**River Engineering**
Dr. Subashisa Dutta
Department of Civil Engineering
Indian Institute of Technology-Guwahati

Lecture - 10
Flood Wave Celerity and Loop Rating Curve

Good morning all of you for these lectures. It is quite interesting lectures on flood wave celerity loop rating curve and at the introductions level of the sediment transport. If you look at that whenever you have a flash floods when you have a dam break and the conditions where you have a glacier lake outburst floods if that the floods is propagates like a wave and what is the celerity of that flood propagations?

That is what today we will discuss it along with we will discuss about loop rating curves.

(Refer Slide Time: 01:10)
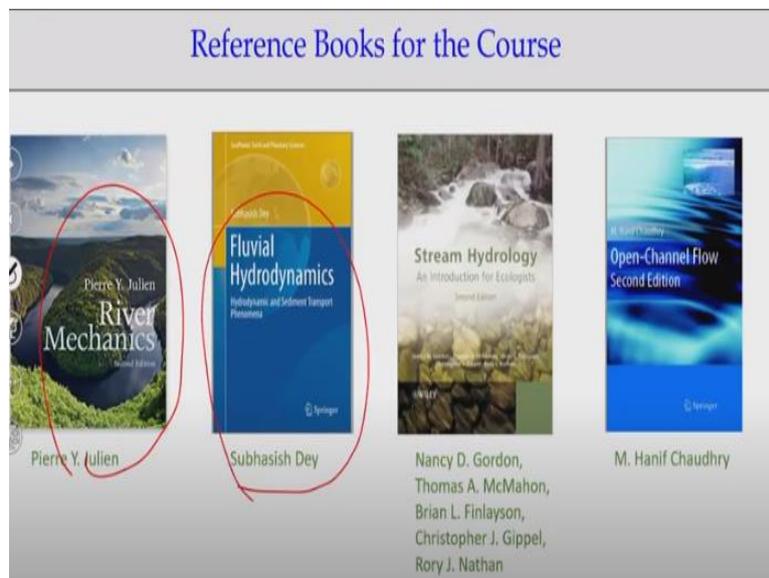
And also we will give a descriptions on introduction levels descriptions on sediment transport. So mostly, I am following these books okay. And the partly we are following this book for these lecture materials.

(Refer Slide Time: 01:26)

Contents of Lecture

1. River Floodwaves
2. Loop Rating Curve
3. GLOF propagation in Tawang River
4. Sediment transport in rivers

If you look at what we are going to talk about as I said it the river is morphological active when you have extreme floods. The extreme flood happens because of a flash flood happening because of glacial lake outburst or flash flood is happening because of dam break. Those flood events, how these flood wave propagates it. What is the celerity of the floodway propagations?

That is what we discuss mathematically as well as the graphically we should understand it. Then we will talk about loop rating curve. So rating curve what we get it, it is not a constant functions. It has a loop activity. Then we will have a case studies which we conducted studies, long back glacier lake outburst floods propagations in Tawang Rivers. Then I will give you a brief presentations on sediment transports in river.

(Refer Slide Time: 02:24)

Wave Celerity

The celerity is defined as the wave velocity with respect to the velocity of the medium in which the wave is traveling.

Now if you look at next part as I discussed earlier is that whenever you create a disturbance like this, okay and we derived the class that we will have a celerity that means, the wave velocity with respect to velocity of medium with which the wave traveling. So we are talking about what the wave velocities moving it when you create a disturbance of that.

(Refer Slide Time: 02:51)

And the last class also we discussed that, when you have it that conditions it depended upon with a simple derivations, we can see that the wave celerity is a functions of the flow depth and it depends upon whether the flow is subcritical, supercritical or the critical. So in case of the subcritical flow, the wave will propagates in the both directions both upstream as well as the downstream directions.

But in case of supercritical flow, both the components of the celerity of this part, which will be indicates the flow the wave propagations in towards the downstream only. But in case of critical which is the rare situations it happens it that we will have only this downstream directions. Because based on this concept, we try to look at whether is upstream controls or the downstream controls.

That is what we discussed in the last class. Let us today go for further that if they reach a flood wave, how it propagates it. How we can derive the celerity for that.

(Refer Slide Time: 03:59)

If you look at the next slides, what we are talking about, what is a wave celerity. We if I considering a one dimensional equations okay, we are simplifying it. So we have a one dimensional channels. We are looking at the flood wave propagations along the longitudinal directions. If dQ is functions of space and time, I can consider the dQ variabilities along these lines, you will have a dQ/dx.

It is just a simple calculations that you can define it. What is the celerity? The celerity is the points where this is what the propagates it. That is the reasons by definitions, c=dx/dt. That is where they define the locations where the flow become steady, when Q equal to dQ equal to 0. That is what it comes.

The dQ = 0. So if I just considering the Q variabilities and the definitions of the celerity I can write c is a function of these ones. This simply the substituting these ones and if I consider is one dimensional flow mass conservations equations as dQ/dx,

if there is no lateral flow as we derive in the classes that if there is no lateral flow we can derive the change of the storage equal to the rate of change of volumetric flux along the x direction.

That part if I equate it, I am getting $c = dQ/dA$. C in terms of Q and flow across sections. That is what is called flood wave celerity which is Kleitz-Seddon law. Now if you look at this part which I will discussing with you this derivations will do in latter part, but let me look at that the concept wise understandings of this part. Dynamic wave, kinematic wave, diffusive wave.

So if you look at this part when you have a dynamic waves, that means what it actually happens is that you have a conditions when you have the wave like this propagations is coming it. So when you have these type of wave propagations in that case the you will have celerity at this point and if you take the two sections A and B if I compute the celerities I will see that cB will be lesser than cA.

The celerity at the point of A and B which is a distance l apart if I look at that as s_f is greater than s_o and these case s_f will be less than s_o values. So, cA will be the lesser than the cA. In that case, what will happen it after certain distance if this wave travels, the travels flood wave amplifications happens. That means, this will be traveling faster than the B point.

Because of that, the peak will be increasing it, amplified it. Will be amplified it the distance l here in the same AB locations l_2 will be lesser than l_1. That is the conditions happens if you look at higher flow numbers. If you look at the diffusive wave, this is a kinematic wave. If you look at the diffusive wave cases, what it actually happens it just reverse of that.

In this case, if you look at the flood wave which is having a two point A and B apart from a distance l_1 the cA and cB, cB is larger than the cA. cB the celerity will be larger than the cA. In that case, the length will be increased between A and B. So the flood will be attenuated. The peak will be reduced. So that is what It is happens for the dynamic wave.

But in case of kinematic wave which maybe sometimes happens is that where is very simplified momentum equation is s_f the friction slope is equal to the bed slope s_o. If that is the conditions what it happens is that the cA is equal to cB celerity point of view which is l_1 distance the same way it is propagated same distance entity.

So if you look at the graphically if you have a different type of waves like a dynamic wave, diffusive wave and kinematic wave, the flood wave can attenuate it or amplified it all it depends upon the celerities. So now let us derive that celerity part in the next slides.

(Refer Slide Time: 09:18)

If we look at the celerity part if I consider that wide rectangular channels, if I consider the channels which is much larger, big, wide. That definitions is quite valid when you talk about the rivers. So we have a wide rectangular channels, you can define these area per unit width can have a functions with a power functions with the flow depth. That is what we can define is a power functions of the flow depth.

Whereas the power coefficients α and β are unknown for us. That what can vary from river to river. So we can define this unit discharge of the Q in terms of the flow depth. If I use that same concept, okay? This is what will have a basic definitions, because we are considering h is the flow depth and h is the function of the space and time.

So if you can look it and derive this dh/dt, which should be equal to 0. That substitution if you could do it. And that what will come it back to this the same

derivations what you can do it. And substituting this power functions, you can see that celerity is a β times of P. Okay, celerity is a functions for a wide rectangular channels. Celerity can consider as a multiplications β times of V, and β is the power exponent of the discharge and the β values.

So that reasons, the wave celerity is always faster than the flow velocities because when β is greater than 1. That is what you can see this very simple relationship. The celerity of the flood wave increases with the flow depth. That is already we derived it. The larger the flood wave we have a larger flow depth. That is what is propagates faster than the smaller flood wave.

So larger the depth, so you have more the celerities. And that is the reasons it propagates faster. Its travel time takes lesser. The smaller flood wave, it takes larger time steps. It is as the celerity is less. So that what we should try to understand it, what it happens for a larger flood wave, what it happens as a smaller flood wave.

Because of that, there is a nonlinear propagations of the flood wave. So what we use the linear techniques based on these superpositions concept like a unit hydrograph it does not valid for the river, where you have extreme flood events happens it, when you have the flash floods happens it. The wave celerity is quite large. So it indicates that method of isochrons we used in hydrology is also not applicable for the river.

So like for example, if I talk about the Himalayan rivers where the large flash floods occurs it, the simple concept of the linear superimpositions and this isochrones methods does not valid for us. So we should try to locate that what it happens the flood wave, how propagation happens. Like if you talk about the celerity of the flood wave increase with the flow depth, and that the case is a larger flood wave takes the lesser time to propagate from A to B locations.

But the same locations when you have a smaller flood wave it takes the longer time. So it make a nonlinearity functions. That is the reasons we cannot use the linear hypothesis what we have in hydrology. That is, we do this flow routings based on the linear concept but that is what it is not valid when you talk about the flood wave.

And as a morphologist as we look at the river mechanics, as you know it the flood waves play the major role for the change of the morphologies. That is the reason its extreme conditions. That is try to understand that how the flood waves are happening.
(Refer Slide Time: 13:46)

Now if we look at the next part if I like try to look it the derivations, which is there in the book of Julien book, if then V can be defined in terms of functions of h and β-1 and then V can define like this. If I look it write it again with some simplifications of St. Venant equations, what we derive for the dynamic conditions the friction slope will have a bed slope plus there is a components will come it which is functions of beta and the flow Froudes numbers.

And you have a temporal components here. So if we combine a continuity equations. And dV is this ones then you get it the s_o is these values . So that derivations please do it. So what you can see is very interestingly that we have a flood wave diffusivity terms, okay. dh is there and these term is defined is a flood wave diffusivity, which is a functions of β, flow Froude numbers.

So if we look at that if β=1 and flow Froude numbers equal to one, which is the critical flow conditions. And in that case you may have this value comes out to be 0 and you will have only diffusive factors is comes to be 1. So what I am telling it if is β=1 so you will have the Froude diffusivity value equal to 1. Or you can show this, it is a functions of Fr.

So if Fr is the flow Froude numbers is close to the 1 then it only depends upon the β value. But if you use the Manning's equations, which is the functions of the velocity and hydraulic radius and s_o s_f of if you use that values and combining it you will get these functions like this.

So we are not going step by step derivations please follow this the book which is there by Pierre Julien's so that where Froude wave diffusive terms it depends upon the value of β and the flow Froude numbers. So these ratio between these terms which is defined is the flood wave attenuations at the low value of the flow Froude numbers.

(Refer Slide Time: 16:44)

Now if you try to understand it if I define in another is called the diffusivity ratios, okay which can be written is that how much of diffusivity ratio is happening it. That is what also can be written in terms of dh/dx will be a functions of dQ/dt with the β functions, s_o functions, α and β value. And Manning equations if you consider β =5/3.

The diffusivity ratio is comes out to this. So, the rapid change in the discharge increase the flood wave diffusivity. That is correct. That means if I suddenly increase the flow in temporal domains i.e. suddenly from 3000 cumecs of discharge, it goes up to the 10,000 cumecs of discharge. The sudden dQ/dt will be much larger value.

So it will increase the flood wave diffusivity, increase the flood wave. That is what it happens in flash floods. Suddenly the discharge which is much lesser, it just jump it to one order or two orders. So that is the reasons it started the flood wave diffusivity. So

given the flood wave the Q and dQ, diffusivity increase with the Mannings of coefficients of n and decreases with the channel slope.

So decreases with the channel slope, like the Himalayan rivers the channel slope is much larger. So you can see that it can decreases with channel slope. Channel straightening higher bed slopes channel lining the lower and decreases the flood wave diffusivity of the natural slope. So why you do the channel straightening. So we are so what it happens it? Change the bed slope.

The higher the bed slopes or channel lining, why do we do it? Lowering these roughness values, Manning's roughness coefficients. That what also helps to decrease the flood wave diffusivity or natural channels.

(Refer Slide Time: 19:04)

That is we should have also components what you look it. If I look it in terms of the velocity applying this the basic equations of Manning's equations and substituting these s_f value what we derive it, you will get it that. It is a very simple derivations. If you look it that you will have s is that. The celerity will be β times of V, you will have this part. Now let us interpret it this part which is there in the text.

The flood wave diffusivity play the dominant role alterations of the flood waves. That is correct, okay. Dynamic waves in a steep channels when you have the channel is very steep, okay. Θ is very high for the channel slope. In that case Θ is very high, channel slope tends to form a pulsating flow or surges rolling waves. When you have

a laminar flow the roll waves can theoretically form when the flow Froude number greater than 0.5.

The steep flows are possible for the subcritical flow when the flow Froude numbers greater than 0.7. In turbulent flow, I am not emphasizing laminar flow as the river we have the turbulent flow. So in turbulent flow when you consider β is 5/3 the roll waves develop very steep smooth channels under the supercritical flow.

Just try to understand it what it happens in a rivers when you have turbulent flow and you have the flow Froude numbers more than 1.5, it can create a roll waves, okay. The wave will have a roll waves will be there. Roll waves supercritical flow should be avoided in open channel flow. That is we should try to understand it because it causes the surface disturbance.

And the cross waves incurred by perturbation of the bank and the bed. So when you go for the supercritical flow, it is will have the roll waves and supercritical flow should be avoided from open channel design, but in case of the river does it happens it? It can be best to achieve increase the boundary roughness to extend the flow, which should be remained at the subcritical flow.

So basically if there is a boundary roughness which will make it the subcritical. But in a reach of the river, if there is a supercritical and the flood wave propagates it which generate the flood roll waves and that the surface is interact with the instability and the cross waves. That is the reasons sometimes the river flood is so chaos.

So turbulent structures is created, because of maybe the localized formations of supercritical flow, localized formations of supercritical flow with the flood wave, it can create the roll waves and can propagate like a tsunami type of the waves which will be totally destroyed it instability and cross waves. So it happens it but localized conditions, but it can talk about the extreme conditions what it happens it

(Refer Slide Time: 22:38)

- Kinematic waves are obtained when $Fr = 1/(\beta - 1)$
- In the case where the bed and the friction slopes are identical, wave and discharge increase solely with flow depth
- In most rivers, the flow is subcritical and flood routing is adequately described by the diffusive-wave approximation of the St. Venant equation.
- In such cases, the wave celerity and discharge do not vary solely with flow depth but also depend on the gradient of flow depth in the downstream direction
- Floodwave attenuation is most effective when the Froude number is low, and $\partial h/\partial x$ is large compared to S_0

Now if you look it that if our kinematic waves when you have flow Froude numbers of these values, in this case, the bed and friction slopes are identical, wave and discharge increases slowly on to the flow depth. In most of the flood flow is subcritical, okay. Flow routing is generally described by the diffusive wave propagations of St.Venant equations.

But in localized conditions, extreme conditions like the flood propagations in Himalayas where large scale of the bed elevations variations are there. So in that case, flow may go for the critical conditions. Otherwise, flow is a subcritical. That is the reasons we use the St. Venant equations and try to solve it. In such case the wave celerity and discharge do not vary with the flow depth.

But also depends on the gradient of the slope flow depth in the downstream directions. That is flow wave attenuation is most effective the flow Froude number is less dh/dx is large compared to the bed slopes. So that is the understanding you should have to know it what it actually happens when you have the flood waves.

(Refer Slide Time: 24:03)

Loop-rating curve of the Mississippi River at Vicksburg

Source: River Mechanics, P.Y.Julien

Now if you look it the next components as you go it is called the loop rating curves. Just you try to understand it that the relationship between the discharge and the elevations we call the rating curve. Are they it is a power functions or it is a loop? That is what actually happens it is a loop rating curve. If you look at this rating curve of a Mississippi rivers at a particular locations the x axis is the discharge y axis the elevations.

What is actually happens it as the discharge increases it follow this path, then come back it like that. So if you look at it this way, when you have again, I am to repeat it that the loop rating curves. That means as the discharge is increasing in channels it increases with the elevations, but after the maximum discharge reaches it when its falls is comes it, it have a higher flow depth as compared to the rising stage.

Why does it happens it. So when if you look at that when you have a rising stage you have a dh/dt is increasing trend. And we have the decreasing trend when you have the delta the temporal variations of h is a negative directions. So if you look at this the discharge if I look it in terms of the same equations, we are writing this as with multiplying the velocity into area we know this hydraulic depth that is dh/dx, then this is a flood diffusivity constants and these value.

Now if you look it when you have a rising stage s_f not equal to s_o. That is what it happens it. When you have falling levels of the water hydrograph the loops are induced by the rating curve relationship, okay. So if you look it that, it depends upon

this rating curve relationships if you look at during the rising period as a counterclockwise loop is often between a relations between stage and discharge.

The elevations versus in most of the river channels you would have received. The maximum discharge reached before the maximum flow depth okay. But bed shear stress if I can compute it, which is governed by the shear stress equal to the unit weight of the waters hydraulic radius and the friction slope. If you just substitute the friction slope I will be getting like this.

It is a functions of dh/dx, okay. Functions of flow Froude numbers, functions of s_o. Function of flow Froude numbers and functions of s_o. If I look it this way, what it actually happened the shear stress at a given flow depth, the shear stress and bed sediment transport are larger than the rising limb than the falling limb, okay.

So what it actually happen it when you have the larger rising limbs if you try to understand these equations you will have a more sediment transport okay as the bed load transport than the falling limb. So the Meyer-Peter formulas, which we will discuss later on, which is a giving a reasons between the access stress between the applied shear stress and the critical shear stress as a power functions with a bed load.

That is what. So bed loads also depends upon that as your asset value is changing between the rising limb and the falling limb, you will have a more bed load sediment transport in case of the rising limb as compared to the falling limb, okay. So more detail you try to understand these situations and you can interpret it that how does it happen it.

(Refer Slide Time: 28:29)

Source: River Mechanics, P.Y.Julien
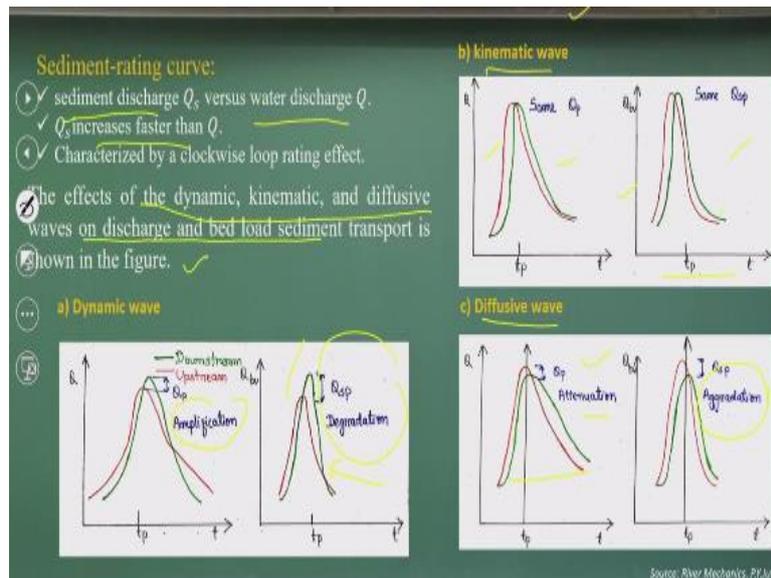
Now let it look at the sediment rating curves, what it actually happens the relationship between sediment discharge versus the water discharge, okay. Q_s increases faster than the Q. That is what if you look at that if you have a kinematic waves, just look the figures okay, kinematic wave case, you if you look at that, if we have a red color is a t1 time and the green color after dt time the flood wave will have a change from the red to the green, okay.

So you can have the kinematic wave. So the peak will not unrouted it, but the sediment will go like the same way if you look at that, sediment discharge versus time. But in case of the dynamic wave, you can see that there will be the amplifications. That is the red color is upstream hydrographs, green color is a downstream hydrographs and you can see these amplifications happens it.

Because of these amplifications of things, you will have a bed degradations will happen it, bed erosions process will happen it during these amplification process. And you can see that the downstream and upstream sediment graphs with the times which will change it. The same way if you look it if you have a diffusive wave the flood is attenuated. The peak decreases and the length of the base increases.

In that case what will happen the channel bed aggradations will happen, the aggradations will happen the depositions will be started, when you have the flood attenuation process that. The effects of the dynamic kinematics on the discharge and

bed load transport is can be shown it and we should try to understand it how the sediment transport happens during these flood wave propagations, river flood wave.

(Refer Slide Time: 30:29)
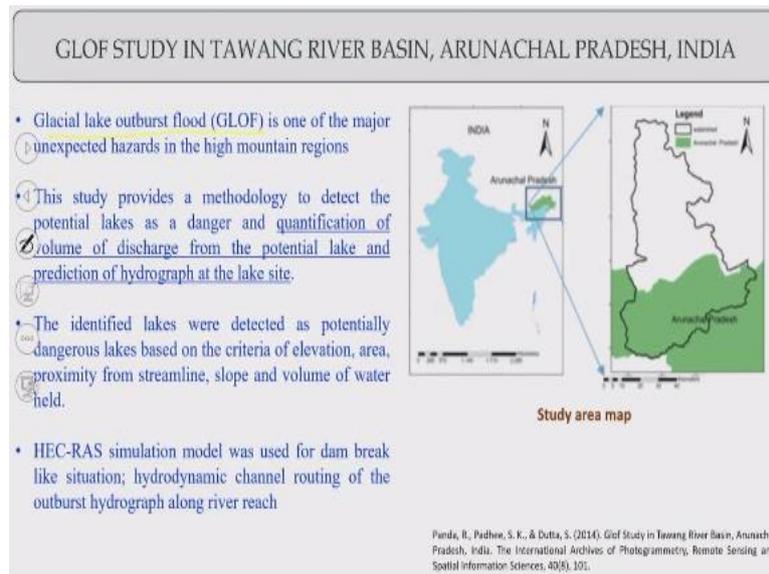
Let I go it a very a simple case studies what we have done it for glacial lake outburst floods which is the publications here. If you look it that, what you have done it for a lake which is a danger is quantifications of discharge potential lake. And that is what we have used a mathematical models and use a dam break and hydraulic flow routing hydrographs.

(Refer Slide Time: 30:56)
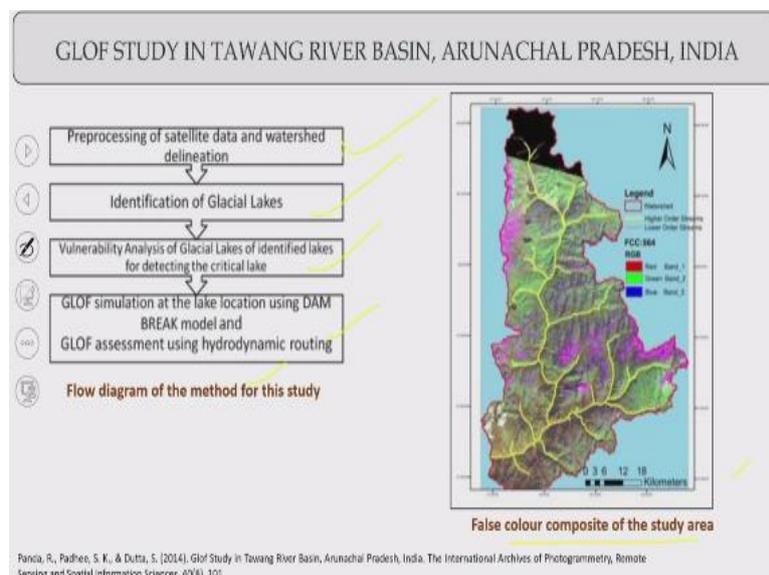
So if you look at that part, so what is there we have done the identifications of glacial lake, vulnerability of the glacier lakes which identify lakes for detecting a critical lake and you use the lake location as a dam break and graph assessment using a

hydrodynamic routings. That is what if you look at this the study area false color compositions.

(Refer Slide Time: 31:21)
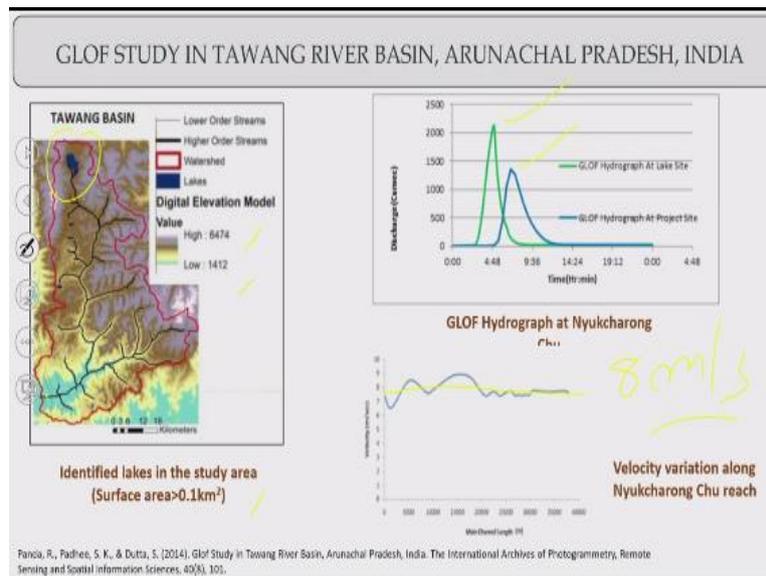
And if you try to look it that this is the lake locations and we are looking at these outer locations what will be the flood hydrographs. So it is showing it the water sets, and you can see that how the velocity varying it. It goes up to the 8 m/s is much more higher, okay. And you can see that the lake side hydrographs and the hydrograph at the project sides, okay, you can see that.

The flood attenuations are happen it and that is what we got it. And this can go as high as 2000 cumecs and at the dam site, the project side it can reduce to the 1500 cumecs and most often if you look at this the velocity variations which is 8 m/s, which is much larger, okay. You can try to understand it in Himalayan regions if have the GLOF type of conditions the velocity of the GLOF is a range of the 8 m/s.

So this is the case studies what we did it and it is a quite interesting to you with all these recently geospatial database, we have used to derive what could be the celerities, what could be the flood attenuations because of GLOF, Glacier Lake Outburst Flood.

(Refer Slide Time: 32:49)
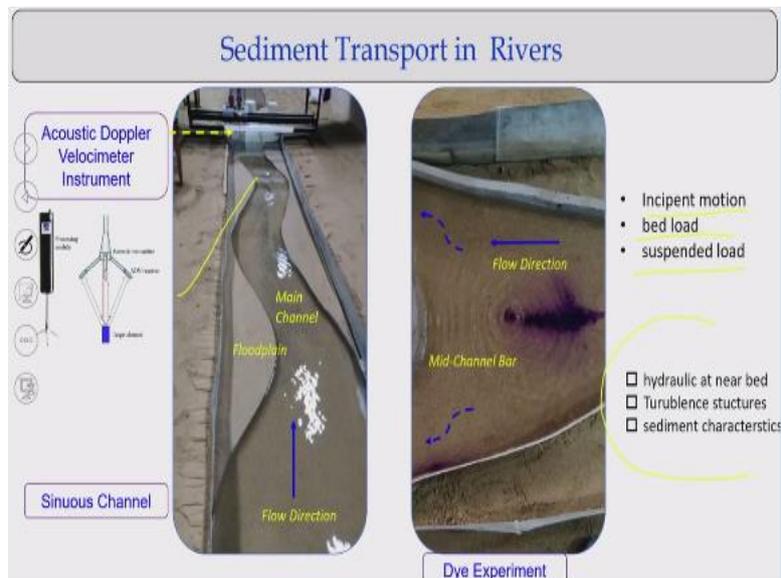
Now let me I come back to very interesting topic as introductions level I will talk it today and more detail will go later on. See if you look it that there are bigger issue of the sediment transport the issue 1950s onwards. It was started that we should try to understand the sediment transport mechanism conducting the channel flow. As you have seen this is a channel flow with a sinuous channel or you can have a non-sinuous channels.

And if you increase the flow depths as you know that it will have the more the shear stress. As you increase the flow depth and you have a more the shear stress the bed particles which would be there, they will start motions, okay start moving from the bed. That is the conditions we call incipient motions.

And if you further increasing the flow depth then what will happen it, a layer of the bed will be move it, a bed particles will move it and they can go for a different process okay with a rolling, jumping bed particles will go it and you can have a the bed particles can contribute a partly to layers which is moving along the bed and there will be part which is above of that which remains as a suspended conditions.

All these things are happens it we look it in a very microscopic scales because the last two decades there are lot of study has been done it look it the very microscopic level at the near bed conditions. What it does it happens. What is the hydraulic conditions happen the near bed? What is the turbulent structures are there? Why the bed particles are detaching from the bed?

What the hydraulic condition also it is depend upon the sediment characteristics. If you try to understand this case and if you look at this flow behaviors and if you put the color dyes and it shows that how the flow things are happening it okay. So it is easy nowadays. If you have the flow, you can conduct the experiment to know it the quantifications of turbulent structures, incipient motions, the bed load, the suspended load.

All these experiment we can conduct it and we can try to establish the relationship between the hydrodynamic characteristics, sediment characteristics and with a sediment transport processes.

(Refer Slide Time: 35:16)
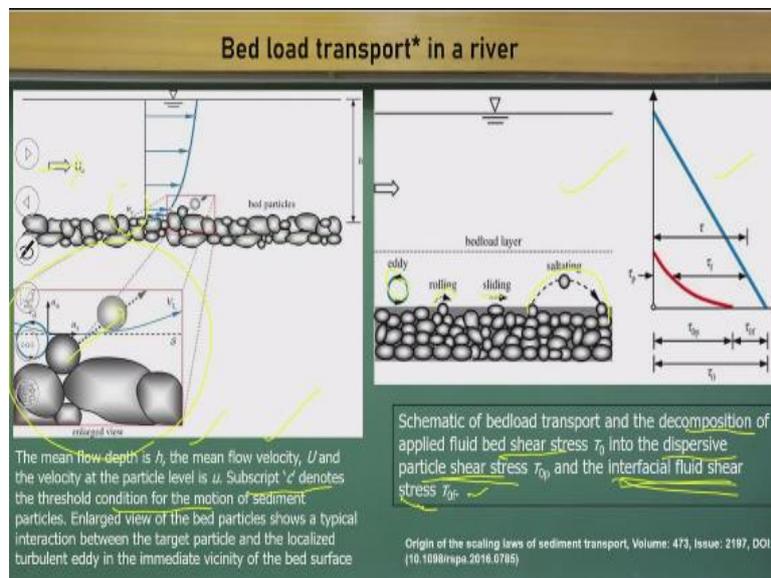
Now one of the process is what is done it cases if you look at the bed load transport in a rivers, which is looking at very microscopic scale, if you look at these figures okay. If you say that the u_c is the velocity is coming which is at the incipient motions the conditions at the bed okay the bed particles are just starting the moving incipient is a average velocity u_c is coming it at the particle levels can have a the velocity which is small u_c.

The particle levels which is a critical velocity just push that sediment particle from the bed one positions to other positions or it can go to the suspended loop. More detail enlarge view or microscopic if you look it at the sand particles microscopy are these

you can see that there will be the velocity components and these particles are having the trajectory detaching from that, okay detaching from that.
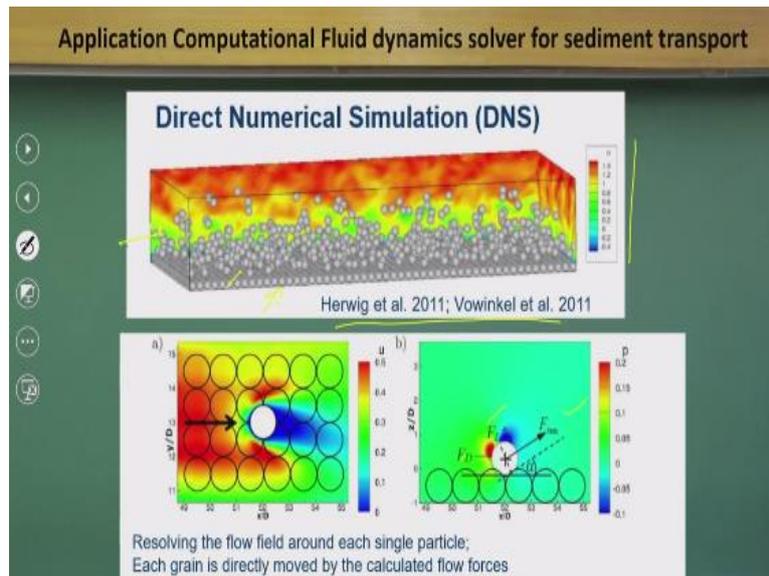
That is what is there the flow velocity depends upon the flow velocity, it depends on the mean flow velocity. It depends upon the sediment particle sizes, the d50 d90s. It depends upon subscript stands for the threshold conditions of motion of the sediment particles is incipient motions. And typically if you look it the target particles are moving. So nowadays people are looking that level how these target particles are moving it.

Same way if you look it that, how the shear stress distributions are happening it. If you look it, it has two component. The decomposition of the fluid is bed shear stress into dispersive particle shear stress, interfacial fluid particle stresses. That is what is happening it. If you look it that, it has two components. One is dispersive of particle shear components, okay τ_o which is high as you go up it reduces.

And interfacial the fluid shear stress particles. And if you look at these particles, the bed layers okay, it is a very good and the bed compositions if you look it try to understand it and there is eddies formations and the rolling, sliding will happen it. So more microscopically if you look it that how the shear stress acting it along the rivers, along the channels.

In that case you can clearly interestingly look it that the particle shear stress, which is much more higher, that is what is going to decrease along the depth where is the interfacial fluid shear stress which generally in fluid we talk about that that is what is also have a increasing trend. And we should know it and more detail if you can follow these recent publications on scaling large of the sediment transport.

(Refer Slide Time: 38:13)

Application Computational Fluid dynamics solver for sediment transport

Direct Numerical Simulation (DNS)

Herwig et al. 2011; Vowinkel et al. 2011

Resolving the flow field around each single particle;
Each grain is directly moved by the calculated flow forces

Not only that, the people nowadays use the CFD solvers to know the sediment particles how it moves it. You see these velocity is there. CFD solutions are there and the particles are considered a solid rigid circular balls and each force components are there and we can use the CFD as a multi-phase flow concept. Try to know it how the sediment particles are dethatching from the bed, remains and suspension states are falling to the bed, how this happens in this process.

So if you look it that, at the microscopically we can know it nowadays because we have a tools to measure the velocity distributions and all as well as we have also the computational capacity now to run a CFD softwares very detail to try to for a multipath flow, try to know it that how the particles are dethatching from that or starting the incipient motions, how long it will remain as a suspension stage.

And how it is going to fall it and where it is going to fall it all detail can be studied using the CFD softwares or you can conduct the fluid experiments with detail velocity measurements, turbulent structures, we can understand it. But in this courses I will not to go to that microscopic scale more which are interested they can follow this Subhasish Dey's book on fluvial hydrodynamics.

But here we will go to as a grass levels, how the characteristics which happens it. In the next class we will talk about gross characteristics how the sediment transports process happens as a bed load, suspended load, incipient motions, those are things we will discuss much details.

If you look it that, what we should discuss is that by ending these lectures what I can say that Barry Stevens said it very rightly that do not oppose the rivers, it flows by itself, okay. That is what is we should understand as a river engineering. We should not too much push the rivers from the courses. And it flows by itself. That is the characteristic we should understand it. That is what is our basic motto on these courses. Thank you.