Surface Water Hydrology
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Lecture – 24
Estimation of Runoff Volume: Conceptual Models

In this specific lecture-24, we are discussing the different conceptual models for the estimation of runoff volume.

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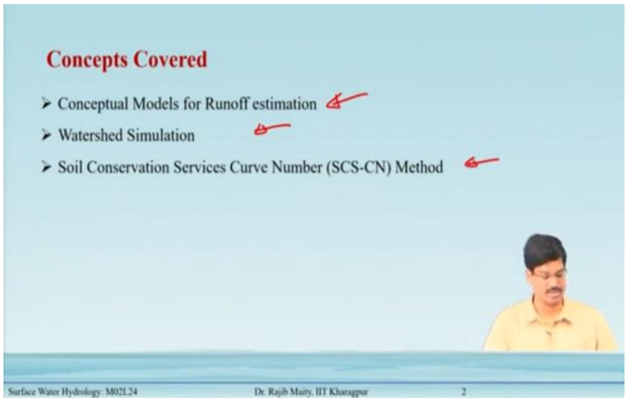

We will be covered in this lecture; the concept of the models for runoff estimation. And two things that we will cover, the watershed simulation as a general approach, what is generally utilized in the conceptual model. And then a specific model which is known as the Soil Conservation Services Curve Number is SCS-CN method will be utilized in this.

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The outline goes like this, introduction to the conceptual model for runoff estimation. And under these two types, one is that watershed simulation, which is a general approach of course; and there are many modeling schemes follow this one. Then the Soil Conservation Service-Curve Number method; There are other types of models are also there, that will just briefly touch upon and then summary.

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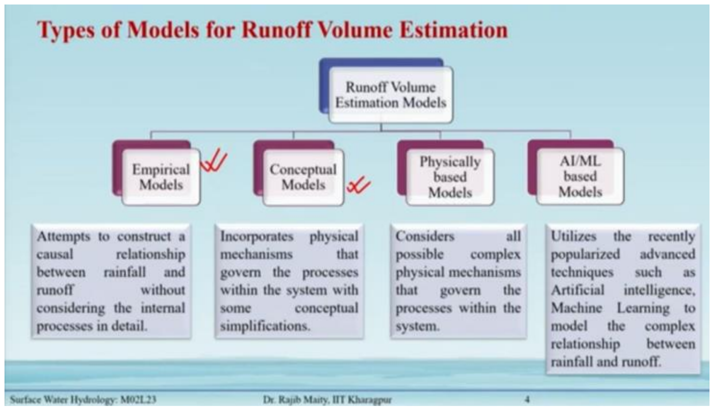

In today's lecture, we are considering this conceptual model mainly; and some brief descriptions also will be given for this physically-based model and AI/ML-based model.

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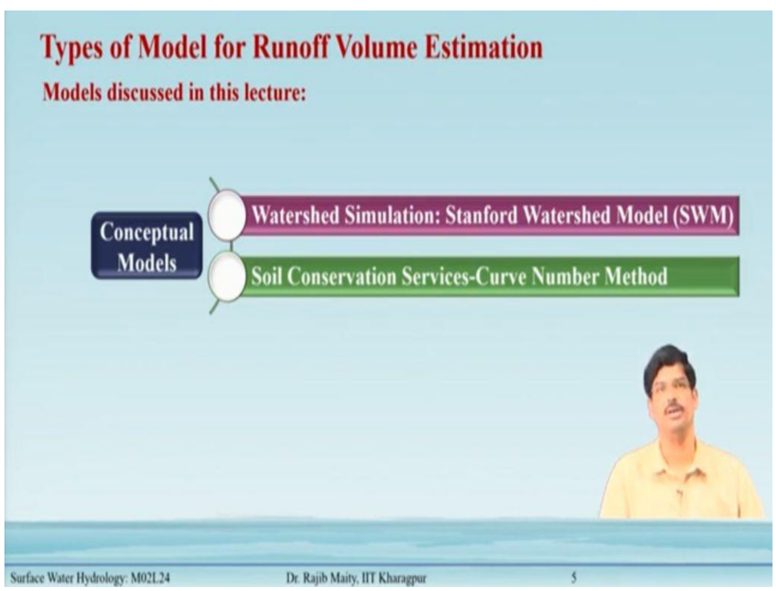

Conceptual Models

Under this category, we are discussing here only two models which are popular

I. Watershed Simulation: Standard Watershed Model (SWM)

II. Soil Conservation Services-Curve Number Method

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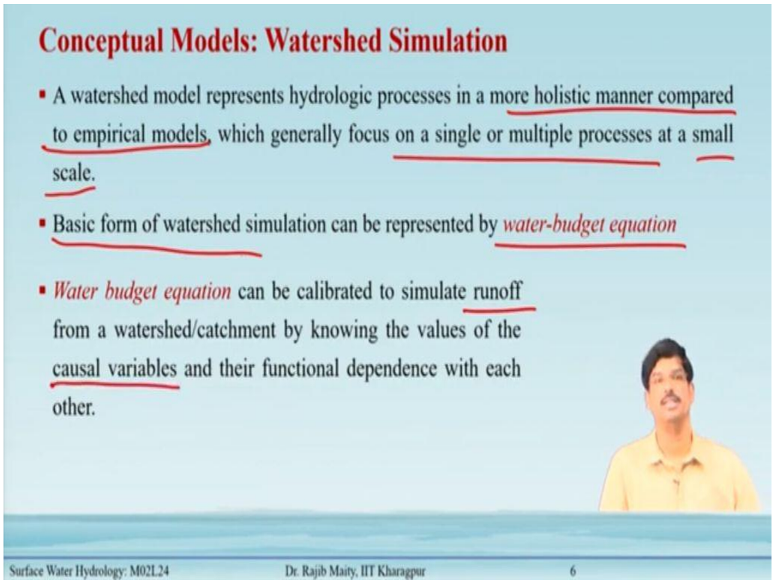

Conceptual Models: Watershed Simulation

A watershed model represents hydrologic processes more holistically compared to empirical models, which generally focus on single or multiple processes at a small scale.

The basic form for any watersheds simulation model comes from the popular water-budget equation; so that we will see how these water-budget equation has been done. So, the fundamental concept is that this water-budget equation is calibrated to simulate the runoff from a watershed or the catchment, by knowing the values of the causal variables, and their functional dependence with each other.

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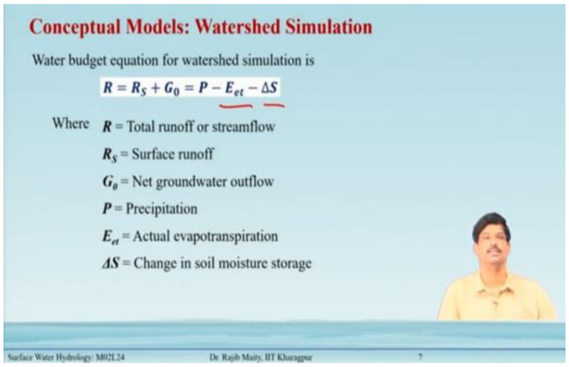

The water budget equation for watershed simulation is

$$R = R_S + G_0 = P - E_{et} - \Delta S$$

Where R = Total runoff or streamflow

R_S = Surface runoff

G_0 = Net groundwater outflow

P = Precipitation

E_{et} = Actual evapotranspiration

ΔS = Change in soil moisture storage

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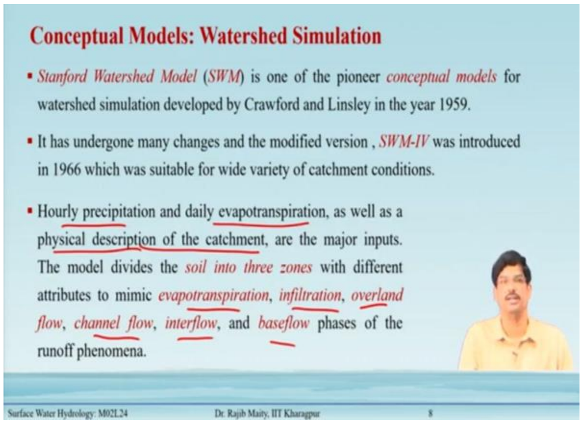

Stanford Watershed Model (SWM) is one of the pioneer conceptual models for watershed simulation developed by Crawford and Linsley in the year 1959. It has undergone many changes and the modified version, SWM-IV was introduced in 1966 which was suitable for a wide variety of catchment conditions.

Hourly precipitation and daily evapotranspiration, as well as a physical description of the catchment, are the major inputs. The model divides the soil into three zones with different attributes to mimic evapotranspiration, infiltration, overland flow, channel flow, interflow, and base flow phases of the runoff phenomena.

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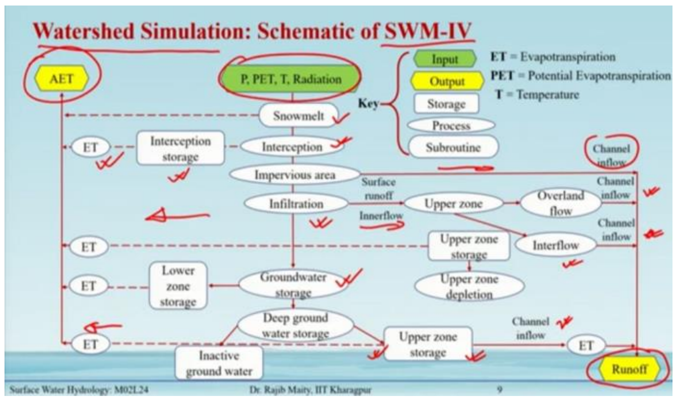

Watershed Simulation: Schematic of SWM-IV

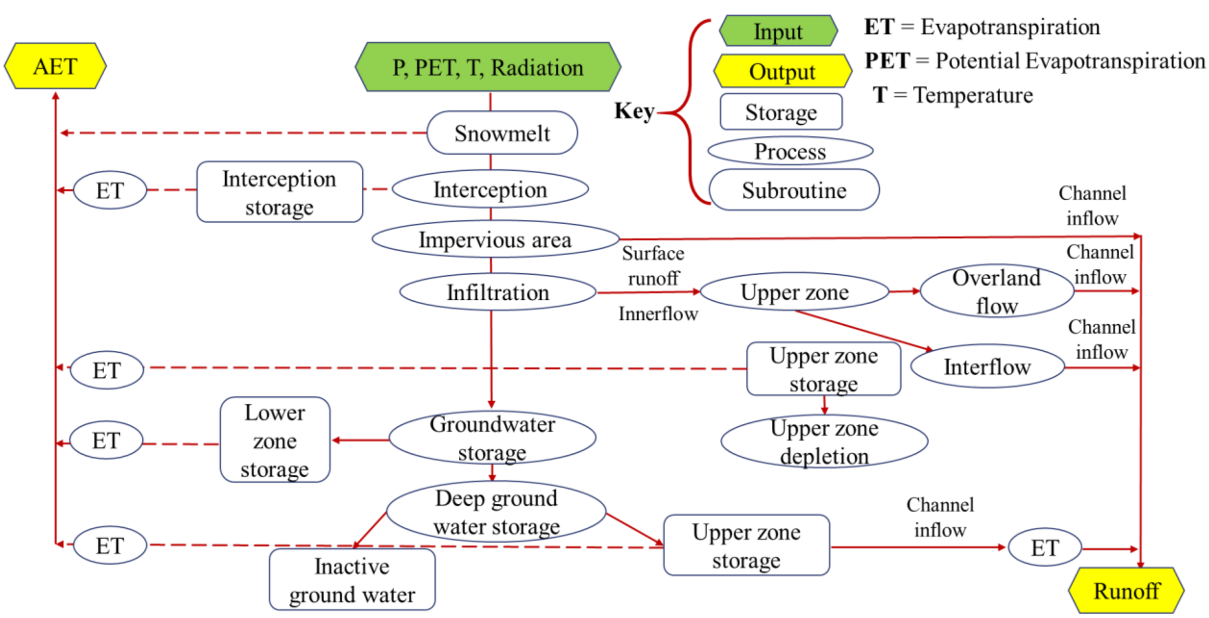

Fig.1 shows the Schematic diagram of the SWM-IV

On a watershed scale, all the quantities and all the processes are modeled into the three different zones; and the schematic diagram can be shown in fig.1. The causing the input to the system, input to the modeling scheme is the precipitation, then potentially evapotranspiration, then temperature and radiation. And it causes different processes; it influences the snowmelt in influence the interception. So, these all contribute to some extent that goes through the actual evapotranspiration.

So, that is also one side of it, because whatever the input comes in terms of the precipitation; as you see that in this modeling flowchart, goes towards the left-hand side, going via evapotranspiration as a loss to this. And similarly, for the different precipitation that comes to the right-hand side, it comes to different processes again. So from the impervious area, it directly goes to the channel flow.

If it goes through the process of infiltration, some part goes to the groundwater storage, and some part goes to the via interflow and goes to the upper zone. And from the upper zone, it goes to the again back to the overland flow and can join to the channel flow. Some parts can go to the interflow, and again then join the channel flow. Similarly, when it comes to the groundwater storage here, this groundwater storage can go to the deep groundwater storage part; that again comes to the uppers zone depending on the topography at some other region.

And which again joined to the channel flow, mainly through the base flow. And that comes through the ET and it joins to this final output as a runoff. From this deep groundwater storage, some inactive groundwater where it flows and some part from this upper zone, it can go again to this evapotranspiration and join to the actual evapotranspiration.

In fig.1 the schematic diagram considered by this is SWM; but this kind of conceptualization how it flows, how it is losses in the different processes. Depending on that there are different modeling schemes can be developed.

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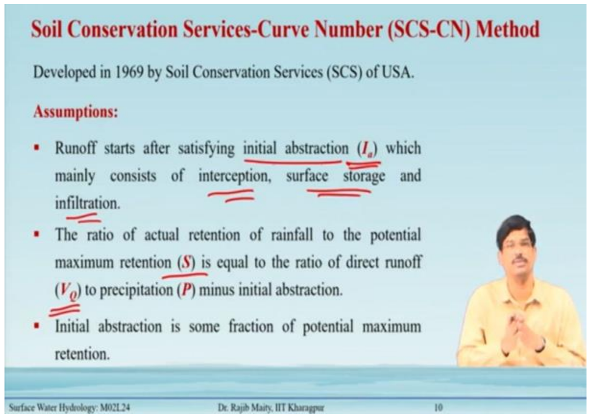

Soil Conservation Services-Curve Number (SCS-CN) Method

Developed in 1969 by Soil Conservation Services (SCS) of the USA.

Assumptions:

- Runoff starts after satisfying initial abstraction ($\boldsymbol{I_a}$) which mainly consists of interception, surface storage, and infiltration.
- The ratio of actual retention of rainfall to the potential maximum retention ($\boldsymbol{S}$) is equal to the ratio of direct runoff ($\boldsymbol{V_Q}$) to precipitation ($\boldsymbol{P}$) minus initial abstraction.
- Initial abstraction is some fraction of potential maximum retention.

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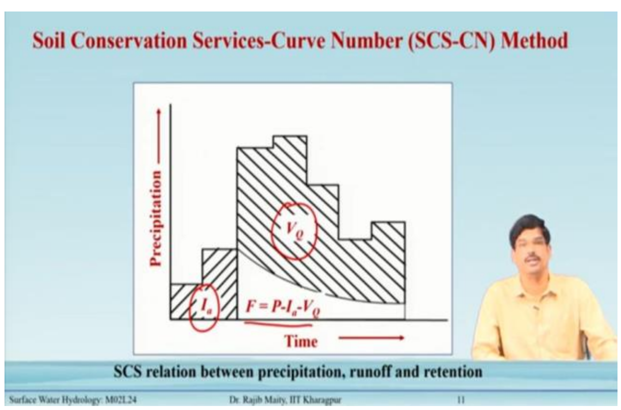

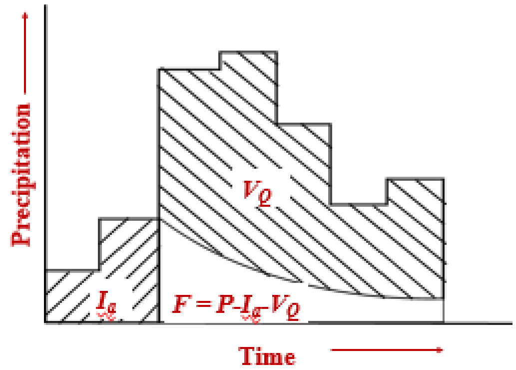

Fig.2 shows the SCS relation between precipitation, runoff, and retention

In fig.2, this is a rainfall hydrograph that intensity is shown over time; and this is some part that is the initial abstraction. And this is a V_Q that comes as runoff and this F part is lost during the process. So, it shows SCS the relation between the precipitation runoff and retention

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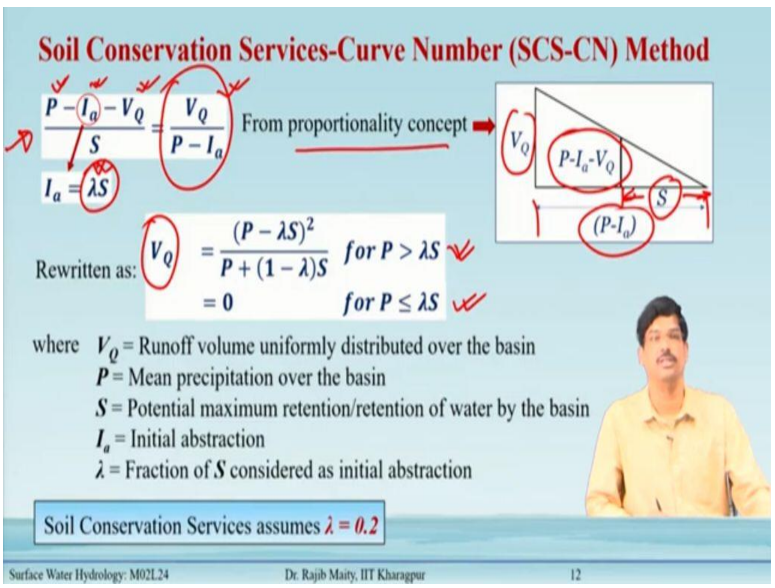
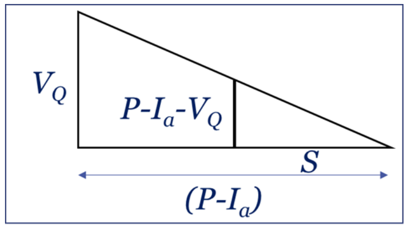


The basic equation from where this SCS-Curve Number method starts as follows.



From proportionality concept

$$\frac{P - I_a - V_Q}{S} = \frac{V_Q}{P - I_a} \qquad\qquad I_a = \lambda S$$

The above equation is rewritten as:

$$V_Q = \frac{(P - \lambda S)^2}{P + (1 - \lambda)S} \quad for\ P > \lambda S$$

$$= 0 \quad for\ P \leq \lambda S$$

where

V_Q = Runoff volume uniformly distributed over the basin

P = Mean precipitation over the basin

S = Potential maximum retention/retention of water by the basin

I_a = Initial abstraction

λ = Fraction of S considered as initial abstraction

Soil Conservation Services assumes $\lambda = 0.2$

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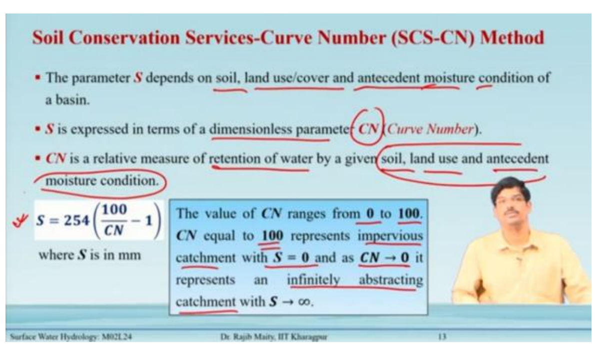

The parameter S is the retention that depends on various factors. It depends mainly on the three major things; the first one is the soil, the second one is the land use/land cover, and the third one is the antecedent moisture condition (AMC). Now, this S the retention is expressed in terms of some dimensionless number, and that is what is known as the curve number CN.

This CN is a relative measure of the retention, relative measure of the retention by a given soil, land use, and the AMC. So, depending on these three factors, this curve number is decided. So, now the relationship is shown here,

$$S = 254\left(\frac{100}{CN} - 1\right)$$

Where S is in millimeter that is retention,

The value of CN ranges from 0 to 100. CN equal to 100 represents impervious catchment with S = 0 and as $CN \rightarrow 0$ it represents an infinitely abstracting catchment with $S \rightarrow \infty$.

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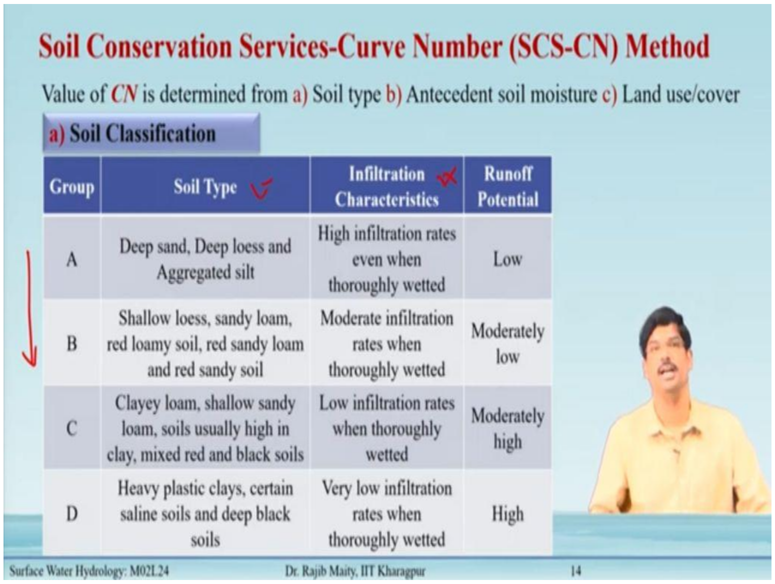
Soil Conservation Services-Curve Number (SCS-CN) Method

Value of *CN* is determined from a) Soil type b) Antecedent soil moisture c) Land use/cover

a) Soil Classification

Group	Soil Type	Infiltration Characteristics	Runoff Potential
A	Deep sand, Deep loess and Aggregated silt	High infiltration rates even when thoroughly wetted	Low
B	Shallow loess, sandy loam, red loamy soil, red sandy loam and red sandy soil	Moderate infiltration rates when thoroughly wetted	Moderately low
C	Clayey loam, shallow sandy loam, soils usually high in clay, mixed red and black soils	Low infiltration rates when thoroughly wetted	Moderately high
D	Heavy plastic clays, certain saline soils and deep black soils	Very low infiltration rates when thoroughly wetted	High

Value of CN is determined from a) Soil type b) Antecedent soil moisture c) Land use/cover

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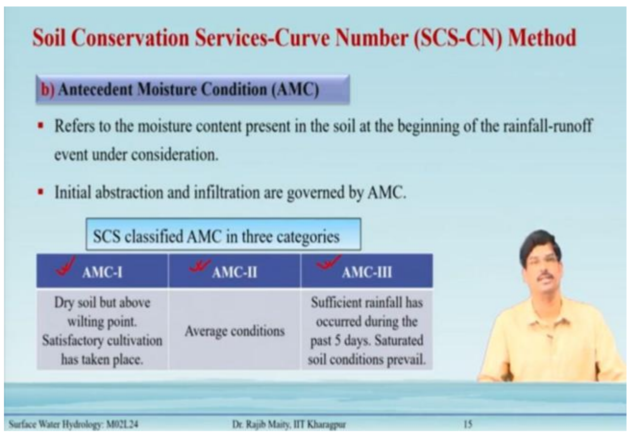

b) Antecedent Moisture Condition (AMC)

Refers to the moisture content present in the soil at the beginning of the rainfall-runoff event under consideration. Initial abstraction and infiltration are governed by AMC.

SCS classified AMC into three categories

AMC-I	AMC-II	AMC-III
Dry soil but above wilting point. Satisfactory cultivation has taken place.	Average conditions	Sufficient rainfall has occurred during the past 5 days. Saturated soil conditions prevail.

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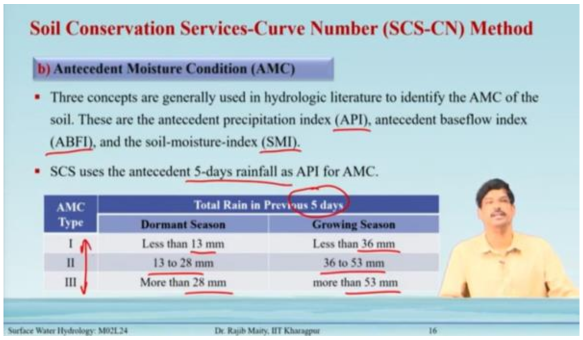

b) Antecedent Moisture Condition (AMC)

Three concepts are generally used in hydrologic literature to identify the AMC of the soil. These are the antecedent precipitation index (API), antecedent baseflow index (ABFI), and the soil-moisture index (SMI).

SCS uses the antecedent 5-days rainfall as API for AMC.

AMC Type	Total Rain in Previous 5 days	
	Dormant Season	Growing Season
I	Less than 13 mm	Less than 36 mm
II	13 to 28 mm	36 to 53 mm
III	More than 28 mm	more than 53 mm

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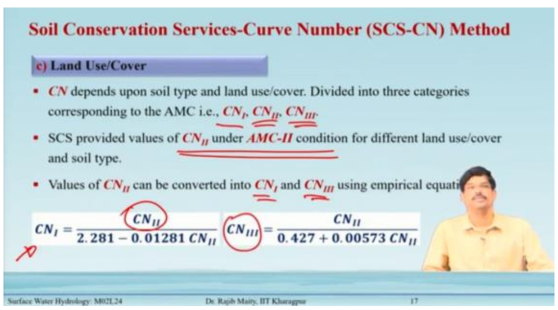

c) Land Use/Cover

CN depends upon soil type and land use/cover. Divided into three categories corresponding to the AMC i.e., CN_I, CN_{II}, CN_{III}. SCS provided values of CN_{II} under AMC-II conditions for different land use/cover and soil types. Values of CN_{II} can be converted into CN_I and CN_{III} using empirical equations.

$$CN_I = \frac{CN_{II}}{2.281 - 0.01281\, CN_{II}} \qquad CN_{III} = \frac{CN_{II}}{0.427 + 0.00573\, CN_{II}}$$

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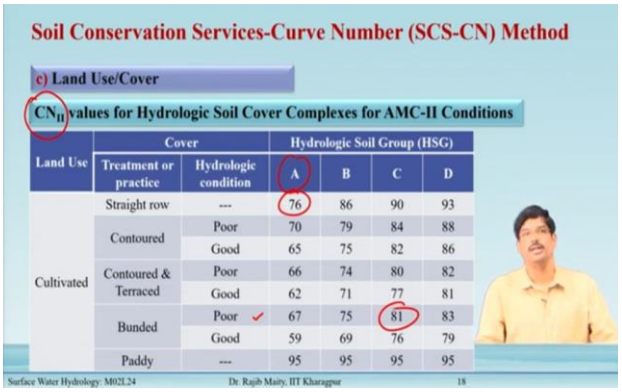
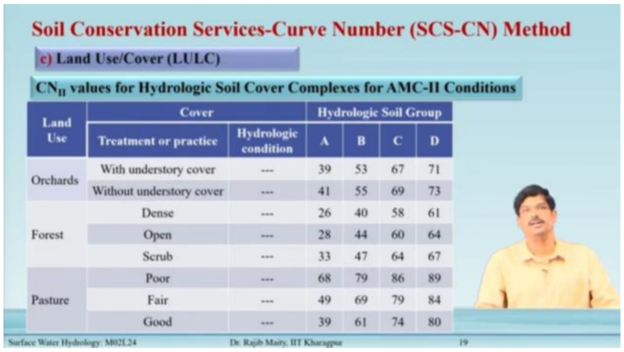
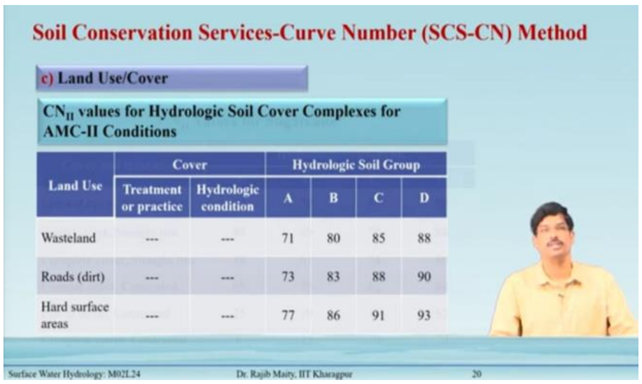


Land Use	Cover: Treatment or practice	Cover: Hydrologic condition	HSG: A	HSG: B	HSG: C	HSG: D
Cultivated	Straight row	---	76	86	90	93
	Contoured	Poor	70	79	84	88
		Good	65	75	82	86
	Contoured & Terraced	Poor	66	74	80	82
		Good	62	71	77	81
	Bunded	Poor	67	75	81	83
		Good	59	69	76	79
	Paddy	---	95	95	95	95



Land Use	Cover: Treatment or practice	Cover: Hydrologic condition	A	B	C	D
Orchards	With understory cover	---	39	53	67	71
	Without understory cover	---	41	55	69	73
Forest	Dense	---	26	40	58	61
	Open	---	28	44	60	64
	Scrub	---	33	47	64	67
Pasture	Poor	---	68	79	86	89
	Fair	---	49	69	79	84
	Good	---	39	61	74	80



Land Use	Cover: Treatment or practice	Cover: Hydrologic condition	A	B	C	D
Wasteland	---	---	71	80	85	88
Roads (dirt)	---	---	73	83	88	90
Hard surface areas	---	---	77	86	91	93

c) Land Use/Cover

CN$_{II}$ values for Hydrologic Soil Cover Complexes for AMC-II Conditions

Land Use	Cover		Hydrologic Soil Group (HSG)			
	Treatment or practice	Hydrologic condition	A	B	C	D
Cultivated	Straight row	---	76	86	90	93
	Contoured	Poor	70	79	84	88
		Good	65	75	82	86
	Contoured & Terraced	Poor	66	74	80	82
		Good	62	71	77	81
	Bunded	Poor	67	75	81	83
		Good	59	69	76	79
	Paddy	---	95	95	95	95

Land Use	Cover		Hydrologic Soil Group			
	Treatment or practice	Hydrologic condition	A	B	C	D
Orchards	With understory cover	---	39	53	67	71
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	Fair	---	49	69	79	84
	Good	---	39	61	74	80

Land Use	Cover		Hydrologic Soil Group			
	Treatment or practice	Hydrologic condition	A	B	C	D
Wasteland	---	---	71	80	85	88
Roads (dirt)	---	---	73	83	88	90
Hard surface areas	---	---	77	86	91	93

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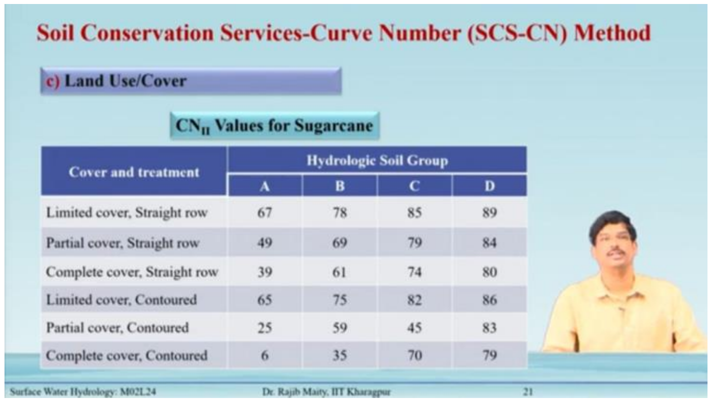

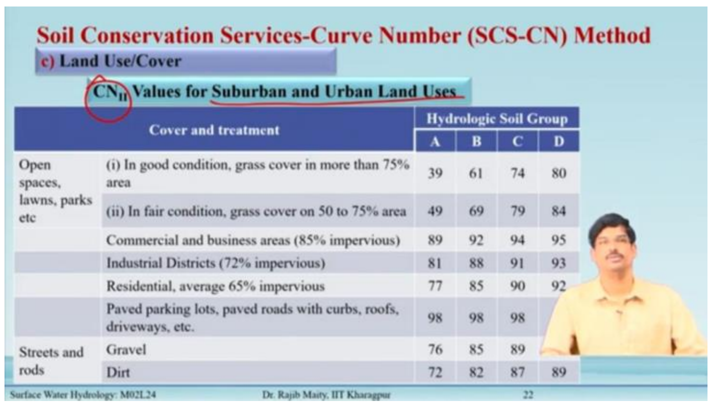

CN_{II} Values for Sugarcane

Cover and treatment	Hydrologic Soil Group			
	A	B	C	D
Limited cover, Straight row	67	78	85	89
Partial cover, Straight row	49	69	79	84
Complete cover, Straight row	39	61	74	80
Limited cover, Contoured	65	75	82	86
Partial cover, Contoured	25	59	45	83
Complete cover, Contoured	6	35	70	79

CN_{II} Values for Suburban and Urban Land Uses

Cover and treatment		Hydrologic Soil Group			
		A	B	C	D
Open spaces, lawns, parks etc	(i) In good condition, grass cover in more than 75% area	39	61	74	80
	(ii) In fair condition, grass cover on 50 to 75% area	49	69	79	84
	Commercial and business areas (85% impervious)	89	92	94	95
	Industrial Districts (72% impervious)	81	88	91	93
	Residential, average 65% impervious	77	85	90	92
	Paved parking lots, paved roads with curbs, roofs, driveways, etc.	98	98	98	98
Streets and rods	Gravel	76	85	89	91
	Dirt	72	82	87	89

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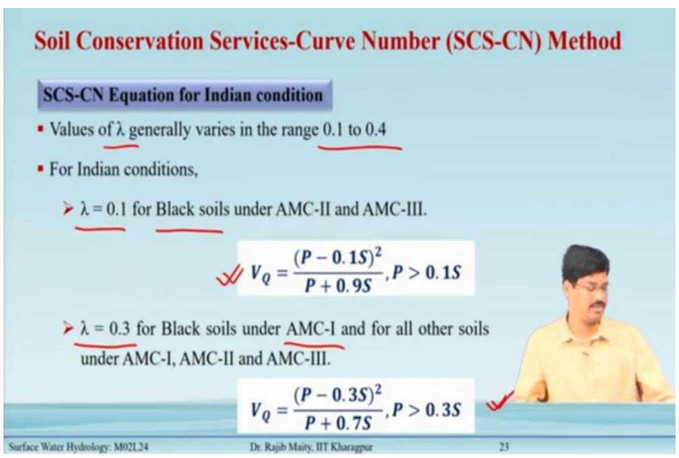

SCS-CN Equation for Indian condition

- Values of λ generally vary in the range of 0.1 to 0.4
- For Indian conditions,
  - λ = 0.1 for Black soils under AMC-II and AMC-III.

$$V_Q = \frac{(P - 0.1S)^2}{P + 0.9S}, P > 0.1S$$

- λ = 0.3 for Black soils under AMC-I and all other soils under AMC-I, AMC-II, and AMC-III.

$$V_Q = \frac{(P - 0.3S)^2}{P + 0.7S}, P > 0.3S$$

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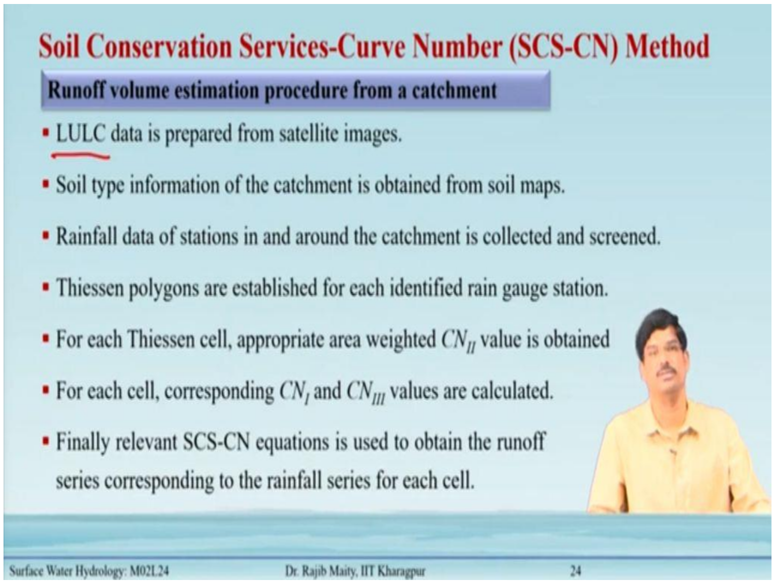

Runoff volume estimation procedure from a catchment

- LULC data is prepared from satellite images.
- Soil type information of the catchment is obtained from soil maps.
- Rainfall data of stations in and around the catchment is collected and screened.
- Thiessen polygons are established for each identified rain gauge station.
- For each Thiessen cell, an appropriate area-weighted CN_{II} value is obtained
- For each cell, corresponding CN_I and CN_{III} values are calculated.
- Finally, relevant SCS-CN equations are used to obtain the runoff series corresponding to the rainfall series for each cell.

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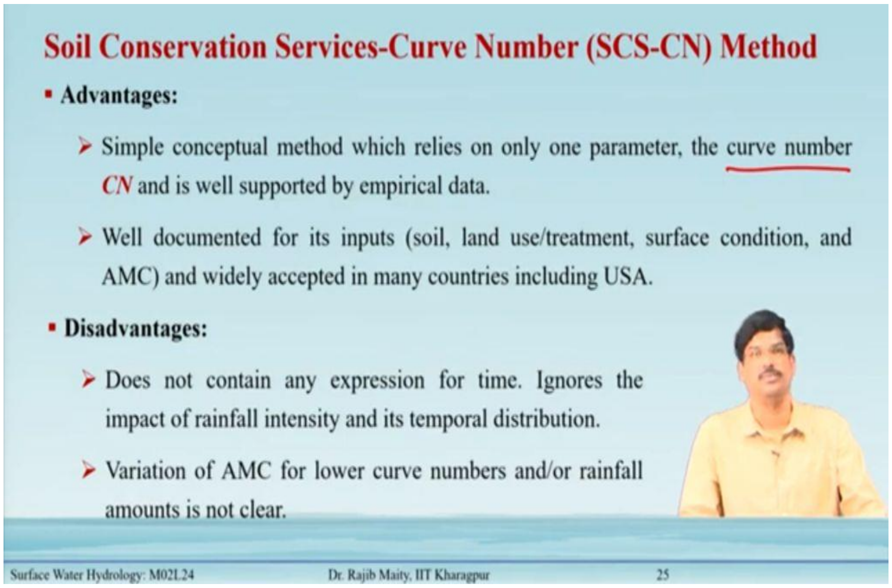

Advantages:

- ➢ The simple conceptual method relies on only one parameter, the curve number ***CN*** and is well supported by empirical data.
- ➢ Well documented for its inputs (soil, land use/treatment, surface condition, and AMC) and widely accepted in many countries including the USA.

Disadvantages:

- ➢ Does not contain any expression for time. Ignores the impact of rainfall intensity and its temporal distribution.
- ➢ Variation of AMC for lower curve numbers and/or rainfall amounts is not clear.

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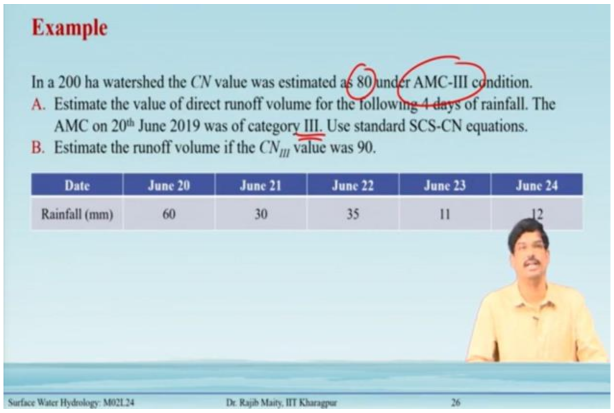

Example

In a 200 ha watershed, the *CN* value was estimated as 80 under the AMC-III condition.

A. Estimate the value of direct runoff volume for the following 4 days of rainfall. The AMC on 20th June 2019 was of category III. Use standard SCS-CN equations.

B. Estimate the runoff volume if the CN_{III} value was 90.

Date	June 20	June 21	June 22	June 23	June 24
Rainfall (mm)	60	30	35	11	12

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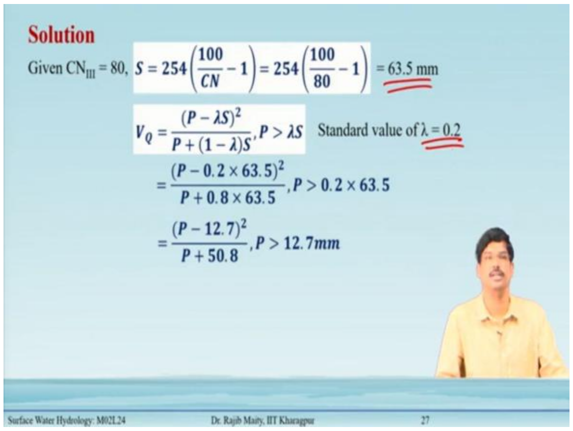

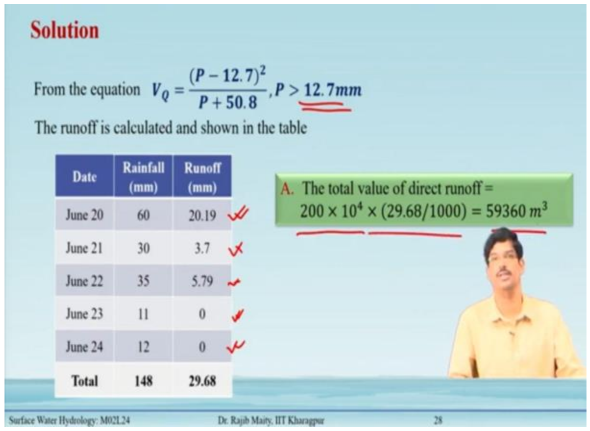

Solution

Given $CN_{III} = 80$, $\boldsymbol{S = 254\left(\frac{100}{CN} - 1\right) = 254\left(\frac{100}{80} - 1\right)}$ = 63.5 mm

$$V_Q = \frac{(P - \lambda S)^2}{P + (1-\lambda)S}, P > \lambda S \quad \text{Standard value of } \lambda = 0.2$$

$$= \frac{(P - 0.2 \times 63.5)^2}{P + 0.8 \times 63.5}, P > 0.2 \times 63.5$$

$$= \frac{(P - 12.7)^2}{P + 50.8}, P > 12.7mm$$

From the equation $V_Q = \frac{(P - 12.7)^2}{P + 50.8}, P > 12.7mm$

The runoff is calculated and shown in the table

Date	Rainfall (mm)	Runoff (mm)
June 20	60	20.19
June 21	30	3.7
June 22	35	5.79
June 23	11	0
June 24	12	0
Total	**148**	**29.68**

A. The total value of direct runoff = $200 \times 10^4 \times (29.68/1000) = 59360\, m^3$

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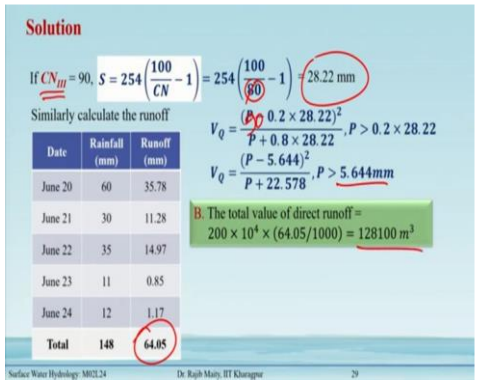

If CN_{III} = 90, $\boldsymbol{S = 254\left(\frac{100}{CN} - 1\right) = 254\left(\frac{100}{80} - 1\right)}$ = 28.22 mm

$$\boldsymbol{V_Q = \frac{(P - 0.2 \times 28.22)^2}{P + 0.8 \times 28.22}, P > 0.2 \times 28.22}$$

$$\boldsymbol{V_Q = \frac{(P - 5.644)^2}{P + 22.578}, P > 5.644mm}$$

Similarly, calculate the runoff

Date	Rainfall (mm)	Runoff (mm)
June 20	60	35.78
June 21	30	11.28
June 22	35	14.97
June 23	11	0.85
June 24	12	1.17
Total	**148**	**64.05**

B. The total value of direct runoff = $200 \times 10^4 \times (64.05/1000) = 128100\, m^3$

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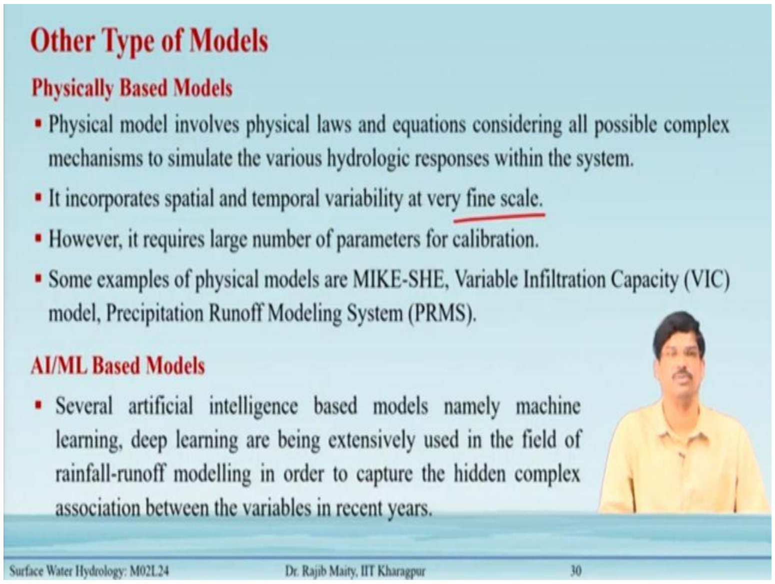

Other Types of Models

Physically Based Models

- The physical model involves physical laws and equations considering all possible complex mechanisms to simulate the various hydrologic responses within the system.
- It incorporates spatial and temporal variability at a very fine scale.
- However, it requires a large number of parameters for calibration.
- Some examples of physical models are MIKE-SHE, Variable Infiltration Capacity (VIC) model, Precipitation Runoff Modeling System (PRMS).

AI/ML Based Models

- Several artificial intelligence-based models namely machine learning, deep learning are being extensively used in the field of rainfall-runoff modeling in order to capture the hidden complex association between the variables in recent years.

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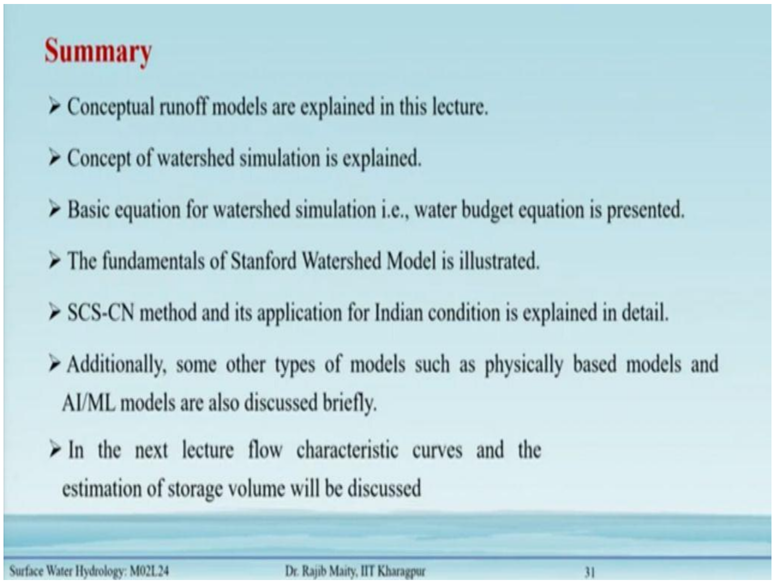

Summary

In summary, we learned the following points from this lecture:

- Conceptual runoff models are explained in this lecture.
- The concept of watershed simulation is explained.
- The basic equation for watershed simulation i.e., water budget equation is presented.
- The fundamentals of the Stanford Watershed Model are illustrated.
- SCS-CN method and its application for Indian conditions are explained in detail.
- Additionally, some other types of models such as physically-based models and AI/ML models are also discussed briefly.
- In the next lecture flow, characteristic curves and the estimation of storage volume will be discussed