Module 4 – (L12 - L18): “Watershed Modeling”

Standard modeling approaches and classifications, system concept for watershed modeling, overall description of different hydrologic processes, modeling of rainfall, runoff process, subsurface flows and groundwater flow

WATERSHED MANAGEMENT

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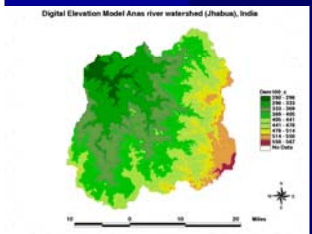
Lecture No - 15 Watershed Modeling Approaches

L15– Watershed Modeling

- **Topics Covered**
- Standard modeling approaches, System concept, Classifications, Black box model, Lumped model, Distributed model, Rainfall runoff modeling
- Keywords: Watershed modeling, System concept, black box model, lumped model, distributed model.



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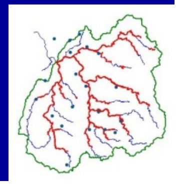
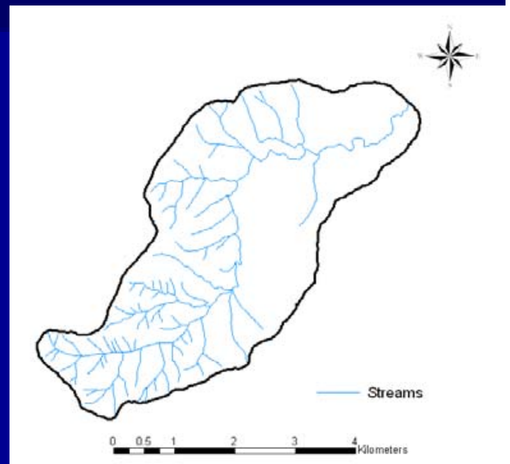
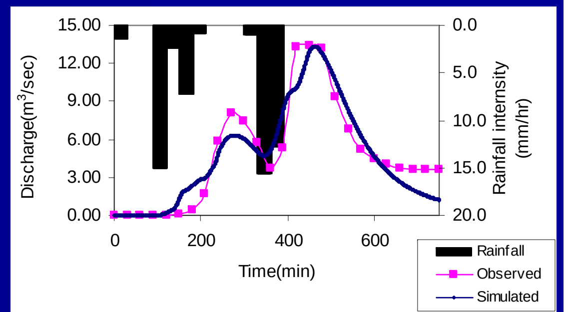


Watershed Model - Introduction



- **Watershed models** - simulate natural processes of the flow of water, sediment, chemicals, nutrients, and microbial organisms & quantify the impact of human activities on these processes.
- **Simulation** of these processes plays a fundamental role in addressing a range of watershed based water resources, environmental, social & economical problems.



Watershed Model

- Main tool in addressing a wide spectrum of environmental and water resources problems
  - water resources planning, development, design, operation, and management; flooding; droughts; upland erosion; stream bank erosion; coastal erosion; sedimentation; nonpoint source pollution; water pollution from industrial, domestic, agricultural, and energy industry sources; migration of microbes; deterioration of lakes; desertification of land; degradation of land; decay of rivers; irrigation of agricultural lands; conjunctive use of surface and groundwater; reliable design of hydraulic structures and river training works etc.

System Approach

- System Approach: problems involves 3 steps;
- i) Describe the system – involves modeling the watershed system; ii) Describe the objective function - – normally stated in terms of economic terms (eg. Minimize flooding; iii) Optimize the system –
- Design problems classified: a) Long-run – design of multiple purpose reservoir system – huge capital investment – benefits after & over a long time
  - Intermediate run – irrigation & cultivation for a season
  - Short- run – how much water to be released for flood control
- Each require – hydrologic modeling
- Most situations – alternative models
- Models: criteria – accuracy, simplicity, consistency & sensitivity

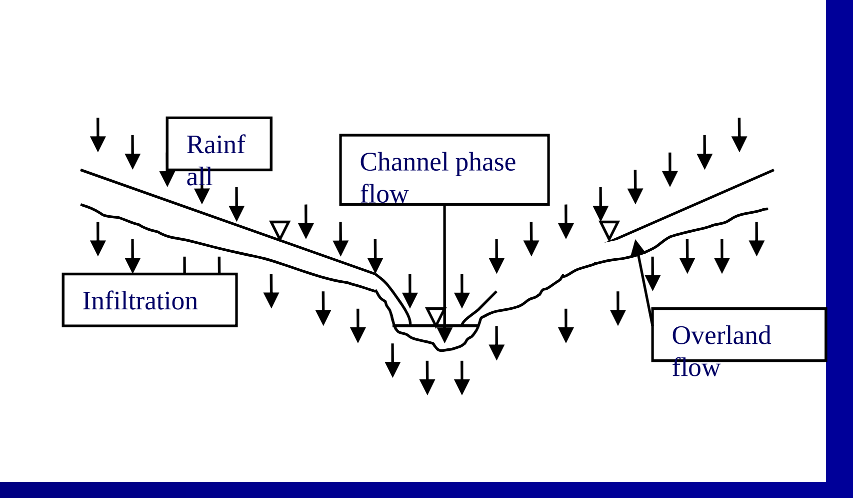
Classification of Models

- Broadly classified into three types
- ***Black Box Models:*** models describe mathematically the relation between variables (eg. rainfall and surface runoff) without describing the physical process by which they are related. e.g. Unit Hydrograph approach; ANN; Rational formula etc.
- ***Lumped models:*** These models occupy an intermediate position between the distributed models and Black Box Models. e.g. Soil Conservation Curve number method, Stanford Watershed Model
- ***Distributed Models:*** These models are based on complex physical theory, i.e. based on the solution of real governing equation. Eg: Model based on unsteady flow St. Venant equations for watershed modeling.

Structure of Watershed Model

Simulation of process that takes place in watershed

- Aim: Gain better understanding of hydrologic phenomena operating in a watershed and how changes in watershed may affect these phenomena
- Watershed modeling steps:
- 1. Formulation
- 2. Calibration/verification
- 3. Application
- Watershed model constitutes
- 1. Input function
- 2. Output function
- 3. Transform function



Hydrologic Models - Types

Event vs. Continuous models

Event model : represents a single runoff event occurring over a period of time ranging from about an hour to several days

- Accuracy of the model output - Depend on the reliability of initial conditions

Continuous watershed model: will determine flow rates and conditions during both, runoff periods and periods of no surface runoff

- Initial conditions must be known or assumed
- Utilize runoff components: direct or surface runoff, shallow surface flow (interflow) and groundwater flow

An event model may omit one or both of the subsurface components and also evapotranspiration

Hydrologic Models – Types...

Complete vs. Partial Models

Complete or comprehensive watershed models

- Solves the water balance equation
- Represents more or less all hydrologic processes
- Increases the accuracy of the model

Partial Models

- Represents only a part of the overall runoff process
- Ex: Water yield model gives runoff volumes but no peak discharges

Hydrologic Models – Types...

- **Calibrated Parameter vs. Measured Parameter Models:**

Calibrated parameter model:

- One or more parameters that can be evaluated only by fitting computed hydrographs to the observed hydrographs
- Necessary - If the watershed component has any conceptual component models
- Period of recorded flow is needed for estimating parameter values

Measured parameter model:

- Determination of parameters from known watershed characteristics
- Area and channel length – Maps and channel cross sections measured in the field
- Usually applied to totally ungauged watersheds

Hydrologic Models – Types...

Lumped vs. Distributed Models

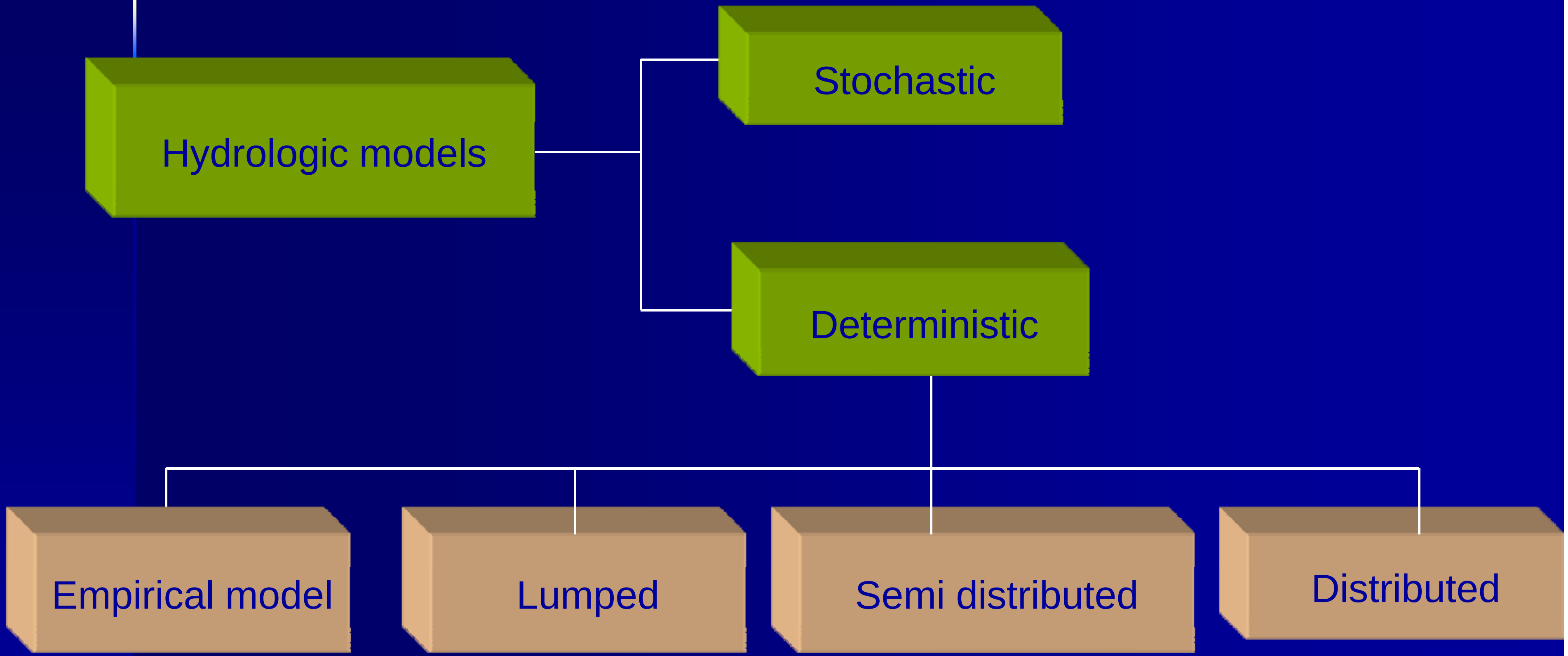
Lumped models

- Implicitly take into account the spatial variability of inputs, outputs, or parameters
- Utilize average values of the watershed characteristics affecting runoff
- lead to significant error- due to nonlinearity and threshold values

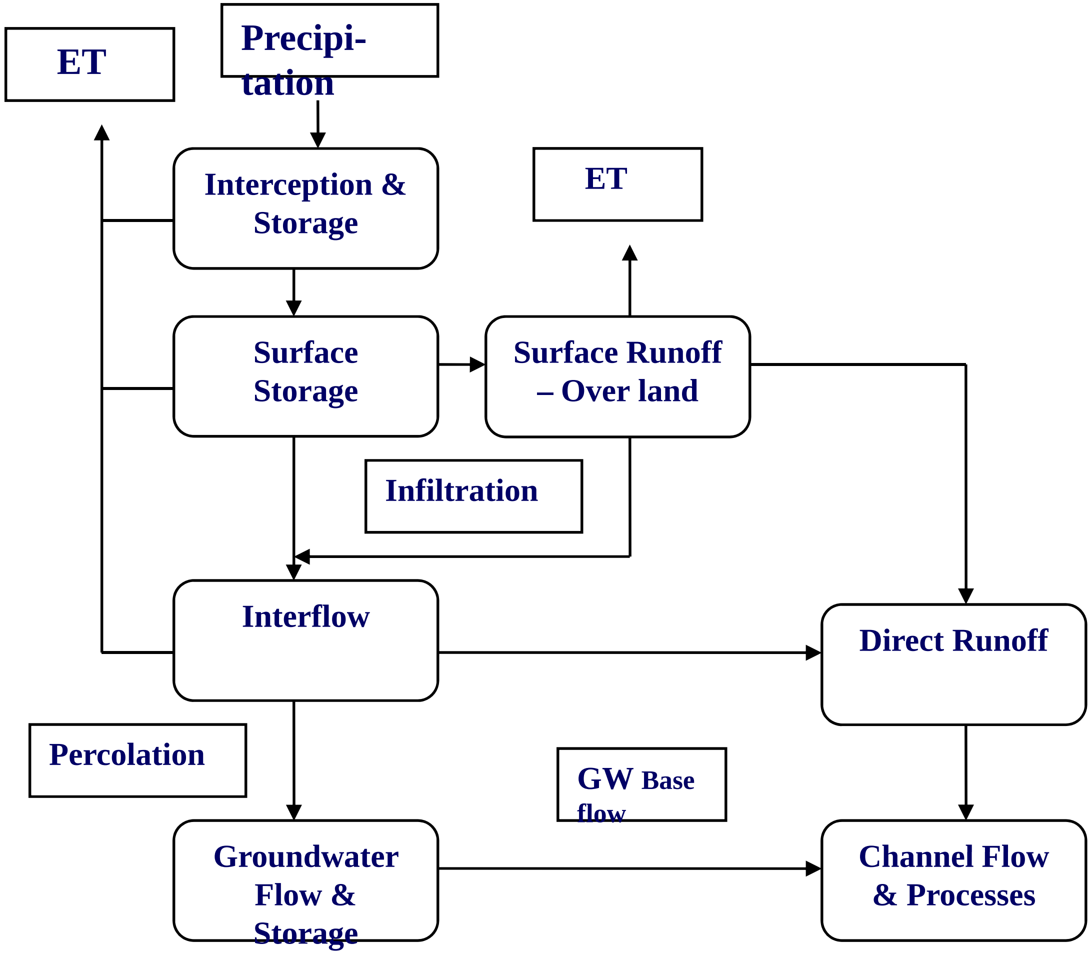
Distributed models

- Include spatial variation in inputs, outputs, and parameters.
- Division of watershed area into a number of elements and calculation of runoff volumes for each element

Hydrologic Models



Hydrologic Modeling



Flowchart of simple watershed model (Based on: McCuen, 1989)

Watershed Simulation Analysis

Model selection criteria

- Assumptions & conceptualization
- Ability of model to predict variables required by the project
- Hydrologic processes that need to be modeled to estimate the desired outputs adequately (single-event or continuous processes)
- Availability of input data
- Expertise available & computational facility
- Price

Surface detention

Watershed Simulation Analysis

Steps:

- Selection of model
- Input data collection: rainfall, infiltration, physiography, land use, channel characteristics etc
- Evaluate the study objectives under various watershed simulation conditions
- Selection of methods for obtaining basin hydrographs and channel routing
- Calibration and verification of model
- Model simulations for various conditions
- Sensitivity analysis
- Evaluate usefulness of model and comment on needed changes.

Estimation of Surface Runoff

- Empirical Equations:
- Rational method (Empirical model)

  Q=C i A or q=0.0028 C i A

where, q=design peak runoff rate m3/s; C=Runoff coefficient;

i=rainfall intensity (mm/hr) for design return period and for

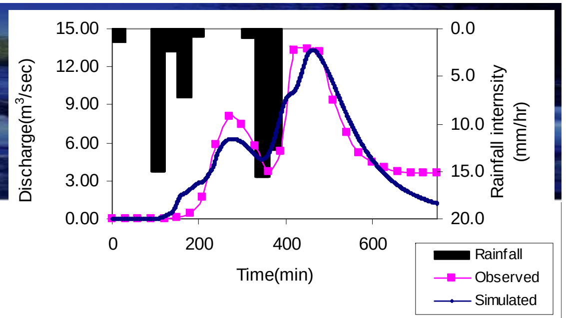
a duration equal to time of concentration of the watershed;

A=watershed area in ha; C= Runoff coefficient (rate of peak runoff rate to rainfall intensity, (dimensionless)); C varies as per slope, land use etc. e.g. available -- 0.3 to 0.6 (0-5 % slope); - 0.1 to 0.3(0-5 % slope).

Watershed of different characteristics:

$$C = \frac{C_1A_1 + C_2A_2 + C_3A_3}{A}$$

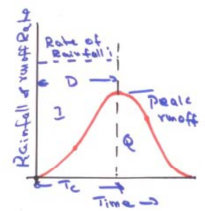
$$A = A_1 + A_2 + A_3$$



Rational Method

- Assumptions: Rainfall occurs at uniform intensity, Tc- equal to the time of concentration of watershed
- Rainfall occurs at the uniform intensity over whole area
- Max. runoff is directly proportional to rainfall intensity
- Peak discharge probability is same as rainfall probability
- Runoff coefficient does not change with storm type
- **Time of concentration:** It is the time needed for water to flow from the most hydrological distant point in the watershed to the outlet once the soil has become saturated and minor depressions filled
  - When duration of rainfall storm equals time of concentration, all parts of watershed contribute simultaneously to the runoff at the outlet

Surface detention



Rational Method…

- Kirpich (1940) formula for Tc

$$Tc = 0.0195 L^{0.77} S_g^{-0.385}$$

where, T_c- in minutes

L- Max. length of flow in m

S_g- Watershed gradient in m/m (difference between outlet and most remote point divided by length L

- Modified Kirpich equation: Where, L_o- Length of overland flow in m

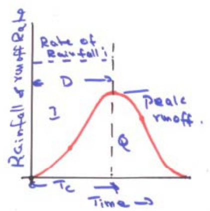
S_0- Slope along path in m/m

n- Manning's roughness coefficient

$$Tc = 0.0195 L^{0.77} S_g^{-0.385} + \left[\frac{2 L_o n}{\sqrt{S_o}} \right]^{-0.467}$$

Eg: Poor grass, cultivated raw crops n=0.2; smooth impervious n=0.02

- Rational method limited to area less than 800 Ha



Other Empirical Equations

- **Dicken's formula:** $$Q = CA^{0.75}$$

  where, Q→ Peak rate of surface runoff in m^3/s

  A→ Area in km^2; C→ Coefficient e.g. 11.45 for annual rainfall : 610 to 1270 mm

- **Ryve's formula:** $$Q = CA^{0.67}$$

- Same Q and A and C varies from 6.76 to 40.5 depending on location of watershed (suitable for South India)

  Based on practical experience and long term observations

Other Empirical Equations

- **Cook's method**
  - Evaluated by relief, soil infiltration, vegetation cover and surface storage
  - Approximate weightage are aligned for those parameters

$$Q = P\,R\,F\,S$$

Where, Q→ Peak runoff for specific region;

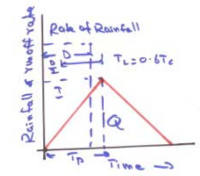
P→ Peak runoff from groups;

R→ Geographic rainfall factor from groups

F→ Return period from groups;

S→ shape factor from Table

Soil Conservation Service (SCS) Method(1999)



- Evolved for uniform rainfall using assumptions for a triangular hydrograph; Assumptions of rational method and corresponding SCS triangular hydrograph

Time for peak flow

$$T_p = \frac{D}{2} + T_L = \frac{D}{2} + 0.6T_c$$

T_p- Time of peak; D- Duration of excess rainfall; T_L- Time of Lag; T_c- Time of Concentration; $T_c = T_L / 0.6$

L- Longest flow length in m.

N- Runoff curve number and

S_g- average watershed gradient in m/m

$$Tc = \frac{L^{0.8}\left[\left(\frac{1000}{N}\right) - 9\right]^{0.7}}{\left[4407\left(S_g\right)^{0.5}\right]}$$

SCS Method

Peak flow rate(m³/s)

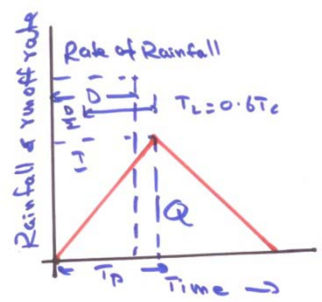
$$q = q_n A Q$$

q_n= unit peak flow rate (m^3/sec per ha/mm of runoff)

A-Watershed area in ha

Q-Runoff depth in mm from curve number method

Unit peak flow rates are developed for a particular region using time of concentration and ratio of initial abstraction to 24 hour rainfall



Curve Number Method

- Developed based on observation in agricultural watersheds in USA for long time—rainfall and runoff by USDA.
- SCS-CN method –NRCS (Natural Resources Conservation Service)
- Based on recharge capacity of a watershed
- Recharge capacity based on antecedent moisture content and physical characteristics of watershed
- Curve Number is an index that represents combination of a hydrologic soil group and antecedent moisture conditions

SCS-CN Method

- **Hydrologic Soil Groups: SCS(1972)**
- **Group A** (Low runoff potential):-Soil with high infiltration rates when thoroughly wetted, consisting mainly of deep well to excessively drained sands and gravels
  - High rate of transmission
- **Group B** (Moderately low runoff potential)
  - Moderate infiltration rates:-moderate rate of water transmission
- **Group C** (Moderately high runoff potential)
  - Slow infiltration rate
- **Group D** (High runoff potential) –slow infiltration
- Eg. Clay pan or layer

SCS-CN Method

- **Antecedent Moisture Condition (AMC)**
- Index of watershed wetness which is determined by total

runoff in 5 days period preceding a storm

- AMC I
  - Lowest runoff potential
    - soil dry enough for cultivation
- AMC II
  - Average condition
- AMC III
  - Highest runoff potential
    - practically saturated

SCS-CN Method...

Potential maximum retention storage of watershed is related to curve number (Dimensionless); 0 to 100

- Let I_a is the initial amount of abstractions (interception, depression storage & infiltration). It is assumed that ratio of direct runoff Q and rainfall P minus initial loss ($P-I_a$) is equal to ratio of actual retention to storage capacity, S

$$\frac{Q}{P-I_a} = \frac{P-Q-I_a}{S} \qquad (1)$$

where, I_a -Initial amount of abstraction;

I_a is assumed to be a fraction of S on an average $I_a=0.2S$

SCS-CN Method…

- Therefore, Equation (1) becomes

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S}$$

Knowing P and S, value of Q can be

Computed. Q has same units as P (in mm)

For convenience in evaluating antecedent rainfall, soil conditions and land use practices, curve number

$$CN = \frac{25400}{254 + S}$$

where, S- recharge capacity of watershed

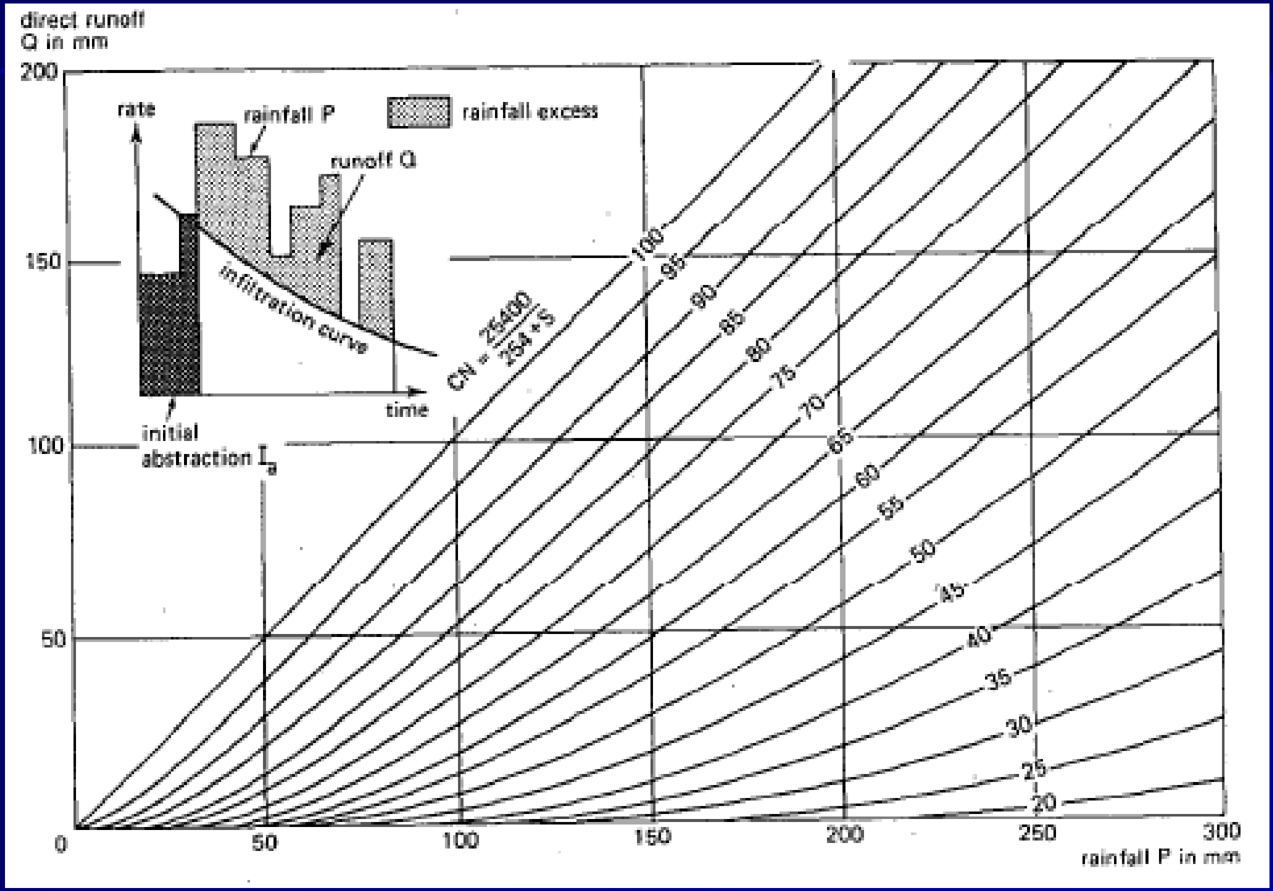
SCS-CN Method- Runoff CN for different hydrologic soil

Cover			Hydrologic Groups			
Land Use or cover	Treatment or practice	Hydrologic condition	A	B	C	D
1	2	3	4	5	6	7
Fallow	Straight row	----	77	86	91	94
Row crops	Straight row	Poor	72	81	88	91
Row crops	Straight row	Good	67	78	85	89

SCS-CN Method...

- Above Table, given for antecedent rainfall condition II ; Average condition
- Various tables available for various conditions
- Heterogeneous watershed may be divided into sub areas with different numbers and then a weighted curve number can be computed for those watershed
- Also CN can be developed for local conditions depending upon soil & other conditions.

SCS-CN Method…



Relationship between rainfall & runoff curve number CN (after Soil Conservation Service 1972)

Example Problem

- Calculate the runoff from a watershed of 50 Ha for the following data using SCS-CN method. Depth of rainfall=150mm; Antecedent Moisture condition, AMC I. Row crop, good condition in 30 Ha; Woodland, good condition in 20Ha.

Type of crop	CN at AMCII	AMCI
Row crop, good	82	82x0.8= 65.6
Woodland, good	55	55x0.65= 35.75

Weighted CN = (65.6 x 30 + 35.75 x 20)/ 50 = 53.66

Using $CN = \frac{25400}{254 + S}$; S= 219.35

$Q = \frac{(P - 0.2S)^2}{P + 0.8S}$ Q = 34.606 mm; Runoff in response to 150mm rainfall

References

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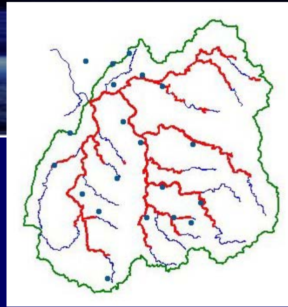
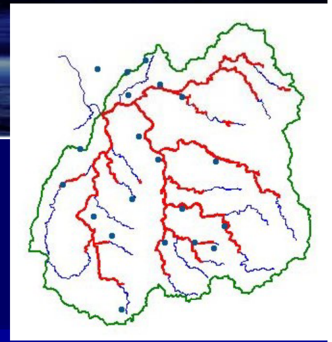


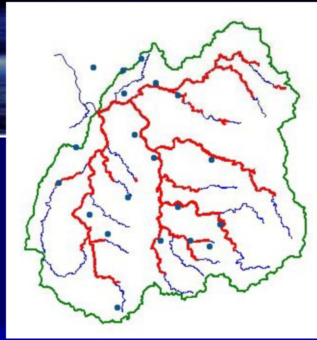
Tutorials - Question!.?.

- Study the different types of models used for runoff calculations for a given rainfall. Compare the black box models, lumped models and physically based models, with advantages and limitations of each.
- For a typical watershed, compare various Empirical equations available in literature for the calculation of runoff for the given rainfall.
- For a given rainfall depth, calculate the runoff using each method & compare the results.
- Get necessary standard values for each method from the literature.



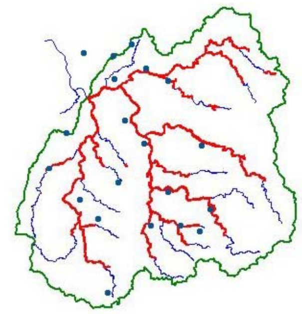
Self Evaluation - Questions!.

- Why models are required for watershed planning & management?.
- Differentiate between black box models, lumped models & distributed models.
- What are the important model selection criteria in watershed modeling?.
- Discuss important Empirical equations used for runoff calculations for a given rainfall.



Assignment- Questions?.

- Which are the different processes that can be simulated using models in a watershed.
- Differentiate between: a) event based & continuous models; b) lumped & distributed models.
- Illustrate the Rational method for runoff estimation, with its advantages & limitations.
- Describe the SCS-CN method for runoff estimation with its advantages & limitations.



Unsolved Problem!.

- For your watershed area, for a given rainfall depth, calculate the possible runoff using a) Rational Method; b) SCS-CN method, and compare the results.
- From the topographical & land use details, obtain the runoff coefficients for various areas & find the average runoff coefficient based on literature values.
- Based on the land use pattern, and possible antecedent moisture conditions, identify the possible curve number and get the weighted average.
- Compute the runoff based on the average runoff coefficient & curve number.

THANK YOU

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