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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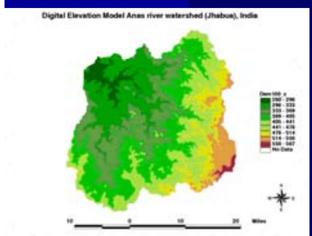
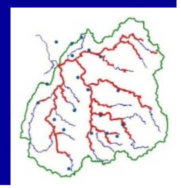
Lecture No - 16 **Hydrologic Modeling**

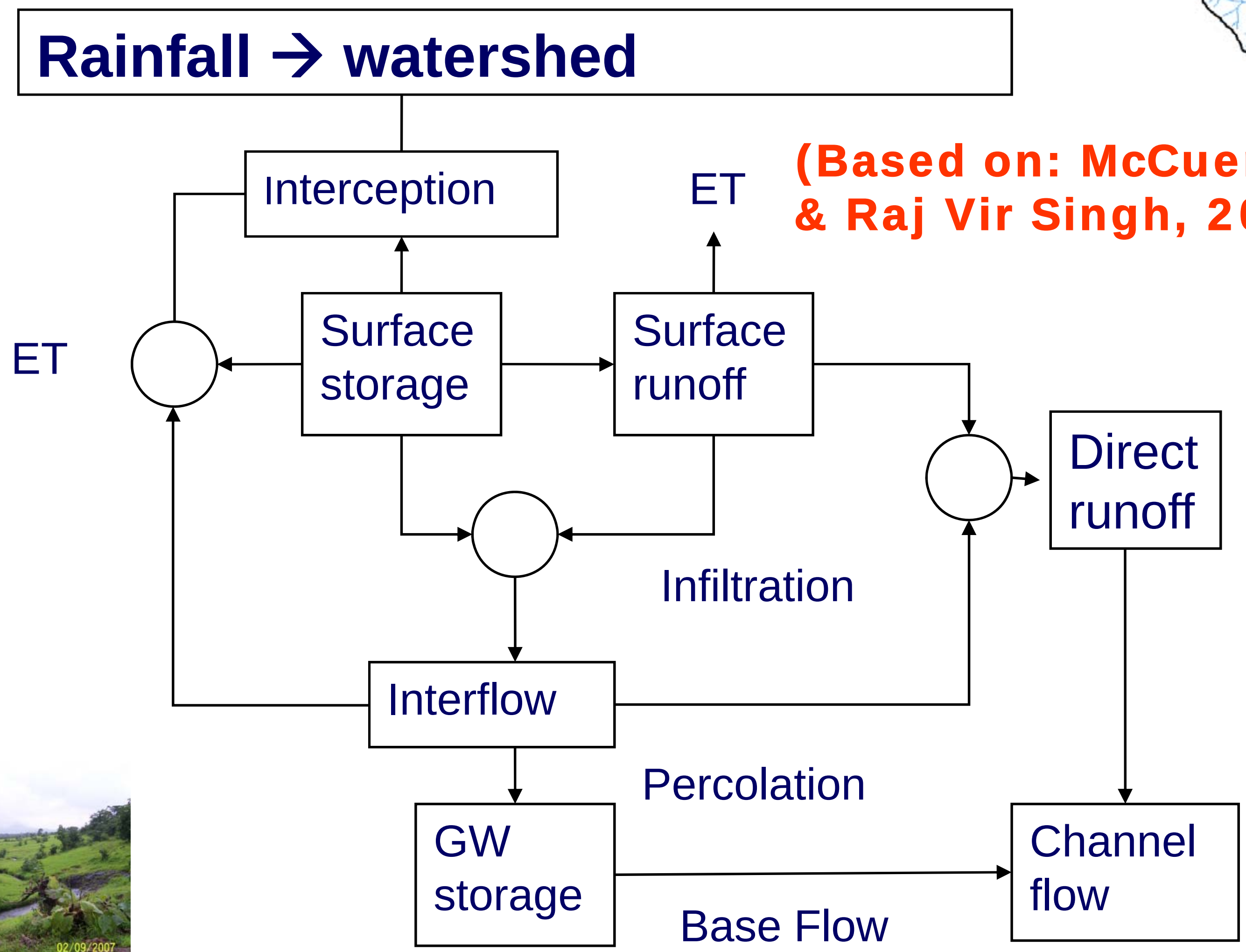
L16– Hydrologic Modeling

- **Topics Covered**
- Rainfall runoff modeling, Runoff process, Physical modeling, Distributed model
- Keywords: Rainfall runoff modeling, Physical modeling, distributed model.

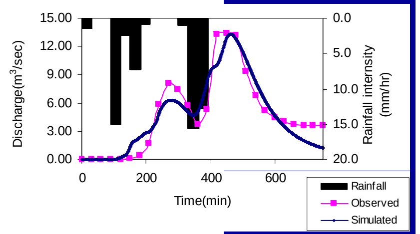




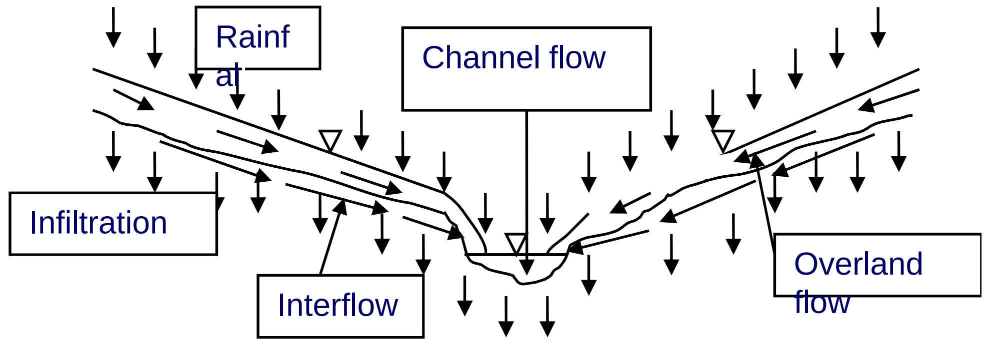
Watershed Model



(Based on: McCuen, 1989, & Raj Vir Singh, 2000)



Watershed models



- Formulation
- Calibration
- Application

- **Watershed model constitutes**
- 1. Input function
- 2. Output function
- 3. Transform function

Physically based watershed models

- Overland flow
- Channel flow

Deterministic Hydrologic Model

- Three main categories: Lumped, Semi-distributed & Distributed
- Lumped models: Parameters do not vary spatially within the basin & response is evaluated only at the outlet, without explicitly accounting for the response of individual subbasins.
  - Parameters do not represent physical features of hydrologic processes; model parameters – area weighted average
  - Not applicable to event based processes
  - Discharge prediction at outlet only
  - Simple & minimal data requirements, easy use
  - Eg. SCS-CN based models; IHACRES, WATBAL etc.

Deterministic Hydrologic Model..

- **Semi – distributed models:** parameters are partially allowed to vary in space by dividing the basin into a number of smaller subbasins
- Mainly two types: Kinematic wave theory models (eg. HEC-HMS model) - simplified version of surface flow equations of physically based model
- Probability distributed models – spatial resolution is accounted for by using probability distributions of input parameters across the basin.
- Advantage: structure is more physically based than lumped models
- Less demanding on input data than distributed models
- Eg: SWMM, HEC-HMS, TOPMODEL, SWAT etc.

Deterministic Hydrologic Model

- **Distributed models:** parameters are fully allowed to vary in space at a resolution chosen by the user.
- Attempts to incorporate data concerning the spatial distribution of parameters variation together with computational algorithms
- Requires large amount of data
- Governing physical processes are modeled in detail.
- Results at any location & time
- Highest accuracy in the rainfall-runoff modeling – if accurate data is available
- High computational time, Cumbersome, experts required
- Eg. HYDROTEL; MIKE11/SHE, WATFLOOD etc.

Physically based Watershed Model…

Physically based deterministic models:

- Aim: Gain better understanding of hydrologic phenomena operating in a watershed and how changes in watershed may affect these phenomena
- Complex processes → simplified by lumping process in space and time
- Laws of Physics→ Conservation of mass, momentum and energy
    - Continuity equation, equation of motion, equation of energy
- One or more of these laws and several empirical relations are used in physical model development
    - Models may be fully distributed or semi distributed.

Physically based Watershed Model…

Scope of physical modeling → Occurrence, movement, distribution and storage of water and their variability in space and time

Technology of Physical Modeling

- Hydrodynamic Models →theoretical, physical based or hydraulic models. e.g Dynamic wave model for overland flow
- Overland / channel flow → By continuity equation and momentum equation
- Modeling: May be in 1D, 2D or 3D
- Based on requirements & data availability

Physically Based Model -Flow Equations

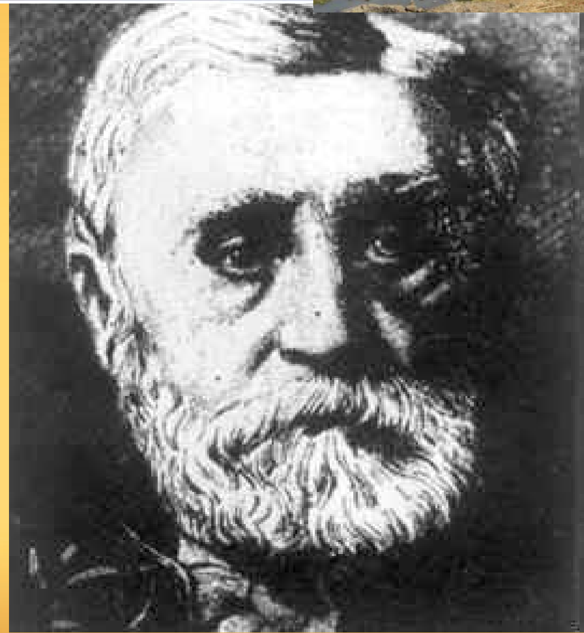
First proposed by St. Venant in 1871 based on fundamental laws of continuity & conservation of momentum

Continuity equation

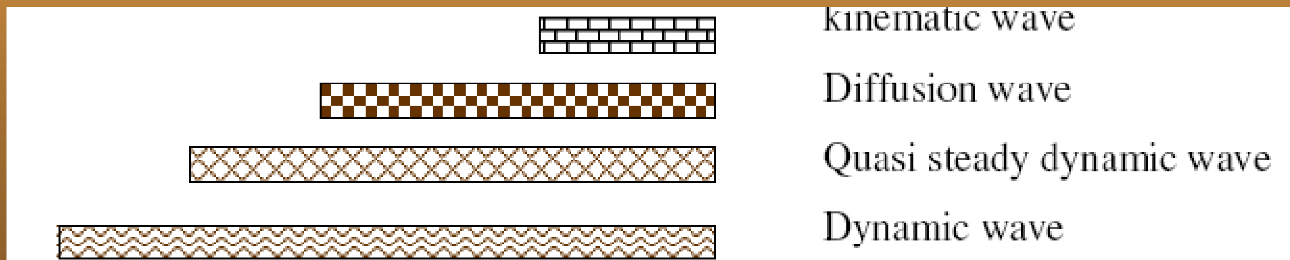
$$\frac{\partial A}{\partial t} + \frac{\partial (vA)}{\partial x} - q = 0$$

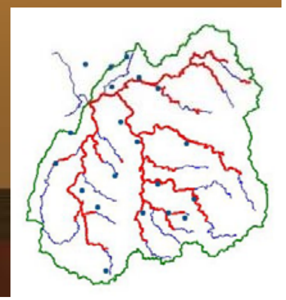
Momentum Equation

$$\frac{\partial Q}{\partial t} + \frac{\partial (vQ)}{\partial x} + gA\left(\frac{\partial y}{\partial x} - S_0 + S_f\right) = 0$$



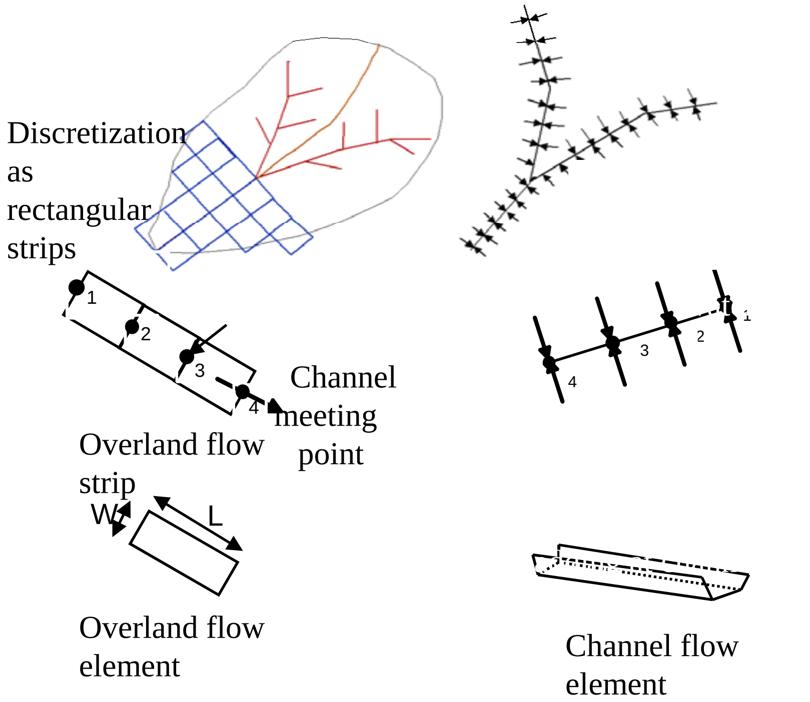
De Saint-Venant (1797-1886)





St. Venant Equations - Assumptions

- Flow is one-dimensional
- Hydrostatic pressure prevails and vertical accelerations are negligible
- Streamline curvature is small
- Bottom slope of the channel is small
- Steady uniform flow equation such as Manning's / Chezy equation can be used to describe resistance effects
- The fluid is incompressible



Terms in Momentum Equation

$$\frac{1}{A}\frac{\partial Q}{\partial t}+\frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)+g\frac{\partial y}{\partial x}-g(S_o-S_f)=0$$

Local acceleration term | **Convective acceleration term** | **Pressure force term** | **Gravity force term** | **Friction force term**

$$\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial x}+g\frac{\partial y}{\partial x}-g(S_o-S_f)=0$$

Kinematic Wave

Diffusion Wave

Dynamic Wave

St. Venant Equations

- **Applications of different forms of momentum equation**

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + g\frac{\partial y}{\partial x} - g(S_o - S_f) = 0$$

- **Kinematic wave:** when gravity forces and friction forces balance each other (steep slope channels with no back water effects)
- Diffusion wave: when pressure forces are important in addition to gravity and frictional forces
- Dynamic wave: when both inertial and pressure forces are important and backwater effects are not negligible (mild slope channels with downstream control)

Overland Flow (St. Venant's equations)

- Continuity equation:

$$\frac{\partial \bar{u}h}{\partial x}+\frac{\partial \bar{v}h}{\partial y}+\frac{\partial h}{\partial t}=r_e \qquad r_e = r_i - f_i$$

Where, h-depth of flow;
re-excess rainfall (mm); f_i-infiltration

- Momentum equations in 2-D

$$\frac{\partial \bar{u}}{\partial t}+\bar{u}\frac{\partial \bar{u}}{\partial x}+\bar{v}\frac{\partial \bar{u}}{\partial y}+g\frac{\partial h}{\partial x}-g(s_{ox}-s_{fx})+r_e\frac{\bar{u}}{h}=0$$

$$\frac{\partial \bar{v}}{\partial t}+\bar{u}\frac{\partial \bar{v}}{\partial x}+\bar{v}\frac{\partial \bar{v}}{\partial y}+g\frac{\partial h}{\partial y}-g(s_{oy}-s_{fy})+r_e\frac{\bar{v}}{h}=0$$

g-acceleration due to gravity; S_{ox}-slope of watershed element in x-direction; S_{oy}-slope in y-direction; S_{fx}-frictional slope in x-direction

Overland Flow – Diffusion & Kinematic

Diffusion wave form in 1D

$$\frac{\partial q}{\partial x} + \frac{\partial h}{\partial t} = r_e$$

$$\frac{\partial h}{\partial x} = S_0 - S_f$$

$$q = \bar{u}\, h = \alpha\, h^{\beta}$$

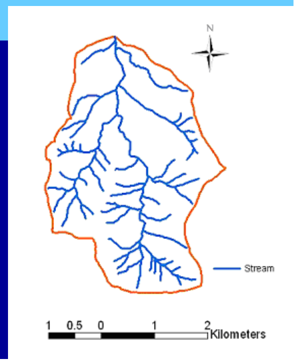
- α, β-coefficients obtained from Manning's equation
- Initial condition, t=0, h=0, q=0 at all nodal points

$$\beta = \frac{5}{3}$$

- **Kinematic wave form 1D**

$$\frac{\partial q}{\partial x} + \frac{\partial h}{\partial t} = re \; ; S_0 = S_f$$

- Initial conditions
- Boundary conditions



Gov. Equation for Channel Flow

Equation of continuity

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} - q = 0$$

- Momentum equation

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) = gA\left(S_0 - S_f\right) - gA\frac{\partial h}{\partial x}$$

- q-lateral inflow; Q-discharge in the channel; A-area of flow in the channel, S_0-bed slope; S_f-friction slope of channel.

Channel Flow- Diffusion & Kinematic

- Diffusion

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} - q = 0$$

$$\frac{\partial h}{\partial x} = S_o - S_f$$

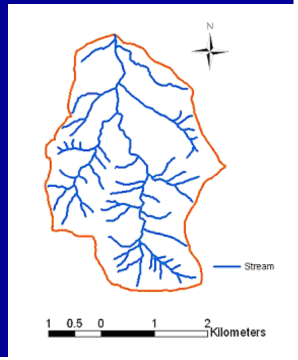
$$Q = \frac{1}{n} R_h^{2/3} S_f^{1/2} A$$

- Initial conditions
- Boundary conditions

- Kinematic:

$S_0 = S_f$

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} - q = 0$$



Use of Numerical Simulation Models

- Hydrologic simulation models use mathematical equations to calculate results like runoff volume or peak flow
- Computer models allows parameter variation in space and time – with use of numerical methods
- Ease in simulation of complex rainfall patterns and heterogeneous watersheds
- Evaluation of various design controls and schemes
- Effective use of land use and land cover parameters
- Improves quality of modeling using spatial characteristics

Examples of Hydrodynamic & Empirical Models

Physical Process	Hydrodynamic Models	Empirical
Surface runoff	i. Kinematic ii. Diffusion iii. Dynamic iv. Conceptual models	i. Rational method ii. Unit Hydrograph iii. SCS method
Infiltration	i. Richards equation ii. Kinematic iii. Green-Ampt iv. Philip-two term	i. SCS method ii. SCS-CN iii. HEC iv. Algebraic
Groundwater runoff (Base flow)	i. Model based on Groundwater flow equation	i. Algebraic e.g.Horton eqn. ii. Algebraic equations
Evapotranspiration (ET)	i. Penmann-Montelith i.Morten method	i. Blaney criddle

Examples of Hydrodynamic & Empirical Models

Physical Process	Hydrodynamic Models	Empirical
Flow over porous bed	i. Kinematic wave ii. Dynamic wave iii. Volume balance	SCS model
Flow in channel	i. Kinematic ii. Diffusion iii. Dynamic	Muskingum Hydrograph analysis
Solute transport	Model based on advection-dispersion Fickian models	Algebraic
Sediment transport	i. Kinematic ii. Dynamic iii. Einstein bed load	i. Sediment graph models ii. Regression equation

Hydrologic Models

ILLUDAS (ILLinois Urban Drainage Area Simulator)	• Sizing of storm sewers (basin runoff characteristics, design rainstorm, layout of sewer network are inputs) • Routines for estimating detention storage volumes • Limitation: Constant Outflow from detention facility
PSRM (Penn State Runoff Model)	• Single-event model • Components: overland runoff , channel routing etc.
HSPF (Hydrologic Simulation Program-Fortran)	• Continuous or Single-event model by EPA • Simulations for both quality and quantity
STORM (Storage Treatment Overland Flow and Runoff model)	• Developed for original application to the San Francisco master drainage plan • Conceptualized view of urban drainage system

Contd….

SWMM (Storm Water Management Model)	• Routing for surface, subsurface and groundwater • Fully dynamic hydraulic flow routing
HEC -1 **HEC-HMS**	• DOS/ Window (difference between two models) • Calculates runoff hydrograph at each component i.e. channels, pumps, conduits etc.
WMS	• Provide the link between spatial terrain data (GIS) and hydrologic models • Including models like HEC-1, TR-55, TR-20 etc.
IHACRES	• Simulation of stream flows from basins of various sizes • Unit hydrograph approach to lumped modeling

Steps In Watershed Simulation Analysis

- 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

Ex: Overland flow model: Kinematic wave model (Gottardi and Venutelli 1993; Jaber and Mohtar, 2003; Reddy et al. 2007):

$$\alpha = \frac{\sqrt{S_f}}{n_o}$$

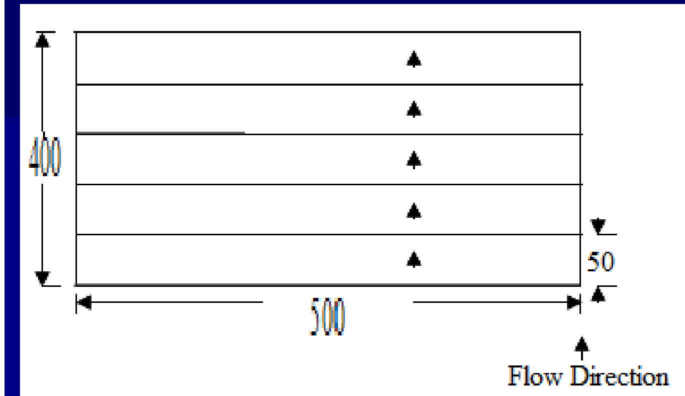
$$\beta = \frac{5}{3}$$

$$t_c = \left(\frac{L_w}{\alpha_y r_e^{\beta-1}}\right)^{(1/\beta)}$$

$$q_y = \alpha_y (r_e t)^{\beta} \qquad 0 \le t \le t_c,$$

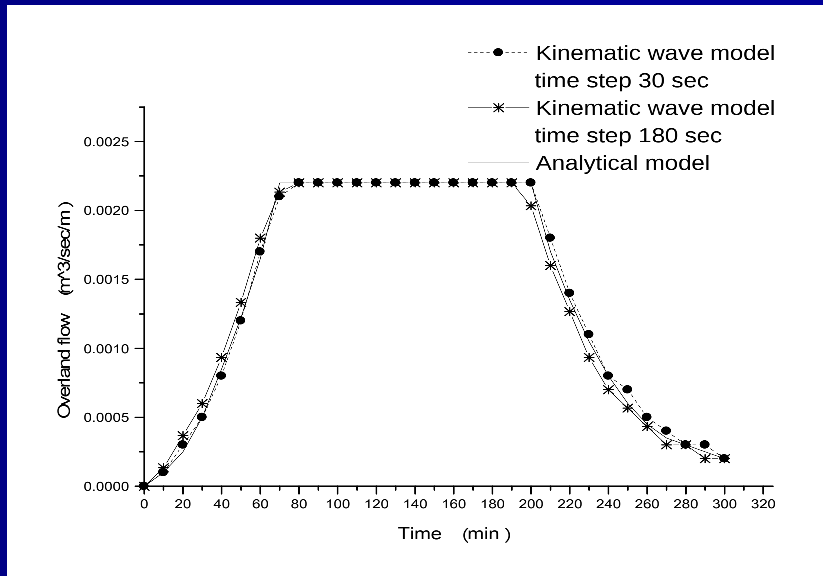
$$q_y = \alpha_y (r_e t_c)^{\beta},\ t_c \le t \le t_r,$$

$$q_y = r_e L_w - r_e \beta \alpha^{(1/\beta)} q_y^{(\beta-1/\beta)} (t - t_r),\ t_r \le t \le t_f$$



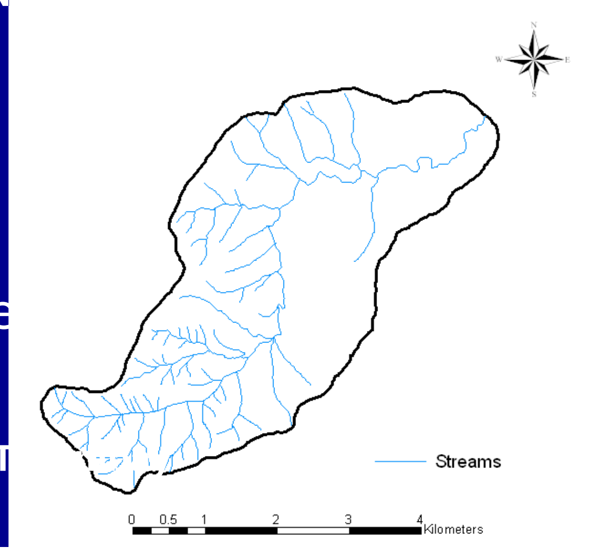
Analytical solution for one-dimensional kinematic wave equations is given by above equations (Jaber and Mohtar, 2003); *tc is time of concentration (sec); tr is rainfall duration (sec); tf is the simulation time (sec); Lw is the length of watershed (m) in the direction of main slope.*

400 m x 500 m, slope So = 0.0005, Manning's coefficient = 0.02 $m^{-1/3}$ sec, uniform excess rainfall R = 0.33 mm/ min, and duration of rainfall 200 min.



Case study: Banaha Watershed
(Venkata Reddy et al., 2007)

- Location- Chatra district in Jharkhand State, India
- Area- 16.72 km^2 ; Major Soil class – Sandy loam.
- Remotely Sensed Data- IRS1D LISSIII imagery of Jan. 1998
- Thematic Maps- Drainage, Slope and LU/LC
- Map generation & analysis- ERDAS IMAGINE & ArcGIS
- Slope map- ArcGIS; LU/LC map - ERDAS IMAGINE
- Manning's roughness map- Based on LU/LC map
- Finite Element Grid map- ArcGIS; Grid map overlaid on slope & Manning's roughness maps
- Mean value of slope and Manning's roughness- Each element of the grid; Nodal values- Average of adjacent element values



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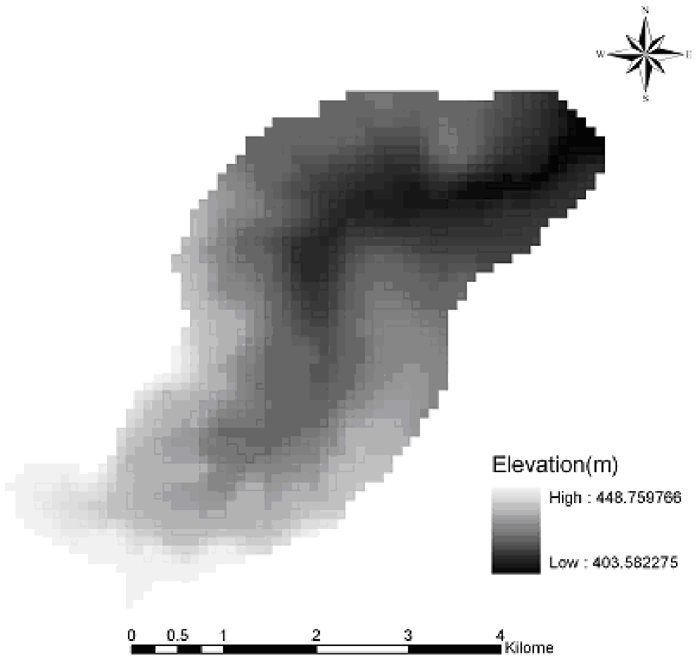
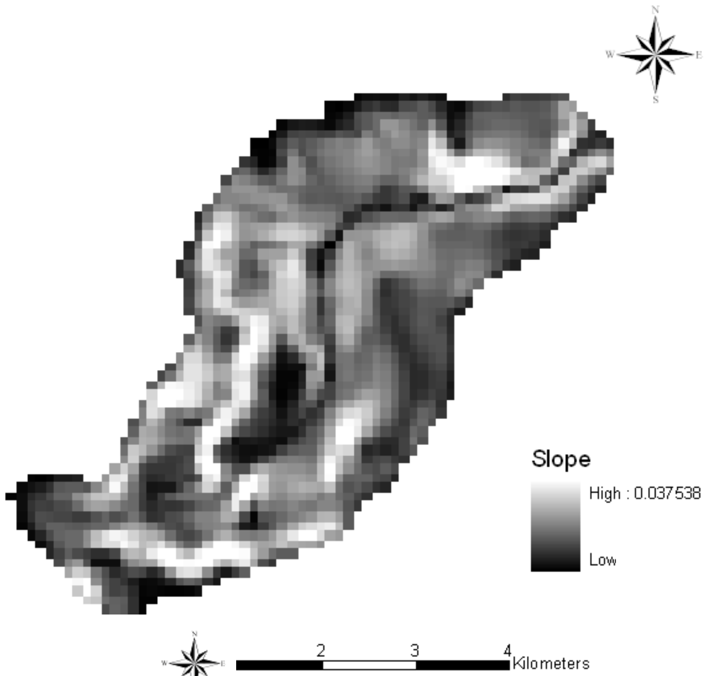
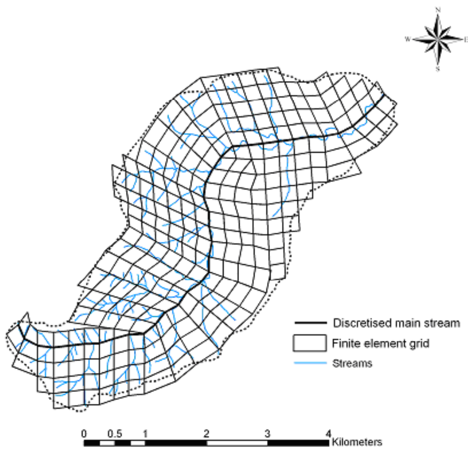
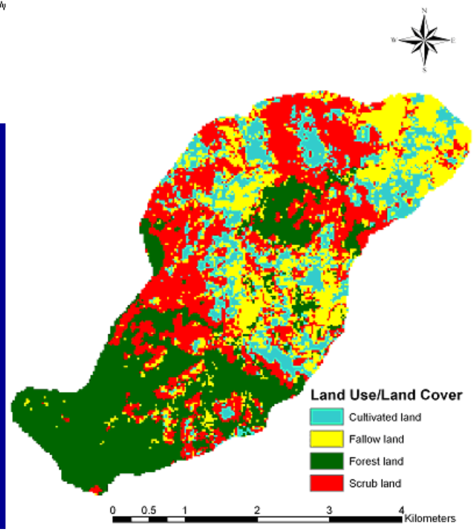
Case study: Banaha Watershed









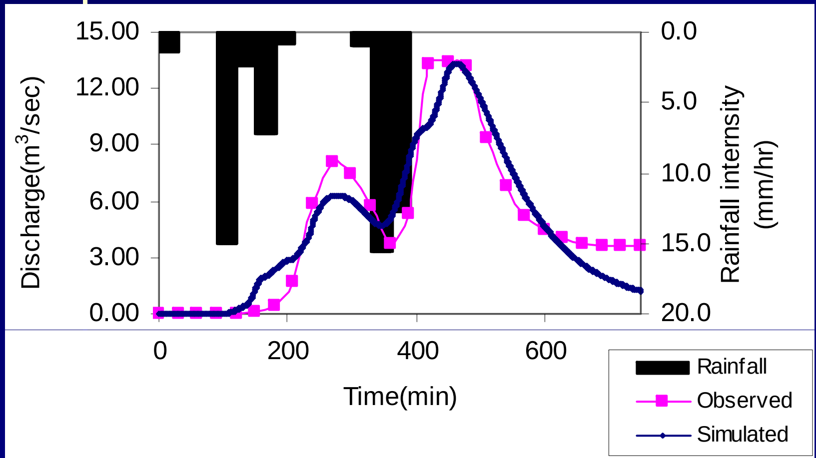
Results and Discussion

- Diffusion wave- Philip model
- Calibration - 4 Rainfall events
- Validation - 3 Rainfall events

Calibrated parameters for rainfall events (Banha Watershed)

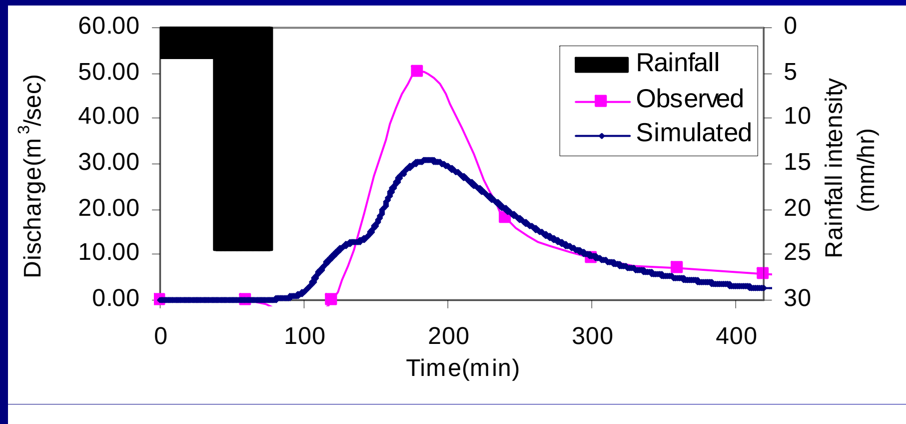
Date of rainfall event	Saturated hydraulic conductivity (K_s (cm/hr))	Initial soil saturation degree (s_{ini})	Pore size distribution index (λ)	Effective porosity (η)
July 24, 1996	0.21	0.7	0.23	0.33
August 18, 1996	0.44	0.69	0.38	0.36
August 23, 1996	0.125	0.77	0.25	0.35
August 30, 1996	0.225	0.7	0.2	0.29

Results and Discussion



Calibration event, July 24, 1996

Validation event, August 17, 1996



Observed and simulated hydrographs of rainfall events (Banha), (Venkata Reddy et al., 2007)

References

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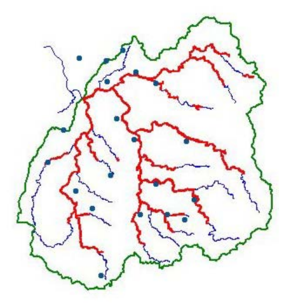
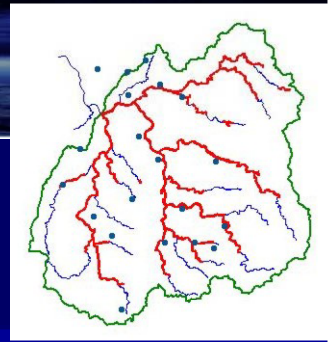


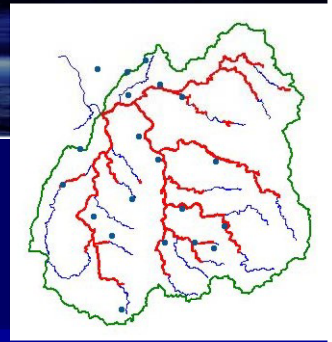
Tutorials - Question!.?.

- Illustrate various hydrological processes from rainfall to runoff in watershed based modeling.
- For a typical watershed, assess the important hydrological processes and discuss various models available to analyze these processes. Describe the merits & demerits of each models.
- For a selected watershed, how to find the runoff for a given rainfall event?. Illustrate with examples.



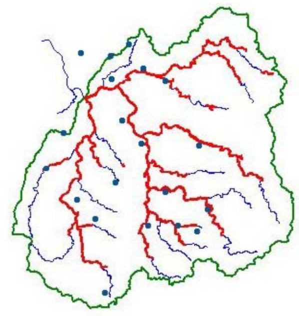
Self Evaluation - Questions!.

- Describe different categories of deterministic hydrologic models?.
- What is the importance of physically based watershed modeling?.
- Describe the St. Venant equations with its applications, assumptions and importance.
- Compare the following lumped, semi distributed and distributed models: HEC-HMS; SWMM & MIKE 11 models. Discuss the applications, advantages & disadvantages of each model.



Assignment- Questions?.

- Differentiate between lumped, semi distributed and distributed models used in hydrologic modeling.
- How physically based watershed modeling is done?. Illustrate the step by step procedure. What are advantages & limitations.
- What are the important steps in the watershed simulation analysis?.
- Illustrate various types of hydrodynamic & empirical models used in hydrology.



Unsolved Problem!.

- For your watershed area, discuss the possibility of applying a physically based model for runoff/ flood analysis. Identify the data required for physical modeling. Develop a conceptual model by giving the detailed steps for rainfall runoff modeling.
- Identify how to model evapo-transpiration, interception & infiltration for the area considered. With respect to available data, choose specific models to model these processes.
- Discuss how to add these processes in the rainfall-runoff modeling.

THANK YOU

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