Course Name: Watershed Hydrology

Professor Name: Prof. Rajendra Singh

Department Name: Agricultural and Food Engineering

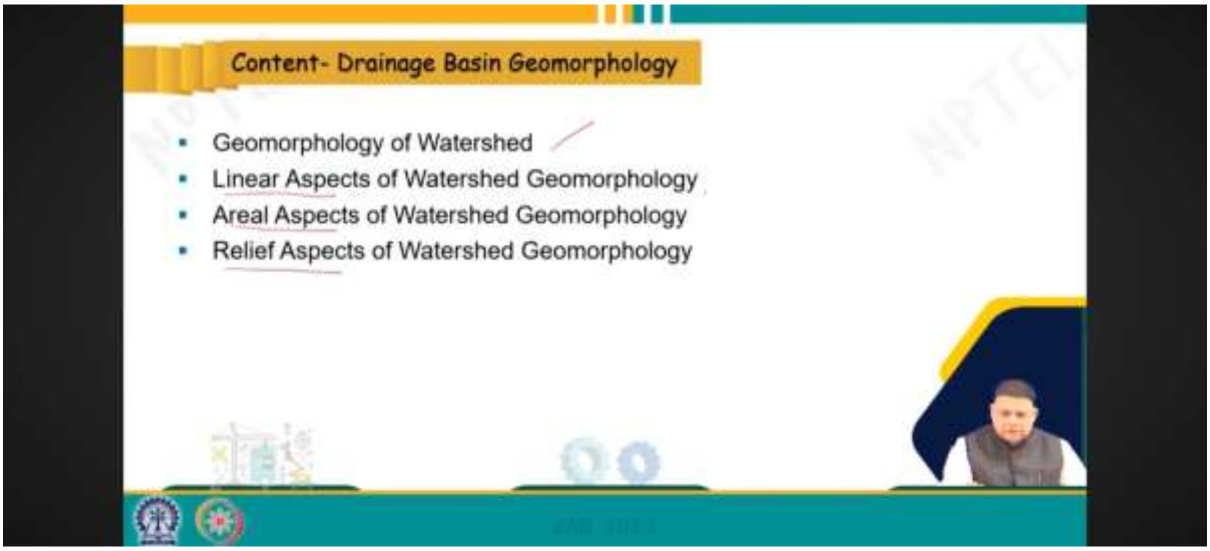
Institute Name: Indian Institute of Technology Kharagpur

Week: 07

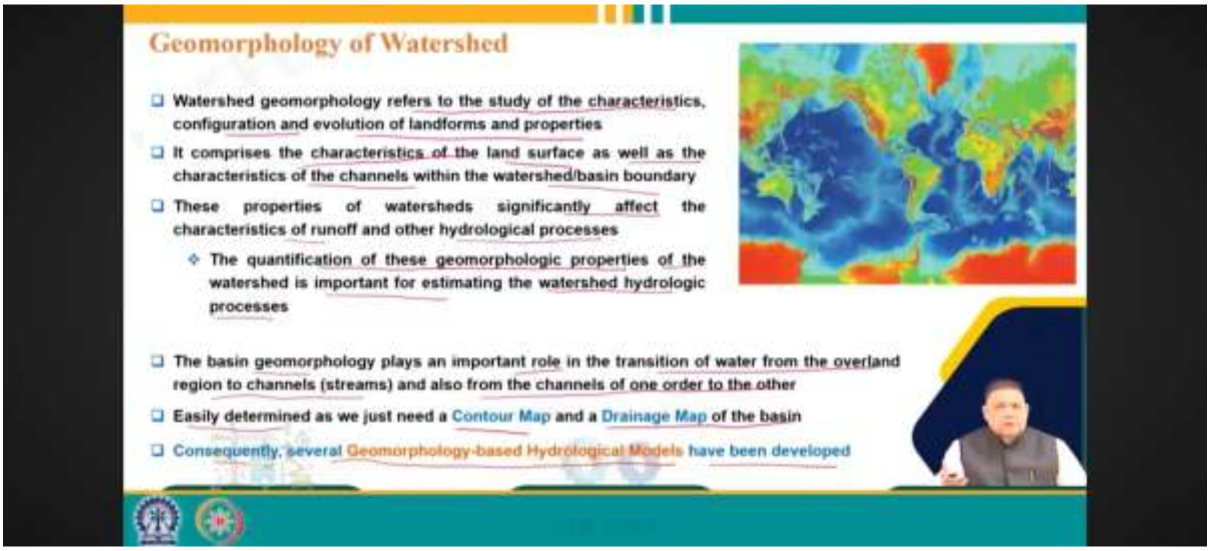
Lecture 32: Drainage Basin Geomorphology

Hello friends, welcome back to this online certification course on Watershed Hydrology. I am Rajendra Singh, a professor in the Department of Agriculture and Food Engineering at the Indian Institute of Technology Kharagpur. We are in Module 7, this is Lecture number 2, and the topic is drainage basin geomorphology.

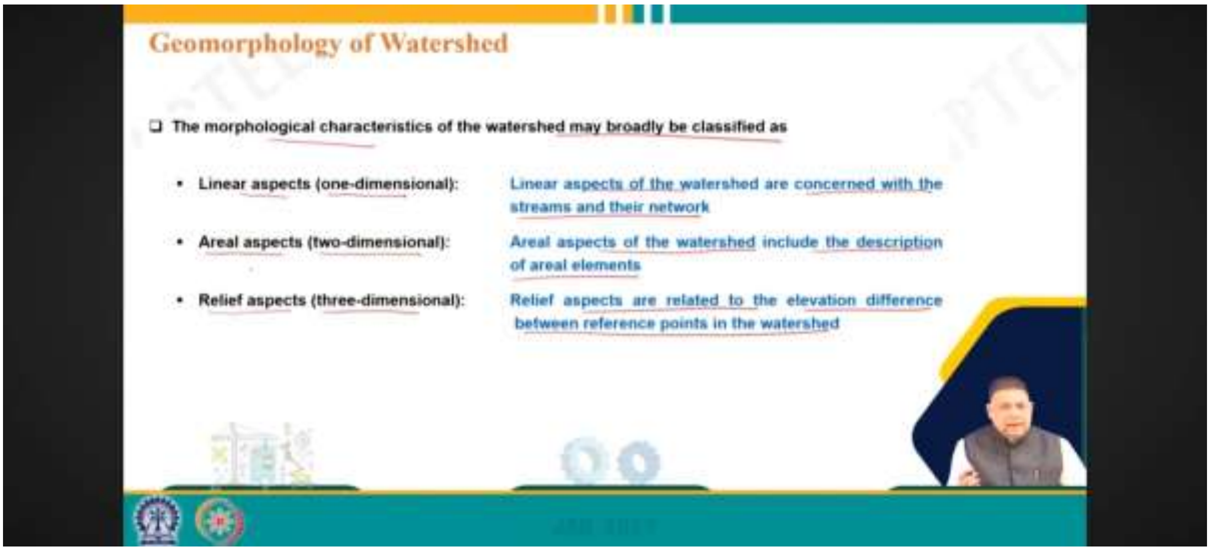
In this lecture, we will talk about the geomorphology of watersheds, and then we will discuss linear aspects, aerial aspects, and relief aspects of watershed geomorphology.



Now, coming to geomorphology, it refers to the study of the characteristics, configuration, and evolution of landforms and their properties. That means anything to do with the landform and its properties falls under geomorphology, and it comprises the characteristics of the land surface as well as the characteristics of the channels within the watershed or basin boundary. As we discussed in the previous lecture, typically, when we talk about a watershed, there are two phases: the land phase or overland phase, and the channel phase. So, basically, geomorphology talks really about the characteristics of both the land phase and the channel phase, and we know that both the land phase and channel phases form the important characteristics of types of watersheds. Now, these properties of watersheds, that is geomorphological properties of watersheds, significantly affect the characteristics of runoff and other hydrological processes. We have already seen various factors affecting runoff and the hydrograph shape, and of course, most of them fall under geomorphological characteristics. The quantification of these geomorphological properties of the watershed is important for estimating the watershed hydrological processes, including runoff, as we have already discussed. Now, basin geomorphology plays an important role in the transition of water from the overland region to channels or streams and also from channels of one order to another. Basically, geomorphology governs the flow of water. So, obviously, we know that when the runoff or overland flow starts, it is only in the overland phase or the land phase that the flow takes place, then water reaches the streams, and then, of course, from one stream order to the next order, that is how water reaches the outlet. The basin geomorphology or geomorphological characteristics play an important role in the entire process. One good thing or the positive characteristic of geomorphological characteristics is that they are easily determined because we just need a contour map and a drainage map of the basin. So, in order to determine the geomorphological features of a watershed, we just need two simple things: a contour map and a drainage map, and these are readily available with any watershed authority. They are easily available, or even you can easily determine the contour map or the drainage map of the basin. That is why they are easily determined and they do not require any kind of gauging of a particular watershed because there is no gauge data; these are all standard stationary data for a watershed. Consequently, several geomorphological-based hydrological models have been developed because of the simplicity through which these characteristics could be derived. That is the prime reason why there are several geomorphological-based hydrological models. And moreover, because there are several, as we have already discussed, ungaged watersheds around the world still, and in India, plenty of watersheds are still ungaged, and that means you do not have major rainfall runoff data. So, in order to study those watersheds or the runoff features of those watersheds, you have to take the help of the geomorphological characteristics, and geomorphological-based hydrological models play an important role. We have already discussed a little bit about it in synthetic hydrographs, that is, for ungauged catchments, how the hydro characteristics are related to the basin characteristics, and then we find out different features of the hydrological hydrograph. Similarly, geomorphological-based hydrological models target different hydrological processes.



The morphological characteristics of a watershed may broadly be classified as linear aspects, which are one-dimensional characteristics including linear aspects of the watershed, and that is streams and their network; basically, all the channel characteristics fall under this. Then we have aerial aspects, or the two-dimensional characteristics, which include the description of area, and other aspects. Lastly, we have relief aspects, which are three-dimensional, related to the elevation difference between the reference points in the watershed. So, basically, here the elevation plays a role in monitoring. So, one-dimensional aspects are related to streams and their network, two-dimensional aspects mostly relate to the area, and relief aspects where the elevation of the area is also considered. These are the three different types of characteristics.



Now, talking about the pretty typical characteristics under linear aspects, aerial aspects, and relief aspects, we can have several parameters under each category. For example, under linear aspects, we have basin length, width, and perimeter, stream order, stream number, bifurcation ratio, stream length, length ratio, and length of overland flow. So, these are all related to the length of the stream or the length of the basin, some length, the linear aspect. Then we have aerial aspects. Under aerial aspects, we have watershed area, stream area ratio, watershed shape, drainage density, constant of channel maintenance, stream frequency, and then under relief aspects, we have watershed slope, watershed relief, relief ratio, dissection index, and rugged net index. We will see one by one all these geomorphological features of the watershed slowly.

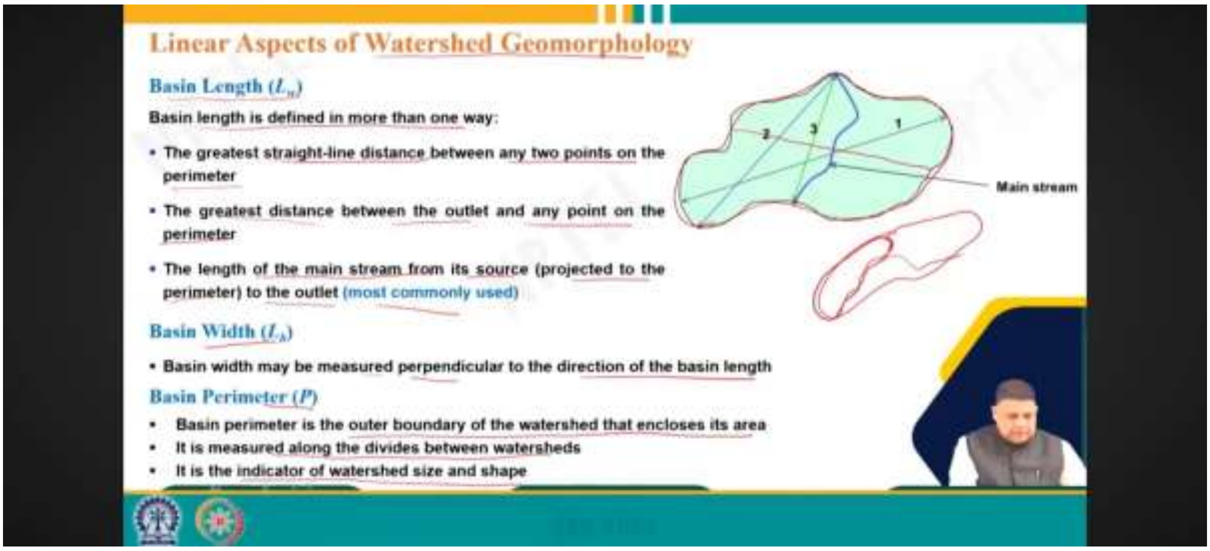
Now, coming to the linear aspects of watershed geomorphology, let us start with the basin length, Lw , and we have already discussed this. The basin length is defined in more than one way. So, the possibilities are:

1. The greatest straight-line distance between any two points on the perimeter. So, you find out any two points where the distance is the longest, that could be called a basin length.

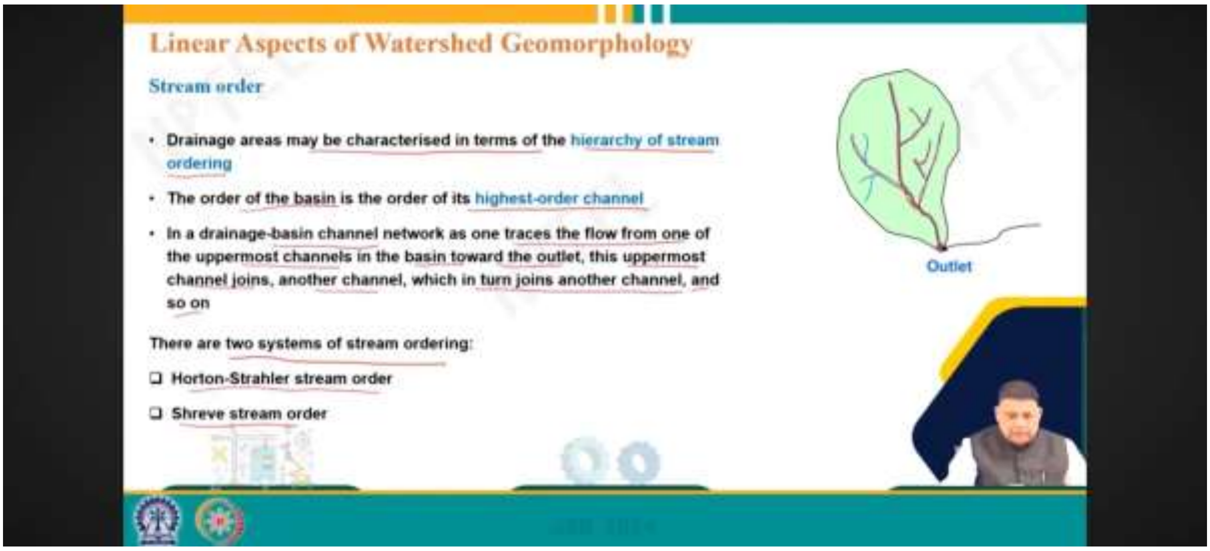
2. The greatest distance between the outlet and any point on the perimeter. So, in this case, the outlet is fixed, and with respect to the outlet, you can find out any point which is farthest, and then you can measure this distance.

3. The third and the most commonly used one is the length of the main stream from its source projected to the perimeter to the outlet. So, basically, it is measured along the length from the outlet to the stream which is projected to the perimeter. So, you measure along this length. Of course, here you see a lot of meandering, but generally may not have so much of meander in the main stream.

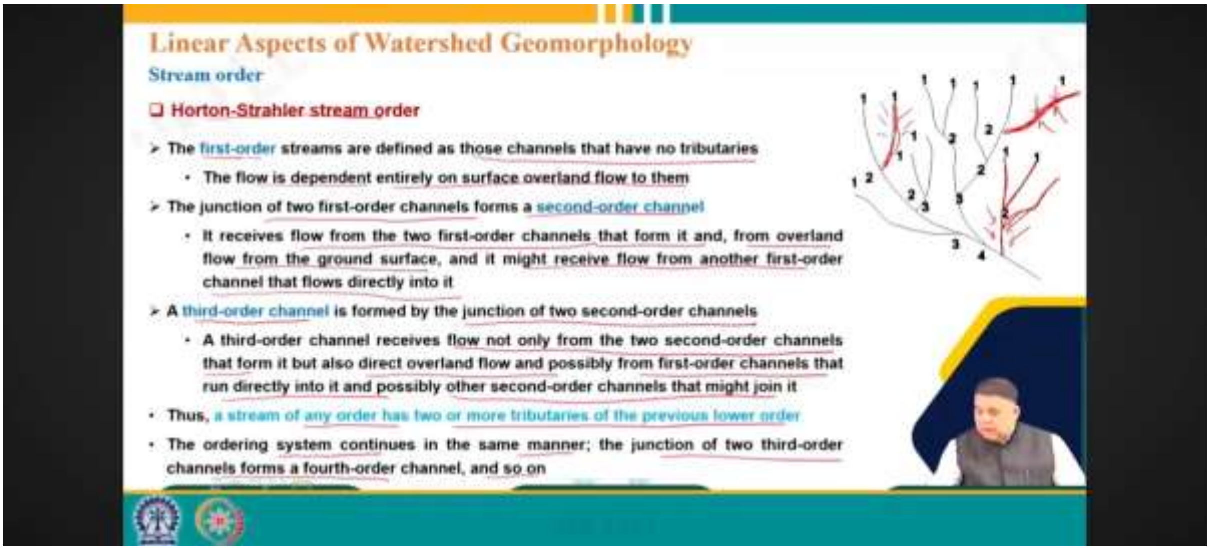
The next one is the basin width Lb , and it may be measured perpendicular to the direction of the basin length. So, once you have found the basin length, then the basin width will be nothing but if you consider that a green line is your length, then you draw a line perpendicular to this. This will tell you the basin width. Next, the basin perimeter is the outer boundary of the watershed, measured along the divides between the watersheds, and it is an indicator of the size and shape. So, basically, if this is your watershed boundary, you measure the perimeter. That is the basin perimeter, and of course, if you have multiple watersheds, then this particular point that is measured along the divides between watersheds becomes more visible. For example, if you have say two different watersheds or multiple watersheds they are identified, then obviously, you will measure along this divide line to get the perimeter, and of course, it reflects because it takes you can see that it includes both the length and width. So, basically, it talks about the size and shape of the watershed.



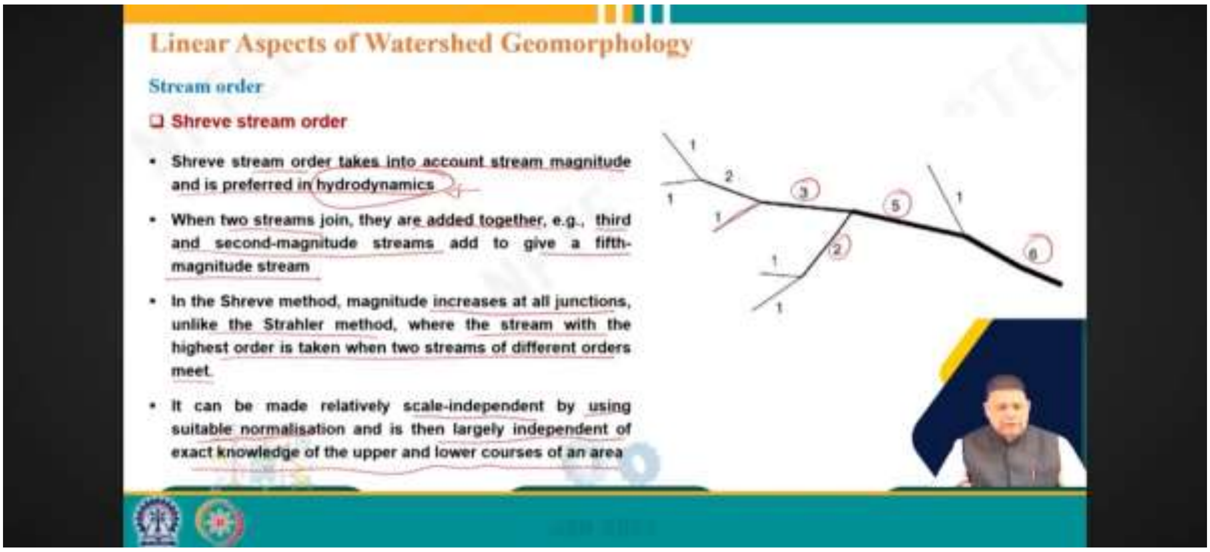
Then we come to the next one, that is the stream order, and drainage areas may be characterized in terms of the hierarchy of stream ordering, that is how the streams are located within a particular watershed. The order of the basin is the order of the highest order channel, which we will come to a little later on. In a drainage basin channel network, one traces the flow from one of the uppermost channels in the basin towards the outlet. The uppermost channel joins another channel, which in turn joins another channel, and so on. So, obviously, if you trace from here or here, then this channel comes, this channel joins this one, then this joins here, and this comes here. Similarly, this comes here from here, and these two join, then they are joined by this one also, and then finally, they move to the outlet. This is how one can trace the channel network. And basically, there are two systems of stream ordering; the first one is Horton-Strahler stream order, which is, of course, the most popular one, and then there is a Shreve stream order. So, there are two different ordering schemes available.



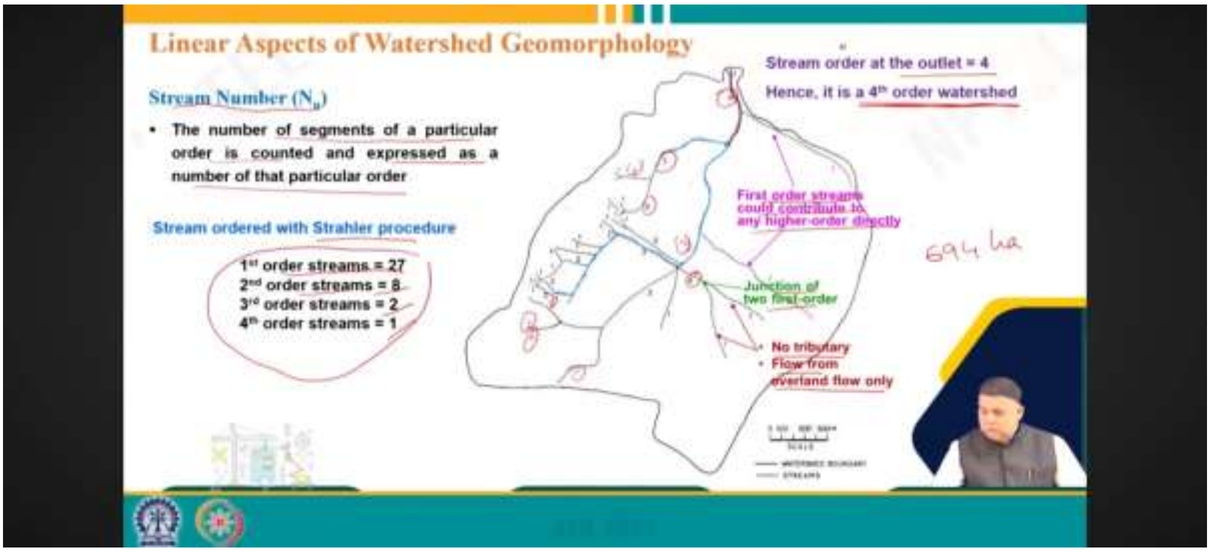
Talking about the Horton-Strahler stream order, then the first-order streams for Horton-Strahler stream order are defined as those channels that have no tributaries, that is, flow is dependent entirely on surface overland flow to them. So, obviously, as you can see, any channel you say, this channel, you see that it has no tributary. The only water it is receiving is through overland flow; there is no channel which is supplying water to this one. So, any such channel is referred to as a first-order stream, the flow of that first-order stream is entirely dependent on surface overland flow. Here also, you can see this channel also; this is a first-order stream because there is no tributary joining to it, and then whatever water is flowing to this through this, that is only through overland flow within the boundary. Then the junction up to the first order of channels forms a second-order channel. It receives flow from two first-order channels that form it and from overland flow from the ground surface. It might also receive flow from another first-order channel that flows directly into it. So, obviously, when two first-order channels meet, it is referred to as a second-order channel. So, obviously, this second-order channel will receive water from these first two, it will also receive water from the overland area contributing directly to it, and maybe an independent first-order stream may also join here to this, like here the first-order joining the third order. So, a first order can join any other higher-order stream. Similarly, a third-order channel is formed by the junction of two second-order channels, and it receives flow not only from the two second-order channels that form it but also directly from overland flow and possibly from first-order channels that run directly into it and possibly other second-order channels that might also join it. So, obviously, any two lower orders. So, a stream of any order has two or more tributaries of the previous lower order. So, any two previous lower orders form the next higher order stream as per Horton-Strahler stream ordering. And of course, such a stream can not only get water from these two which form it but also from overland flow and also from the other lower-order channels directly joining the particular stream. The ordering system continues in the same manner; the junction of two third orders make a fourth order and so on, and so this is the Horton-Strahler ordering scheme.



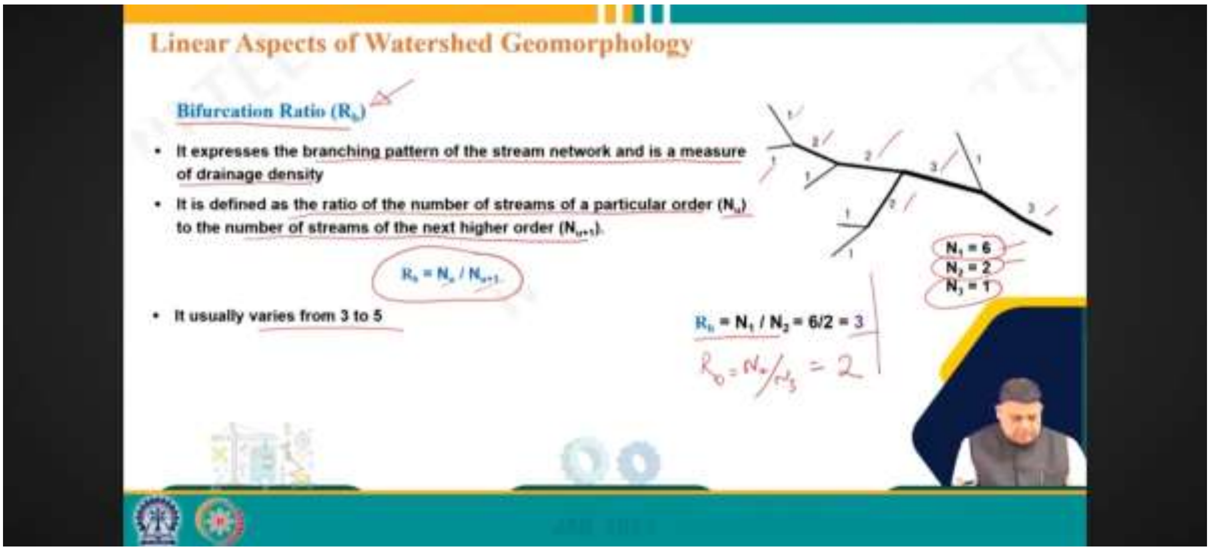
Then we have the next one, which is called the Shreve order, and the Shreve order takes into account stream magnitude and is preferred in hydrodynamics. So, the specific purpose of this is all hydrodynamic models typically prefer Shreve stream ordering. In this case, when two streams join, they are added together, that is, a third and second magnitude streams add to give a fifth magnitude stream. So, here, as you can see, one and one is two in the Horton stream; if one joins two, then it still remains two, but in this case, two and one sum and then become three. Similarly, three and two join and make five, five and one join and make six. So, the stream ordering, goes like this, that is why addition takes place in this case. So, magnitude increases at all junctions, unlike the Strahler method where the stream with the highest order is taken when two streams of different orders meet. So, obviously, this point is very clear in the case of Horton order; two lower orders form the next order, and unless two similar orders move, the next order is not made; if a lower order joins, then the previous higher order continues. So, say two joining first, joining a two, then two will continue further, which is not true in the case of Shreve order. And it has a certain advantage that it is relatively scale-dependent by using suitable normalization, and it is then largely independent of exact knowledge of opponent lower courses of any area, and because of this disadvantage, it is preferred in hydrodynamic modelling . But overall, if you ask, then Horton-Strahler stream order is more popular in geomorphology compared to Shreve stream ordering.



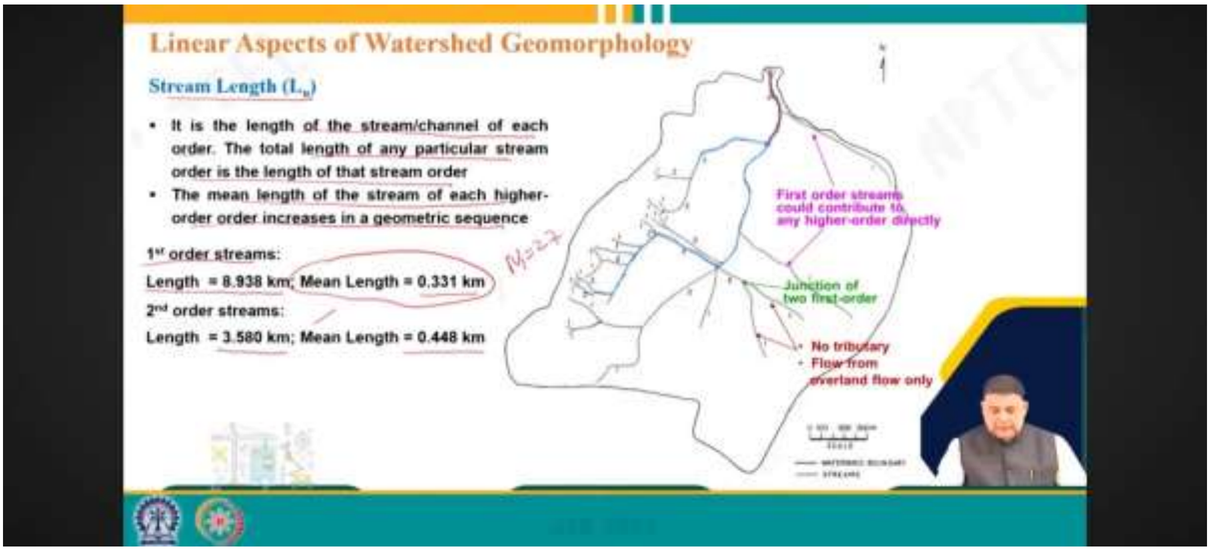
Now, we can continue with this further. Now, the next one is the stream number, Nu, and it is the number of segments of a particular order that is counted and expressed as a number of that particular order. So, obviously, this is a true picture of a watershed which is located near IIT Kharagpur, and it is a 694-hectare watershed. The area is, and as you can see here, the stream ordering done using the Strahler procedure or Horton procedure. So, obviously, as you can see, number streams are numbered one and one, that is, no tributary flow, only overland flow. So, these are referred to as one, as you can see here, these two, then junction up to the first order form a second order, as you can see here. Then a first order can join a second order, then the junction up to the second order, like here and here, they form a third order, and then two third orders, this is the third order from here this point is third order. So, two third orders meet here, and from here the fourth order, and remember we said that the stream order at the outlet, which is in this case is 4, that shows the order of the watershed or water of the basin. So, because the fourth order stream is at the outlet. So, this is a fourth-order watershed. So, if you talk about the large river systems, they can be 16, 20 kind of orders also. Now, stream numbering, coming back to stream numbering, now we can see that we have located one, one, one, two, and so on, and so on. So, then we can count these numbers, and here also, before I go to counting, I can show you that a first-order stream could contribute to any higher order directly. So, here, first-order joining a third order, first order joining a fourth order, and that could be set for second order also joining third order, and so on. So, if you count the number of streams, the first-order streams, they are 27, second-order streams, their number is 8, third-order streams' number is 2, and of course, the fourth order because it's the highest order. So, there is one. These are the different numbers. So, these are stream numbers; they are referred to as stream numbers, that is n1, n2, and u is the order. So, n1, n2, n3, and n4, which will be mentioned for this particular watershed. Now, we come to within the linear aspects, a very important ratio, which is referred to as the bifurcation ratio. It is important because earlier I mentioned that there are geomorphological models of various kinds. So, basically, these geomorphological models, they could use directly the stream characteristics, geomorphological features, but most of them also use the ratio directly. So, this is one of the ratios; there are three ratios. We will come to the other ratios when we go into other aspects.



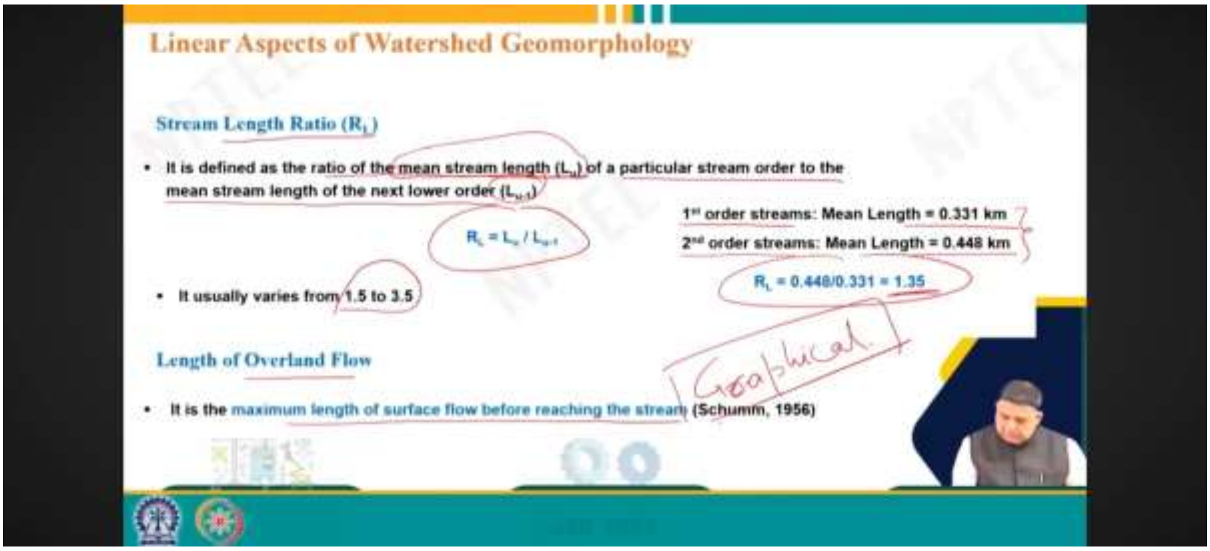
So, in linear aspects, we have the bifurcation ratio, which expresses the branching pattern of the stream network and is a measure of drainage density, that is how well the drainage network is spread in the particular watershed. It is defined as the ratio of the number of streams of a particular order Nu to the number of streams of the next higher order Nu+1. So, Rb, that is, the bifurcation ratio, is defined as Nu/ Nu+1. If you consider, say, this particular distribution and here it is order 1, 1, 2, then 2, 1 joins 2, that remains 2, here 2 and 2 join then becomes 3, 3 and 1, 3. So, this is 3. If you count the number, N1 is 6, N2 is 2, N3 is 1. So, obviously, Rb, we can calculate: N1 /N2 is 3, N2/N3 is 2, and so on and so forth. Usually, the value varies between 3 to 5. So, typically, as you can see in this case, if you calculate Rb using N1 and N2, you get 3, but if you calculate Rb using N2 / N3, then you only get a value of 2. So, there could be a large variation in Rb , the bifurcation ratio or other ratio values when you use this way. So, typically, we use a graphical procedure for determining the mean value of these ratios for a watershed, but I am not discussing that here; that is beyond the scope of this particular lecture, but this is how we really do it.



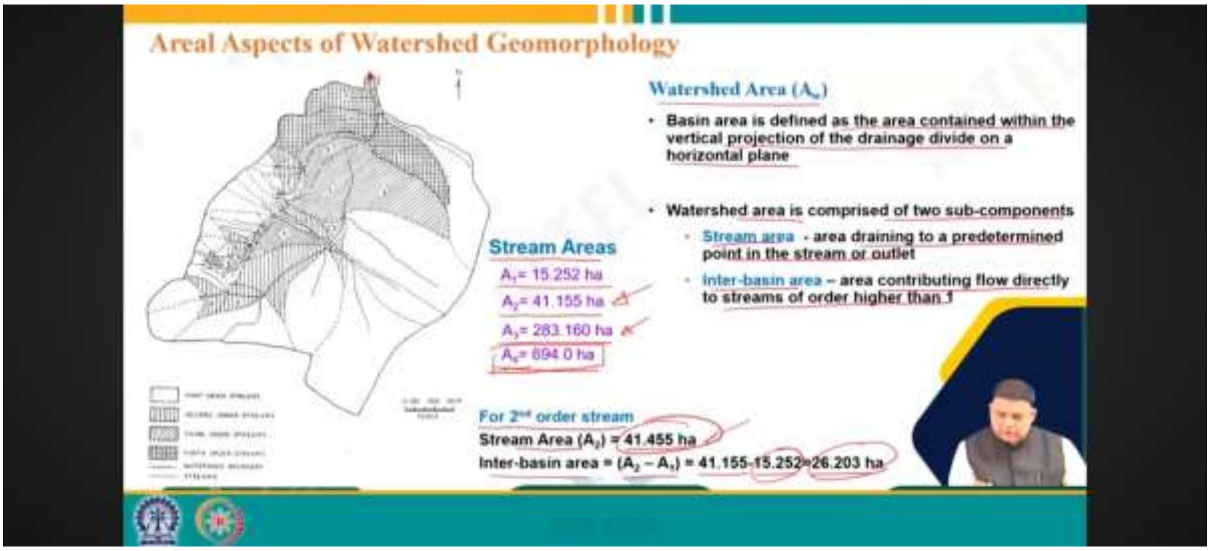
Next comes stream length after number is the length. So, the length of the stream channel of each order, the total length of any particular stream order is the length of that particular stream order, and the mean length of streams of each higher order increases in a geometric sequence. So, obviously, we have already identified different orders of streams numbers. So, obviously, we can measure their length and then we find that, for example, the first-order streams, the total length is 8.938 kilometre, but typically we use the mean length because total length has no meaning. Mean length is basically total length, and if you remember this watershed, we had N1 equal to 27. So, if you divide this length by 27, you get the mean length of 0.331 kilometre. So, the second order has a total length of 3.580 and mean length of 0.448 kilometre. This way, we can find out the stream length and the mean length of the streams of different orders. So, we can measure basically.



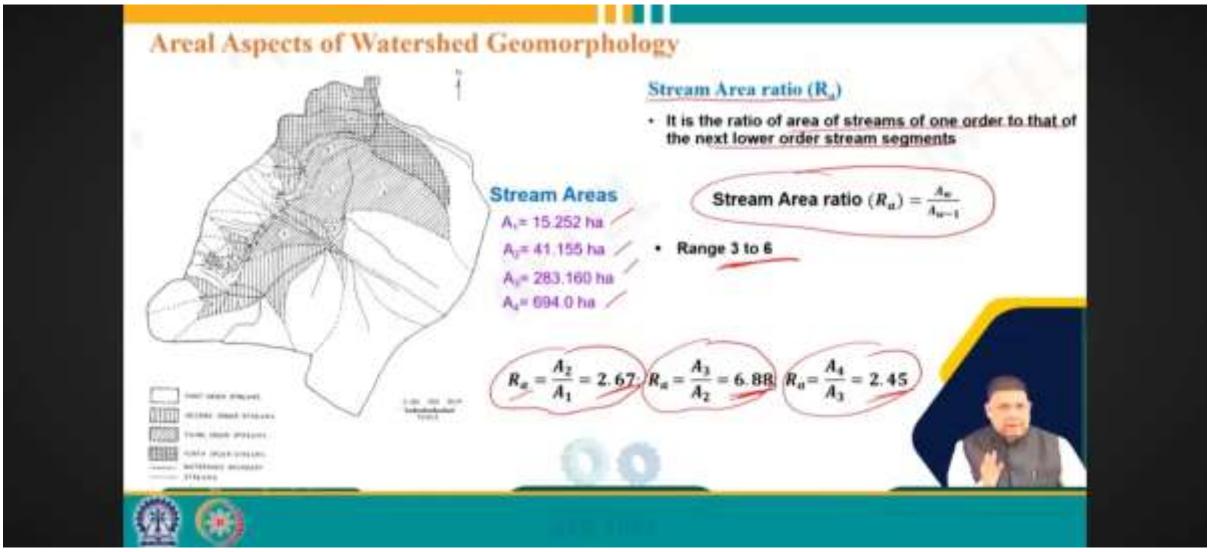
Then this is the second ratio I was talking about, stream length ratio, and it is defined as the ratio of the mean stream length, remember we had 2 lengths. So, mean stream length Lu of a particular stream order to the mean stream length of the next lower order Lu-1. So, RL is Lu/Lu-1. So, this is the second one after the bifurcation ratio, and for first-order streams for a particular watershed, mean length was 0.331 kilometre ; second-order mean length was 0.448. So, Lu comes out to be 1.35, and typically its value ranges over 1.5 to 3.5. I mentioned that just by considering unusual streams or 2 streams, if you calculate Lu value, there can be large variations for a particular watershed, and we typically use a graphical procedure for finding out these ratios. We typically use a graphical procedure. Then we have a length of overland flow, which is the maximum length of surface flow before reaching the stream, defined by Scum in 1956.



And then we go into the aerial aspects of the watershed, and aerial aspects for the first one is the watershed area, and the basin area is defined as the area contained within the vertical projection of the drainage divide on the horizontal plane, of course. I mean, if you identify the watershed, you know which part to measure for finding out the area. So, there is no confusion there, and typically, watershed area is comprised of two subcomponents: stream area and inter basin area. Stream area is the area draining to a predetermined point in a stream or outlet, whereas inter basin area is the area contributing flow directly to streams of other orders higher than 1. For example, if we, for this particular basin, we identified the different order streams. So, of course, we can also find out, knowing the contour map of the area, which particular area contributes to which particular channel, and based on that, the total stream areas we found are: A1 equal to 15.252 hectares, A2 is 41.155 hectares, A3 is 283.160 hectares, and A4 is 694 hectares. So, that is what I mentioned; this is the outlet, the total area is 694, and it's the fourth-order outlet. So, the total area draining to the fourth-order outlet A4 is 694, that is the total area. Similarly, we know that when we say A3 is equal to this. So, if we have, we can find out a single outlet for third-order streams, and this will be the total area that will be dealing with the third-order stream. And if just to understand this stream area and inter basin area, say, for example, for a second-order stream, if you take the example, then the stream area A2 is, that is here, 41.155 hectares, that is the typical area that is draining to, for, I mean, if you measure the second-order area, all sum, and then that is what. And inter basin area will be A2 - A1 , that is 41.155 - 15.252 = 26.203. So, that simply means that this is the total area which is draining to the second-order stream, and this 15.21 area is the area draining to the first order. So, that is contributing, and this is basically the direct overland flow that is being contributed to the second-order stream. So, inter basin area basically refers to the direct overland flow that is being contributed to a particular order stream higher than 1, and stream area, of course, includes the total area contributing to that particular watershed. So, this is the watershed area.

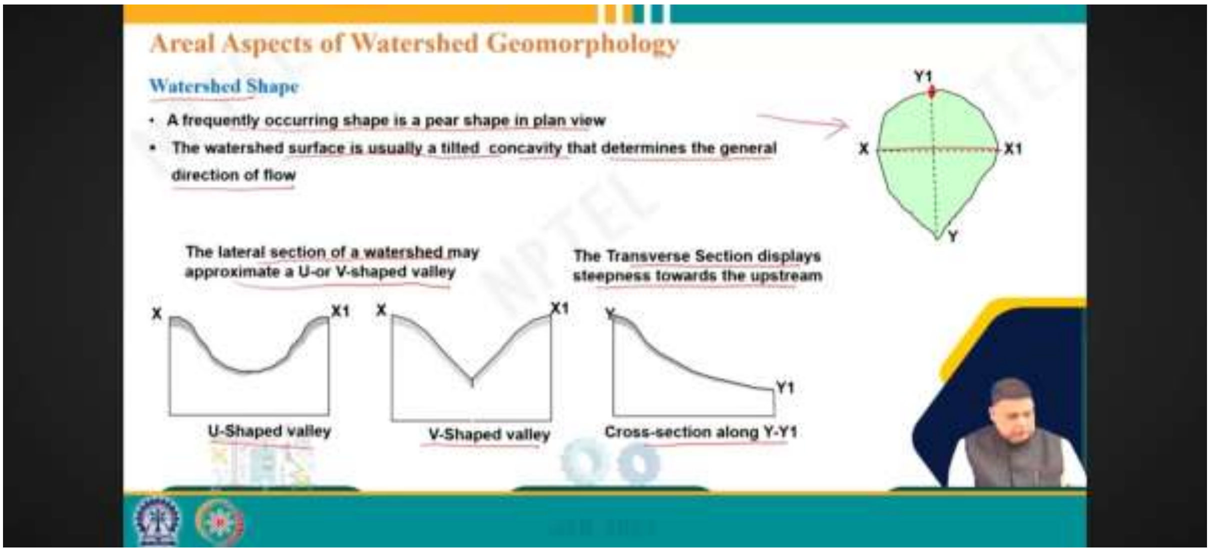


And then we come to the third ratio, which is the stream area ratio, the ratio of the area of streams of one order to that of the next lower order. So, stream order ratio is Aw / Aw-1. So, here we have A1, A2, A3 , and A4 we know. So, that is why Ra value we can calculate A2 / A1 , which comes out to be 2.67. As I already mentioned, in usual cases, A3/A2 will give you a value of 6.88, and if you take 4 by 3, then it gives you a value of 2.43. The typical range is 3.326, but as you can see, there is a large variation from 2.45 to 6.88. In larger order streams or watersheds, you can find out there will be still larger variation, and that is why we do not take these values, but we use a graphical procedure to find the mean value of these ratios for a particular watershed. But typically, this stream area ratio changes over 3 to 6. So, as I said, we have discussed three ratios: the bifurcation ratio, length ratio, and area ratio, and these ratios play a significant role in geomorphological modeling of watersheds.

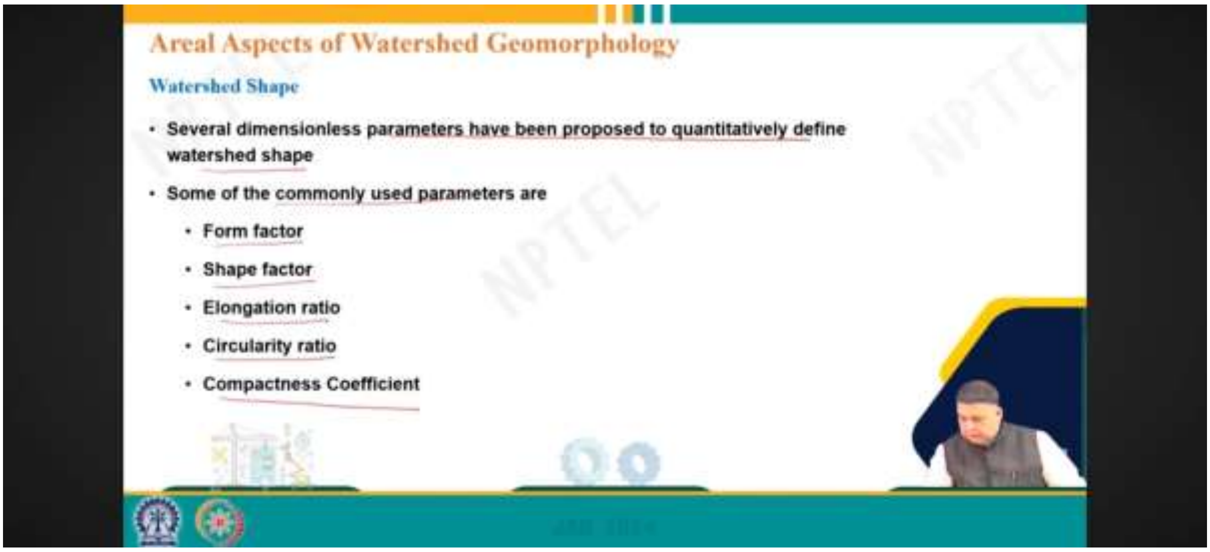


The next characteristic is watershed shape. A frequently occurring shape is a pear shape in plan view, as you can see in this picture here. The watershed surface is usually a tilted concavity that determines the general direction of flow. Of course, if I can show my hand,

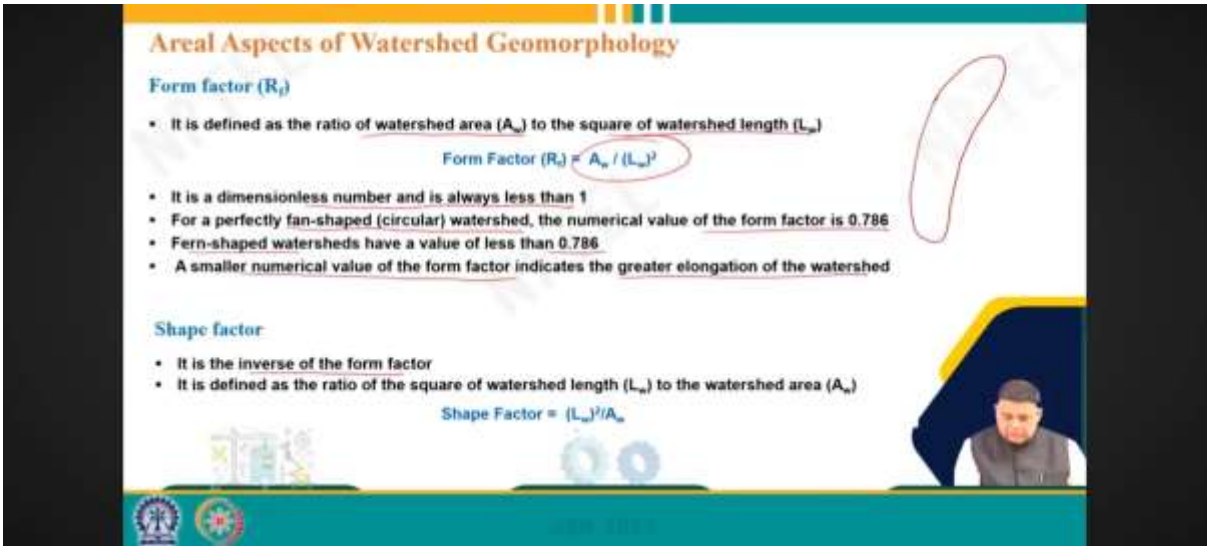
this will be kind of like this, and this will be clear also if you look at the sections. If you look at the lateral section of the watershed, it may approximate a U or V shape valley. So, if you talk about this particular section, here if you look at this section, it could be a U-shaped valley or a V-shaped valley. So, there will be, I mean, the flow will be coming towards the centre first, and then it will be flowing towards the outlet. And the transverse section displays stiffness towards the upstream, that is, if you talk about Y Y1. So, Y is upstream. So, that shows that this is the outlet of this particular basin. So, the cross-section along Y Y1 could be that kind of slope, that is, an elevation change from Y to Y1 as you can see. So, water flows from the sides, water flows to the centre, and then it is carried out to the outlet. That is a typical shape of a watershed.



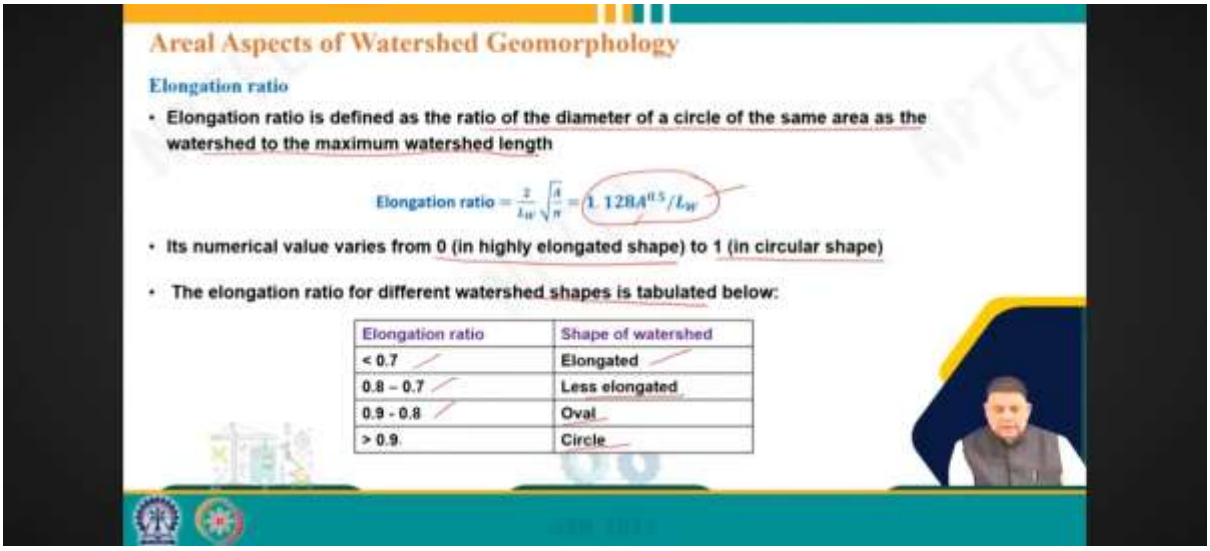
Then several dimensionless parameters have been proposed to quantitatively define what shape is, and some of these are form factor, shape factor, elongation ratio, circulatory ratio, compactness coefficient. So, any of these could be used to define the watershed shape.



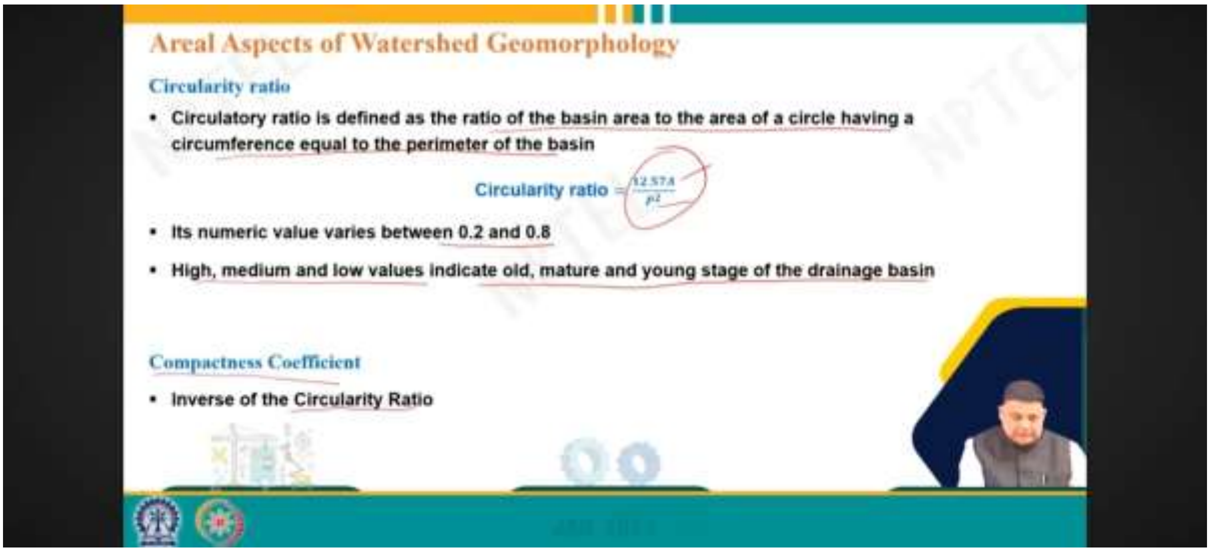
If we talk about the form factor, it is defined as the ratio of the watershed area to the square of the watershed length LW, which is $AW / (LW)^2$. We have measured AW and calculated LW, so we can calculate the form factor. It is a dimensionless number and is always less than 1. For a perfectly fan-shaped or circular watershed, the numerical value of the form factor is 0.786. For a fern-shaped watershed, as we discussed earlier, the value is less than 0.786. A smaller numerical value of the form factor indicates greater elongation of the watershed. So, if it is an elongated watershed like this, then obviously, the form factor will be lower. Then we have the shape factor, which is the inverse of the form factor, just the inverse of that, $(LW)^2/ AW$, and of course, then values you can find out.



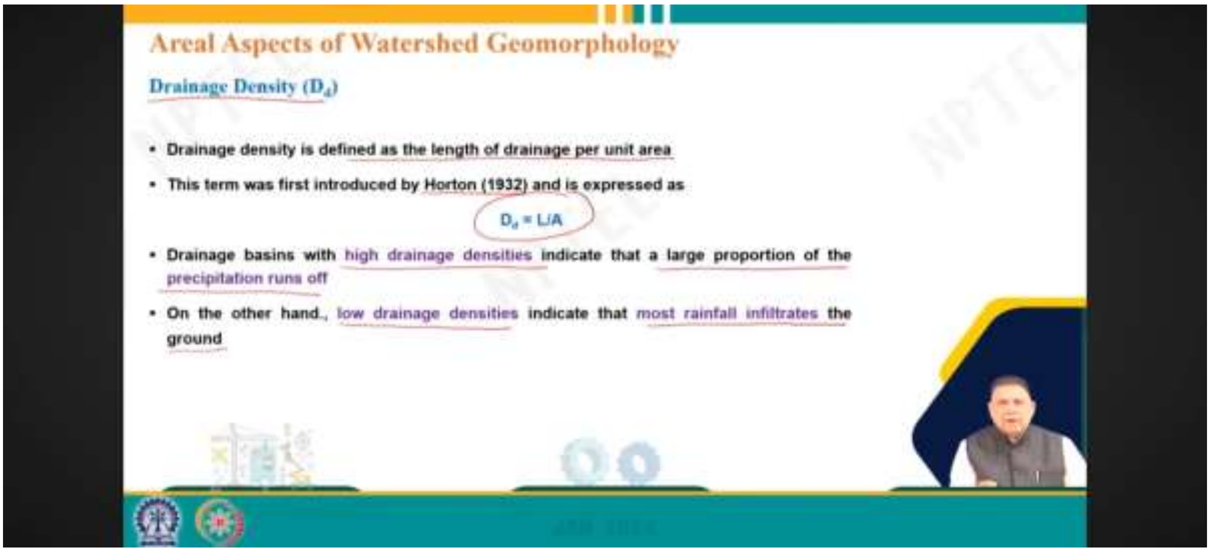
Then the elongation ratio is defined as the ratio of the diameter of a circle of the same area as the watershed to the maximum watershed length, which is given by this. And the final form of the equation for the elongation ratio is this, where the area and LW are known. So, we can find out, and its numerical value varies from 0 in a highly elongated shape to 1 in a circular shape; that is the elongation ratio. So, it talks about the elongation basically. The elongation ratio for different watersheds can be given here: an elongated watershed is less than 0.7, less elongated is 0.728, oval shape is 0.829, and for circular, it is greater than 0.9. So, this is the elongation ratio.



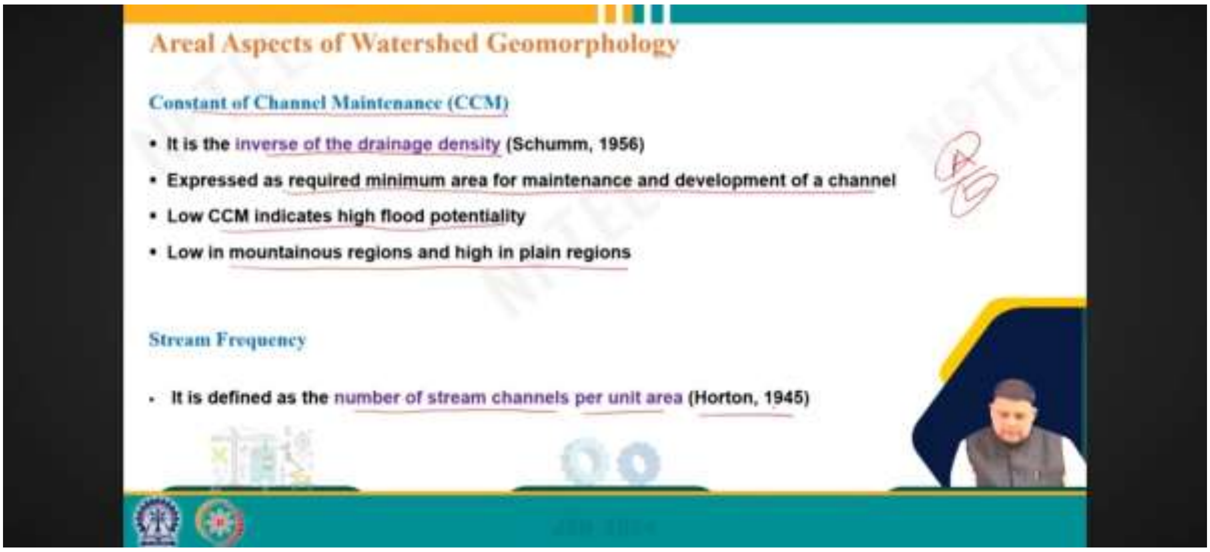
Then, the circulatory ratio is the ratio of the basin area to the area of a circle having a circumference equal to the perimeter of the basin. So, basically, it comes to this: $12.57A/P^2$. So, A we know, perimeter we have measured, so we can find out the value of the circulatory ratio, and the numerical value varies between 0.2 to 0.8. High, medium, and low values indicate old, mature, and young stages of the drainage basin. That reflects on how the drainage network, the life of the drainage network basically, in a particular drainage basin. Then, the inverse of the circulatory ratio is referred to as compactness coefficient also, P^2 by 12.57A.



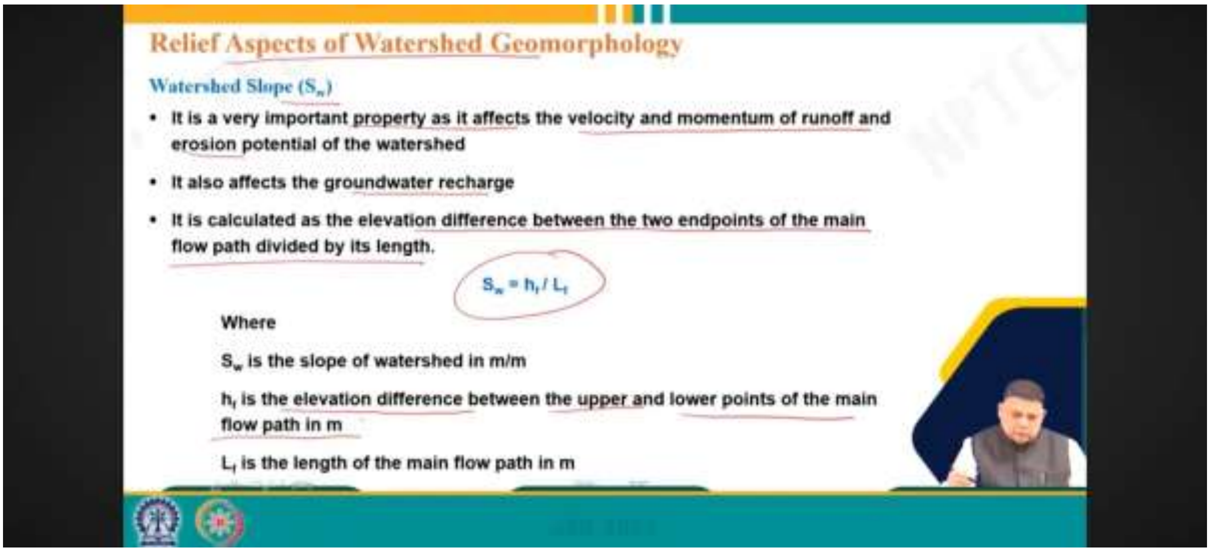
Then we come to drainage density, which is defined as the length of drainage per unit area. It was introduced by Haughton in 1932, and it is expressed like this: Dd = L/A. Drainage basins with high drainage densities indicate a large proportion of the precipitation runoff. So, it really gives you the length of the drains per unit area. So, obviously, if the drainage density is high, that means the network development is very good, and that means a large portion of your water will run off. On the other hand, low drainage densities indicate that most rainfall infiltrates the ground, so it will not be reaching the outlet if the drainage density is lower.



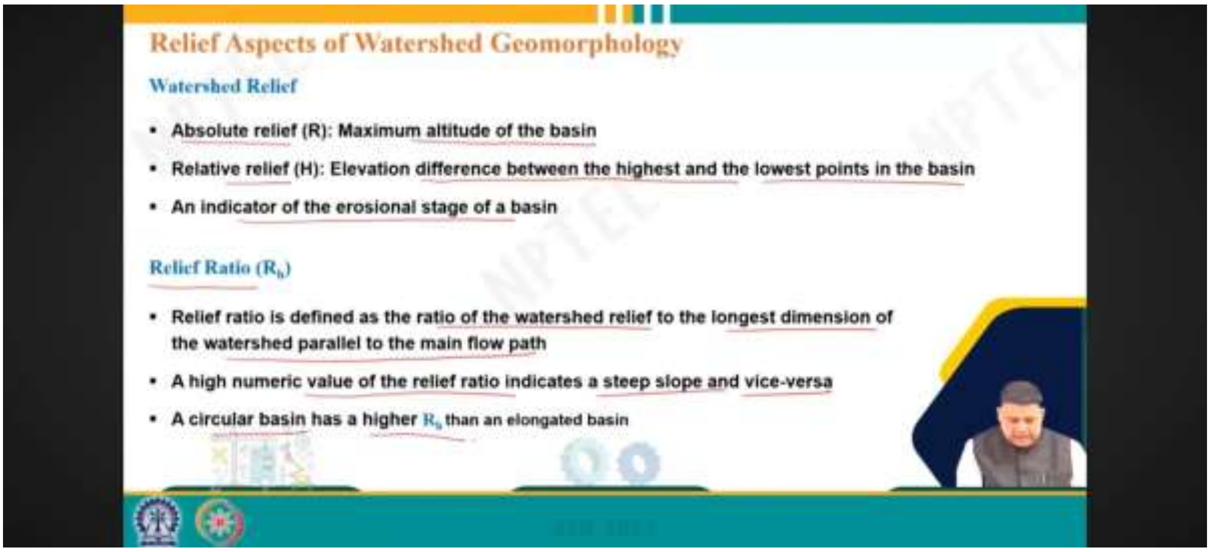
Then the constant of channel maintenance, which is the inverse of drainage density, is referred to as the constant of channel maintenance (CCM), and it is expressed as the required minimum area for the maintenance and development of the channel, which means it is A/L. So, the area required to maintain a certain length of channel. Low CCM indicates high flood potentiality and is low in mountainous regions and high in plain regions. This is quite obvious because mountainous regions will have lower potentiality due to fewer streams. Stream frequency is defined as the number of stream channels per unit area, as given by Haughton in 1945. So, the number of stream channels we know, and the area we know, so the number of stream channels per unit area we can find out, and then we call it stream frequency.



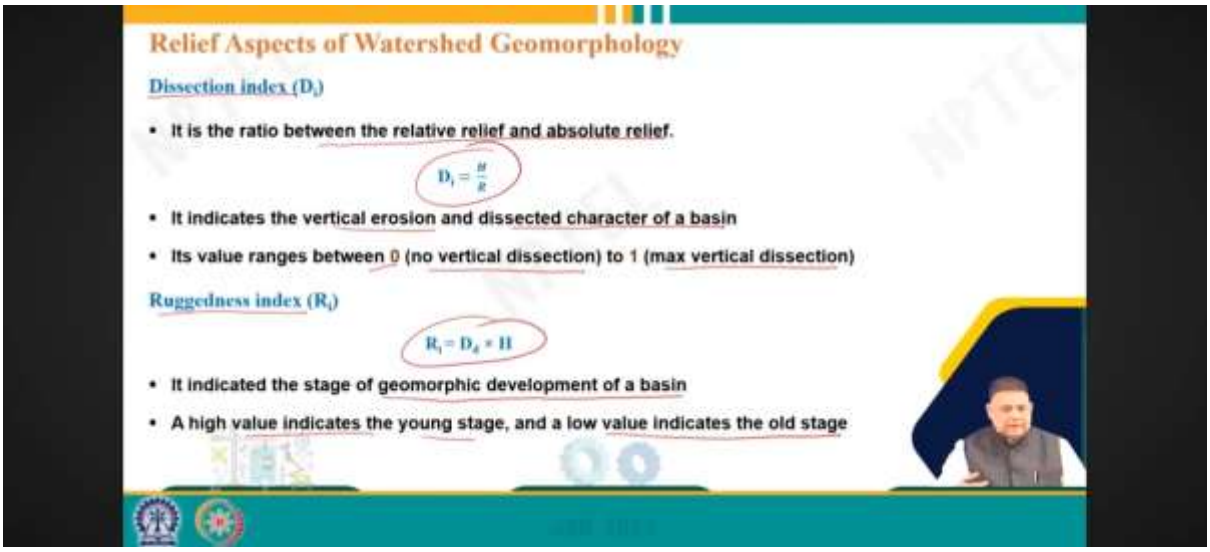
Then we come to relief aspects of watershed geomorphology. Watershed slope (Sw) is an important property because we know that the velocity and momentum of flow, and erosion, are governed by watershed slope. It also affects groundwater recharge; if the slope is more, the groundwater recharge will be less. It is calculated as the elevation difference between the two endpoints of the main flow path divided by its length, which means hf/ Lf, where hf is the elevation difference between the upper and lower points of the main flow path in meters, from the outlet.



A watershed relief has a couple of terms: absolute relief is the maximum altitude of the basin, and you know the maximum elevation. Relative relief is the elevation difference between the highest and lowest points in the basin, and it is an indicator of the erosional stage of the basin. So, relative relief ratio is also another ratio that is used, which is defined as the ratio of watershed relief to the longest dimension of the watershed parallel to the main flow path. A high number or curve value of relief ratio indicates a steep slope, and vice versa, a circular basin has a higher Rh than an elongated basin. So, this is another ratio, but not so popularly used in modeling.



Then we have the last two indices. One is the dissection index (Di), which is the ratio between the relative relief and absolute relief, that is H/ R, and it indicates the vertical erosion and dissected character of the basin, ranging between 0 (no vertical dissection) to 1 (maximum vertical direction). Ruggedness index (Ri) is Dd * H, and it indicates the stage of geomorphic development of a basin, where a higher value indicates the young stage and a low value indicates the old stage. As you can see, various definitions and features have been defined, and various characteristics have been generated in order to utilize the watershed characteristics and its definition. Each one reflects a certain aspect of the watershed characteristics, and that is why in geomorphological models, we may use any one or many of these characteristics.



With this, we come to the end of this lecture where we discussed the geomorphological features of the watershed, some of the very vital ones which are used popularly in geomorphological models. Thank you very much. Please give your feedback and raise your questions or doubts; we will be happy to answer them on the forum. Thank you.


THANK YOU