Course Name: Watershed Hydrology

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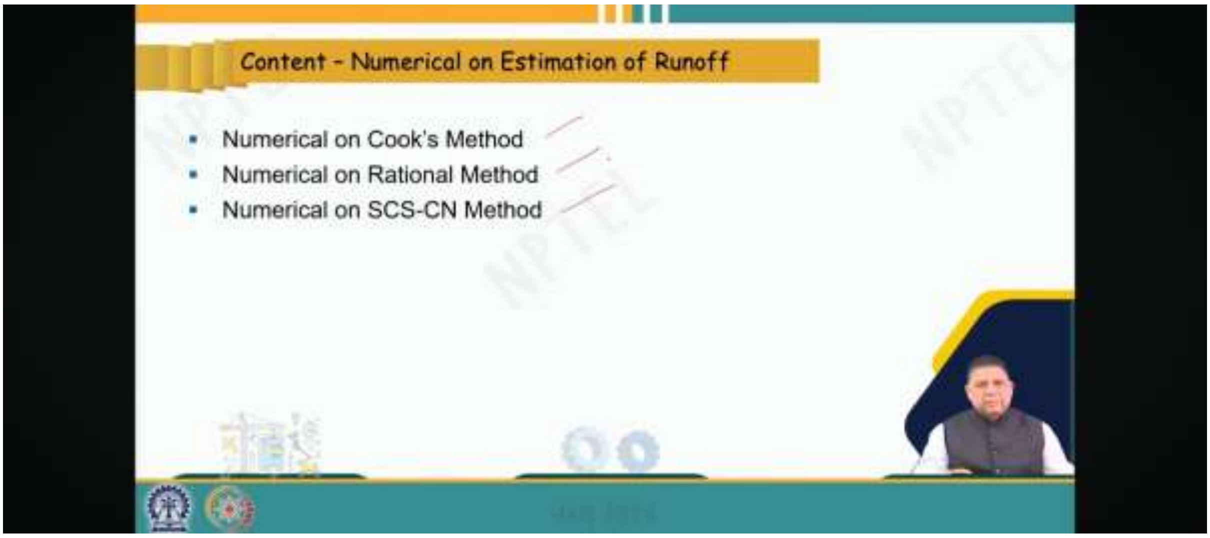
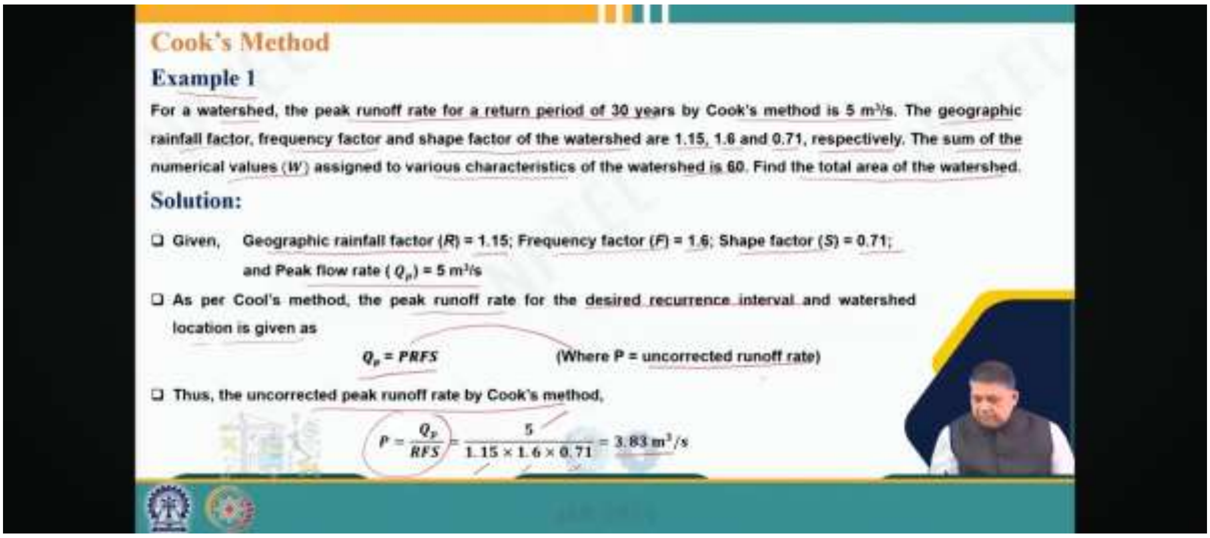
Week: 04

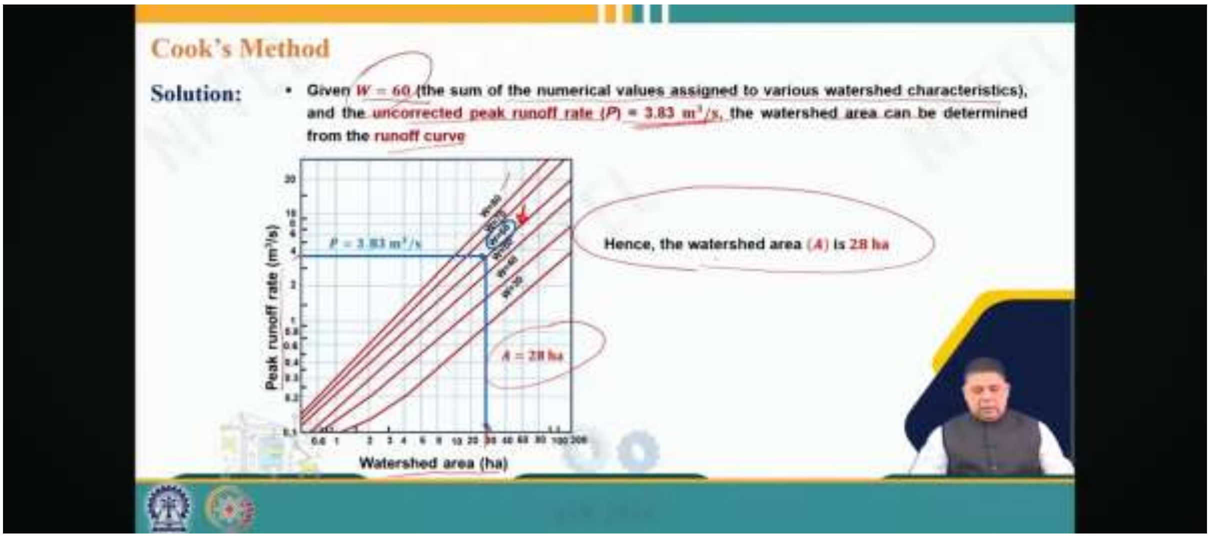
Lecture 20: Numerical on Estimation of Runoff



Hello, friends! Welcome back to this online certification course on Watershed Dental 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 4, and this is Lecture 5, which is the last lecture of this module. Here, we will take up numerical estimation of runoff. So, in the previous few lectures, we have been discussing various methods of estimating runoff. We discussed Cook's method, the rational method, SCS curve method and of course, we did take numerical examples while discussing these methods. Because runoff is a very important topic and questions are always asked in various competitive examinations including GATE, it will be a good idea to cover some more numerical examples on these methods.



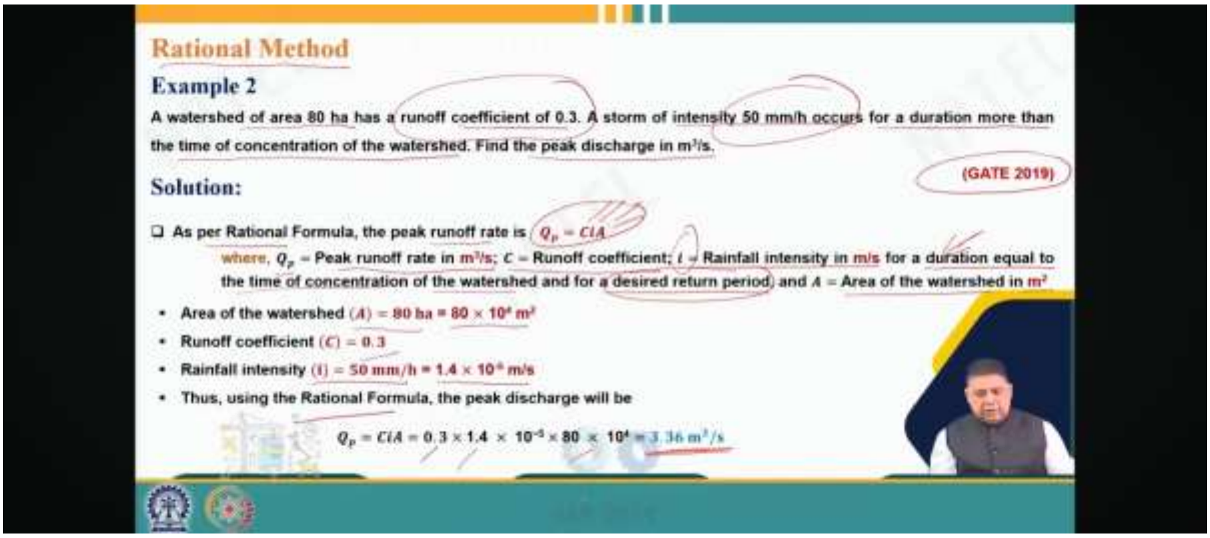
We will start with Cook's method example 1. For a watershed, the peak runoff rate of a return period of 30 years by Cook's method is 5 cubic meters per second. The geographic rainfall factor, frequency factor and shape factor of the watershed are 1.15, 1.6 and 0.071 respectively. The sum of the numerical values assigned to various characteristics of the watershed is 60. Find the total area of the watershed. So, that is an inverse problem where we have been given the discharge and various other characteristics and we have to find the total area of the watershed.



Coming to the solution, the information provided to us is the geographical rainfall factor R is 1.15, frequency factor F is 1.6, shape factor S is 0.71, and peak flow rate is 5 cubic meters per second as per Cook's method. The peak runoff rate for the desired recurrence travel and watershed location is given as follows: Q_p= P_r* F * S, where P_r, F and S we already saw. P is the uncorrected runoff rate. In this case, P is the uncorrected runoff rate and the uncorrected peak runoff rate by Cook's method is ah, thus knowing this information, we can calculate using this a relationship: $P_P = Q_p \cdot r_f \cdot s \cdot s_s$ and the values of Q_p, $r_f, s\ and\ s_s$ are known. So, the value of P_P we get is the uncorrected runoff rate, which is 3.83 cubic meters per second for the given data. Now, given W, that is the sum of numerical values assigned to various watershed characteristics and the uncorrected peak runoff rate P_P = 3.83 cubic meters per second, we can determine the watershed area using the runoff curve that is used in the ah Cook's method.

So, if you remember, this is the runoff curve we use where this uncorrected peak runoff rate is related to watershed area and then there are curves a different curve for different W values, that is the sum of the numerical values. Now, in this case we know $W = C_P$ and $W = 60$. So, obviously, we have to target this particular line, $W = 60$ lines, this line and also the uncorrected peak runoff rate value we know is 3.83 cubic. So, of course we have to read from here 3.83 cubic.

So, if we draw a horizontal line cutting ah W equals to 60 curve and then we draw a vertical line then of course, we can read the watershed area from here for the given data and the watershed area from the curve comes out to be 28 hectares. The watershed area for which we have been given the data ah, including the um peak runoff rate estimated by Cook's method, is 28 hectares as per the procedure followed. We take another example: a watershed of area 80 hectares has a runoff coefficient of 0.3. A storm intensity of 50 millimeters per hectare occurs for a duration more than the time of concentration of the watershed. So, the moment we are in time of concentration, that means we are talking about the rational method to find the peak discharge in cubic meters per second. So, we have to find the peak discharge in cubic meters per second, and this question has been taken from GATE 2019 examination.



So, we know that as per rational formula, the peak runoff rate is given by this equation: $Q_P = CiA$ where Q_P is the peak runoff rate in cubic meters per second, C is the runoff coefficient which we have to get from a table, i is the rainfall intensity in meters per second for a duration equal to the time of concentration of the watershed and the desired return period. So, just to ah once again remind you that when we define i, there are two things it is correlated to. One is the duration which should be at least equal to the time of concentration of the watershed, and the other is the return period for which we want to find out the peak discharge and A here is the area of the watershed in square meters, and I, as I said, that ah, we are using a straightforward relationship so that we do not have to remember the convergence, etcetera. Otherwise, ah, textbooks, as I mentioned earlier also, we have the formula $Q = 0.36CiA$ where i and A have certain units which you have to remember. So, the area of the watershed is given here is A hectares.

Given:

- Runoff coefficient (C) = 0.3

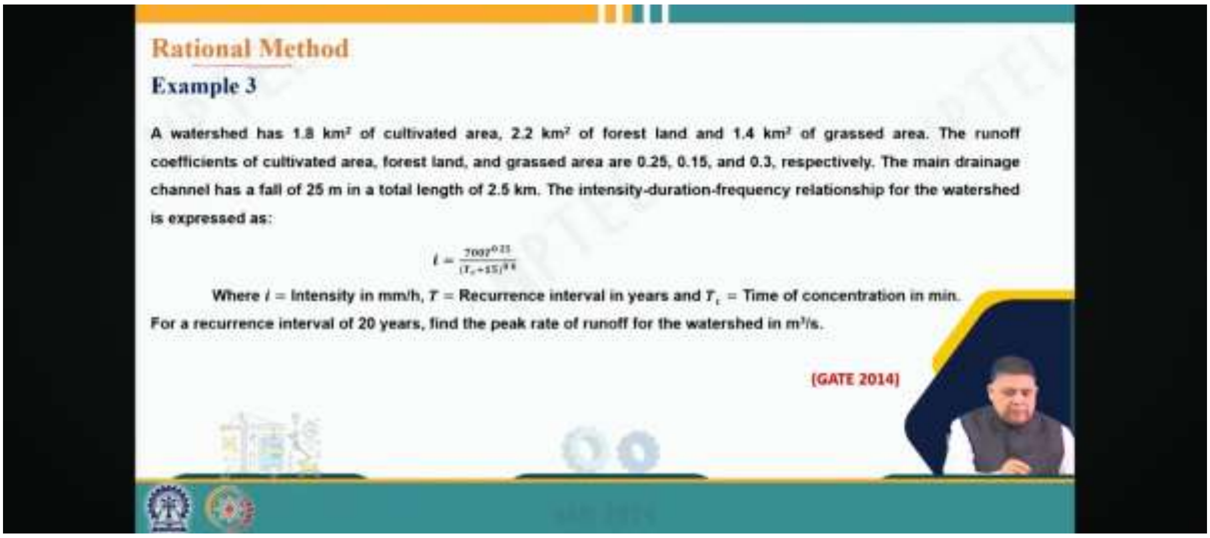
- Rainfall intensity (i) = 1.4×10^{-5} meters per second
- Area (A) = 8×10^{4}square meters

Using the Rational Formula: $Q_P = C \times i \times A$

Substituting the given values: $Q_P = 0.3 \times 1.4 \times 10^{-5} \times 8 \times 10^{4}$

Q_P = 3.36 cubic meters per second.

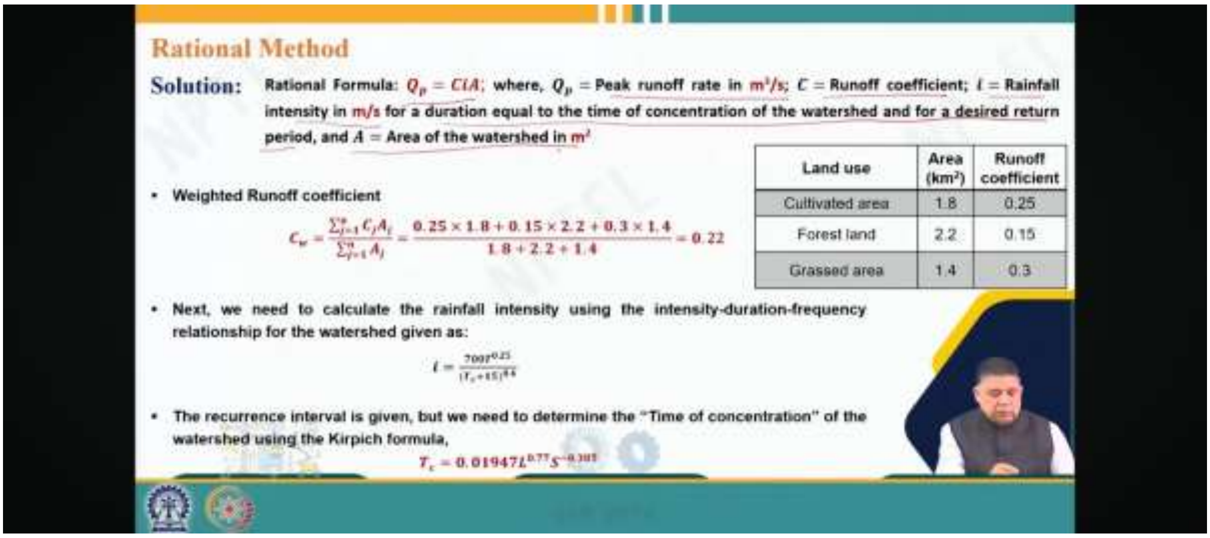
So, for the given data for the watershed, the peak runoff rate (Q_P) is 3.36 cubic meters per second using the rational method.



Now we take another example again on the rational method which is example 3 for this lecture. A watershed has 1.8 square kilometers of cultivated area, 2.2 square kilometers of forest land, and 1.4 kilometers of grassland area. The runoff coefficients of cultivated area, forest land, and grassed area are 0.25, 0.15 and 0.3 respectively.

The main drainage channel has a fall of 25 meters in the total length of 2.5 kilometers. The intensity duration frequency relationship for the watershed is expressed as i equals to 700 T to the power 0.25 where capital T is the recurrence interval in years, and in the denominator, we have T c plus 15 to the power 1.

For a recurrence interval of 20 years, find the peak rate of runoff for the watershed in cubic meters per second, and this question has been taken from GATE 2014 examination. So, the rational formula just repeats Q_P = C i A where Q is the peak rate of runoff in cubic meters per second, C the runoff coefficient, i is the rainfall intensity in meters per second for the duration equal to the time of concentration of the watershed and for the desired return period and a is the area of the watershed in square meters. So, that is what we know about the rational formula.

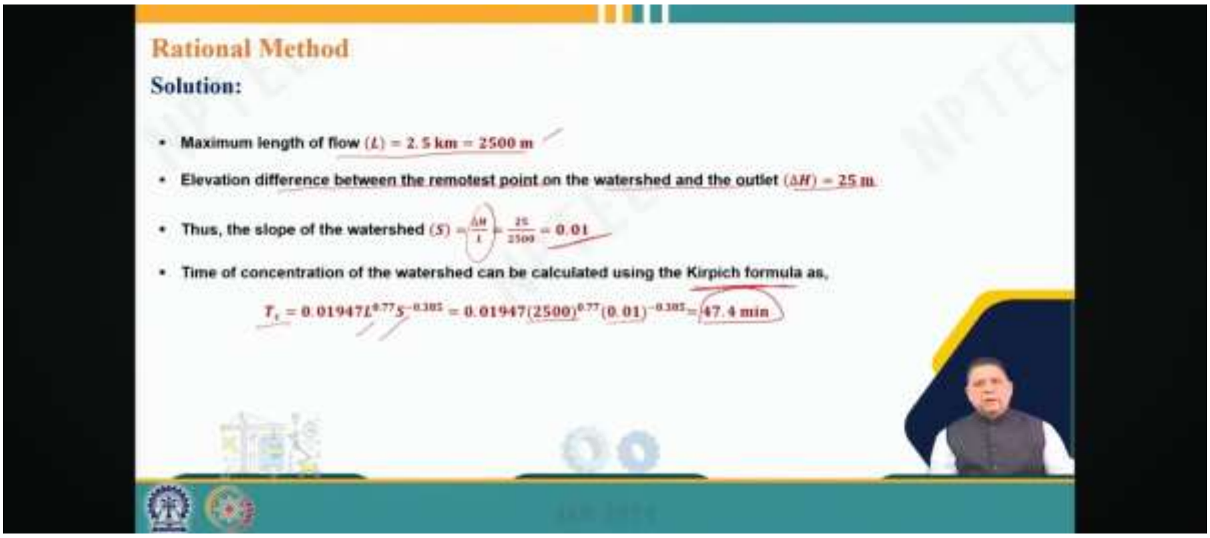


Now, because this particular watershed has multiple land uses, so obviously, we have to use the weighted runoff coefficient. As per data, we have cultivated area, forest area, and grassed area, the area under each category of 1.8 square kilometers, 2.2 square kilometers, and 1.4 square kilometers, respectively. We have also been given the values of the runoff coefficient applicable to these land uses: for cultivated area, it is 0.25; for forest land, it is 0.15 and for grass area, it is 0.13.

So, obviously, using the information, we can easily calculate the weighted runoff coefficient, which will be used in the rational formula as the sum of j from 1 to n of $C_j * a_j$ divided by the sum of the total area, where j is a number of lands uses here. So, in this case, it is 3, so that is why it is 0.25 times 1.8 for cultivated area, 0.15 times 2.2 for the forest area, and 0.3 times 1.4 for the grassed area. Then we have the total sum area of the entire land which is the sum of all these 3.

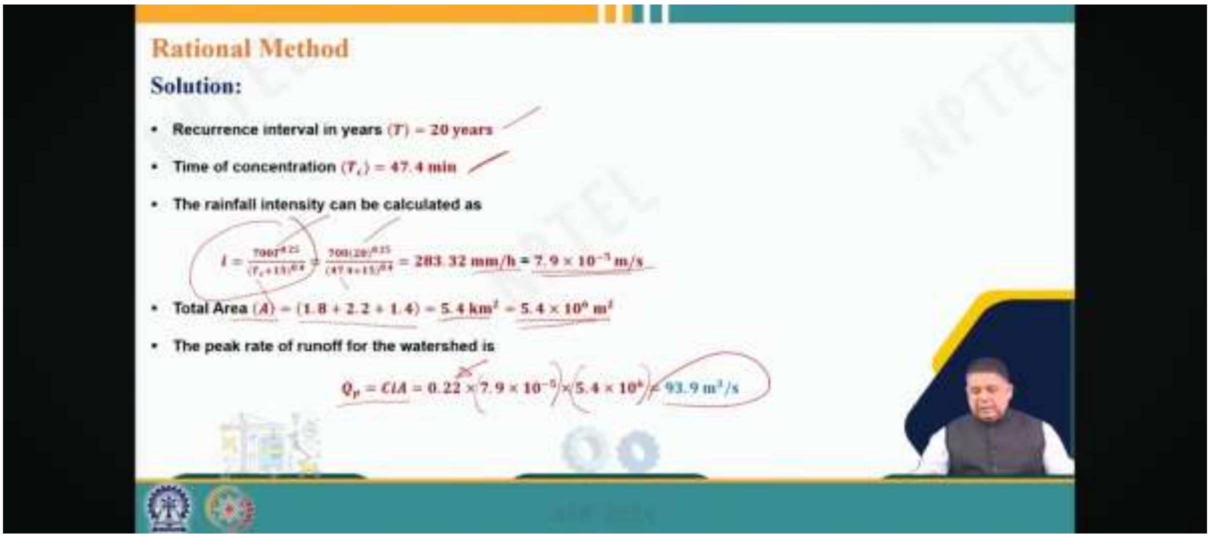
Using this, we get a weighted runoff coefficient of 0.22, wherein we saw that the runoff coefficient varies from 0.15 to 0.3 for different land uses but in our final application, we will use a runoff coefficient value of 0.25. Next, we need to calculate the rainfall intensity which obviously, we have to use the given intensity-duration curve relationship, which is given here.

Now, the recurrence interval is already given to us in the problem, but we need to determine the time of concentration of the watershed. And as we mentioned, there are several methods, but the Kirchhoff formula is the most formula for determining the recurrence interval, and as per this formula, T_c is 0.01947 times L to the power 0.77 times H to the power -0.385, where L is the flow length as the land slope or the watershed slope, and these are in meters. T_c is given in minutes as per this Kirchhoff formula. So, the maximum length of flow value is already given in the problem; it is 2.5 kilometers.



So, when we convert it to meters, it comes out to 2500 meters. The elevation difference between the remotest point of the watershed in the outlet delta H is given as 25 meters. So, obviously, the slope will be calculated by this ratio: delta H by L. So, from here, we get the slope of the watershed as 0.01 and thus, ah, we can calculate the time of concentration because we know L, we know S.

So, by putting these values of L equals to 2500 and S equal to 0.01, we get a value of T_c as 47.4 minutes from the ah Kirchhoff formula. And now we know the return period and also the time of concentration we have determined. So, that means the recurrence interval is 20 years and the time of concentration just now we determined is 47.4.



So, obviously, using the rainfall intensity duration frequency relationship which is given here. So, by putting the value of T = 20 and T_c = 47.4, we can get the value of intensity which comes out to be 283.32 millimeters per hour or because we want it in meters per second.

$$Q = CIA$$

Where:

- Q represents the peak flow rate in cubic meters per second (m33/s),

- C is the runoff coefficient,
- I is the intensity of rainfall in meters per second (m/s) and
- A is the area of the watershed in square meters (m^2).

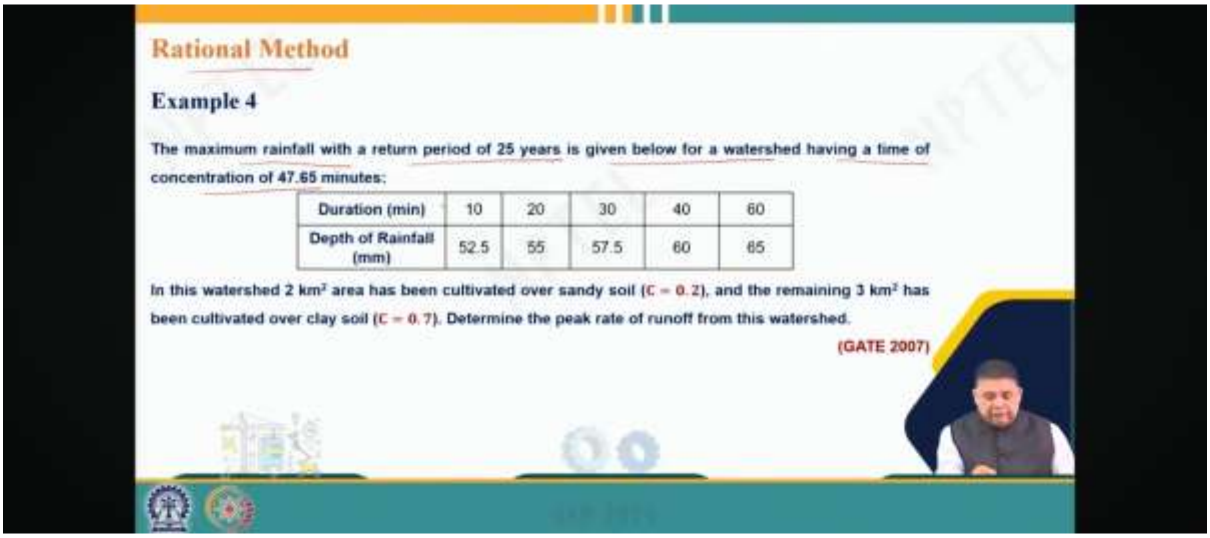
Given:

- C = 0.22 (runoff coefficient),
- $I = 7.9 \times 10^5$meters per second (intensity of rainfall),
- $A = 5.4 \times 10^5$ square meters (area of the watershed).

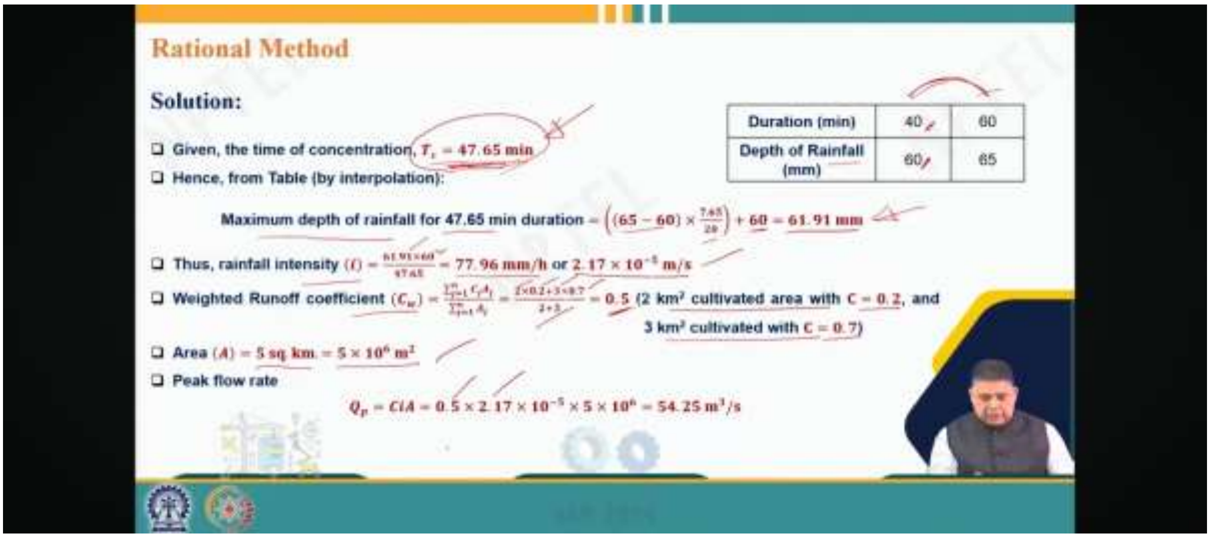
Putting the values into the formula:

$$Q = (0.22) \times (7.9 \times 10^5) \times (5.4 \times 10^6)$$

So, this is I, this is A, and then simply we get Q P value of 93.9 cubic meters per second, that is the discharge, the peak rate of runoff from the watershed is 93.9 cubic meters per second with the given information, that is the final answer of this particular question. Then we go to example number 4 again; we still remain in the rational method, another variant of this particular problem.



So, that is the maximum rainfall with the return period of 245 years is given below for a watershed having a time of concentration of 47.65 minutes. So, we have been given time of concentration and maximum rainfall of return period of 24 hours is given for different durations like you see duration and depth of rainfall. So, duration 10 minutes, 20 minutes, 30, 40, 60 and we have a rain depth of rainfall is 52.5, 55, 57.5, 60, and 65. So, this information is already provided to us in this watershed 2 square kilometers area has been cultivated over sandy soil where C value is 0.2 and the remaining 3 square kilometers has been cultivated over clay soil where C equals to 0.7. Determine the peak rate of runoff for this watershed and this question has been taken from GATE 2007 question paper. So, of course, we have been given time of concentration here.



So, and also, we have given for different durations what is the depth of rainfall. So, obviously, using these 3 pieces of information, we have to determine the maximum depth of rainfall that would occur over this time of concentration of 47.65 minutes and obviously, I have just used the truncated table here because our time of concentration lies between these 2, 40 and 60 minutes. So, of course, we have to have linear interpolation here. So, we will use 40 and the depth of rainfall 60 as the base values which are here, and then we will know that over these 20 minutes the rainfall is 5 mm.

So, that means, 5 by 20 multiplied by 7.65, so that means, we will get the maximum depth of rainfall for a 47.65-minute duration as 61.91 millimetres which is, of course, in between these 2 values as you can see, which is expected also. Now, we know that for a given duration what is the depth of rainfall.

So, we can find out the rainfall intensities. So, the rainfall intensity will be 61.91, which we calculated, divided by the duration 47.65, and of course, multiplied by 100 in order to get the value in millimeters per hour. So, it is 77.96 millimeters per hour but because we use meters per second.

Given:

- Rainfall intensity (I) = 2.17 × 10^{-5} meter per second
- Area under land use with runoff coefficient (C) = 2 square kilometers with C = 0.2 and 3 square kilometers with C = 0.7
- Total area (A) = 5 square kilometers = 5 × 10^{6} square meters

We need to calculate the peak discharge (Q_p) using the Rational Formula:

$$\boldsymbol{Q_p = C \times I \times A}$$

Step 1: Convert area to square meters:

$$A = 5\times10^{6} \text{ square meters}$$

Step 2: Calculate the weighted runoff coefficient (C_w):

$$C_w = \frac{\sum(C \times A)}{A}$$

Where:

- C_1=0.2 (for 2 square kilometers)
- C_2=0.7 (for 3 square kilometers)
- A_1=2 × 10^6 square meters
- A_2=3 × 10^6 square meters

$$C_w = \frac{(0.2 \times 2 \times 10^6)+(0.7 \times 3 \times 10^6)}{5 \times 10^5}$$

$$C_w = \frac{400{,}000 + 2{,}100{,}000}{5{,}000{,}000}$$

$$C_w = \frac{2{,}500{,}000}{5{,}000{,}000}$$

$$C_w = 0.5$$

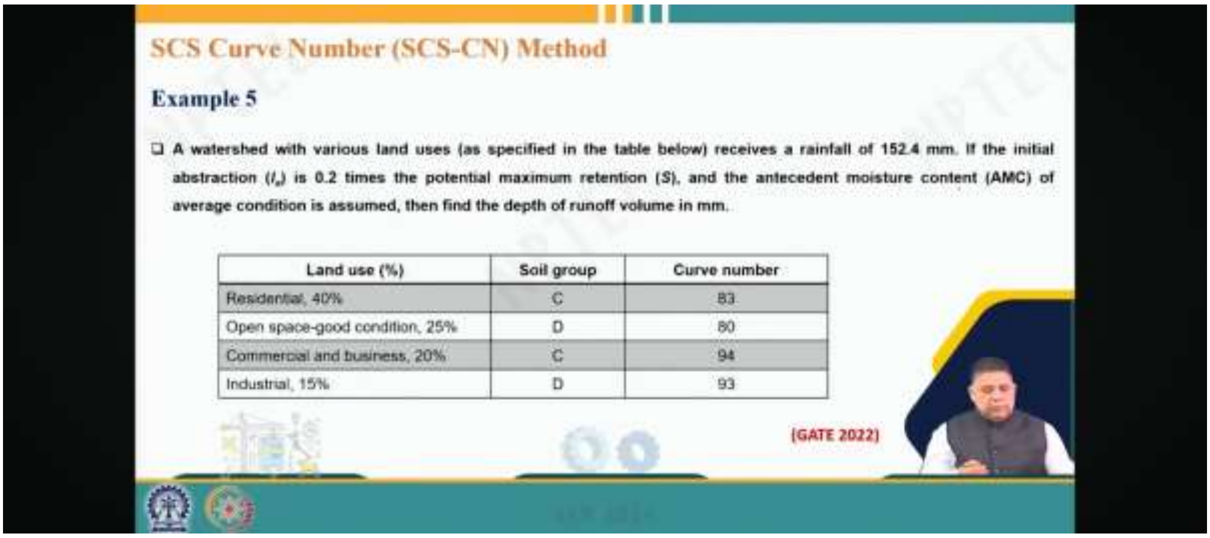
Step 3: Calculate peak discharge:

$Q_p = C_w \times I \times A$

$Q_p = 0.5 \times 2.17 \times 10^{-6} \times 5 \times 10^6$

Q_p = 54.25 cubic meters per second

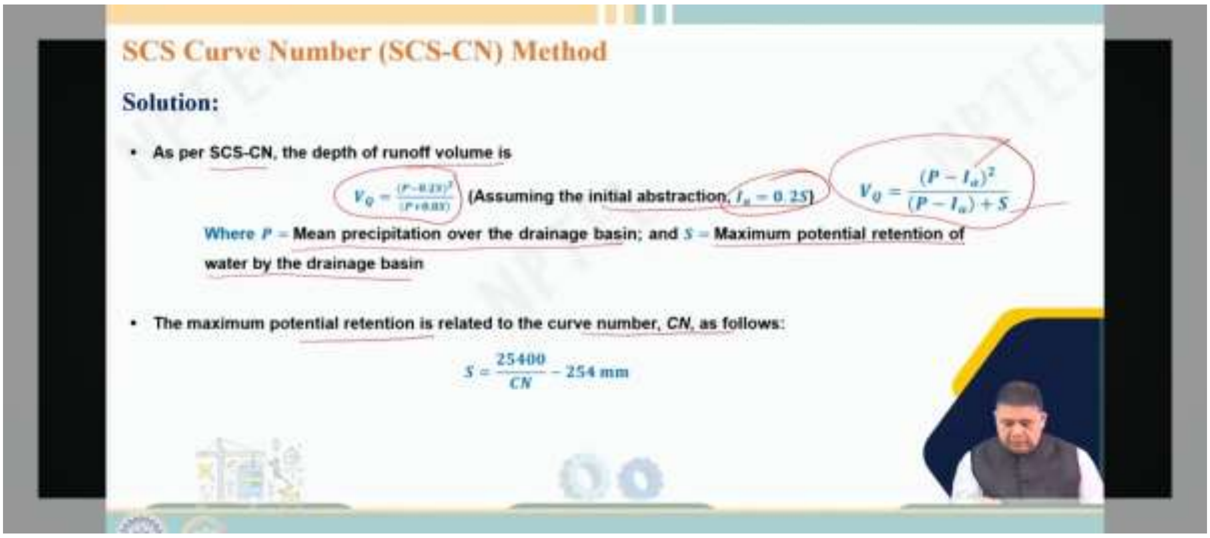
Thus, for this problem the peak discharge (Q_p) is calculated to be 54.25 cubic meters per second.



Land use (%)	Soil group	Curve number
Residential, 40%	C	83
Open space-good condition, 25%	D	80
Commercial and business, 20%	C	94
Industrial, 15%	D	93

Now, we go to the next example where we start with SCS curve number method example 5. A watershed with various land usages is specified in the table here, receives a rainfall of 152.4 millimeters. If the initial abstraction is 0.2 times the potential maximum retention, the antecedent moisture content (AMC) of average condition is assumed, then find the depth of runoff volume in millimeters.

So, almost all the information is given here and you have land use percentages as follows: 40 percent under residential, 25 percent under open space in good condition, 20 percent under commercial and business, and 15 percent industrial. Soil groups are also categorized into 2 cases of soil group C and 2 other cases of soil group D. The applicable curve numbers are also provided here, and this question is taken from the GATE 2022 question paper.



The runoff volume equation with the initial abstraction (IA) and maximum potential retention (S) terms is given by:

$$\boldsymbol{V_q = P - 0.2S^2 + P + 0.2SI_A}$$

Where:

- V_q is the depth of runoff volume (in millimeters).
- P is the mean precipitation over the drainage basin (in millimeters).
- S is the maximum potential retention of water by the drainage basin (in millimeters).
- IA is the initial abstraction (in millimeters), representing the loss of water before runoff begins.

When $IA \neq 0.2S$, we can set IA=$0.2S$ and rewrite the equation as:

$$\boldsymbol{V_q = P - IA + P + IA}$$

$$\boldsymbol{V_q = 2P}$$

This simplification assumes that the initial abstraction (IA) is equal to 0.2 times the maximum potential retention (S).

We can then use the raw version of this formula in terms of IA and S. If IA could be other than $0.2S$, we can manipulate this formula accordingly. Maximum potential retention (S) is related to the curve number and this relationship will give us S in millimeters.

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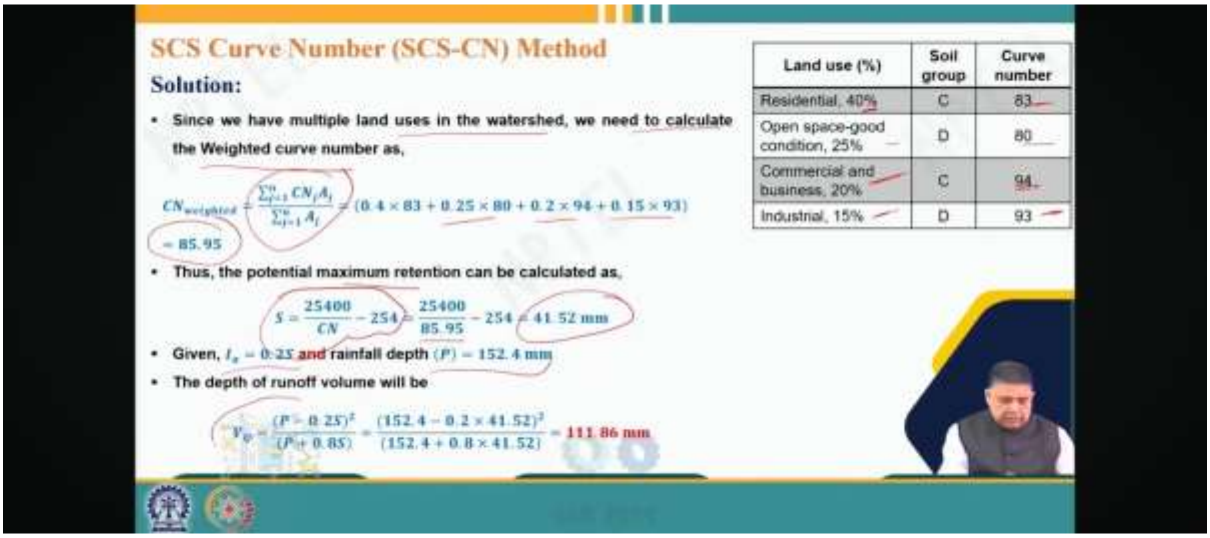
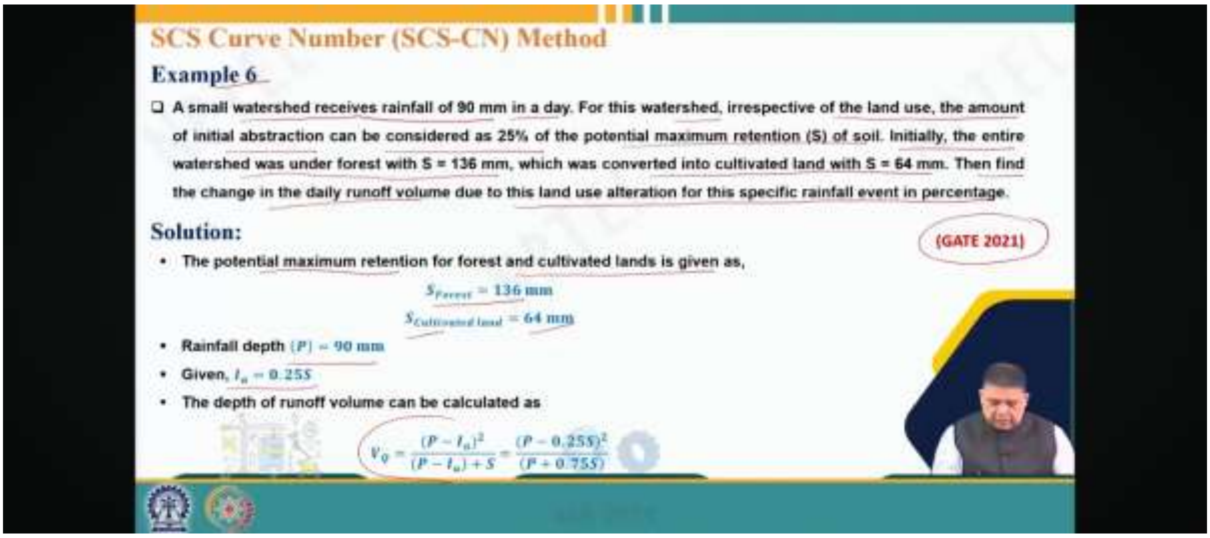
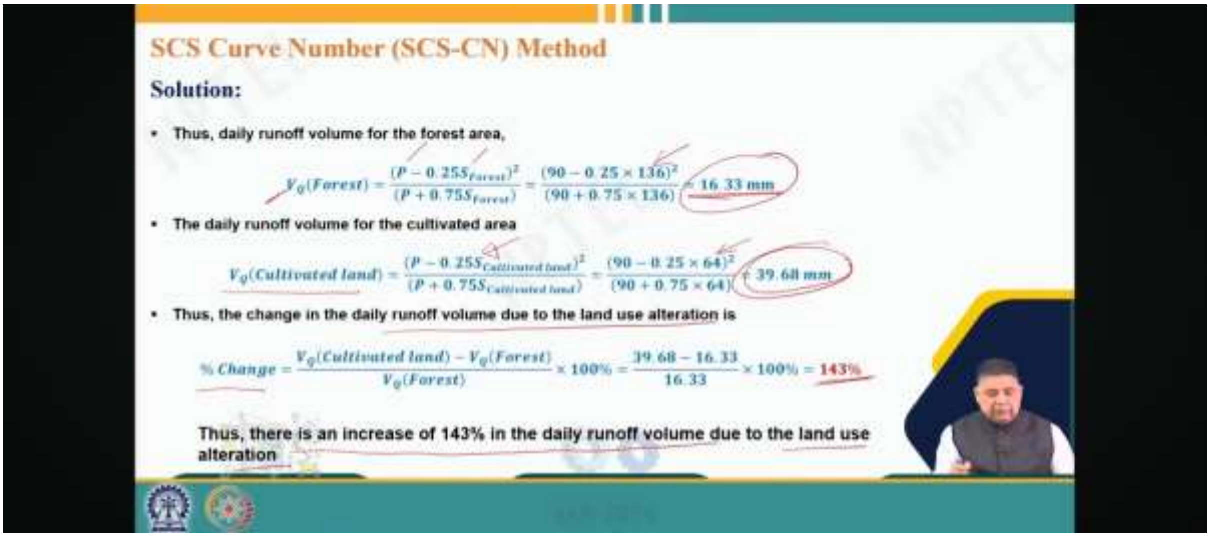
Now, since we have multiple land uses in the watershed, the same table is reproduced with different curve numbers. Therefore, we obviously need to use the weighted curve number and the same formulation used for the runoff coefficient earlier. We apply a similar formula in this case.



So, of course, it is already given in percents. So, 0.4 × 83, that is the value for residential area, 0.25 × 80 for open spaces, 0.2 × 94 for commercial and business and 0.15, which is 15 percent area, that is 0.15 into 93 for industrial area. So, we get a weighted curve number of 85.95 and once we know the curve number, we can determine S using this relationship and by putting the curve number of 85.95, we get potential maximum retention as 41.52 millimeters. And we already know that IA is given as 0.2S and rainfall depth is 1,152.4 mm. So, obviously, we can use it because IA = 0.2S. So, we can use this formulation directly, meaning if we have to just put the value of P and the value of S here. P value is already given and S value we have determined. So, by putting this value, we get the rain runoff depth volume, which comes out to be 111.86 millimeters per SCS curve number method. So, this is one application of SCS curve method for a given problem.



Then we go into example 6, and this example says that a small watershed receives rainfall of 90 millimeters in a day. For this watershed, irrespective of land use, the amount of initial abstraction can be considered as 25 percent of potential maximum retention of soil. So, here you see there is a variation. It is IA is not 0.25 S, but 25 percent, 0.25. Initially, the entire watershed was under forest with S equal to 136 mm, which was converted into cultivated land with S equals to 64. Find the change in daily runoff volume due to this land use alteration for the specific rainfall event in percentage and this question is from GATE 2021. And as you can see, the material potential maximum retention for the forest and cultivated lands are given. So, S forest, just for distinction, we are writing as far as 136 mm and S cultivated land is 64 mm. Rainfall depth is given as 50, P = 90 millimeters, and IA is given as 0.25 S. So, that means, we have to use the original formulation P - IA. So, also putting IA equals to 0.25 S, we can get in terms of S.

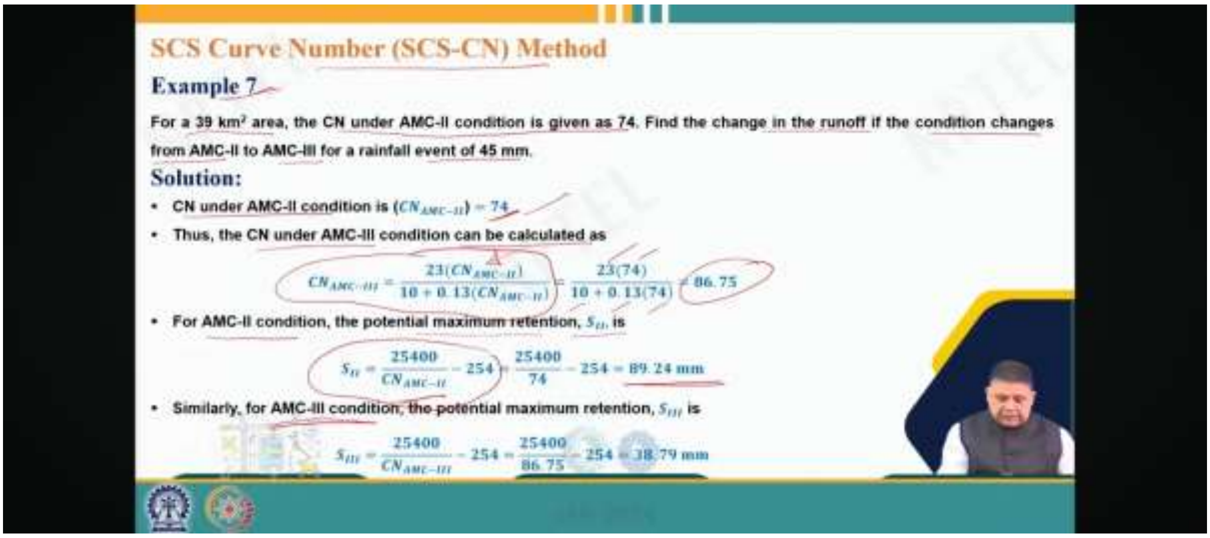


This is the formulation. So, instead of calculating IA separately, we are just manipulating this formula.

$$P - \frac{0.25S^2}{2P} + 0.2 \times 0.75S$$

Now, we know the value of P and we know the value of S for forest as well as for cultivated land. So, we can calculate runoff depth volume for both types of land uses. So, VQ forest by putting the values of P and S forest we get a value of 16.33 millimeters and the daily runoff volume for cultivated area again for cultivated area we have to change the value of S, which is 64 against 136 here.

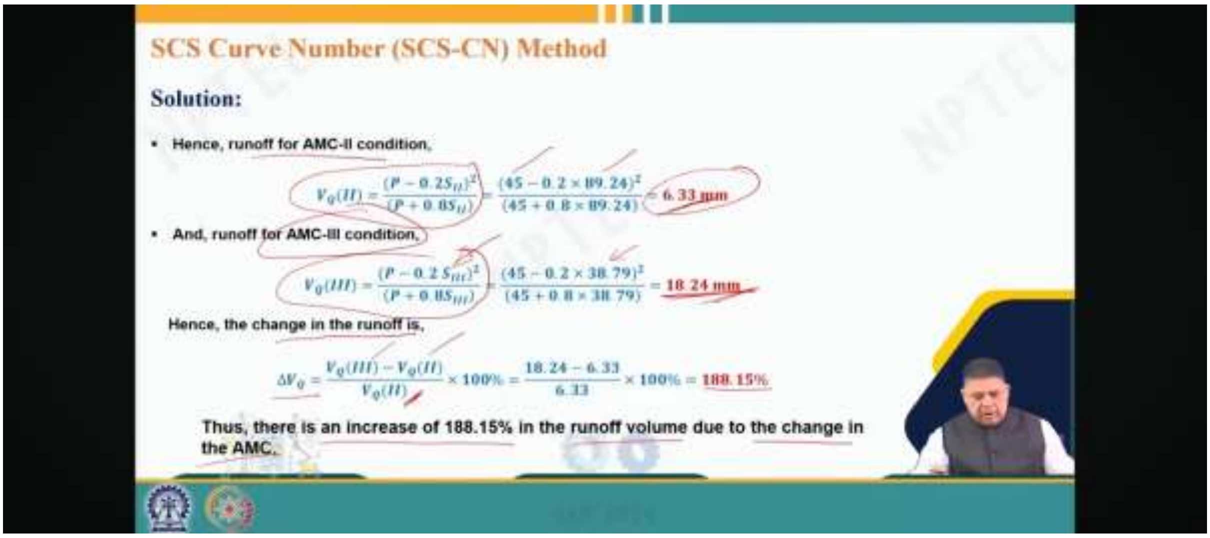
So, we get a value of 39.68 millimetres. Thus, the change in daily runoff volume due to land use alteration is, of course, in the forest case it was 16.33, now it is 39. So, it is quite expected that if land conversion is there from forest to cultivated land, we will get higher runoff. So, that is why the percentage change; there is an increase in runoff volume and that is a 143 percent increase. So, there is an increase of 143 percent in daily runoff volume due to land use alteration, that is from forest land to cultivated land runoff goes up by 143 percent.



Now, we get into example number 5 and example number 7, sorry again we are with SCS curve number method. So, for a 39 square kilometre area, the curve number under AMC_2 condition is given as 74. Find the change in runoff if the condition changes from AMC_2 to AMC_3 for a rainfall event of 45 mm. So, that is the problem, and coming to solution we have already been given CN under AMC_2 condition is 74. So, CN AMC_2 is 74 and thus the CN under AMC_3 condition can be calculated, we already saw that we have both table as well as direct formula.

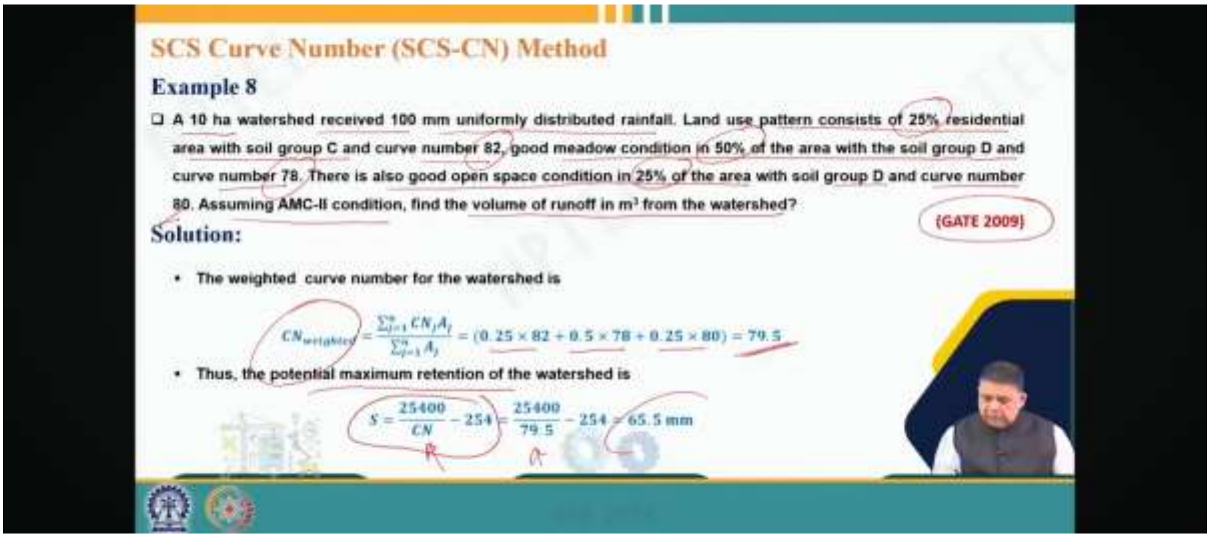
So, we can use the formula where CN AMC_3 is related to CN AMC_2 in the following form, and then knowing CN AMC_2, which is curve number for AMC_2, which is 74, we replace in this equation or substitute in this equation. So, we get 23 times 74 10 plus 0.13 times 74 and the curve number for AMC_3 comes out to be 86.75 higher because we remember that AMC_2 condition is the various condition where AMC_3 is wet condition, that means we will be having higher runoff in this case because the already wet condition is there. So, for AMC 2 condition, the potential maximum retention S 2 is, we are using this relationship, we know the curve number value.

So, this value comes out to be by putting the value of curve number AMC_2, we get is 89.24 mm and similarly for AMC_3 condition, the potential maximum retention S 3 is, by putting these values, AMC 3 of 86.75, we get S S 3 value is 38.79 millimeters.



So, both conditions, we know the S value or potential maximum retention. Now, runoff for AMC 2 condition, because we already know the S value. So, using this formulation, we also know that I is 0.2 times S; it is given already in the problem. So, using this formulation by putting the value of P and the value of S, we can calculate the value of V q, which comes out to be 633 mm, that is when AMC 2 condition is there in the watershed. If when the condition changes to AMC 3, then again, we have to use this relationship; the value of S in this case will be different, and it is now we are using 38.79, and it comes out to be 18.24 mm. So, from 633 mm to 18.23, that means there is an increase in runoff which is expected because of the weight conditions in AMC 3.

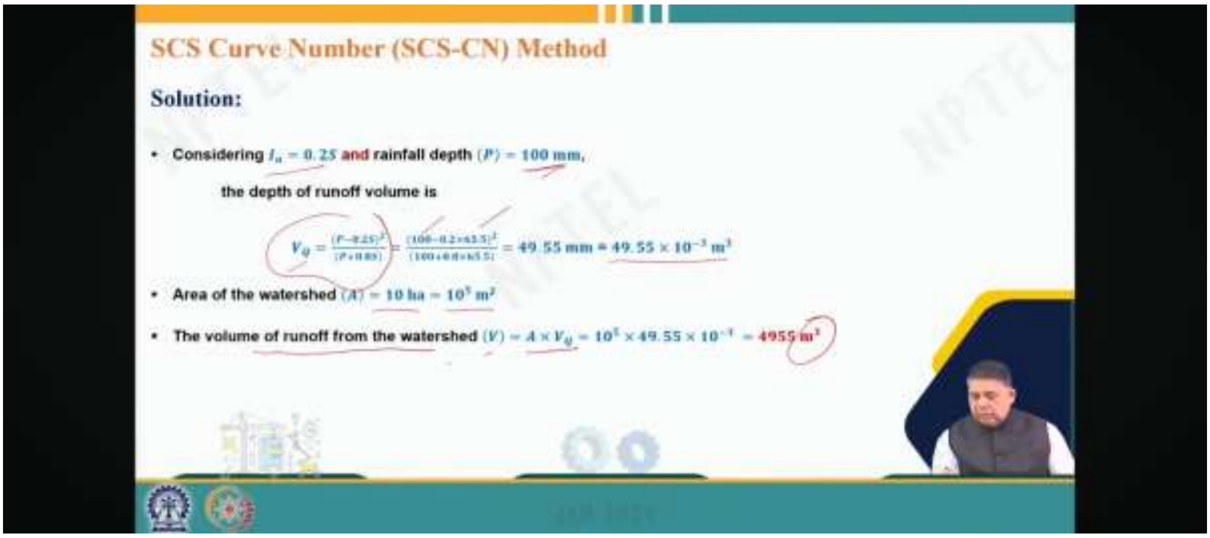
Hence, the change in runoff we can calculate is $\frac{VQ_3 - VQ_2}{VQ_2}$ because with reference to VQ_2 we are calculating, that is why the denominator is V q 2, and that is why we find that there is a positive value, that is 188.15 percent, which shows that there is an increase of 118.15 percent in the runoff volume due to the change in the AMC condition. So, this is yet another variation of ACS curve number problem. Of course, the concepts remain the same, but the variations could be different terms.



So, now we take the last problem, that is, a 10-hectare watershed received 100 mm uniformly distributed rainfall. The land use pattern consists of 25 percent residential area with soil group C and curve number 82. Good meadow condition at 50 percent of the area with the soil group D and curve number 78. There is also good open space condition in 25 percent area with soil group D and curve number 80. Assuming AMC_2 condition, find the volume runoff in cubic meters from the watershed. This question has been taken from GATE 2009. So, of course, we know that procedure by this time when there are multiple uses, land uses, multiple conditions, then obviously, the curve numbers will vary.

So, we have to, in that case, we have to first calculate the weighted curve number. In this case, we have three different conditions. So, it is given clearly that 25 percent of the area has a curve number of 82 here, 50 percent of the area has a curve number of 78, and the remainder 25 percent of the area has a curve number of 80.

So, it is here. So, the weighted curve number we get is 79.5. So, this is the curve number we get. So, obviously, once the curve number is obtained, the next thing we do is obtain the potential maximum retention of the watershed using this standard relationship. So, by putting the curve number as 79.5 which we have determined, we get a value of 65.5 mm, that is the potential maximum retention of the watershed.



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And, considering IA equals to 0.2S and a rainfall value of 100 mm which is there, the depth of runoff volume will be by this standard relationship where IA equals to 0.2S already put and then putting the value of P and ah equal to 100 and S equal to 65.5, we get VQ equals to 49.55 into 10 to the power minus 3 cubic meters. The area of the watershed is 10 hectares, that is 10^5 square meters. So, the volume of runoff from the watershed V equals to A times V_Q which is in depth units. So, total because we have to give an answer in cubic meters. So, that is why the volume of runoff from the watershed in volumetric unit is 4955 cubic meters. So, we saw that different variants of problems we have seen for Cook's method or rational method or SCS curve number method and I am sure that with the theoretical background we discussed in previous lectures you will be able to solve problems.

Of course, you have to practice a greater number of problems to be efficient. So, that you can solve it at a faster pace. Please give your feedback and also raise your doubts or questions which we can answer in the forum.

Thank you very much.