Advanced Hydraulics
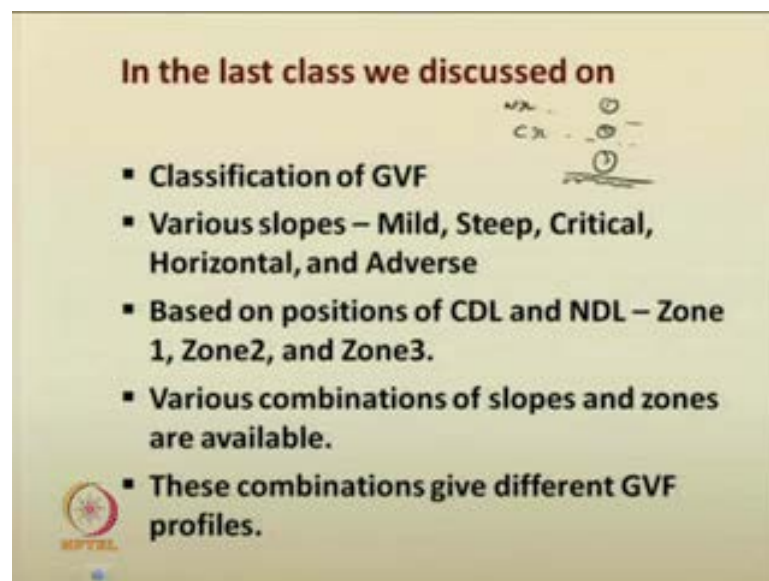**Prof. Dr. Suresh A. Kartha**
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Module - 3
Varied Flows
Lecture - 5
Gradually Varied Flow Profiles
with Change in Bed Slopes

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We are again back into our lecture series on advanced hydraulics. We are in the third module on varied flows. If you recall in the last class; last class we had discussed on various classifications of the gradually varied flow. We have also discussed on the various slopes; that is the mild slope, what is meant by mild slopes, steep slope, critical slope, horizontal slope, adverse slope and all. Based on the positions of critical depth and normal depth in a flow, you were also suggested about the various zones; that is zone 1, zone 2, and zone 3.

If you recall them, say if I just draw it here, say if you have the bed channel like this, then if this is your critical depth line, this is your normal depth line, then zone one, zone two, zone three like this; you had classified the various zones of fluid where the water surface can exist. Then the various combinations of the slopes; that is mild, steep,

critical, horizontal and adverse as well as the zones; zone 1, zone 2, and zone 3. You can have different types of gradually varied flow that also we have discussed.

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- **Curvature of water surface described using d^2y/dx^2**

$$\frac{d^2 y}{dx^2} = S_0 \frac{dy}{dx} \frac{3y^2\left(y_n^3 - y_c^3\right)}{\left(y^3 - y_c^3\right)^2}$$

dy/dx = +ive always for Zone 1 and Zone 3
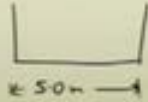dy/dx = -ive always for Zone2

We also suggested to you the curvature of the water surface. Based on the curvature of water surface, one can determine whether your water surface, the slope of the water surface is positive or negative. And using this particular equation you had which was discussed on the last class; you have seen that dy by dx is always positive for zone 1 and zone 3 whereas dy by dx is always negative in zone 2. So, these things are very much evident.

Today, we will discuss on the gradually varied flow profiles with various change in bed slopes. How with different bed slopes if a channel with one particular bed slope merged with another channel with another bed slope. How the flow becomes, how the gradually varied flow becomes and all, how the profile will be; these things we will see in today's lecture. So, before that I think it is better to solve a problem for you to understand the concepts of the various zones of liquid and various slopes in the flow and all.

Problem

Q:) A rectangular channel is carrying a steady discharge of 1.60 m3/s from Farakka Barrage to Malda Town. The bed slope of the channel is 0.00085. The depth of water at the entrance to Malda town in the channel is observed as 0.35 m. Assume Manning's n=0.016. Determine the type of gradually varied flow at this entrance.

$B = 5.0$ m
$S = 0.00085$
$Q = 1.60$ m³/s
$n = 0.016$

So, let us see the today's problem. The following is the problem; you can just note the question. A rectangular channel is carrying a steady discharge of 1.6 meter cube per second from Farakka barrage to Malda town. The bed slope of the channel is 0.00085. The depth of the water at the entrance to Malda town; it was measured at the entrance to Malda town in the channel. The depth of the water was observed as 0.35 meter, you can assume Manning's roughness coefficient as 0.016. Now you are requested to determine the type of gradually varied flow at this entrance.

At this entrance location, you determine what is the type of gradually varied flow? So, you take all the details from the question. You can see that this is a rectangular channel; a rectangular channel of width 5 meters. This is given to you and so I can write this as B is equal to 5 meters. Its bed slope it is given as S 0 is equal to 0.00085. The steady discharge is 1.6 cumecs or meter cube per second. Manning's roughness coefficient is given as 0.016. So, you have to determine the type of gradually varied flow.

So, now recall your first module; recall critical flow computations from module 1. From module 1, we have extensively studied on critical flows and its computations and all; you recall them. So, how was the critical flow in rectangular channel determined or how was it considered? You see that, I hope you are able to recall. The critical depth in a rectangular channel for a given discharge is given as Q squared by B squared g whole to the power of 1 by 3. I am not coming back into how you have obtained this equation; we have derived it very clearly in the module one of this course and all.

So, you substitute the quantities you know Q, you know B. So, 1.6 squared by 5 squared into 9.81 the whole quantity raised to 1 by 3. You calculate that, you will get this quantity as 0.2185 meter. So, this is the critical depth of the flow. So, you are suggested means you are given that rectangular channel. So, the critical depth for the given discharge; so the critical depth, this is y c is equal to 0.2185. Your actual flow depth is y is equal to 0.35 meter is the actual depth observed; therefore, y greater than critical depth. So at present, the flow is in subcritical condition; that you can understand now because y is greater than y c. Now the next thing is that you have to determine the normal depth for this particular discharge, what could be the normal depth?

Again normal depth for the given discharge, you use Manning's equation Q is equal to 1 by n AR to the power of 2 by 3 S naught to the power of half. So, Q is given as 1.6, Manning's n is 1 by 0.016; a, what is a? It will be 5 into normal depth, then wetted perimeter P or you can say hydraulic radius R; this is equal to B y n by B plus 2 y n. You recall these relationships, substitute it here; so 5 n into 5 n by 2 to the power of 3 into S naught, so 0.00085 whole to the power of half. So, you have this following relation.

You rearrange the terms; you know the quantities many of the quantities, only y n is unknown quantity here. So you rearrange the things, you will get y n to the power of 5 by 3 by 5 plus 2 y n; this is equal to 0.060059. So, just for your benefit this is here; it is the width of the channel; Of course it is B; B is equal to 5 you know that. So, you just substitute it 5 there, so 0.06. Now in this non-linear equation, you have to adopt the trial and error procedure to obtain the exact value of y n. How do you do that? I can write the following relationship now.

y n to the power of 5 by 3; this is equal to 0.060059 into 5 plus twice y n. So, this you can give it as equation one if you want to search that. Now as the depth of flow, here the depth of flow observed y is equal to 0.35 meters which is greater than the critical depth 0.2185. This is greater than this thing. Therefore, let us assume initially y n is also greater than y c. Let us consider it as a mild slope because most of the cases you may observe mild slopes in the things and all especially for distribution channels and all; you may not think that much of steep channels.

So, let us assume if this not true then like, you can come back again and assume normal depth as less than critical depth; that is it is a steep slope and then you can start the computations but let us for our trial and procedure; trial and error procedure is considered . Therefore, begin with you can take any value of y n greater than y c; I am just beginning with y n is equal to 0.30 meter, just want to see that. So if you substitute in this equation, if you substitute in equation one y n is equal to 0.3 see whether the equations are matching or not or you can see equation one can be rewritten as y n is equal to 0.1201186 y n plus 0.3002966, the whole thing raised to 3 by 5; like this you can get an equation. So left hand side, there is one y n existing and right hand side there is another non-linear terms of y n existing there. You have to match both of them in the trial and error procedure.

So, this is trial y n and this is the RHS y n. So, if I start in the first case with 0.300; as a trial value of y n if I suggest y n as 0.3, you are getting your RHS as 0.5200. I am just trying; let me give y n as now 0.522 instead of point whatever was there in the RHS. Again on incorporating y n as 0.52 in this equation, you are getting the RHS of this equation as 0.54422. Just in the next iteration incorporate y n as 0.54422. So you will see that it is coming, it is almost reaching convergence. So, there is not much change in the depth in the RHS and LHS value; if you want to further proceed you can just see that.

Next iteration again I am incorporating y n LHS as 0.54683 and the corresponding RHS term, I am getting this as 0.54711. If you want you can again go for an iteration but it is almost converged in open channel flow in such large scale problems and all you need not go further; it is almost considered at 0.547 could be there. So, I am not going further. You can see normal depth approximately equal to 0.5471 meter. So, what does this mean? Your normal depth is equal to 0.471 greater than critical depth which is equal to 0.2185 meter. So therefore, here the flow means it is a mild channel; that is the normal depth is above the critical depth or the normal flow line is above the critical flow line; therefore, it is a mild slope channel. Now your depth y is greater than critical depth.

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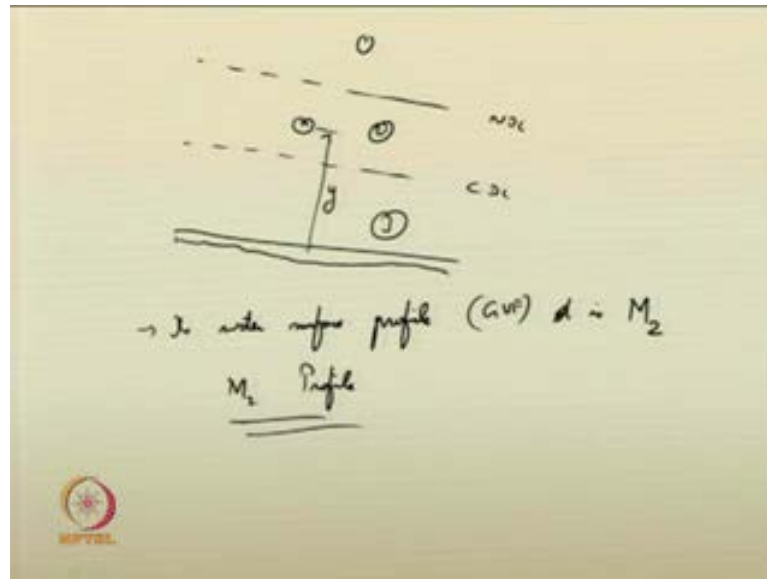
So, just recall that; if I draw the bed, your critical depth line, your normal depth line and your actual flow depth is somewhere here, why? So, at this stage this is in the zone 2 of the water surface profiles. So the water surface profile that is the gradually varied flow profile at the entrance to the Malda town in that channel it is M 2 profile. Because it is a mild slope channel and it is in the second zone; therefore, it is M 2 profile. Like this you determine the various flow profiles or if you are given the data you can determine or if you are given the water surface data and all from that you can easily identify whether it is in the zone 2; if it is a M 2 profile or if it is an M 1 profile or it is an S 2 profile like that. So, today as we suggested we will just go through if the prismatic channels if two prismatic channels of different slopes are connected, how the gradually varied flow profiles will be observed or how can you observe the gradually varied flow profile, in which zones or in which slopes it exist; these things let us go through them.

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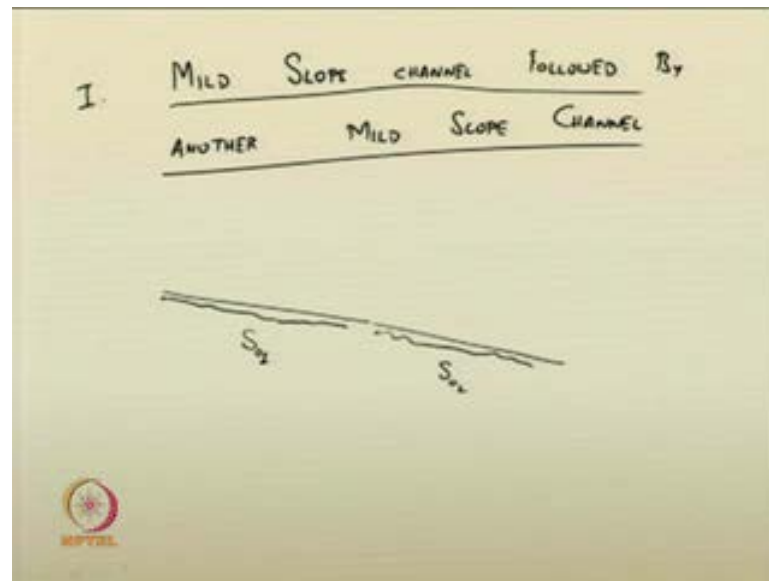
First, the first case which you are going to do is, say, if you have a mild slope channel followed by another mild slope channel; if you have such a condition, how are you going to determine the gradually varied flow profiles? Just imagine, say I have a mild slope channel and it is followed by another mild slope channel or different slope; see here this is the first channel, it is having slope as 0 1 bed slope I am talking about the bed slope and here the bed slope of the second channel it is S 02. So, both are mild channels. So, like that way one can easily now try to interpret what could be the profiles due to the change in channels, how the profiles can change one can easily determine.

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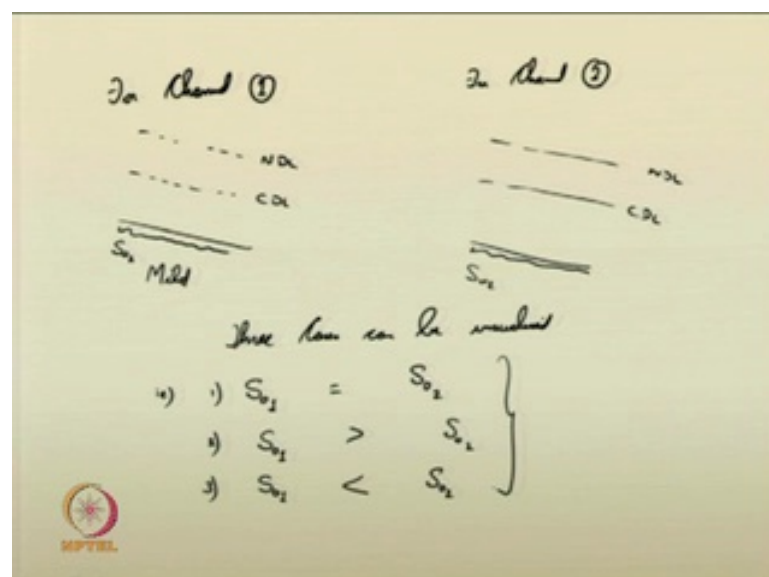
You see that for channel one it is a mild slope channel. So, there will be a critical depth line and there will be a normal depth line according to the given bed slope S 01 all these things are there. Similarly for channel 2, you can have the bed slope S 02 the corresponding depth line and normal depth line. You can visualize three conditions; three cases can be visualized; that is the slope of the channel 1 the bed slope of the channel 1 and the bed slope of the channel 2. Both are same, S 01 is equal to S 02. This is one particular case.

Another case you can visualize is S 01 is greater than S 02; that is the slope of the channel 1 is greater than slope of the channel 2. How the profiles can change or what could be the water surface profile; this we will study now. Another case you can visualize is S 01 is less than S 02. So, these three cases one can easily visualize. Now based on the magnitude of the slope, say, if S 01 is whichever in these mild channels both are mild channels mild slope channels whichever is having lesser slope it is considered as mild.

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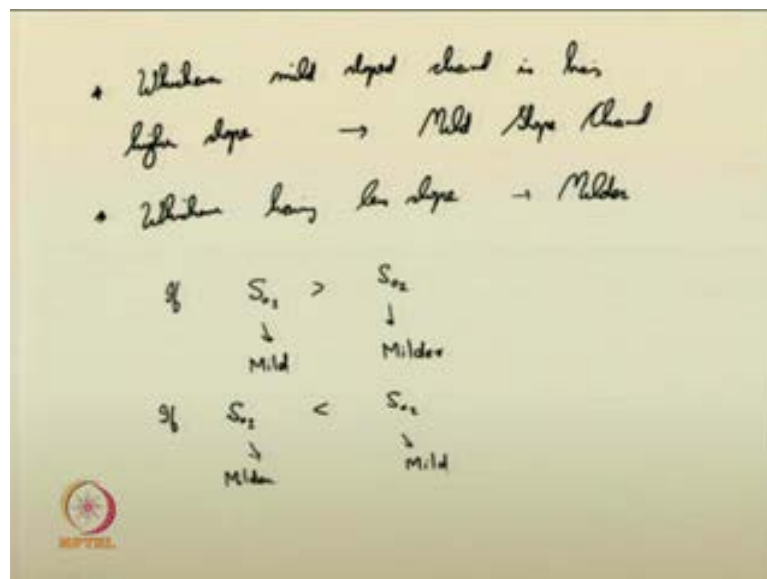
That is whichever mild slope channel is having higher slope it is called mild slope channel and whichever is having less slope; the magnitude of the slope if it is less they are called milder slope channels. So, say, if S 01 greater than S 02 then this is milder slope channel; may I beg your pardon? S 01 greater than S 02; this is mild slope channel and this is channel 2 is milder slope. Similarly if S 01 is less than S 02, then channel 1 is

considered as milder and this channel 2 is considered as mild. So, like that you can say. So, here in this case we are studying with a mild means we can consider three cases; that is the slopes S 01 and S 02 both are same. Second case S 01 greater than S 02; that is the flow is occurring from a mild slope channel to a milder slope channel. Third case is the flow is occurring from a milder slope channel to a mild slope channel like that you can easily visualize the things.

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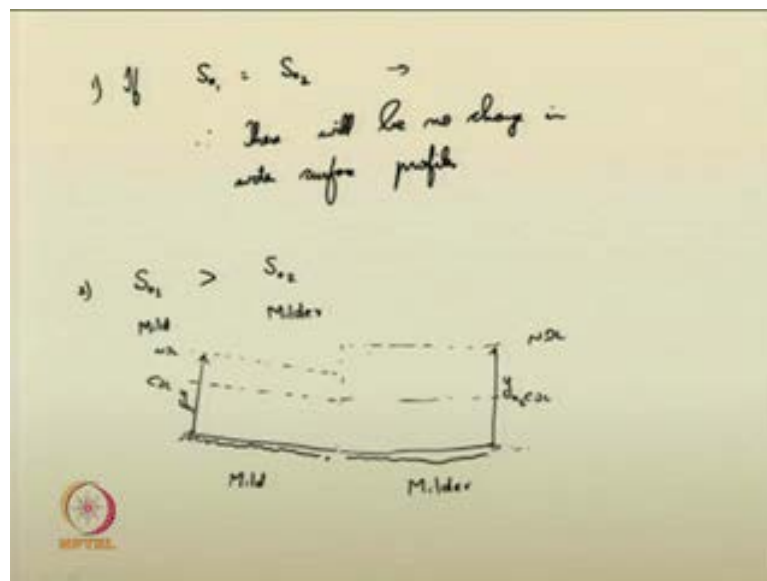
So, if I can suggest now the first case if S 01 is equal to S 02, then the flow properties are same. You know the critical depth line it determines on the magnitude of the discharge and all. So therefore, critical depth lines are same for channel 1 and channel 2 irrespective of the situations. So irrespective of the situations, critical depths are same for both the cases. If S 0 1 is equal to S 0 2 then of course normal depths will also be same. So therefore, there will be no change in water surface profiles. Second case, S 01 is greater than S 02; that is flow is occurring from mild slope channel to milder slope channel. What happens? So, you can just visualize them, say, a mild slope channel; it is having the critical depth. Another mild slope channel, this is mild slope channel and this is still milder.

So, its critical depth is like this. The mild slope normal depth is like this; of course if the bed slopes if it is less, you know that the normal depth will be further higher in this case. So, theoretically then this will be the normal depth for channel 2, this will be the critical

depth for channel 2; critical depth for both the channels are same. So, this is y n 1 and this is y n 2. So, in a steady situation for uniform conditions and all, the flow has to reach the normal depth. Now how the flow occurs, say, if a normal flow was occurring, a uniform flow was occurring in channel 1 in the mild channel. Now due to the presence of a further milder channel, how the profiles will change; that you have to suggest now. Can you imagine? You can think of various situations, say, this is the mild slope channel.

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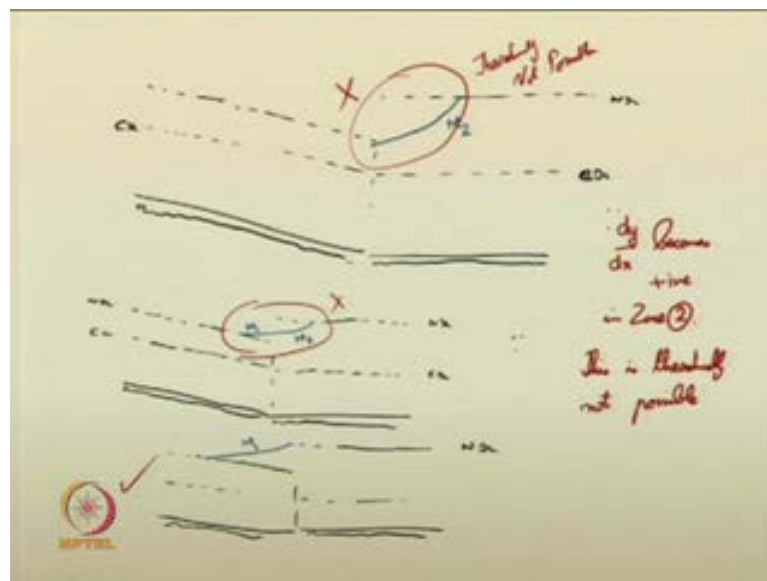
So, this is your critical depth line, normal depth line here, normal depth line here, you can think that. So, I will just change the color. See there may be a chance that the flow means normal uniform flow exist up to this point in channel one and from here a curve goes and merges with the normal depth line; that is the water surface profile from here, it will just go like this and reaches the normal depth line, means, the water surface profile goes in this way. You can imagine like that. Then this will be an M 2 curve in channel 2 but the question is whether this is theoretically possible or not? Another situation is critical depth line. So, in this case one can imagine, say, here partially the flow the water surface profile changes like this, the water surface flow changes like this and that is partially it becomes M 1 here and partially it becomes M 2 here in channel 2 like that. You can visualize like these things.

So, whether this is also theoretically possible or not; you have to think on yourself, we will discuss on that further. This is case one, case two. Third case is mild slope further

mild slope, critical depth, normal depth; the normal depth line is here like this. The water surface it will just start from here like this and on reaching at this junction itself, means, it will be having a gradually varied flow M 1 in channel one and reaches here and from the channel 2 the flow is entirely uniform or it is following the normal depth line like that. So out of these three possible situations, which one do you think that it is correct or which one is theoretically possible? Now if you look in to these things, you look in to these cases; here this situation in this case the n 2 curve in channel 2, it is having a positive slope. The water surface slope is positive here.

So, theoretically not possible, because dy by dx is positive there. So, theoretically it is not possible. So, this portion does not exist; such a water surface profile will not exist. Again in this case, here the M 1 it is theoretically possible but as soon as from this centre line to here in the channel 2, the curve is M 2. It is in the zone 2 and it is positive. So, that is also theoretically not possible. So, this is also theoretically not possible because both the cases dy by dx becomes positive. In zone 2 this is theoretically not possible. So, these two flow profiles will not exist; what about the third one? It is having an M 1 profile in channel 1 and it is theoretically possible. So, this is the only situation that can exist when a flow from a mild channel merges with a flow means when a flow occurs from a mild channel to a further milder channel. So next situation, what is the thing you can visualize.

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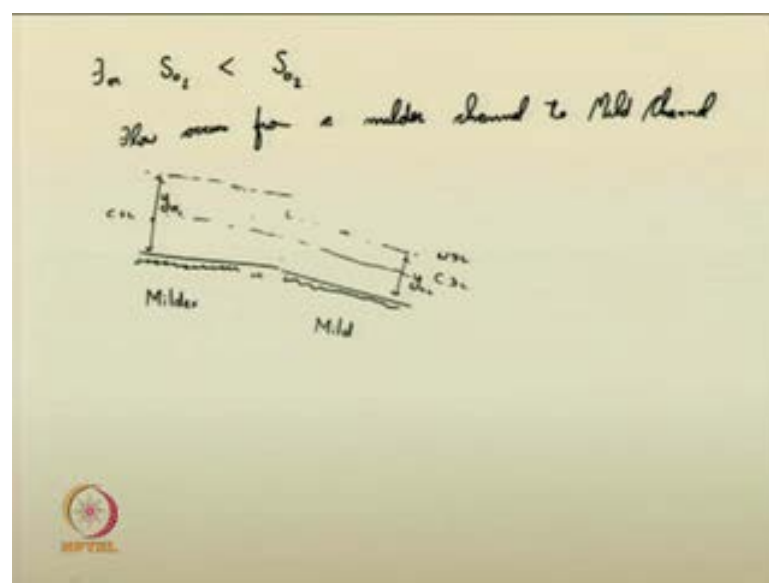
So, the next case is for your bed slope S 01 of channel 1 less than the bed slope of the next channel, channel 2 that is S 02. So, that is the flow here occurs from a milder channel to mild channel; that is you may have a channel, say, this is a milder channel and another channel that is mild. So, both are having mild slope but first one is more milder than the second one. So, of course as you have seen earlier, the critical depths in both the channels will be same critical depth line. Now what happens? In the milder channel, the normal depth will be much much more higher; it will be much much higher and in second channel the normal depth will be more lower. So, this is your y n 2 and this will be your y n 1. So this will be y n 1, y n 2. So, you have in this situation flow occurring from milder channel to mild channel.

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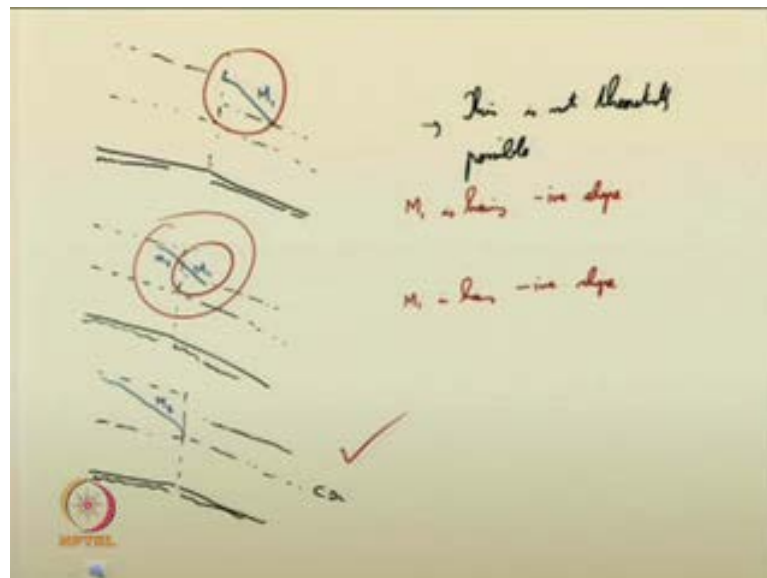
So, the profiles as we have described earlier you can see for such three situations; see in this case, the milder thing followed by a mild channel having both the critical depth same normal depths like this, there may be a chance of low profile connecting like this. So, you may imagine a low profile connecting like this. So, this can be an M 1 profile in channel 2. You can imagine; it is only an imaginary thing I have told that. Theoretically whether it is possible or not you have to verify it. Another situation milder channel followed by mild channel, the critical depths are same; in both the cases the normal depth is in the channel 1 is like this, here it is like this; that is y n 1 is greater than y n 2. Now in this case, one can imagine a type of water surface profile in this junction like

this, say, may be having M 2 profile in channel 1 and M 1 profile in channel 2 whether this one also exist or not, you have to verify it.

Another situation that is possible is critical depth line, normal depth line. Now in this case, you can think of a situation where the entire gradually varied low profile occurs in channel 1; that is it occurs like this or I will just make it in different color. So, the entire flow occurs like this. So, this is an M 2 profile in channel 1 and from here onwards it goes in as a normal flow in channel 2. So, among these three which one do you think that it is practically. So, this portion is not theoretically possible. So, this is not theoretically possible because M 1 is having negative water surface slope. So, that is theoretically not possible. Here also in channel 2, M 1 is having negative slope. So, that is also theoretically not possible; therefore, this entire profile cannot be possible. So, this is the only profile that can exist when a flow occurs from a milder channel to a mild slope channel.

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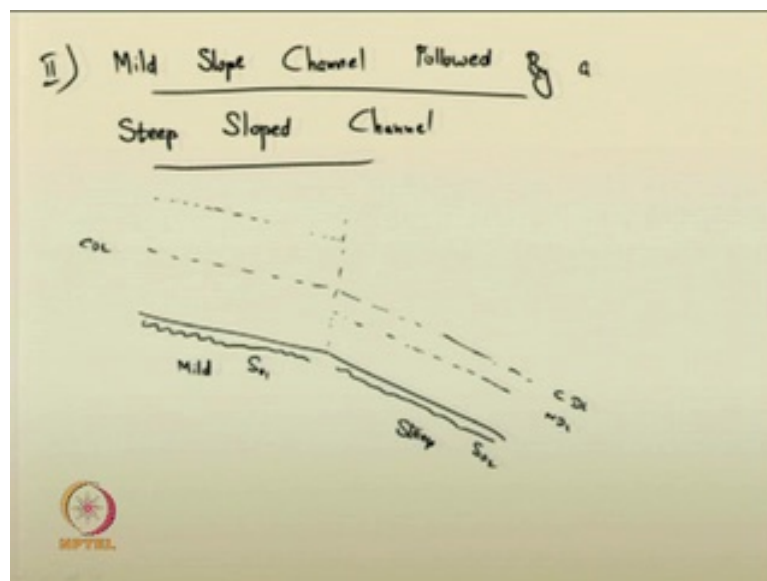
Now the second situation which we would like to discuss is when a mild slope channel followed by a steep sloped channel; what happens if a mild slope channel is followed by a steep sloped channel? You can have a mild slope channel; it is having the corresponding critical depth line, then it is followed by a steep sloped channel. So, I hope you can understand that the critical depth both in the mild slope and steep sloped channels for the given discharge it will be same. So, critical depth it is irrespective of the

bed slope; you have already seen those things. You can again go and recall the module one portions and all.

So, the critical depth line here; so the critical depth both in the channel 2 and channel 1 both are same. But this is a mild slope channel having S 01 and this is a steep sloped channel bed slope is S 02. So, why this is called mild slope because its normal depth is above critical depth line and this is steep slope because here the normal depth is below the critical depth. So, you can now connect various water surfaced profiles, say, in these channels how the water surface can occur; water surface will exist in these portion, whether it will be like this, whether it will be like this, whether it will be like this, you just have to think on that. Now I hope you are able to visualize more things how the water flow surface profiles can change.

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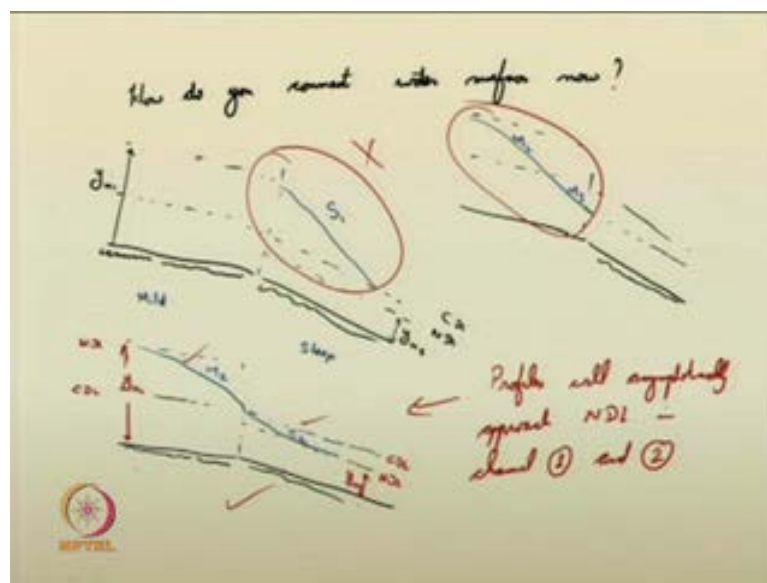
So, let us consider those things. So, how do you connect water surfaces now, say, mild slope channel followed by a critical slope channel; critical depths are same for both. This is the normal depth line for channel 1, this is the normal depth line for channel 2, this is y n 2 and this is y n 1. So, you may possibly think of a situation where the water surface may join in the following form; that is it is having the uniform flow up to this portion up to this junction in channel 1 and then all of a sudden it decreases like this with an M 1 profile. Sorry, may I beg pardon. This is a steep channel. It decreases with an S 1 profile. Is this possible; you have to verify it. Another situation you can imagine is a mild slope

channel followed by the steep sloped channel. Critical depths are same, the normal depth line here, normal depth line here.

In this case up to here up to the critical depth like this, water surface may go like this and like this and try to join like this in the normal depth. So, all the gradually varied flow profiles will be in channel 1 only. So here this is M 2, M 3, like this. So, whether these profiles exist? It is up to you to determine. Now possible third situation is a mild sloped channel followed by the steep sloped channel, the critical depth line, the normal depth line for the channel 1, normal depth line for channel 2. In this case you will see that another possible thing is the curve. It will have an M 2 curve in channel 2, then it will have an M 2 curve in channel 1 and S 2 curve in channel 2; like this a water surface profile may exist.

So, which among them is correct? Again like in the last portion, this is theoretically not possible because S 1 it is giving a negative slope dy by dx is negative in zone 1; that is not possible. Similarly this one is also not theoretically possible because M 3 it is giving a negative slope; that is also theoretically not possible. M 3 is having a negative water surface slope. Now this is theoretically possible because M 2 in M 2 there is the water surface profile is negative in the zone 2 of the mild channel as well as it is negative in the zone 2 of the steep sloped channels also. So, this is theoretically possible.

So, only one situation exists in these cases. So, in both the cases; so here profiles will asymptotically approach normal depth lines in channel 1 and 2. So, here it will asymptotically reach the normal depth line, here also it will asymptotically reach the normal depth line because these are the normal depth line, this is the normal depth line, this is the critical depth line, critical depth line, normal depth line, this depth is y n 1, this depth is y n 2 . So, like that you can think it.

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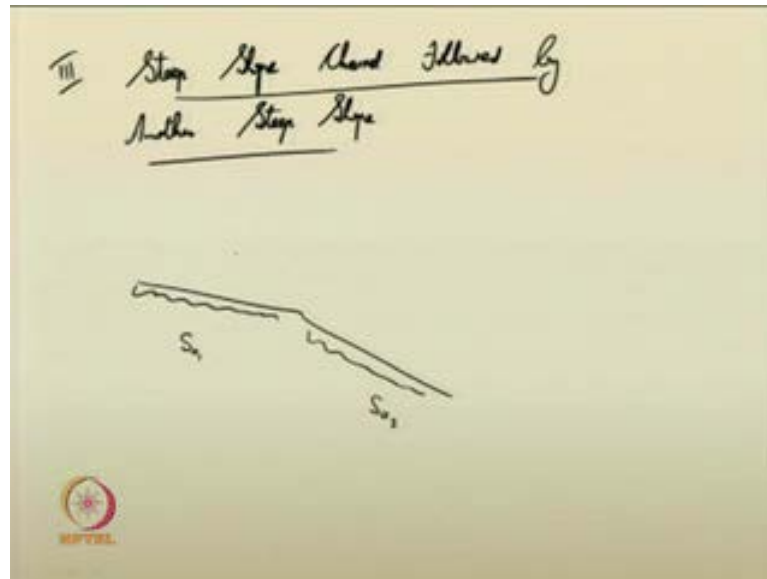
Next portion which I want to discuss is. So, here in the previous case there is only one situation; that is the mild slope channel is meeting a steep slope channel. So, there you need not further elaborate; that means there are no further subdivisions in those cases. Another situation if you have a steep sloped channel followed by another steep sloped channel; what happens if a steep sloped channel is followed by another steep sloped channel? You can again think of the thing; that is a steep sloped channel followed by another steep sloped channel. So, this is having bed slope S 01, S 02; both are steep sloped channels, how the flow profiles can be.

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So, three situations you can imagine; that is S 01 is equal to S 02, S 01 less than S 02. Then in such a situation if S 01 is less than S 02, this is called steep channel and S 02 is called steeper channel. Third situation is when S 01 is greater than S 02. So, in such situation this is called channel 1 is called steeper and channel 2 is called steep. So, like that you can imagine various situations; here this means that S 01 is less than S 02. So, it will look like this. So, again the critical depths are same in both; both will be having normal depths below the critical depth.

So, you can see that for more steeper channel, you will see that the normal depth line will be above, here it will be less. So, in this case y n 1 is less than y n 2 in S 01 less than S 02. And in the next case S 01 greater than S 02, you have like this critical depth; in this case the normal depth it will be like this. This is normal depth y n 1; this is normal depth y n 2. So, how the water surface profiles connect between y n 1 and y n 2. So, this also you can well imagine that.

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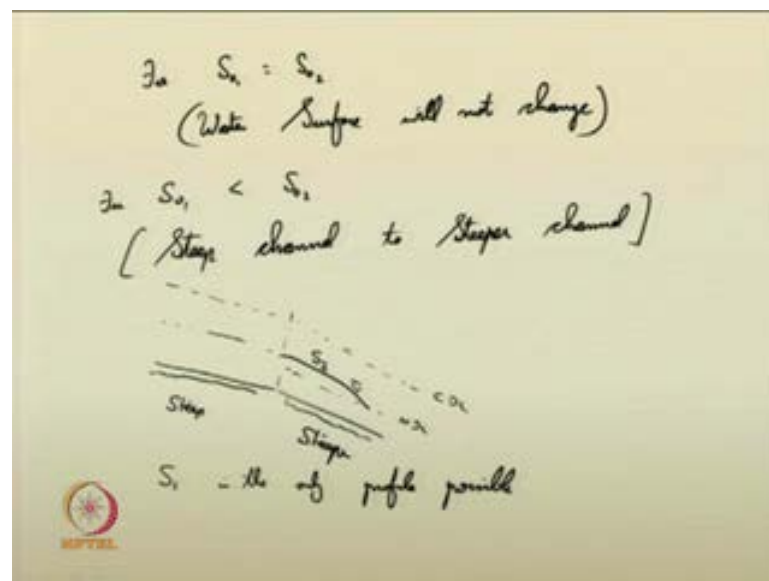


Now again as you have recalled back in the earlier situation for S 01 equal to S 02, there is no change in the dimension, there is no change in the flow patterns; so your slope or your flow will be maintained as it is, the water surface will not change. Water surface will not change; for this situation the water surface will not change. Now for S 01 less than S 02; that is flow is occurring from steep channel to steeper channel if the flow is occurring from steep channel to steeper channel further steeper channel. So, in that case

you will have steep channel and steeper channel. You have these things; your normal depth line here it is like this and here the normal depth line will be like this, critical depth lines are same. So, in this situation you will see that the flow profile theoretically it can be possible which is the theoretically possible thing.

You know here this is zone 1, zone 2 and zone 3; zone 1, zone 2 and zone 3 I, the water surface here if it goes below into the zone 3, the water surface in zone 3 has to be always in positive situation; the water surface slope should be positive in zone 3. So, if it goes below here that will not be possible. Similarly here, you cannot raise the water level in these situations. So, all these things suggest that you can have only one theoretically possible water surface and that is the flow exist in normal condition up to this junction in channel 1 and from there it goes into like this. So, this is having an S 2 profile. So, this is the only profile that is possible when a steep channel is followed by a steeper channel. So, S 2 is the only profile possible; all other things are theoretically not possible, you can verify yourself.

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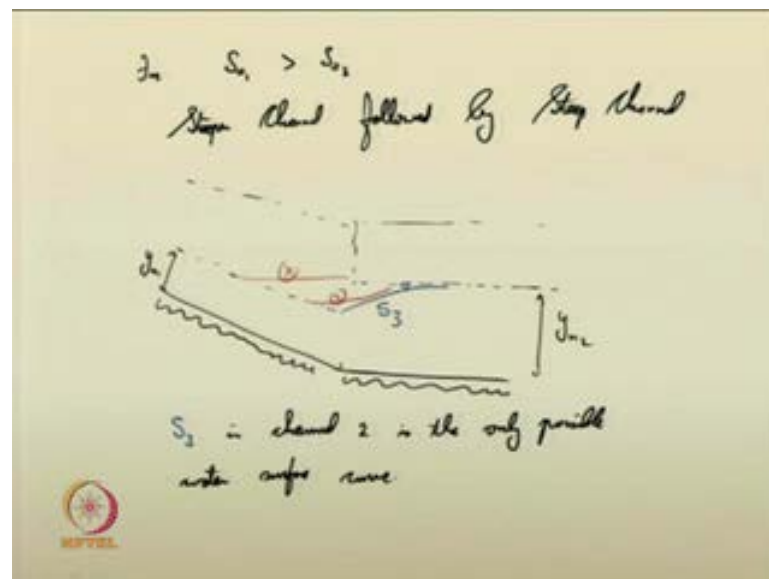
And for S 0 1 greater than S 0 2; so for S 0 1 greater than S 0 2, it is having a steeper channel followed by steep channel. So, in this case a steeper channel followed by a steep channel. So, you have the normal depth line like this. Here the normal depth line is like this, the critical depth lines will be like. This is your y n 1 and this is your y n 2. The only

possible profile in this case is you can imagine here you see that if you want to draw the thing, this is not theoretically possible; such a curve it is not possible.

Even a curve of this manner it is not possible. The only possible curve theoretically it is this is the only possible curve and that is S 3. So, S 3 in channel 2 is the only possible water surface curve for such situation. So, we have seen such three situations; that is the steep channel followed by another steep channel, mild channel followed by another mild channel, mild channel followed by a steep channel. You can also visualize a situation where steep slope is followed by a mild slope.
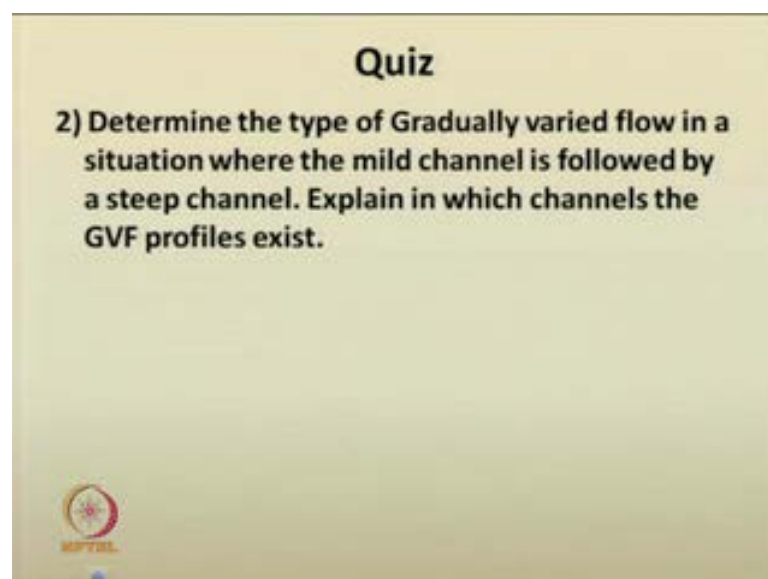
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And surprisingly, say, if you have a steep channel followed by a mild slope channel, I am just telling you; now when you go back home, you just visualize what are various types of profile that can be possible when flow is occurring from a steep channel to a mild channel. So, you have to see that the water surface profile; that is the slope of the water surface profile can be positive only in zone 1 and zone 3, it has to be negative always in the zone 2. So keeping all those things criteria, what are the profiles you can imagine; you just do it as homework. Let us see and I will discuss on this thing; more discussion on this aspect will be in the next module actually. So, we will see them. So this way here we can just conclude today's lecture.

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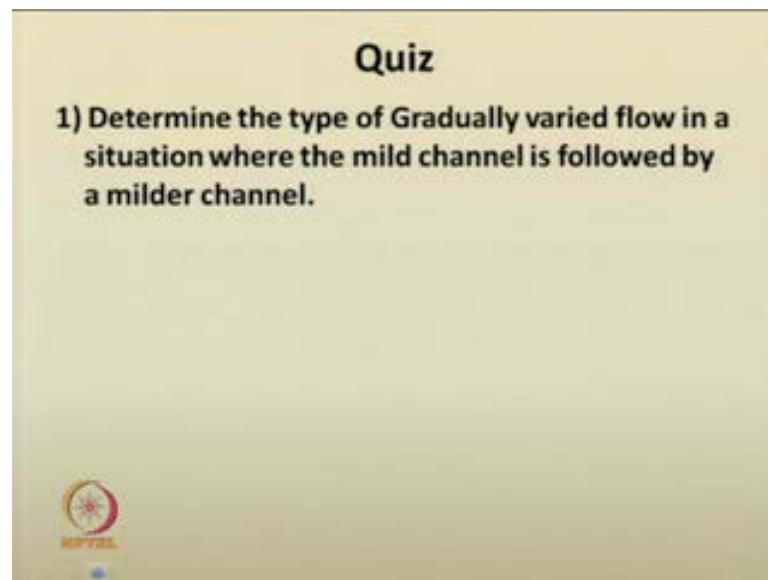
The quiz for the today's lecture we can just give that. The first question I would like to ask you is determine the type of gradually varied flow in a situation where the mild channel is followed by a milder channel; this is the first question.
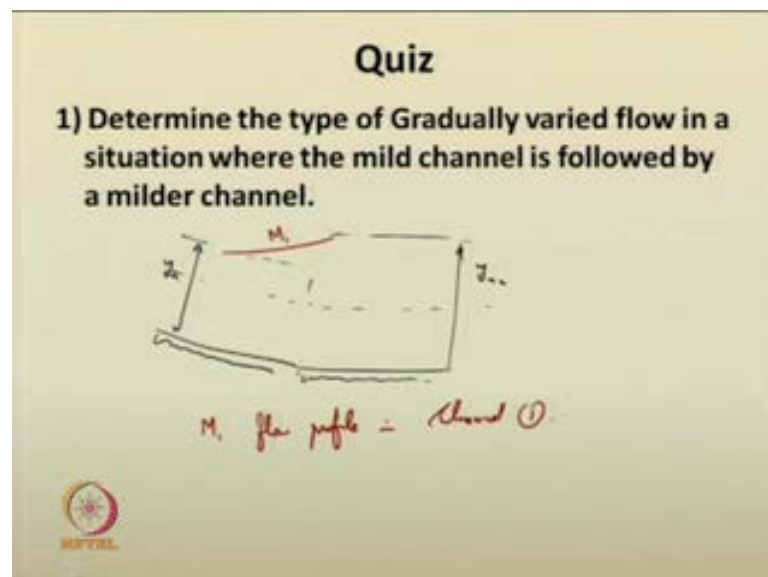
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Your second question is determine the type of gradually varied flow in a situation where the mild channel is followed by a steep channel. Explain in which channels the gradually varied flow profiles exist.
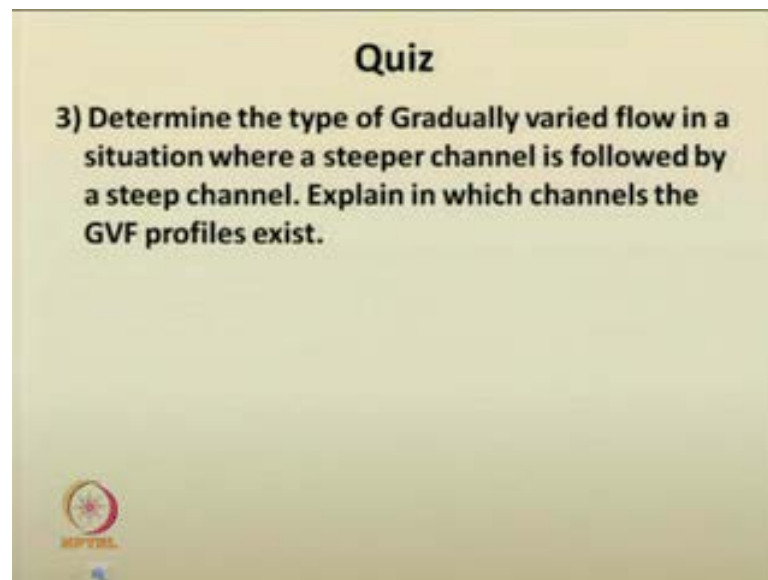
Your third question: Again similarly a similarly type; determine the type of gradually varied flow in a situation where a steeper channel is followed by a steep channel. You can now explain in which channels the gradually varied flow profiles exist. So, here is the solution for today's quiz.

The first question it is very simple and straight forward you are asked to determine the flow profile. So, it is a situation where a mild channel followed by a further milder channel. So, you have the critical depth same for both; the normal depth in mild channel

is less than normal depth in milder channel. Therefore, you will be having a flow profile, M 1 flow profile in channel 1; you will be having M 1 flow profile in channel 1.

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Your next question: You are asked about gradually varied flow in mild channel followed by steep channel; mild channel followed by a steep channel. Your critical depth lines are same critical depth lines; here mild channel will be having normal depth y n 1, here the normal depth will be y n 2. So, according to the theory the only possible curve is having an M 2 curve in channel 2 up to this junction and an S 2 curve. So, this is M 2 and this is S 2 curve in channel 2. So M 2 in channel 1, S 2 in channel 2, these are the only flow profiles that exist.
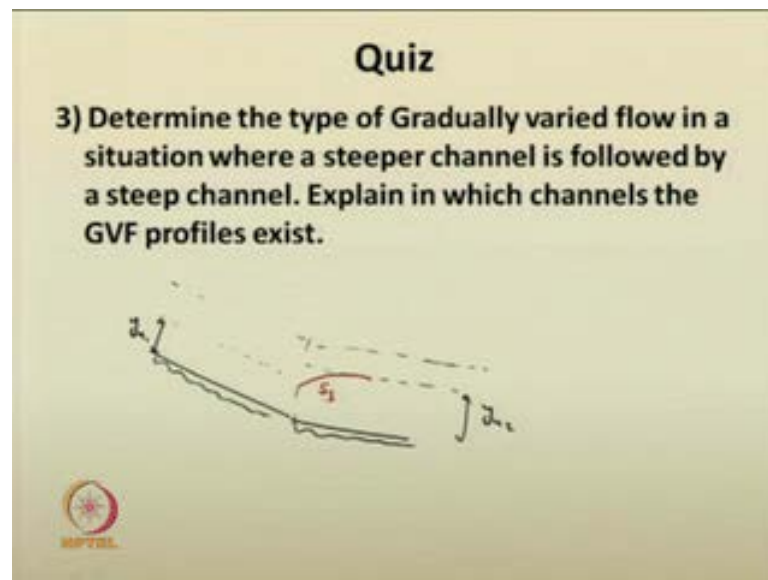
So, the next question asked was GVF in a steeper channel followed by a steep channel, a steeper channel followed by a steep channel. So, you have your critical depths like this. You have here the normal depth is somewhat like this; here the normal depth is y n 2 greater than y n 1. So, the possible curve is an S 3 curve; S 3 is the only possible gradually varied flow profile for such a situation. So, this is the way.

So, today's lecture we discussed on these aspects where the gradually varied flow profiles changes according to the bed slope of the channel and all. So, we have discussed them. So, we will continue these topics in the next class.

Thank you.