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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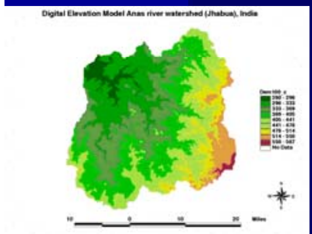
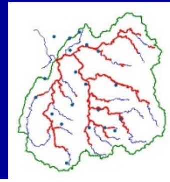
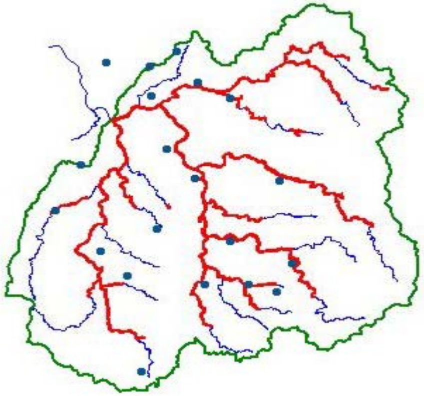
Lecture No - 12 Watershed Characteristics

L12– Watershed Characteristics

- **Topics Covered**
- Watershed characteristics, Geometric representation of watersheds, Linear aspects, Areal aspects, Relief aspects, Drainage & discharge
- Keywords: Watershed characteristics, geometric representation, drainage; linear, areal, relief: aspects





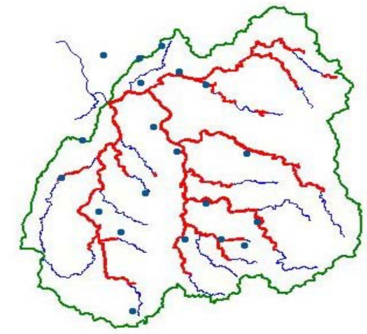


Watershed characteristics

- Important Characteristics
- Size
- Shape
- Physiography
- Climate
- Drainage
- Land use
- Vegetation
- Geology and Soils
- Hydrology
- Hydrogeology
- Socioeconomics

Photos: Singh, 07. 2001

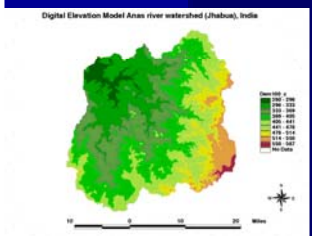
Watershed characteristics..



- **Watershed characteristics:** Biophysical & socioeconomic features prevalent in a watershed.
- Important watershed characteristics need to be identified for management & planning of Watershed.
- Important characteristics of watershed can be broadly categorized into:
- Climate
- Geology and physiography
- Soils
- Land use and cover conditions
- Watershed hydrology
- Socio-economic features/watershed

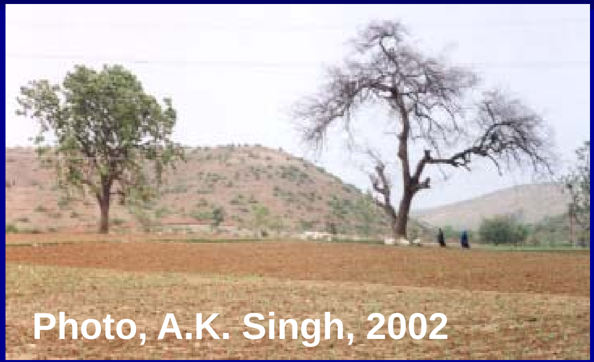
Description of Characteristics

- CLIMATE
  - Precipitation
  - Evaporation
  - Wind
  - Relative humidity etc.
- PHYSIOGRAPHY
  - Size and shape of watershed
  - Elevation
  - Slope and aspect
- GEOLOGY
  - Drainage features (pattern, density, etc.)
  - Parent rock types (igneous, sedimentary, metamorphic)



Description of Characteristics..

- SOILS
  - Soil depth
  - Soil type
  - Soil infiltration capacity
  - Soil erosiveness etc.



- LAND USE AND COVER CONDITIONS
  - Land use types (forest, grassland, agriculture, urban, etc.)
  - Ownership pattern (government, private, industrial)
  - Forest land conditions Major forest types
  - Rangeland condition and types
  - Agricultural practices
  - Road networks and condition
  - Recreational use (resort, wildlife, fish resource, etc.)

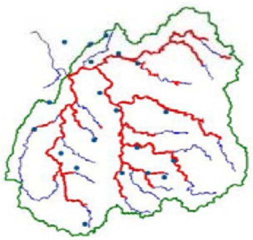
Description of Characteristics..

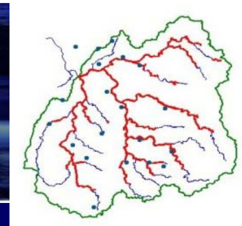
- WATERSHED HYDROLOGY
  - Erosion conditions along streams
  - Floods
  - Stream flow (quantity and quality)
- SOCIO-ECONOMIC FEATURES/WATERSHED USE
  - Water use and needs (sources of water, domestic use, irrigation, industrial, power generation, etc.)
  - Water use problems (erosion, flooding, siltation, water supply, water quality, etc.)
  - Income generation activities associated with watershed management

Photo, A.K. Singh, 2002

Important Watershed characteristics

- **Drainage Area (A): -** most important for hydrologic design; reflects volume of water - generated from rainfall.
  - the volume of water available for runoff may be assumed as product of rainfall depth & drainage area.
  - drainage area input to all models.
- **Watershed length (L):** increases as the drainage increases; L is important in hydrologic computations; L- defined as distance measured along the main channel from the watershed outlet to the basin divide; L is measured along the principal flow path
- A & L- both measures of watershed size; they may reflect different aspects of size. A-indicate potential for rainfall to provide a volume of water; L- used in computing time parameter -measure of travel time of water through a watershed.





Important Watershed characteristics

- **Watershed Slope (S): -** Flood magnitudes reflect the momentum of the runoff. Slope is an important factor in the momentum.
  - Watershed slope reflects the rate of change of elevation with respect to distance along the principal flow path.
  - $S = \Delta E/L$; where ΔE is difference in elevation (between the end points of the principal flow path); L- hydrologic length of the flow path .
- **Watershed shape:** Watersheds have an infinite variety of shapes, and the shape supposedly reflects the way that runoff will “bunch up” at the outlet.
- Eg. A circular shaped watershed would result in runoff from various parts of watershed reaching outlet at the same time

Photo, A.K. Singh, 2002

Basin Shape – Watershed Parameters

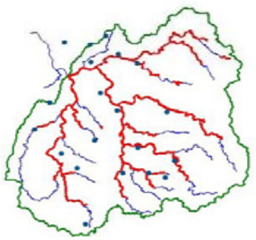
Watershed parameters that reflect basin shape:

- Length to the center of area (L_{ca}): distance in miles measured along main channel from basin outlet to the point on the main channel opposite the center of area.
- Shape Factor (L_1) = $(L\ L_{ca})^{0.3}$; Where L is the length of the watershed in miles
- **Circulatory ratio:** Ratio of basin area (A_u) to the area of circle (A_c) having equal perimeter as the perimeter of drainage basin (Range of Rc-→ 0.6 to 0.7)

$$R_c = \frac{A_u}{A_c}$$

- **Elongation Ratio:** Ratio of diameter of a circle (D_c) having same area as the basin to the maximum basin length (L_{bm})

$$R_l = \frac{D_c}{L_{bm}}$$



Important Watershed Factors

Highly heterogeneous & anisotropic

- Land Cover
- Land Use
- Surface Roughness
- Soil Characteristics
    - Texture
- Soil Structure
- Soil Moisture
- Hydrologic Soil Groups

Channel Geomorphology

- Channel length: used frequently in hydrologic computation.

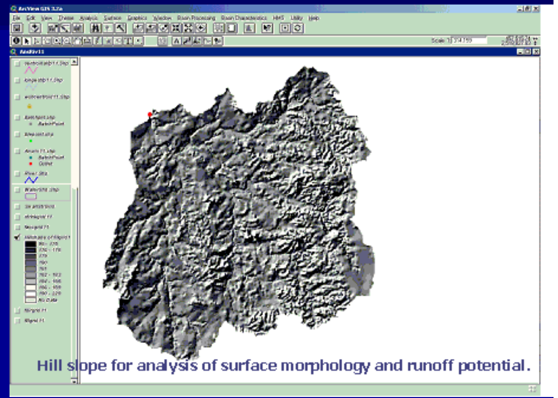
- The distance measured along the main channel from the watershed outlet to the end of the channel.

- Channel slope: $S_c = \Delta E_c / L_c$

Where ΔE_c is the difference in elevation between the points defining the upper & lower ends of the channel & L_c is the length of the channel between the same two points.

- If the channel slope is not uniform- a weighted slope may provide an index -reflects effect of slope on the hydrologic response of the watershed

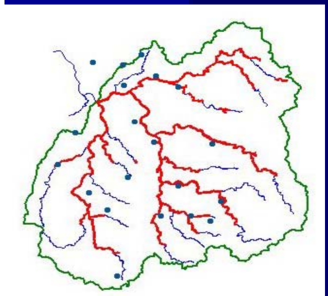
Geometric Representation of Watersheds

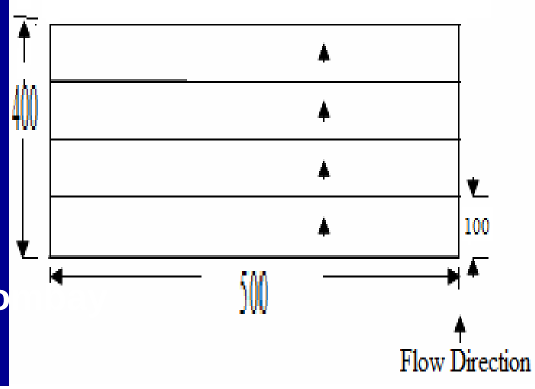


- Grid Method
- Conceptual method

Grid Method:

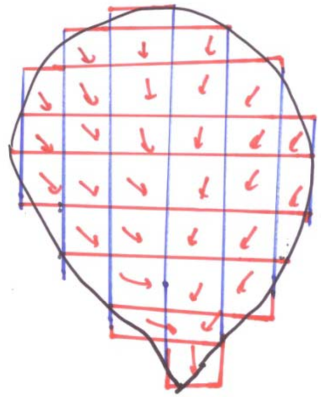
- Triangular or rectangular grids
- Stream channel system:- based on slope, channel dimension, conditions
- Flow in elemental areas:- travel to channel and finally to watershed outlet
- Overland flow and channel flow

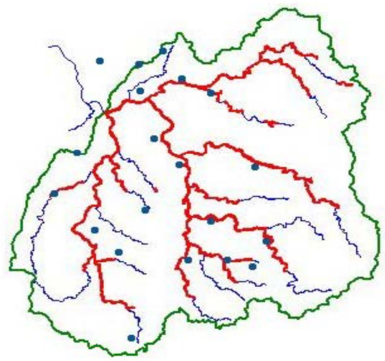




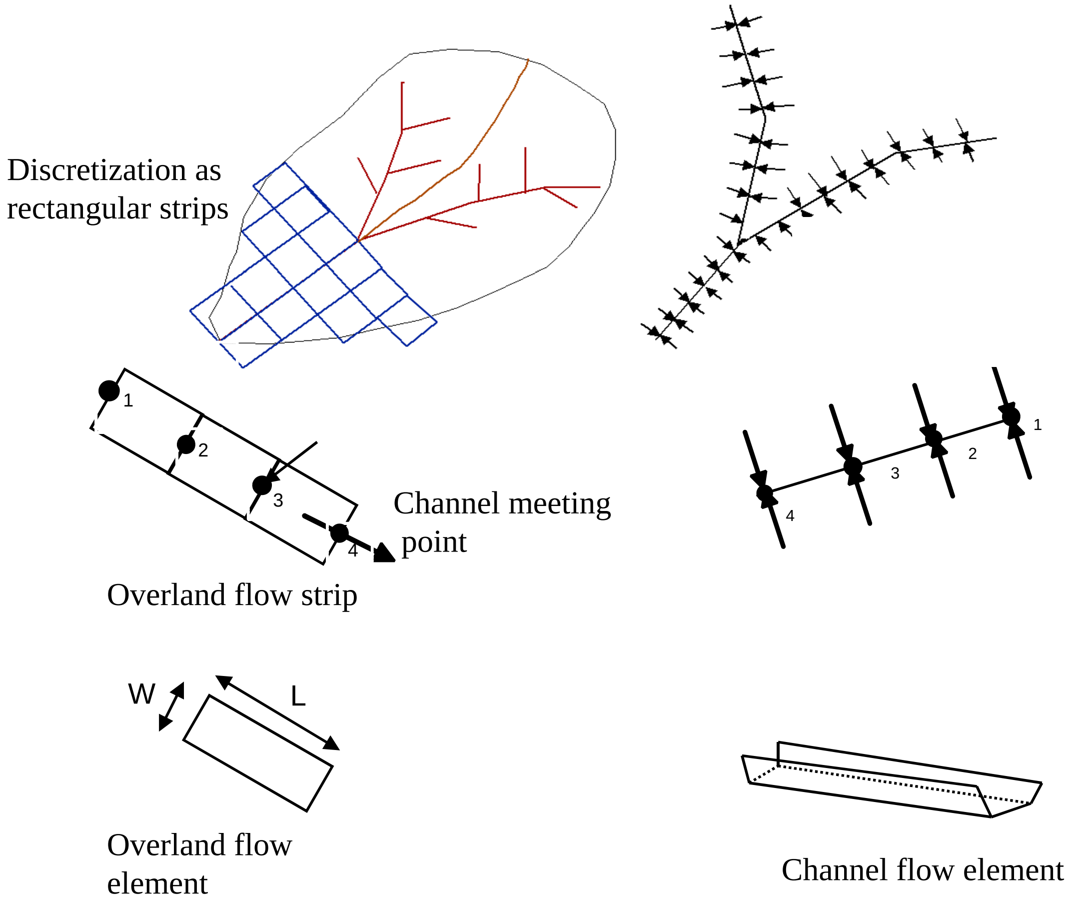
Geometric Representation

- **Steps:**
- A rectangular grid system is superimposed on topographic map of watershed
- Grid size:-watershed boundaries of channels approximated by grid segments
- Overland units are grid units inside watersheds boundaries and channel units may create grid units.
- Principal flow direction of each overland flow determined by landscape
- Water is assumed to flow in direction of land slope to next overland flow unit or adjacent channel: cascade and channel



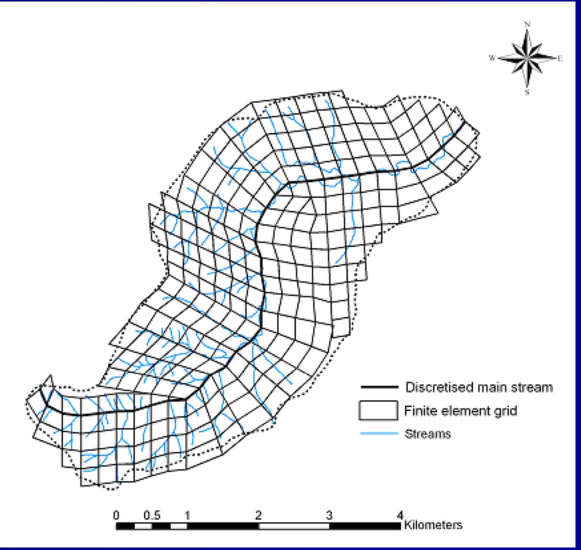


Grid Method


Discretization as
rectangular strips
1
2
3
4
Channel meeting
point
Overland flow strip
1
2
3
4
W
L
Overland flow
element
Channel flow element

Conceptual Method

- **Watershed geometry using a network of elemental sector**
  - Plane; Triangular section ; Converging section; Diverging section
  - Channel
- **Join together:-complete watershed**
  - Plane:-
    - defined by length and width
    - Horizontal or inclined
    - Defined by slope, length and area
  - Converging section
  - Diverging section
  - Triangular element
  - Channel element:- by hydraulic geometry (cross sectional area, wetted perimeter, hydraulic radius, width etc.) and bed profile
  - Sections: - rectangle, trapezoidal, parabolic, semi-circular etc.



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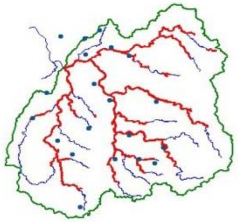
Assemblage of Geometric Elements

- **Assemblage of geometric elements** by topographic characteristics like grade, direction of flow, land use, vegetation, roughness and channel network

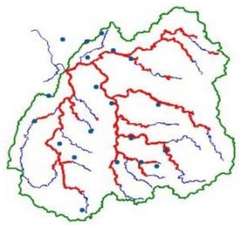
Two methods

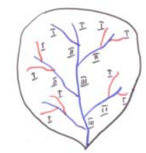
- Based on topographic characteristics :
  - different portions of watersheds are represented by geometric elements
  - one to one correspondence between a portion of watershed and element representing it.
- Geomorphologic characteristics of watershed are used to develop a network representation
  - Model flow paths are analogous to watershed flow paths



Geomorphologic Characteristics

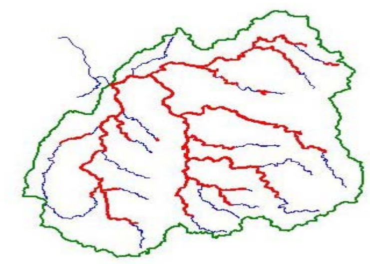
- Quantitative land form analysis: Flowing water & associated mass gravity movements acting over long periods of time – responsible for development of surface geometry
- Geomorphologic characteristics of watershed:-
  - systematic description of watershed
  - geometry and its stream channel system
  - to measure the linear aspects of drainage network,
  - aerial aspects of drainage basin and
  - relief aspects of channel network





Linear aspects of drainage networks

- **Stream order:-**degree of stream branching with a watershed
  - First order:-unbranched tributary
  - Second order:-two or more first order
  - Third order:-two or more second order streams



  - n^{th} order stream is formed by 2 or more stream of order $(n-1)^{th}$ & stream of lower order
- **Bifurcation ratio:-**Ratio of number of stream of any order to the number of stream of the next lower order

$$R_b = \frac{Nu}{Nu+1}$$

where, Nu-No. of stream of u order;

(Nu+1)- No. of stream of u+1 order; Rb- range from 2 to 4 (generally)

High in steep areas; represents effect on maximum flood discharge of the watershed.

Linear aspects of drainage networks

- If bifurcation ratio (Rb) and principal order (k) of stream of watershed are known, then total number of streams of all orders of a drainage network

$$\sum_{i=1}^{K} N_u = \frac{R_b^k - 1}{R_b - 1}$$

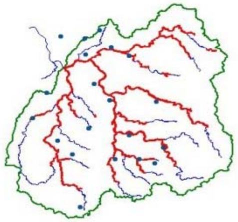
- **Law of stream numbers:** relate number of stream of order u (Nu)to bifurcation ratio and principal order (k)

$$N_u = R_b^{k-u}$$

- **Stream lengths:** reveals characteristics of various components of drainage network and its contributing surface area

$$\overline{L_u} = \frac{\sum_{i=1}^{N} L_u}{N_u}$$

Where $\overline{L_u}$ mean length of channel of order u and Nu-No. of stream of order u



Linear aspects of drainage networks

- **Stream Length Ratio (R_L):** average length of stream of any order to average length of stream of next lower order

$$R_L = \frac{\overline{L_u}}{\overline{L_{u-1}}}$$

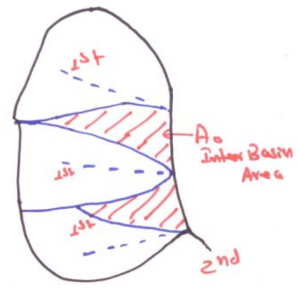
- **Law of stream Lengths:-** relates average length of stream of order u (L_u) to stream length ratio (R_L) and average length of first order streams(L_1)

$$\overline{L_u} = L_1 R_L^{\,u-1}$$

- Law of stream number and stream lengths can be combined to yield on equation for finding total channel length of watershed

$$\sum_{i=1}^{N} L_u = \overline{L_1} R_b^{\,k-u} . R_L^{\,u-1}$$

Areal aspects of watershed

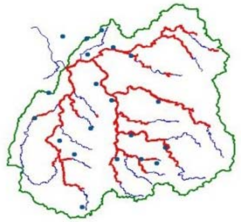


Arrangement of areal elements :-stream basin and inter basin (total)

- Stream basin:-area of steam basin
  - Interbasin area:-contributing surface flow directly to stream of higher order

- **Total basin area (A_u of order u):-**Total area projected on a horizontal plane, contributing overland flow to the stream of given order plus all tributaries of lower order

$$A_u = (\sum_{i=1}^{N} A1 + \sum_{i=1}^{N} A2 + \sum_{i=1}^{N} A3 + ... + \sum_{i=1}^{N} A_{u-1}) + (\sum_{i=1}^{N} A_{02} + \sum_{i=1}^{N} A_{03} + ... + \sum_{i=1}^{N} A_{04})$$



---Stream basin area--- ---Inter basin area---

Areal aspects of watershed

- **Law of Stream Areas:** relates uneven area of basin of order u (A_u) to the mean drainage area of first order (A_1) and the system area rate (R_a)

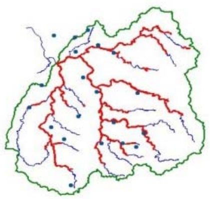
R_a:-average basin area of streams of one order to average area of basin of next lower order

$$\overline{A_u} = \overline{A_1} R_a^{\,u-1}$$

- Analogous to law of stream length
- Relationship between basin area and stream length

$$L = mA^n$$

where, L=stream length; A=basin area; m, n=constants



Drainage & Discharge

- **Relationship between drainage area and discharge**

$$Q = JA^m$$

where, J, m=constants; m –varies from 0.5 to 1.0

Basin shape: is the shape of projected surface area on the horizontal plane of basin map

- It has significant effect on stream discharge characteristics
- Basin can be characterized by: Form factor; Circulatory ratio & elongation ratio.

Drainage & Discharge..

- **Form factor:** Ratio of basin area to square of basin length

$$R_f = \frac{A_u}{L_b^2}$$

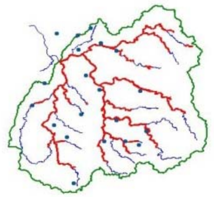
- **Circulatory ratio:** Ratio of basin area (Au) to the area of circle (Ac) having equal perimeter as the perimeter of drainage basin

$$R_c = \frac{A_u}{A_c}$$

...Range of R_c -→ 0.6 to 0.7

- **Elongation Ratio:** Ratio of diameter of a circle (D_c) having same area as basin to maximum basin length (L_{bm})

$$R_l = \frac{D_c}{L_{bm}}$$

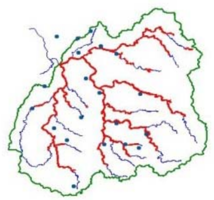


Drainage & Discharge…

- **Drainage Density (D_d):** Ratio of total length of all stream (L_u) of all order within a watershed to the total area of watershed (A_u)

$$D_d = \frac{\sum_{i=1}^{k} \sum_{r=1}^{N} L_u}{A_u}$$

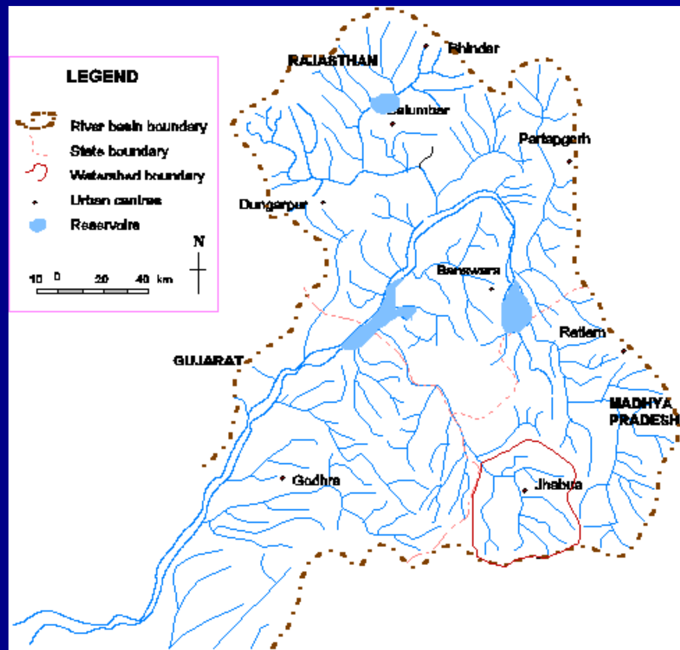
- A high value of the drainage density indicates a relatively high density of stream & thus a Rapid stream response
- Constant of channel maintenance –inverse of drainage density: $C = 1/D_d$



Drainage & Discharge….

- **Stream Frequency:** Number of stream segment per unit area of watershed

$$F = \frac{\sum_{i=1}^{k} N_u}{A_k}$$



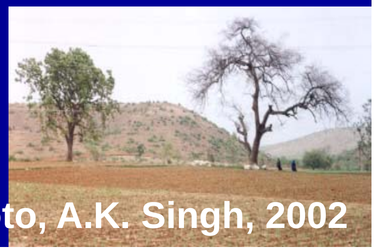
where, N_u—No. of stream segments of u order and A_k—basin area of principle order k

Relief Aspect of Drainage Basin and Channel Network

- **Relief:** elevation difference between reference points located in the drainage basin.
- **Maximum Relief:** Elevation difference between highest and lowest point
- **Maximum basin Relief:** Elevation difference before basin outlet and highest point located in the perimeter of basin
- **Relief Ratio:**

$$R_n = \frac{H}{L}$$

ratio of relief H to horizontal distance on which relief was measured (L)


Photo, A.K. Singh, 2002

Relief Aspect

- **Relative relief:**

$$R_{np} = \frac{H}{p}.100$$

where, H- Max. basin relief; p-basin perimeter

- Channel slope: slope of a channel segment increases with increase in orders
- **Law of stream-slope:** relates average slope of streams of order u(Su) to average slope of first order stream(S1) and stream slope ratio (R_s)

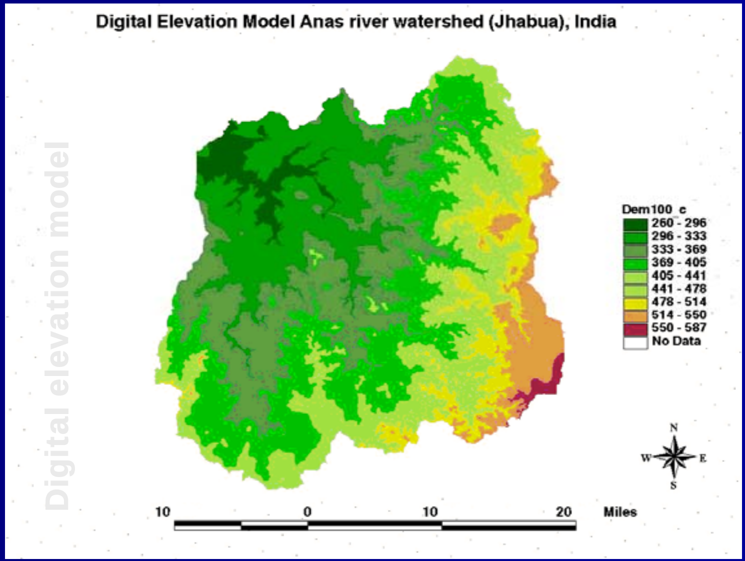
$$\overline{S_u} = \overline{S_1}.R_s^{\,u-1}$$

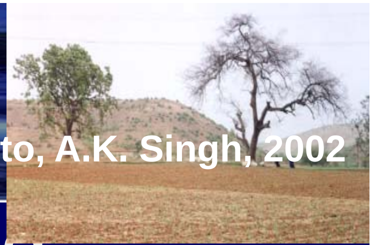
- **Ruggedness number:** product of relief (H) and drainage density (D_d)

$$R_u = HD_d$$

Relief Aspect…

- **Geometric number:** ratio of ruggedness number to ground slope (S_g)
- Geometric number = $\frac{HD_d}{S_g}$





Hypsometric Analysis of watershed

- To develop relationship between horizontal cross-sectional area of watershed and elevation.
- Curve plotted with relative height (h/H) and relative areas (a/A); h=height of given contour; H=relief; a=cross-sectional area of contour; A=total watershed area

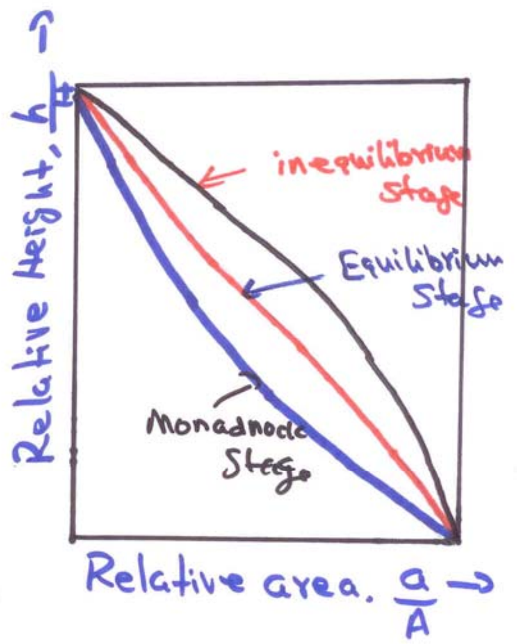
Curve is called ‘ Hypsometric curve’

- Useful for comparing area –elevation characteristics of watersheds
- Slope of hypsometric could be changed with stages of watershed developments
- Watershed development in three stages:
  - Inequlibrium stage
  - Equilibrium stage
  - Monadnock stage

Hypsometric Analysis of watershed

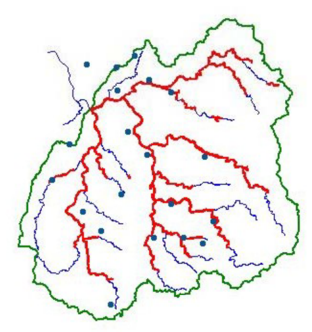
- Inequlibrium stage: young stage : watershed is under development processes
- Equilibrium: Mature stage of watershed – steady state conditions reached
- Monadnock: isolated bodies of resistant rock from prominent hills are found above subdued surface
- Hypsometric curves for different stages of watershed

Hypsometric curves for different stages of watershed



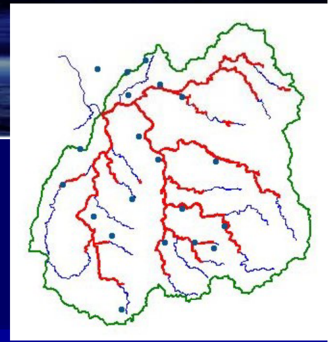
References

- Raj Vir Singh (2000), Watershed Planning and Management, Yash Publishing House
- J.V.S Murthy (1991), Watershed Management, New Age international Publications
- Ghanshyam Das (2000), Hydrology and soil conservation engineering, Prentice Hall of India
- Horton R.E., (1945), Erosional development of streams & their drainage basins: Hydro-physical approach to quantitative morphology. Bull. Geol. Soc. Am. 56:275-370.



Tutorials - Question!.?.

- Critically analyze the important characteristics of a typical agriculture watershed.
- Illustrate various parameters and try to quantify them.
- Discuss the order of importance.



Self Evaluation - Questions!.

- Classify the various watershed characteristics & its importance in watershed management.
- Describe different methods of geometric representation of watersheds.
- Describe linear aspects of watershed & its importance in geomorphological study of watershed.
- Discuss relief aspects of watershed & its importance in geomorphological study of watershed.
- What is Hypsometric analysis of watershed?.

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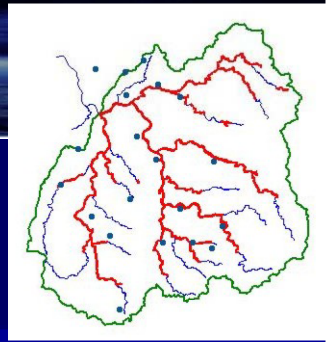
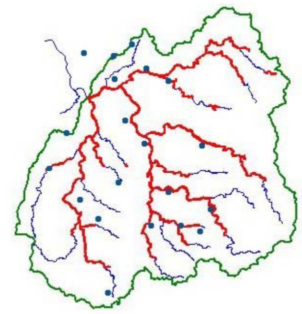


Assignment- Questions?.

- What are the important watershed factors to be considered in watershed management?
- In watershed analysis, what are the important channel geomorphology parameters to be considered?
- Illustrate the geometric representation of watershed step by step.
- Describe the areal aspects of watershed & its importance in geomorphological study of watershed.
- What are the different stages of watershed developments?.



Unsolved Problem!.

- For your watershed, identify various characteristics & list them in the order of importance.
- Analyze the linear aspects of the watershed.
- Analyze the areal aspects of the watershed.
- Analyze the relief aspects of the watershed.
  - Collect data – area, channel length, slope etc.
  - Illustrate the importance of each characteristics in the watershed management plans.

THANK YOU

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