Course Name: Watershed Hydrology

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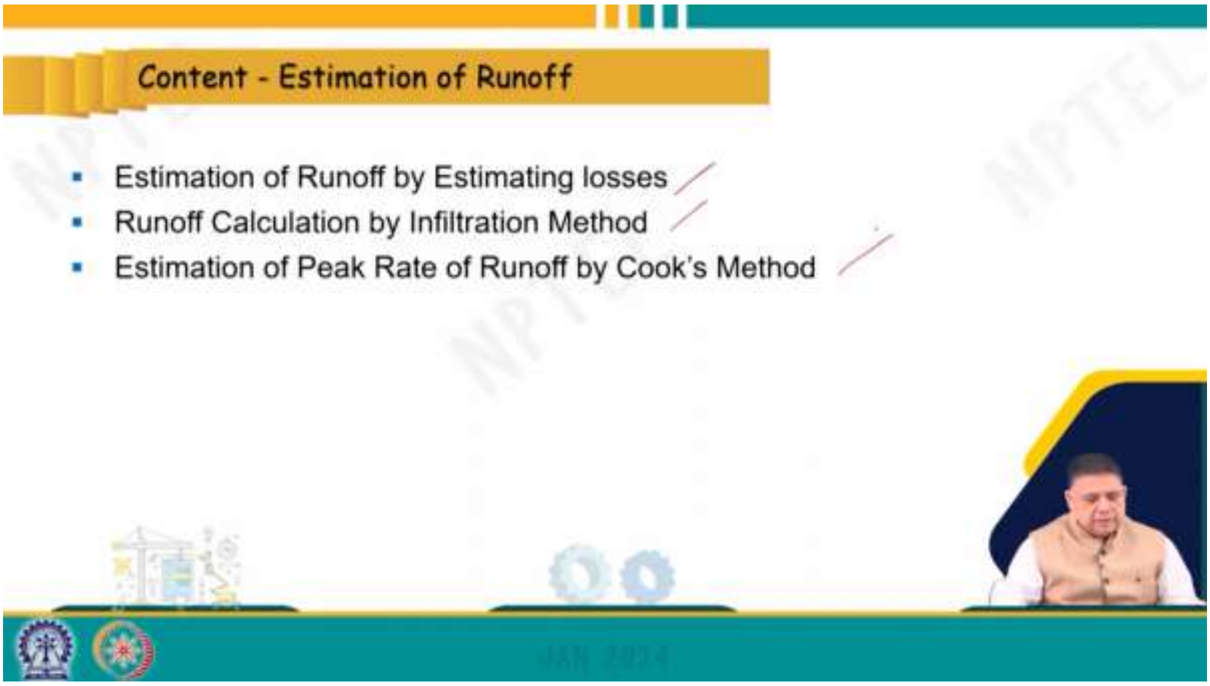
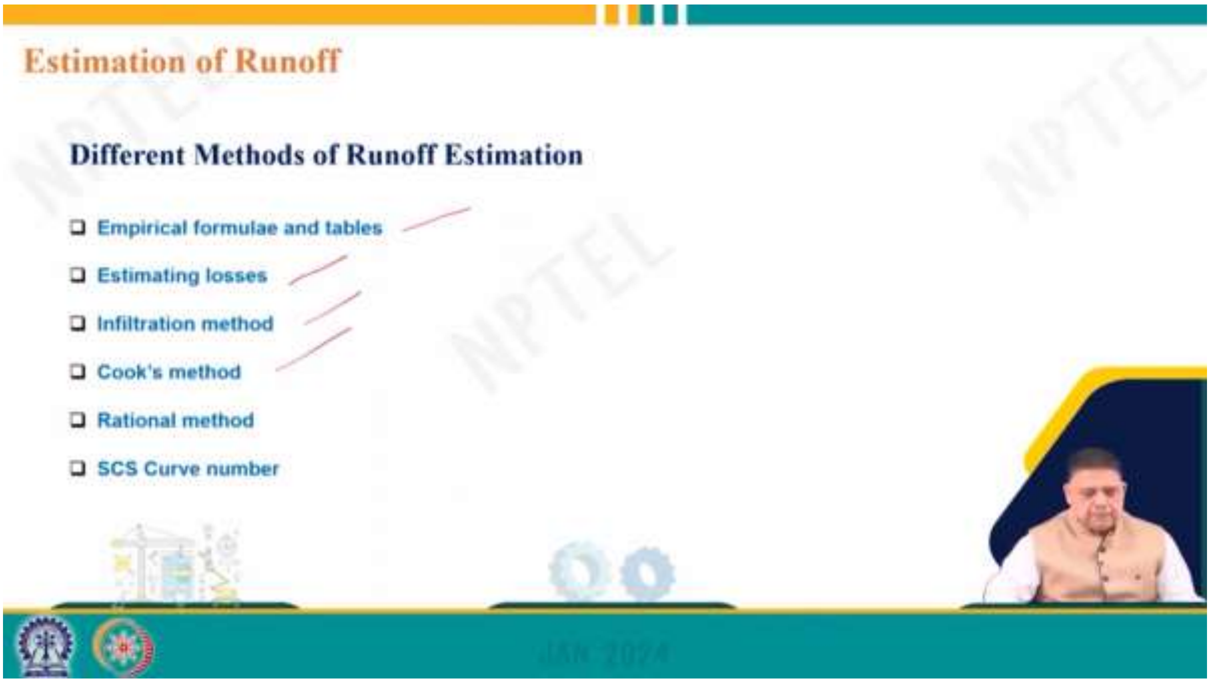
Week: 04

Lecture 17: Estimation of Runoff

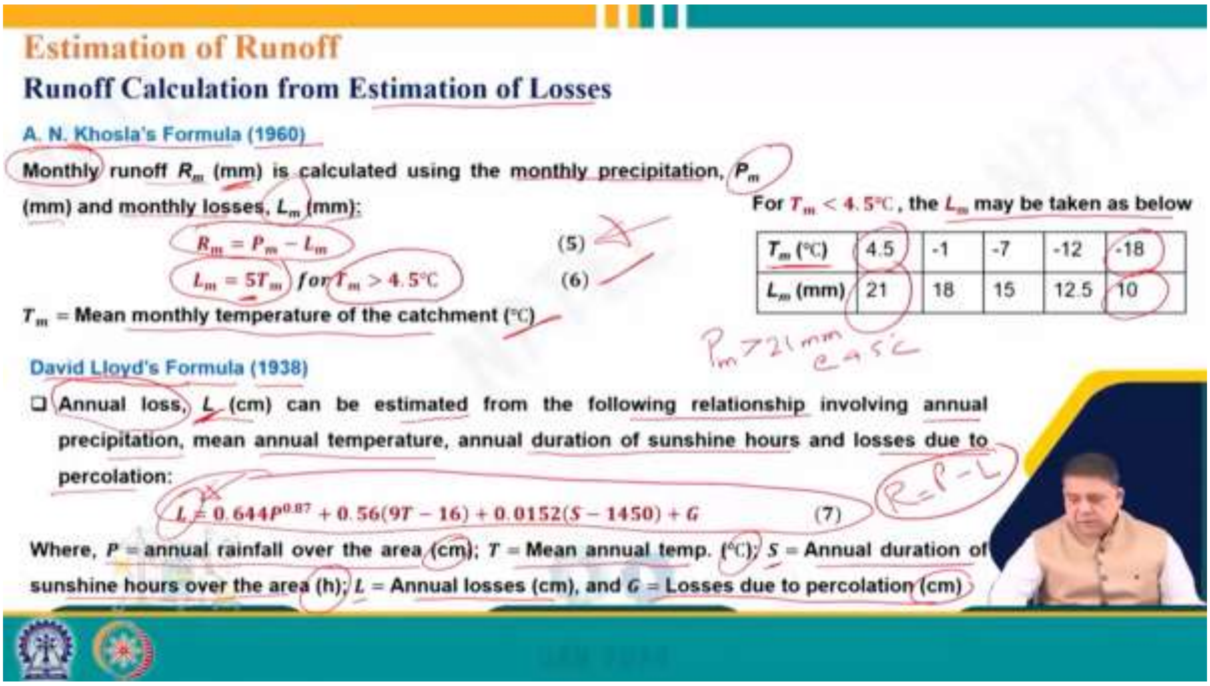
Hello friends. Welcome back to this online certification course on Watershed Hydrology. I am Rajendra Singh, a professor in the Department of Agricultural and Food Engineering at the Indian Institute of Technology Kharagpur. We are in Module 4, this is Lecture number 2, and the topic is Estimation of Runoff.



In this particular lecture, we will be covering estimation of runoff by estimating losses, runoff calculation by infiltration method, and estimation of peak rate of runoff by Cook's method.



Just to recap what we discussed in the previous lecture about the methods of runoff estimation, I gave you a list of methods. In the previous lecture, we discussed empirical formulae and tables. For example, we discussed the Bini's percentage for Madhya Pradesh, Barlow's table for Uttar Pradesh, and English formula for Maharashtra. In today's lecture, we will be discussing about these three methods, and the rest of the methods will be covered in future lectures.



Now, coming to runoff calculation by estimating losses, we have a couple of formulas here. The first formula is A.N. Khosla's formula, which was developed in 1960. This formula calculates Monthly runoff (R_m) in millimetres. It works on a monthly time scale, so runoff in millimetres is calculated using the monthly precipitation P_m and monthly losses L_m, all in millimetres. So, it gives runoff in millimetres and these two equations are used, that is,

$$R_m = P_m - L_m$$

This means runoff is precipitation minus losses, where for estimating losses, we have to use this relationship: $L_m = 5T_m$,

where T_m is the mean monthly temperature of the basin in degrees Celsius. This relationship (equation number 6) we remembered from the previous lecture because we are still discussing estimation of runoff losses. Though we have broken it into lectures, the topic remains the same, which is why we are continuing with the equation numbers from the previous lecture. For using equation number 6, there is a condition that this equation could be used only if the mean monthly temperature of the catchment is greater than 4.5 °C. So, in all instances where the temperature is greater than 4.5 °C, loss can be estimated by multiplying the temperature by 5 times. Then, of course, the runoff can be calculated after deducting the losses from the precipitation value, and monthly 'm' remains, 'm' suffix shows the monthly time scale.

What happens when the temperature is less than 4.5 degrees or equal to 4.5 degrees? If that is the case, then Khosla provided a table where it directly gives us the loss values. So, if the temperature, for example, is 4.5 °C, then L_m value is 21 millimetres. That means, as soon as PM is greater than 21 mm and if the temperature is at 4.5 °C, then we will get a great runoff. As long as rainfall is below 21 millimetres, we will not get any runoff. Similarly, if the temperature goes into minus, for example, -18 °C, then the loss reduces to 10 millimetres.

So, in Khosla's formula, the monthly time step where L_m (losses) are related to all associated mean monthly temperatures. Depending on whether the temperature is greater than 4.5

degrees Celsius or equal to or less than 4.5 degrees Celsius, we can use the equation or the table directly. Then,

$$R_m = P_m - L_m$$

can be used for estimating the runoff loss. The second equation is given by David Lloyd's. It is known as the David Lloyd's formula and it came into being in 1938. Per this formula, annual loss is calculated. So, obviously, this is on an annual time scale and it gives the relationship for loss itself.

In the previous case, we saw that we got a relationship for loss, but then we also had equation number 5. At the annual time step, equation number 5 remains valid for this method also. The only difference is that instead of the equation number 6 which was there in the Khosla method, we will be using equation number 7. Annual loss (L) in centimetres can be estimated from the following relationship, which involves annual precipitation, annual temperature, annual duration of sunshine hours, and losses due to percolation. This is the relationship given by equation number 7:

$$L = 0.644P^{0.87} + 0.56(9T - 16) + 0.0152(S - 1450) + G$$

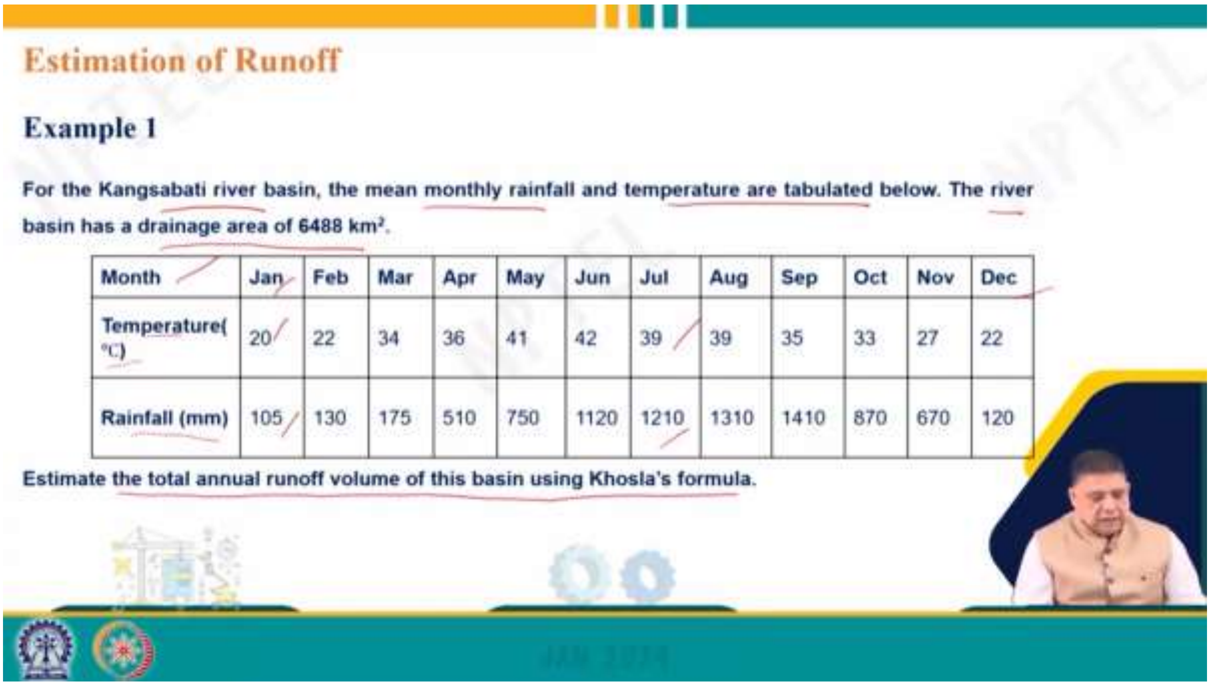
Where:

P is the annual rainfall over the area in centimetres,

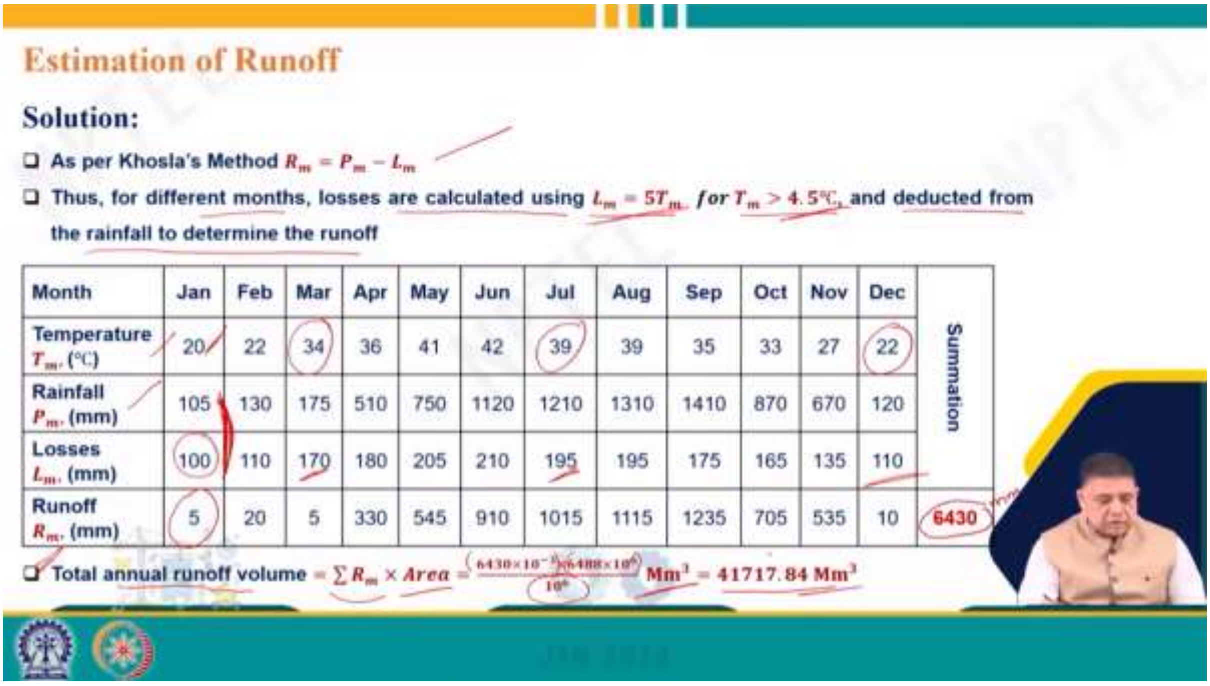
T is the main annual temperature in degrees Celsius,

S is the annual duration of sunshine hours over the area in hours.

So, obviously, knowing the latitude and longitude, we can find out the value of S, and L is the annual losses which we are calculating here in centimetres, and G is the losses due to percolation in centimetre. So, that means, if we know the temperature, annual duration of sunshine hours, losses due to percolation, and also precipitation, we can estimate a loss. And of course, once we know the loss, then obviously, as I already mentioned, runoff will be nothing but precipitation minus loss. So, using this relationship, we can find out how much runoff has occurred in the basin. So, pretty straightforward methods of calculating runoff.



Let us take an example for the Kangsabati river basin. The mean monthly rainfall and temperature are tabulated below. The river basin has a drainage area of 6488 square kilometres. For different months of a year, January to December, we have been given temperature in degrees Celsius and rainfall value in millimetres. So, in January, the temperature is 20 degrees and rainfall are 105, whereas in the month of July, temperature is 39 degrees and rainfall are highest at 1210. We have to estimate the total annual runoff volume for this basin using the Coase loss formula. Since the monthly time step data are given, the equations which are meant for monthly estimation fit well.



So, as per the Khosla's method,

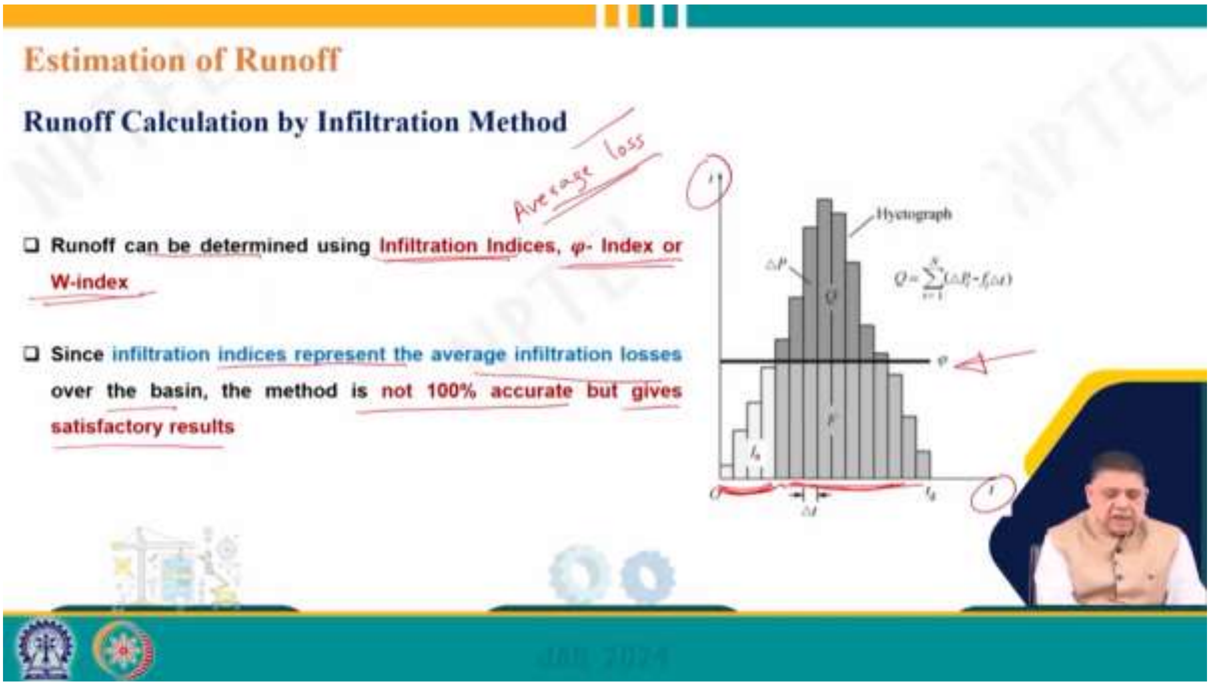
$$R_m = P_m - L_m$$

where monthly runoff is monthly precipitation minus monthly losses. Thus, for different months, losses are first calculated using $L_m = 5T_m$, for T_m greater than 4.5, and then they are deducted from the rainfall to determine the runoff. Kangsabati is in West Bengal. So, obviously, we always expect the temperature to be greater than 4.5 degrees, which is also evident from this table. The lowest temperature was 20 degrees, which means all the time temperatures are greater than 4.

At 5 degrees, we can straight away use this relationship: $L_m = 5T_m$, which was given by question number 6 in the previous slide when we were discussing the method. So, obviously, for each month, we know the temperature, we know the rainfall, and then obviously, losses are nothing but 5 times the temperature. So, for January, it is 100, for March 34 times 5, which is 170, for July it is 39 times 5, which is 195, and for December it is 22 times 5, which is 110. Then, runoff is nothing but rainfall minus losses. So, these two rows will be used. The runoff value comes out to be 5 in January and so on for each month, and the total runoff we get is in depth units, we get is 6430 millimetres.

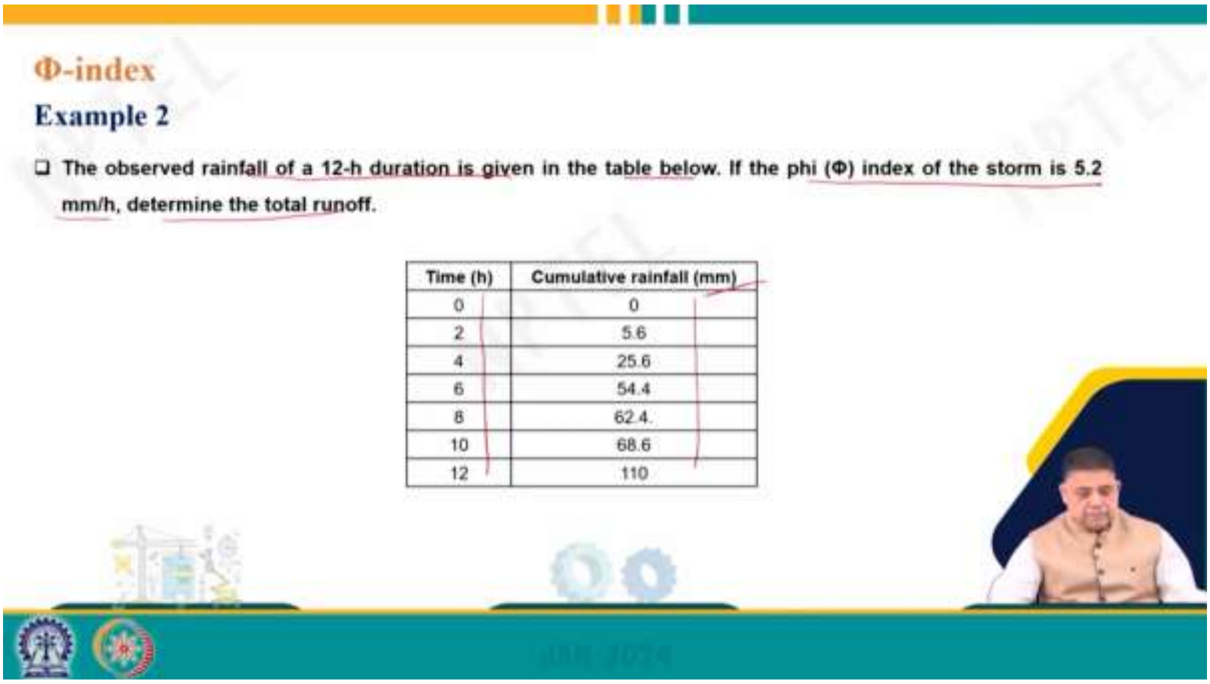
So, that is the total runoff we get, and because we have to get the runoff volume, the total runoff volume will be nothing but if you multiply this runoff depth by the basin area, we will get the runoff volume. So, it is the sum of R_m, which is 6430, and the area, which is already given. The only thing is that we are manipulating the units here. Like here, this 6430 is in millimetres. So, we are putting here 6430 times 10 to the power 5 in meters, 10 to the power 3 in meters.

Similarly, our basin area given is 6488 square kilometres. So, we are putting that in square meters, that is 6488 times 10 to the power 6 square meters. And then, obviously, because we would get a huge number, we are dividing everything by 10 to the power 6 to get the final answer in million cubic meters. Our final answer comes out to be 41717.84 million cubic meters. So, using an Kostla method for the basin, the total runoff volume we get is 41717.84 million cubic meters.

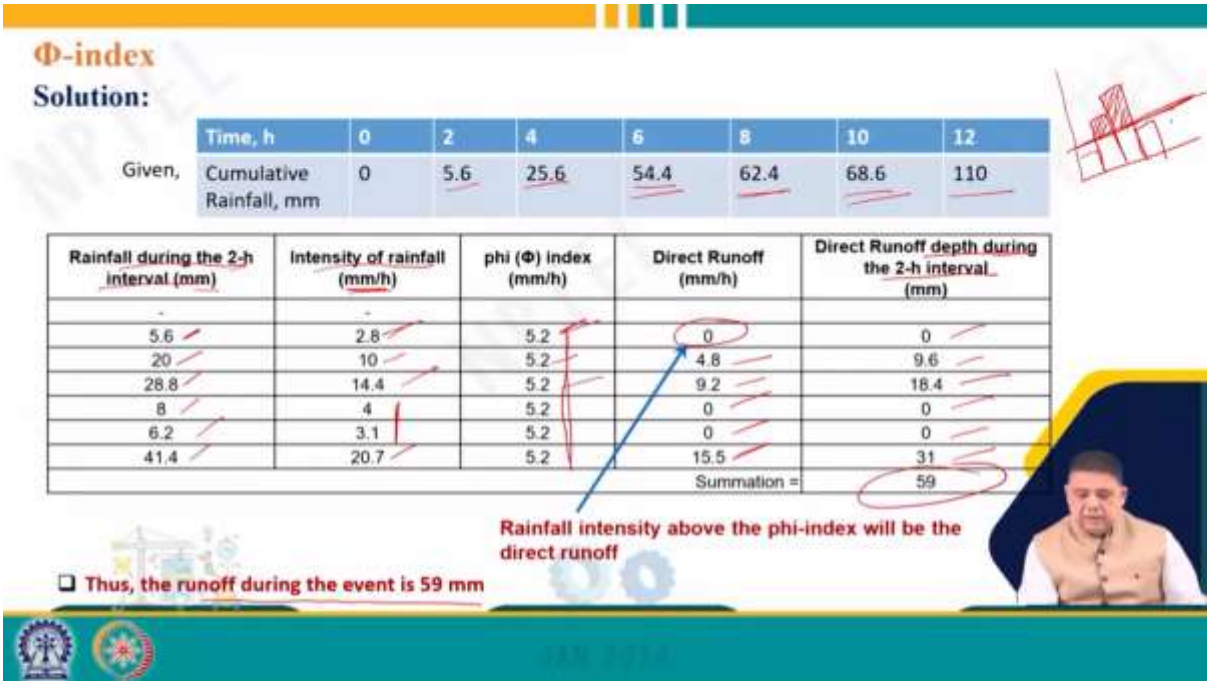


Then, we come to the next method, which is runoff calculation by infiltration method. As we have already discussed while discussing infiltration, we have discussed that runoff can be determined using infiltration indices like the phi index or W index. And if you remember, we said that basically, this phi index or W index, which are infiltration indices, they represent the average loss over the basin. And if you remember, we said that we use a hyetograph in this case, which is a rainfall intensity versus time plot. These hyetographs represent the rain, and then obviously, we draw a phi index line. If we know the phi index, we draw the phi index line, and the volume of runoff, the area under the curve, gives us the runoff volume. So, that means, the area under the curve of the hyetograph, if we get it, then we get the runoff volume. Below that, basically, if you recall, we said that initially there will be initial abstraction, and then obviously, there will be infiltration continued even after runoff initiation.

IA is the abstraction losses, including infiltration before the runoff began, and F basically represents the infiltration after runoff has occurred. Since infiltration indices represent the average infiltration losses over the basin, the method is not 100 percent accurate but gives satisfactory results. I think this point also we discussed earlier because of the simple reason that as we know, infiltration or other abstractions keep on changing from one point to the next, especially infiltration with soil characteristics changing. Infiltration keeps on changing within the basin. So, it may be very difficult to take the actual values of infiltration in estimating losses and then runoff. That is why the concept of this average loss or average infiltration indices, that is phi index or W index, has been taken into consideration or they have been used.



Let us take a simple example: the observed rainfall of a 12-hour duration is given in the table below. If the phi index of the storm is 5.2 millimetres per hour, determine the total runoff. For different durations, that is, 0 to 12 hours at 2-hourly time steps, we have been given cumulative rainfall in millimetres.

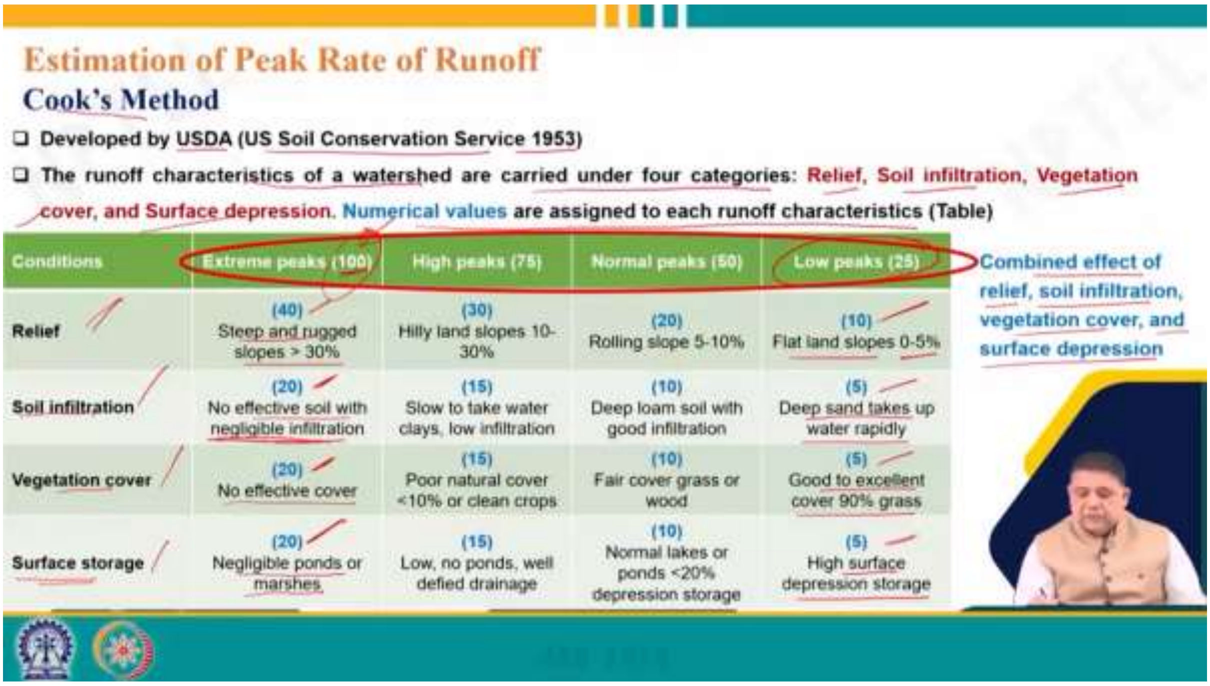


So, obviously, this is what is given at different times; we have been given cumulative rainfall. At 0 hours, it is 0, and then at 2 hours, it is 5.6; at 4 hours, it is 25.6, and so on. So, the first thing we will do is prepare a table, the first column showing rainfall during the 2-hour interval. It is 2-hourly, so that is why we are using a 2-hour interval in millimetres. So, obviously, the first 2-hour interval, 0 hours, nothing. So, the first 2 hours, the rainfall will be 5.6 minus 0, which is 5.6 mm. In between 2 to 4 hours, it is 25.6 minus 5.6, so that means 20; next 54.4 minus 25.6, that is 28.8; 62.4 minus 54.4, then it is 8, and lastly, 110 minus 62.4, that is 41.4.

So, this is the rainfall during the 2-hour interval, and then obviously, we can find out the intensity of rainfall at these 2-hourly intervals. And of course, this is 2 hours, so divided by 2, we will get the value in millimetres per hour.

So, the intensity comes out to be 2.8 in the first 2 hours and then the last 2 hours, it is 20.7 millimetres per hour. We have already been given the value of the phi index, which remains constant throughout. So, this is given as 5.2 millimetres per hour. Now, we have to find out the direct runoff. So, remember that in the previous graph also we said that this is just a typical hydrograph if you plot and if you plot the phi index value, then direct runoff is only contributed by the hydrograph slices which are the bars which lie above the phi index value. So, because in this case, the intensity of rainfall is lower than the phi index, that means there will be no runoff produced here, and the same concept is used in the remainder of that, 10 minus 5.2 is 4.8, 14.4 minus 5.2 is 9.2, and in these 2 also, it is less than the phi index, so that means there will be no runoff generated. And the last slice, it is 20.7 minus 5.2, 15.5 millimetres per hour of rainfall which is generated. Now, because we want the direct runoff depth, so obviously, we have to multiply it by 2 again to get the direct runoff, and that is why we are doing so. 0, 9.6, 18.4, 0, 0, 31. So, the total runoff depth that has been obtained here is 59 millimetres.

Thus, the runoff during the event is 59 millimetres that comes from the calculations here. So, this is a simple procedure; the only thing you have to remember is that only when the intensity is greater than the phi index, only in those durations' runoff will be generated.

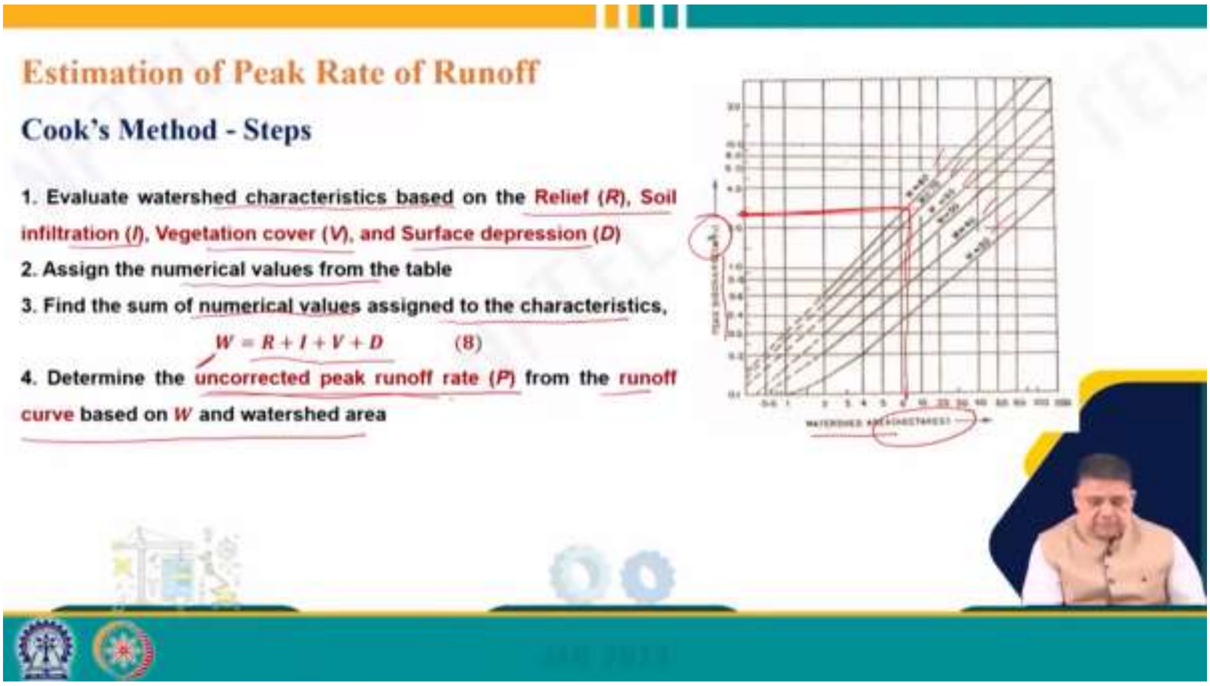


Then we come to Cook's method of estimating the peak rate of runoff. This method was developed by USDA, the US Soil Conservation Service, in 1953, which is the United States Department of Agriculture. The runoff characteristics of a watershed in this method are carried under 4 categories or evaluated, that is, relief, soil infiltration, vegetation cover, and surface depression. Numerical values are assigned to each runoff characteristic, and for that, SCS has provided this table.

Here, these are conditions: relief, soil infiltration, vegetation cover, and surface storage. And on this side, we have 4 columns which basically represent the combined effect of these 4 characteristics: relief, soil infiltration, vegetation cover, and surface depression. So, obviously, when we have the extreme peak column where some of these values come out to be 100, that means the conditions, all conditions, that is, relief, infiltration, vegetation cover, and surface depression are in favouring runoff generation.

For example, relief is when it is a steep and rugged slope greater than 30 percent, that means all the water will flow because of the very steep slope of greater than 30 percent. So, we give a score of 40. Soil infiltration: no effective soil with negligible infiltration. There is no infiltration, that means, entire precipitation will get converted into runoff. So, that is why we give a value of 20. Then vegetation cover: no effective cover, that means, again there is no absorption. So, most of the rainfall will get converted into runoff. So, that means, again we have the highest value of 20 in this category.

And surface storage is negligible, ponds or marshes, that means, there is no surface storage. Then again, the max value of 20, and that is why if you sum all these 4 values, 40 plus 20 plus 20 plus 20, that value comes out to be 100. So, that simply means that almost all the precipitation will get converted into runoff. On the other extreme, we have low peaks, where some value is only 25 under relief, it is flat land slopes lying between 0 to 40 percent. So, we give a score of 10, that is 25 percent of what we gave under extreme peaks. Soil infiltration: deep sand takes up water rapidly, that is, infiltration rate is very high. So, of course, one fourth, you get again 5. Vegetation cover: good to excellent cover, 90 percent grass, so that means, lot of absorption. So, again, we give one fourth, 5, and surface storage: high surface depression storage, that means, most of the water could be stored in the depressions. So, that is why again, one fourth of the value. So, that is why some of these will be 25. So, these values first come from this table.

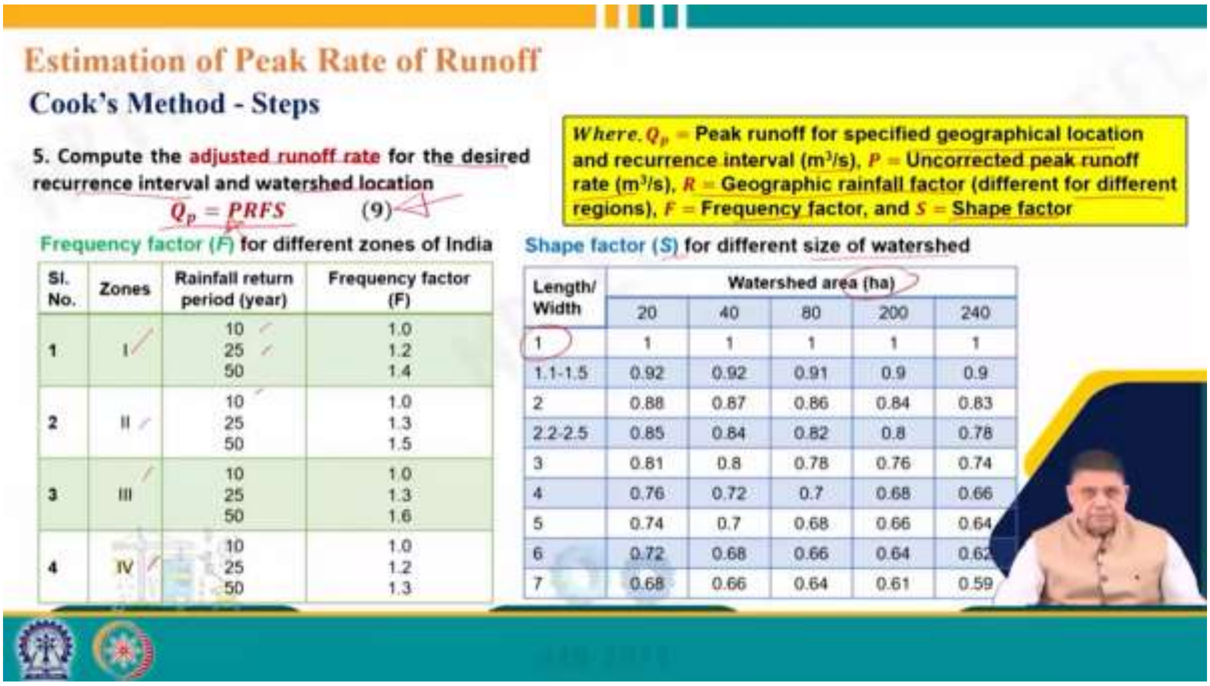


Now, the steps are to evaluate what are the characteristics based on the relief, soil infiltration, vegetation cover, and surface depression. And assign the numerical values from this table, that is, all the basin characteristics you assign the numerical values using the table wherever they fit. And find the sum of numerical values assigned to the characteristic, which is called W Which is sum of

$$W = R + I + V + D$$

that is for all 4 characteristics, some we saw that it could be max 100 and minimum it could be 25. Then determine the uncorrected peak runoff rate P from the runoff curve based on W and watershed area. So, basically, SCS or USDA has provided a readymade curve where peak runoff in cubic meter per second is related to watershed area in hectares.

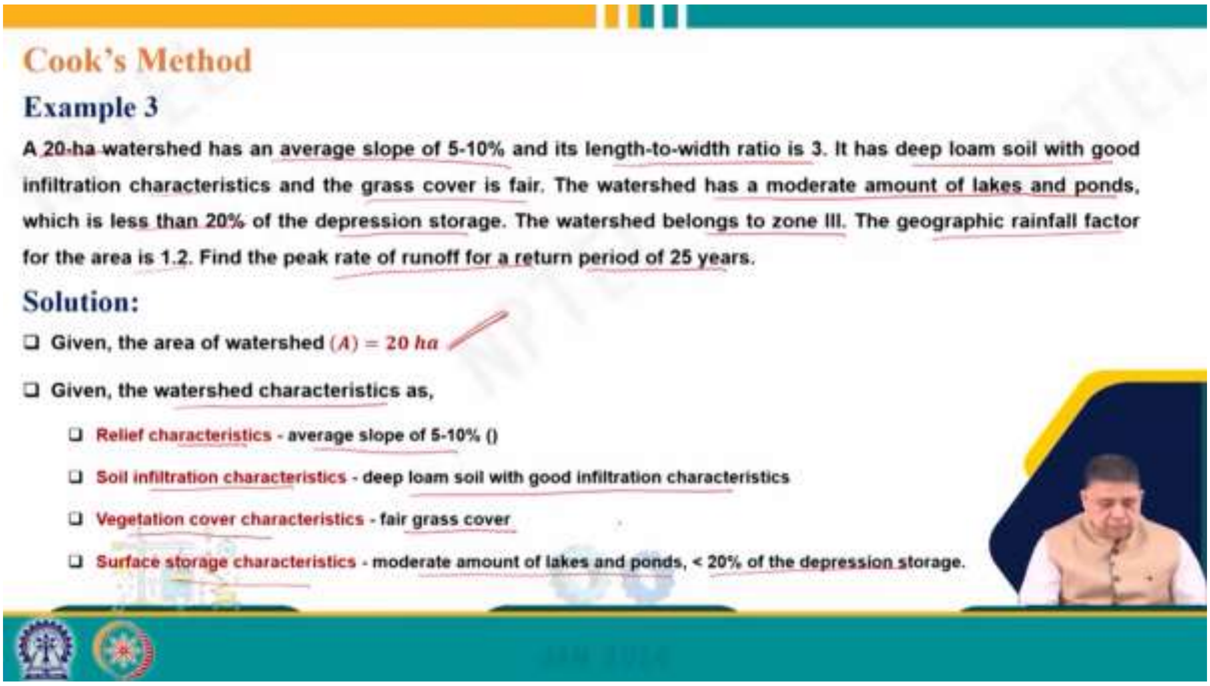
And there are, you can see, different curves for different W values. W, you remember, is sum of the numerical values assigned to these 4 characteristics. So, depending upon whether W is 30, 40, 50, 60, or 80, these curves can be used. So, what happens is that if you use this curve, then for when if you know the watershed area, W value we already know. So, we will find out the discharge from here. Say, for example, if the watershed area is around 8 hectares and W is equal to 80, then we will get the peak discharge here, which is referred to as uncorrected peak runoff rate P in Cook's method.



Now, we compute the adjusted runoff rate for the desired recurrence level and watershed location using this relationship, which is the main Cook's method equation

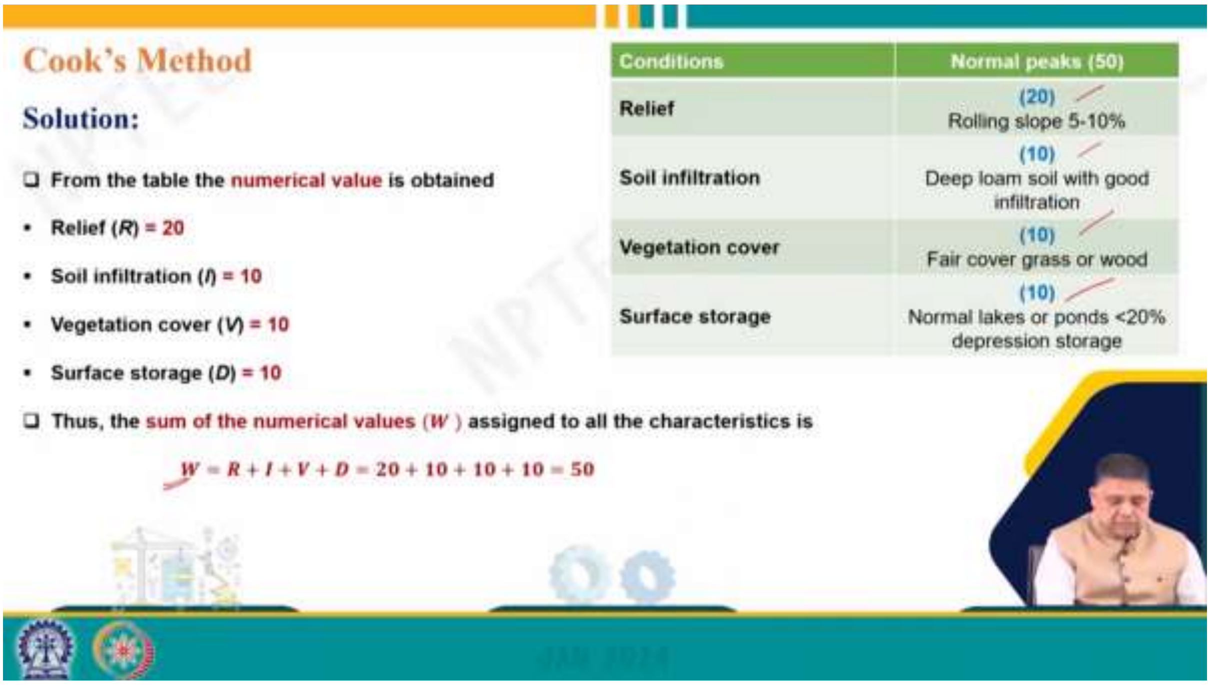
$$Q_P = PRFS$$

where P we have already estimated, which is the uncorrected runoff peak. And Q_P is the peak rate for the specified geographical location and recurrence interval in cubic meters per second. P is the uncorrected peak runoff rate; we have already seen how to determine that. R is the geographical rainfall factor, which is different for different regions and basically depends on latitude and longitude. The frequency factor, F, is the frequency factor, and S is the shape factor. Now, frequency factors for different zones of India are already given, developed for Zone 1, 2, 3, and 4, and for different recurrence criteria, frequency factor values can be read from this table. Similarly, the shape factor for different sizes of watersheds, where basically the length and width ratio are linked to the watershed area, for different areas and for different length and width length ratios, we have values of S. So, F and S we can read from here, P we have already got, R we will get knowing the location, the geographical rainfall factor, and thus we can obtain the PRFS. Using PRFS, we can get the Cook's method example.

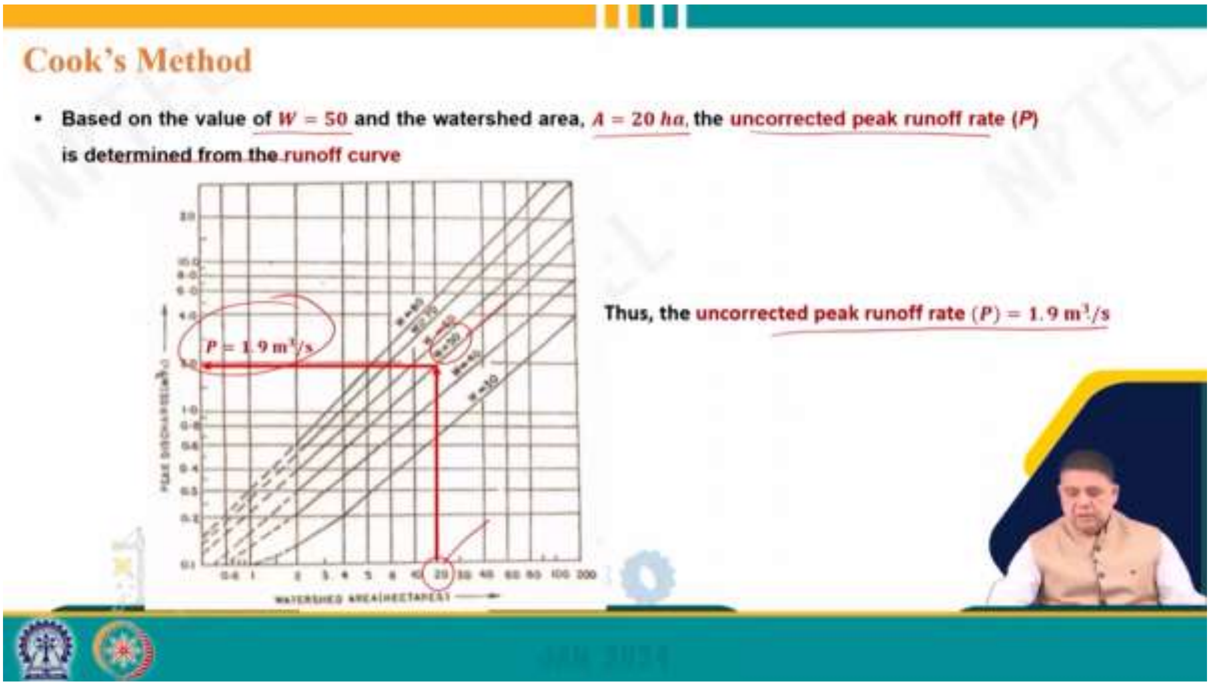


Now, let us take an example: a 20-hectare watershed has an average slope of 5 to 10 percent and its width ratio is 3. It has deep loam soil with good infiltration characteristics, and grass cover is fair. The watershed has a moderate number of lakes and ponds, which is less than 20 percent of the depression storage. The watershed belongs to Zone 3; the geographic runoff factor of the area is 1.2. Find the peak rate of runoff for a return period of 25 years.

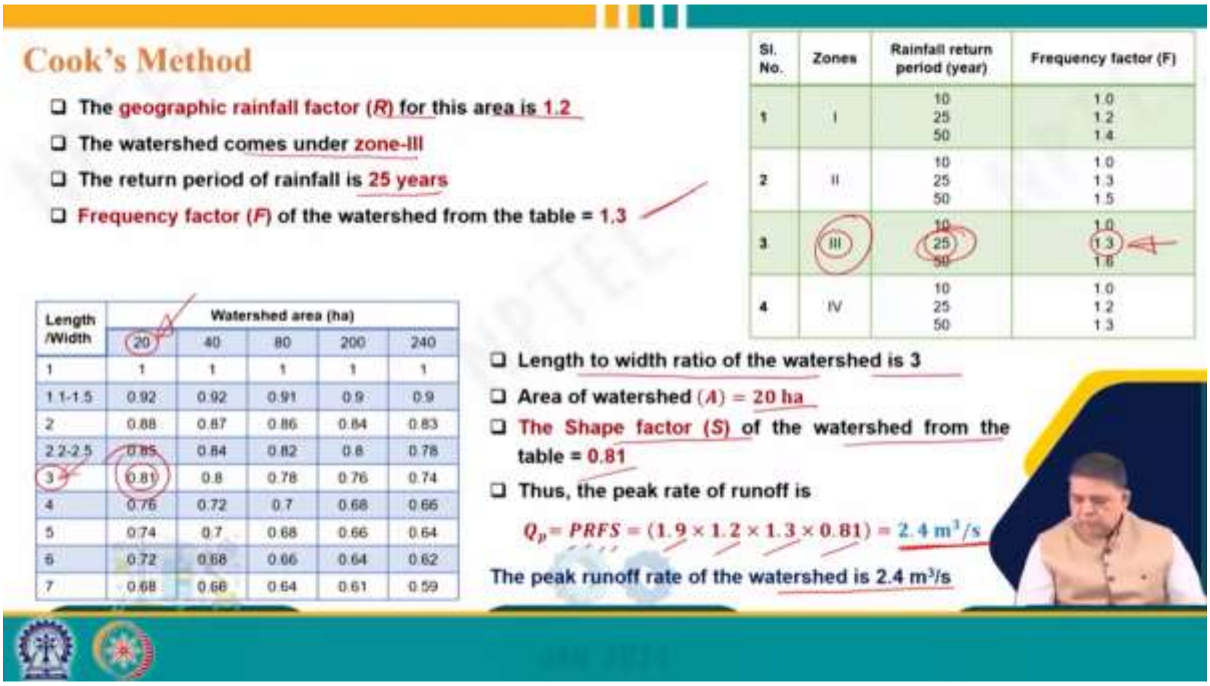
So, it is a simple application of Cook's method. We have been given the watershed area is 20, and different watershed characteristics are given here. So, the relief factor is the average slope of 5 to 10 percent, soil infiltration characteristics deep loam soil with good infiltration characteristics, vegetation covers fair, grass cover, surface storage, moderate number of lakes and ponds, less than 20 percent of depression storage. That means, knowing all these characteristics, we can enter and read the values from the table for obtaining the value of W.



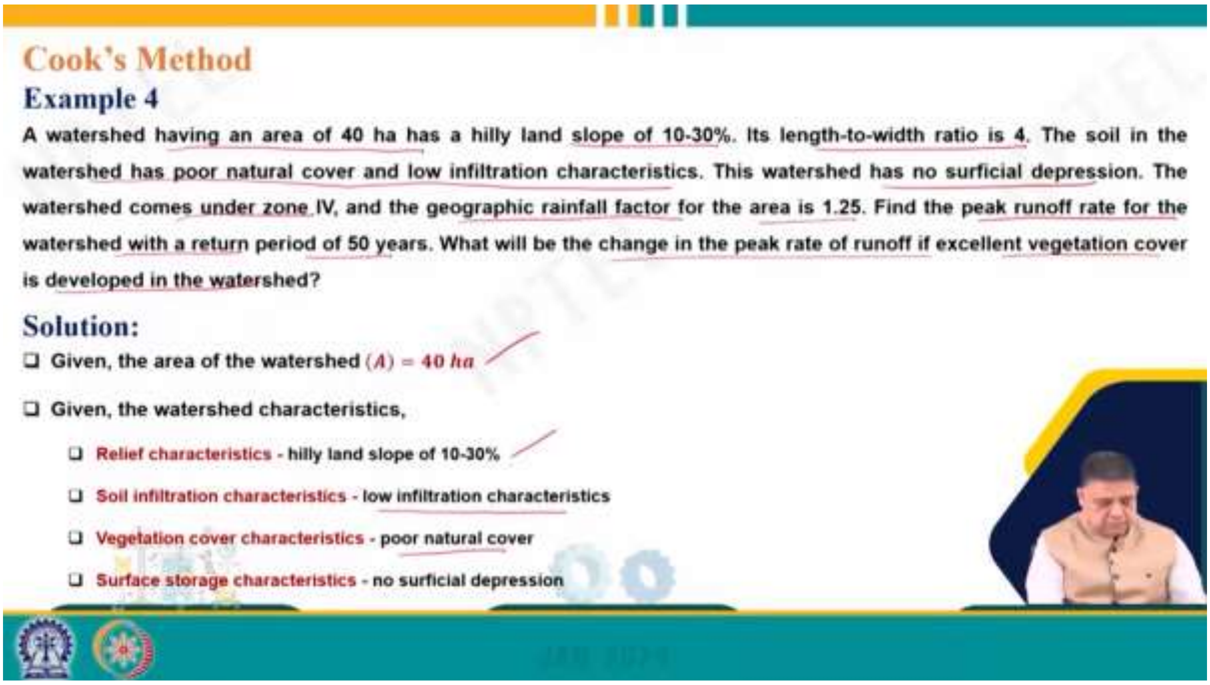
So, here, as per our given description, R is 20, soil is 10, vegetation cover is 10, and less than 20 percent depression storage, remember surface storage is 10. So, that means, the numerical sum of the numerical value W we obtained for this watershed is 50.



So, now, knowing the watershed area of 20 hectares and the W value of 50, which we have obtained using the curve, we can get the uncorrected peak runoff rate from this curve. So, here, W equals 50, watershed area is 20. So, the value of P we get is 1.9 cubic meters per second. So, the uncorrected peak runoff rate is 1.9 cubic meters per second.

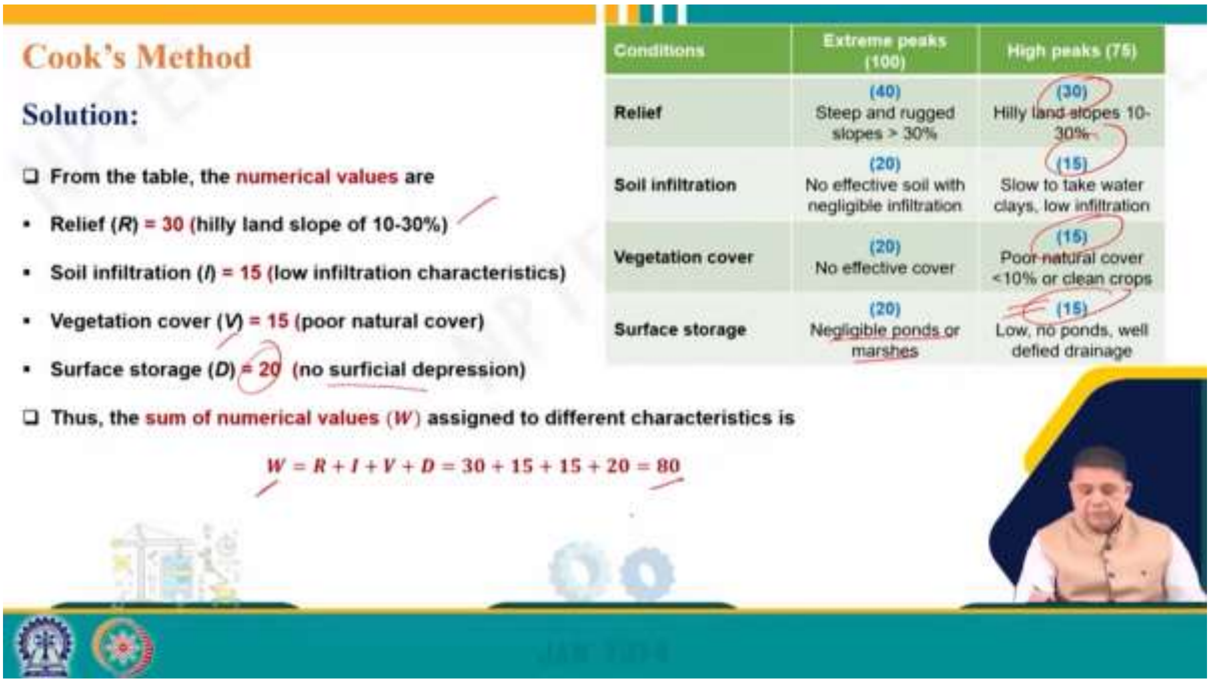


Now, the geographical rainfall factor for this area is already given as 1.2, and the watershed falls under zone 3 with a return period of 25 years. So, obviously, we have to use this table for zone 3 and a return period of 25 years. The value of the frequency factor is 1.3. So, the value of F is 1.3. Similarly, the length-to-width ratio of the watershed is given as 3, and the area of the watershed is 20, and the shape factor of the watershed can be read from the table. This is the length-to-width ratio, watershed area is 20. So, we get a value of the S factor as 0.81. Now, we know all four values of Q_P is PRFS, 1.9, 1.2, 1.3, and 0.81, and thus the peak rate of runoff comes out to be 2.4 cubic meters per second. So, the peak rate of runoff for the watershed is 2.4 cubic meters per second as per Cook's method.

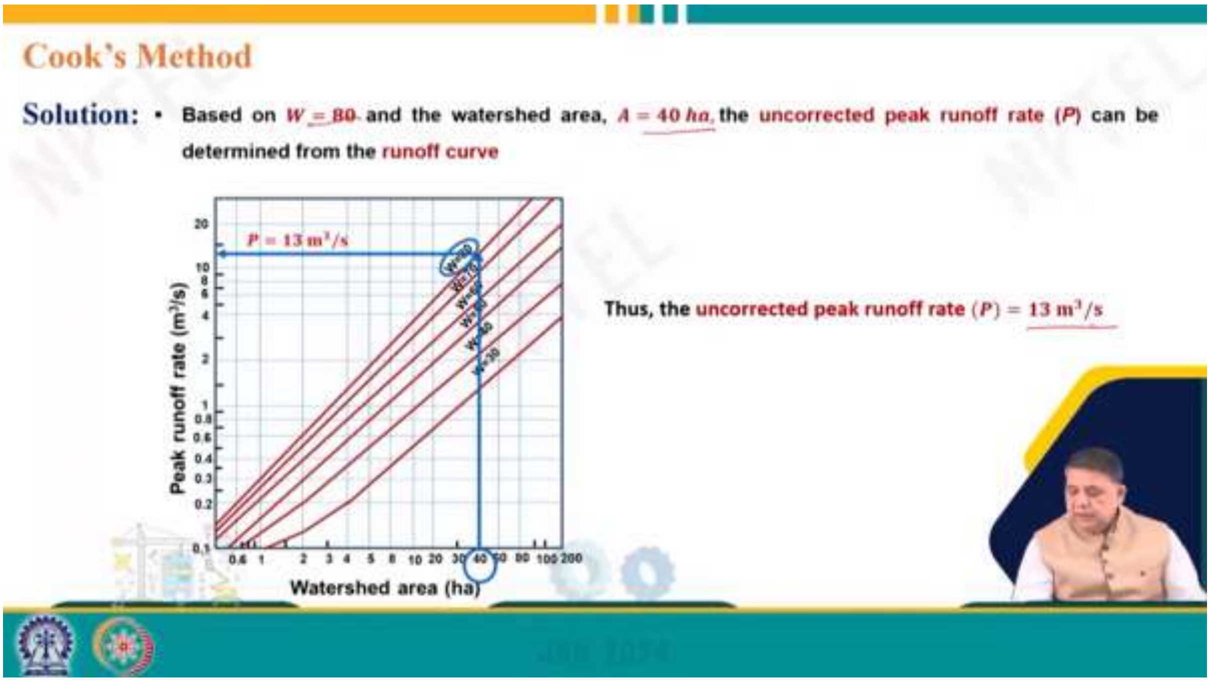


We will take another example: a watershed having an area of 40 hectares has a hilly land slope of 10 to 30 percent, its length-to-width ratio is 4. The soil in the watershed has a poor natural cover and low infiltration characteristics. This watershed has no surficial depression. The watershed comes under June 4, and the geographical rainfall factor for the area is 1.25. Find the peak runoff rate for the watershed with a return period of 50 years. What will be the change in the peak rate of runoff if excellent vegetation cover is developed in the watersheds?

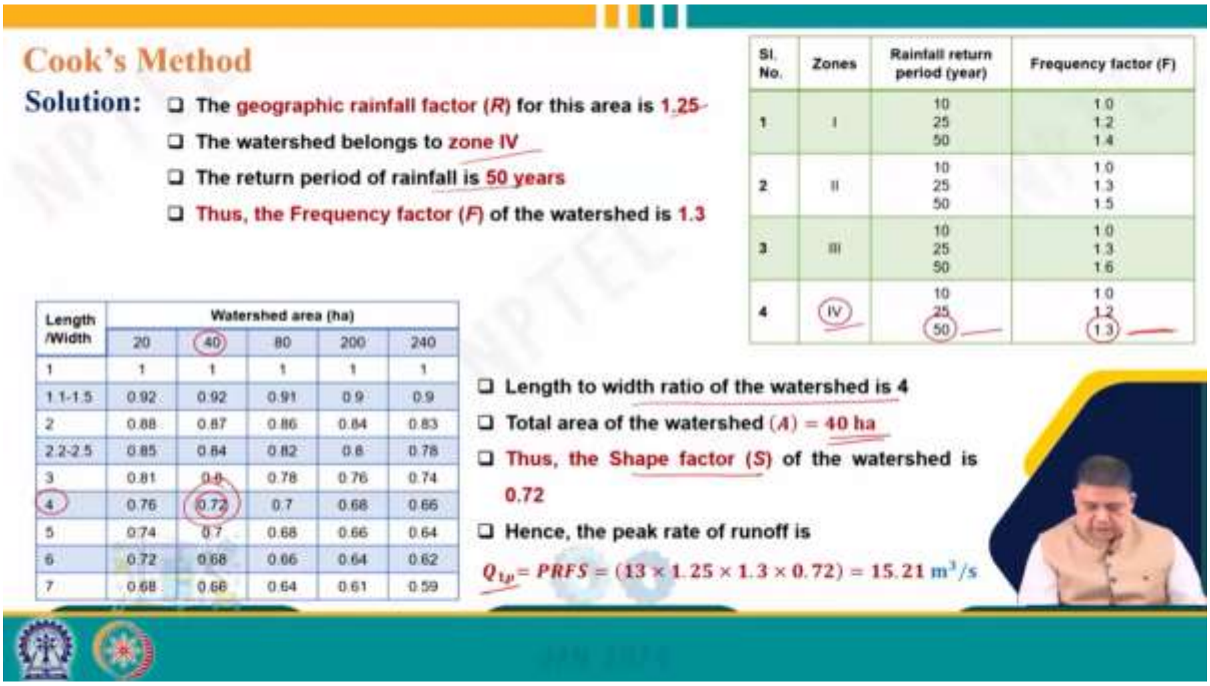
So, that means, we have to first find the value and also the change if vegetation cover changes to excellent. So, we have been given the area of the watershed is 40 hectares, relief characteristics are hilly land slope 10 to 30 percent, soil infiltration characteristics are low infiltration characteristics, vegetation cover is poor, and there is no surficial depression.



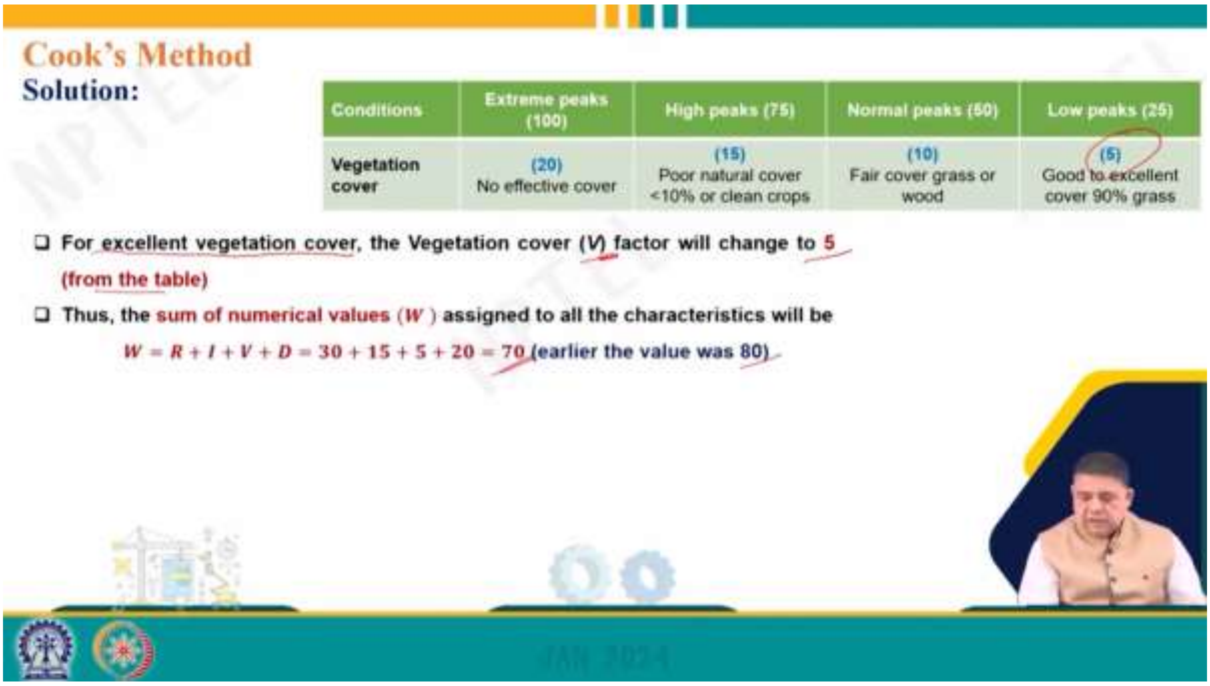
So, knowing this, we can get the values from here: for 10 to 30, we have 30; similarly, for low infiltration characteristics, 15; for poor natural cover, 15; and for surface storage, no surficial depression, we get 20. So, the sum of numerical values we get W equals 80 from the table.



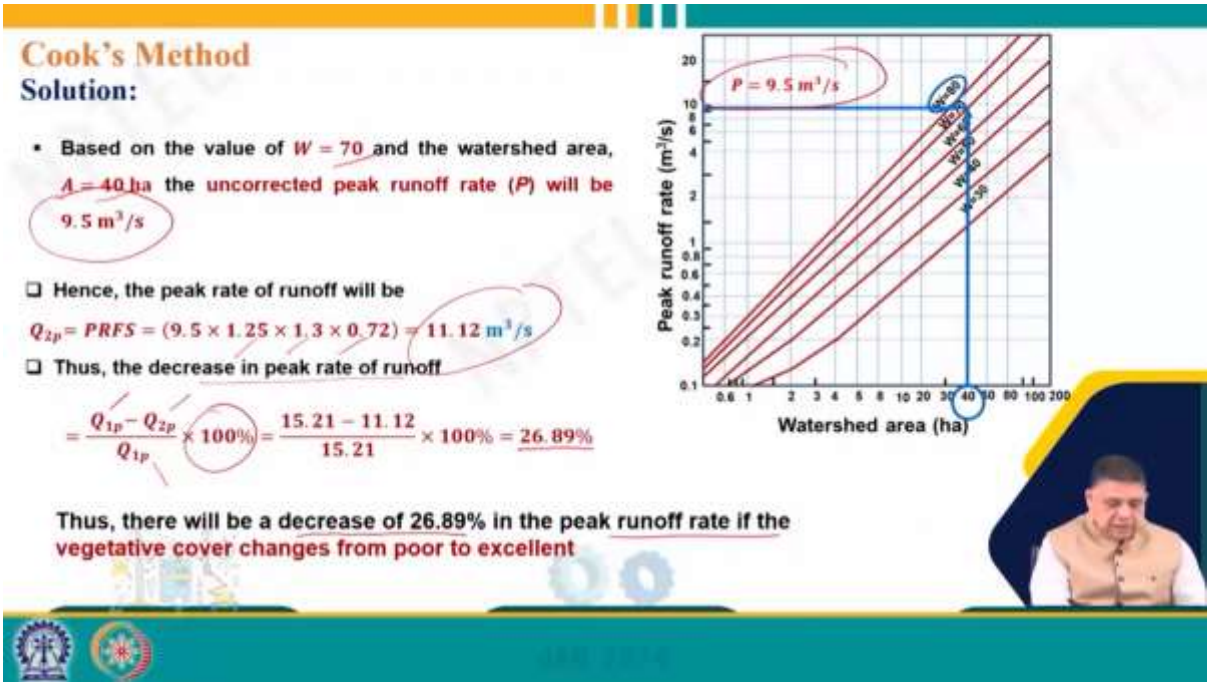
Now, knowing W equals 80 and watershed area is 40, we can get the uncorrected peak runoff rate, which comes out to be 13 cubic meters per second.



Now, the geographical rainfall factor for the area is 1.25, which is already given, and the watershed belongs to June 4, return period is 50 years. For June 4, 50 years, the value comes out to be 1.3. Similarly, the length-to-width ratio of the watershed is given as 4, total area already we know is 40 hectares. So, for 40 hectares and a length-to-width ratio of 4, the value of the shape factor is 0.72. So, now, we know that Q_P, under the given condition PRFS, if you put the value, comes out to be Q_P value comes out to be 15.21 cubic meters per second.



But we also have a condition that what happens if the vegetation cover changes to excellent. So, for excellent cover, the V factor, as you can see here, it will change to 5 as per the table. So, that means, our W value will reduce to 70, whereas it was 80.



So, that is the change we are getting, and that means, for W equals to 70, area equals to 40, we get an uncorrected value of 9.5 cubic meters per second from the graph; all other things remain the same, which means R, F, and S remain the same because no changes are taking place. So, obviously, we get a discharge of 11.12 cubic meters per second. So, there is a reduction in discharge. The decrease in the peak rate of runoff, Q1P minus Q2P divided by Q1P, and of course, percentage, that is why we are multiplying by 100. The value we get is 26.89 percent. So, it shows that there will be a decrease of 26.89 percent in the peak runoff rate if the vegetative cover changes from poor to excellent.

That is how we saw that we can use Cook's method to find out, provided the data, of course, the data requirement is pretty huge, but if you know all the characteristics, then you can use Cook's method for estimating the peak runoff rate. In this lecture, we saw the runoff estimation using losses, using infiltration estimation, and also using Cook's method. Thank you very much. Please give your feedback and also raise your doubts and questions on the forum, which we will be happy to answer. Thank you very much.