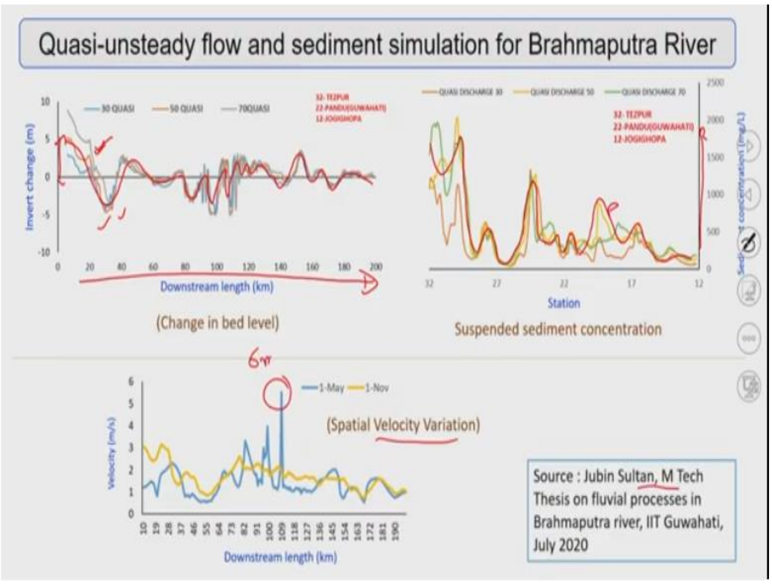


Now, if you look at these results which is a part of the M tech thesis, recently worked on these. First is if you look at that this is a 200 km longitudinal directions, okay and you see that bed level change, quite interesting and some of the locations, bed load level change can have as high of 5 m, this is the depositions part, this is the erosion part, this is the aggradations, this is the degradations.

You can see the cyclic of aggradations, and degradation process, same way you look at the sediment concentrations which is varies from as close 2000 mg/L which is quite high okay. So but if you look at the distributions quite interesting, just you think it, the sediment concentrations also varies quite interestingly that is what makes the river is quite challenging to try to understand how the sediment concentrations varied from locations to location, how the bed degradation, aggradation happens.

Anyway these are theoretical data set, how this functions happens it and if you try to look it which we more interested to look at the velocity distributions during this early flood, the velocity can go as high of 6 m/s, it is quite high but after they receding the floods, you can have the discharge, the velocities will be on average of 2 m/s.

So, these are quite interesting and that is the idea to share with you apart from having the analytical knowledge, use of the river modelling tools like HECRAS and all, it also expands our knowledge on the rivers.

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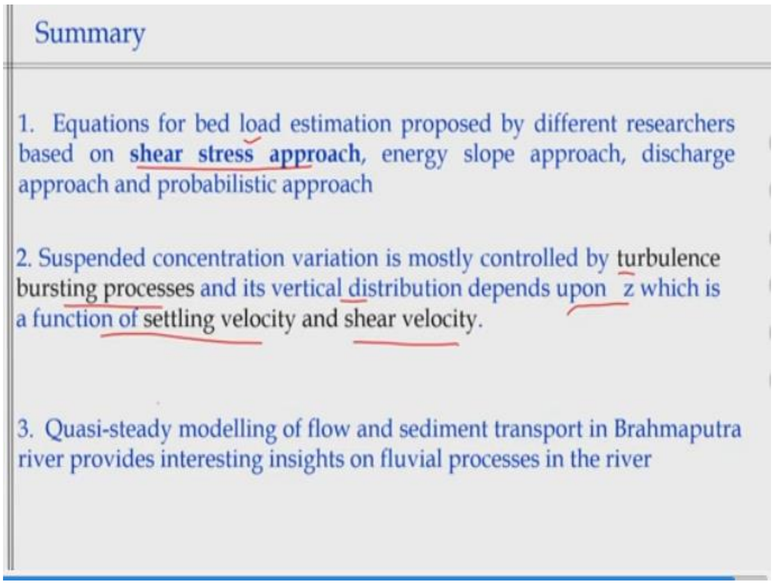


So, with these slides, I conclude today lectures that we discuss more details that there are different type of bed load equations are there and the most the shear stress approach gives a better result for that flume studies but I do not want to tell it that this equation is best for that, that is the reasons as a river engineering, we have to find out take a number of bed load equation, test it and find out which is appropriate.

I cannot say the best equations, I can say appropriate equations to estimate the bed load and more often I can suggest it to have some sample data or the theoretical data, literature data to validate what the bed loads you are estimating it. Suspended sediment concentrations as the last in these centuries we have been talking about turbulence bursting processes and the z, the vertical distributions of its, it is also depends upon z which is the functions of settling velocity and the shear velocity.

And we also given very interesting examples, conducting HECRAS models, quasi unsteadiness of flows and sediment to show this, how the fluvial process happening. With this I wish to conclude this lecture on sediment transports in rivers.

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Let me conclude this lectures by quoting, very interesting quote is that the water is most critical resource issue of our lifetime, our children's lifetime. The health of our water is the principal measure of how we live on the land that is what by Luna Leopold. So, what I am to tell it before concluding this lectures that I just visited japan from north to south, I have seen this so water quality of all these rivers what if they have.

And that water qualities indicates the life of the Japanese peoples, if you look it there, many are they cross more than 100 years life that is what is my objectives to study the river engineering, look our rivers it is not a water flowing body, thank you.