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.
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

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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.)

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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
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.

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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.
  - \( S = \frac{\Delta E}{L}; \) where \( \Delta E \) 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.
### 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** ($L_1$) = $(L \cdot L_{ca})^{0.3}$; 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 $R_c$ → 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 ($L_{bm}$)

  \[ R_l = \frac{D_c}{L_{bm}} \]

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Important Watershed Factors

**Highly heterogeneous & anisotropic**

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

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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**: \( Sc = \Delta Ec / Lc \)

  Where \( \Delta Ec \) is the difference in elevation between the points defining the upper & lower ends of the channel & \( Lc \) 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

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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

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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

Channel meeting point

Overland flow strip

Overland flow element

Channel flow element

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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.
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.

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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

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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 streams
  - 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

\[
R_b = \frac{N_u}{N_u + 1}
\]

where, \( N_u \) - No. of stream of \( u \) order;
\( (N_u+1) \) - No. of stream of \( u+1 \) order; \( R_b \) - range from 2 to 4 (generally)
High in steep areas; represents effect on maximum flood discharge of the watershed.

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Linear aspects of drainage networks

- If bifurcation ratio \( R_b \) 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 \( u \) (\( N_u \)) 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

Where \( \bar{L}_u \) mean length of channel of order \( u \) and \( N_u \)-No. of stream of order \( u \)

\[
\bar{L}_u = \frac{\sum_{i=1}^{N} L_u}{N_u}
\]
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

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

- **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

  \[
  \sum_{i=1}^{N} L_u = \overline{L_1} R_b^{k-u} \cdot R_L^{u-1}
  \]
Areal aspects of watershed

Arrangement of areal elements:
- 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

\[ A_u = (\sum_{i=1}^{N} A_i + \sum_{j=1}^{N} A_2 + \sum_{k=1}^{N} A_3 + \ldots + \sum_{l=1}^{N} A_{u-1}) + (\sum_{j=1}^{N} A_{02} + \sum_{l=1}^{N} A_{03} + \ldots + \sum_{m=1}^{N} A_{04}) \]

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

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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 \( (R_a) \)

  \[ A_u = A_1 R_a^{u-1} \]

  - 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

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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.

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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 \((A_u)\) to the area of circle \((A_c)\) 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 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

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

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

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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)

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Photo, A.K. Singh, 2002
Relief Aspect

- **Relative relief:**
  
  \[ R_{np} = \frac{H}{p} \times 100 \]

  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 \( u \) (\( S_u \)) to average slope of first order stream (\( S_1 \)) 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 (\( D_d \))

\[ R_u = HD_d \]

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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:
  - Inequilibrium stage
  - Equilibrium stage
  - Monadnock stage
Hypsometric Analysis of watershed

- Inequilibrium 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

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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
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.

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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.

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THANK YOU

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