Module 8 – (L31 – L34): "Storm Water & Flood Management":

Storm water management, design of drainage system, flood routing through channels and reservoir, flood control and reservoir operation, case studies.

WATERSHED MANAGEMENT

Prof. T. I. Eldho

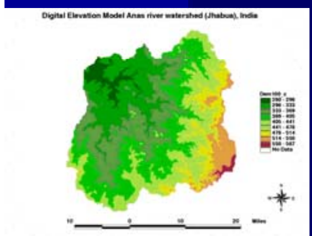
Department of Civil Engineering,
IIT Bombay

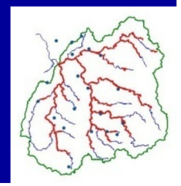
Lecture No - 33

Flood Routing

L33– Flood Routing

- **Topics Covered**
- Flood routing though channels, Reservoir routing, Hydrologic routing, Hydraulic routing, Lumped flow routing, Muskingum method, St. Venant equations
- Keywords: Flood routing, Channel, Reservoir, Hydrologic & hydraulic routing.





What is Flood Routing?

- Watershed – receives rainfall as input- produces runoff as output – outflow hydrograph – differs in shape, duration & magnitude – attribute to storage properties of watershed system.
- Flood (Flow) routing – procedure to compute output hydrograph when input hydrograph & physical dimensions of the storage are known.
- Used for flood forecasting, design of spillways, reservoirs & flood protection works etc.

Flood Routing - Motivation

- **1) Floods**
- predict flood propagation
- protection
- warning
- **2) Design**
- water conveyance systems
- protective measures
- hydrosystem operation
- **3) Water dynamics**
- ungauged rivers
- peak flow estimation
- river-aquifer interaction.

Flood Routing - Classification

- **i) Reservoir Routing** – considers modulation effects on a flood wave when it passes through a water reservoir – results in outflow hydrographs with attenuated peaks & enlarged time bases .
  - Variations in reservoir elevation & outflow can be predicted with time when relationships between elevation & volume are known.
- **ii) Channel Routing** – considers changes in the shape of input hydrograph while flood waves pass through a channel downstream.
  - Flood hydrographs at various sections predicted when input hydrographs & channel characteristics are known.

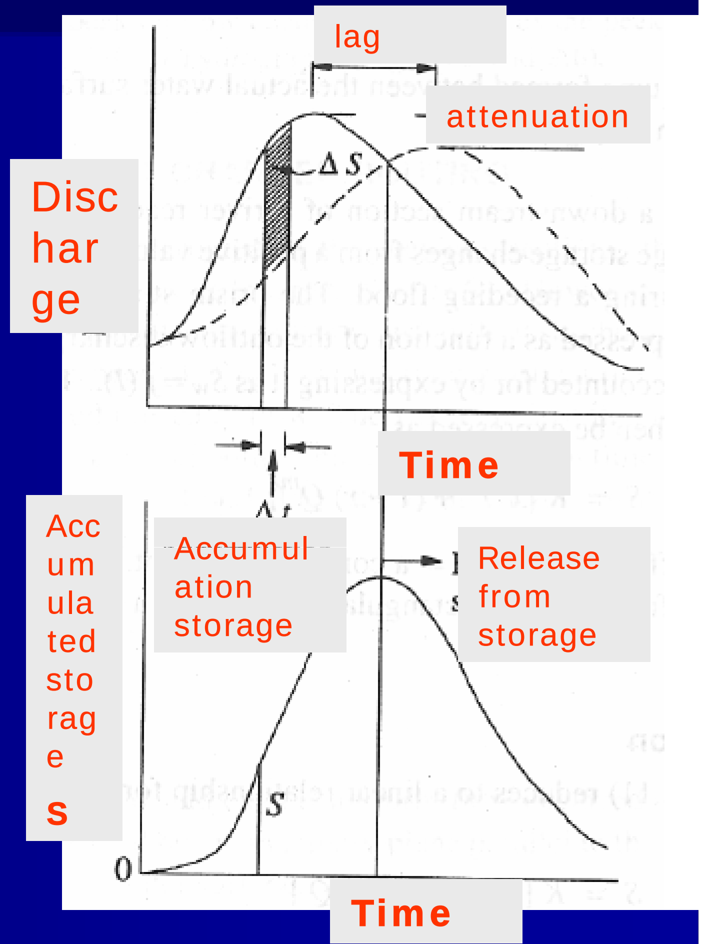
Flood Routing – Procedure

- Flood routing - methods can be classified as hydraulic - in which both continuity and dynamic equations are used - or hydrologic, which generally uses the continuity equation alone

- Hydrologic routing methods - Equation of continuity
- Hydraulic routing methods – St. Venant equations
- Flood routing Applications:
  - -Flood forecasting
  - -Flood protection
  - -Reservoir design
  - -Design of spillway and outlet structures

Flood Routing Technique

- **Flood routing-** technique of determining the flood hydrograph at a section of a river by utilizing the data of flood flow at one or more upstream sections
- **Lumped flow routing**: Flow is a function of time at particular location
- **Distributed flow routing:** Flow is a function of space and time through out the system



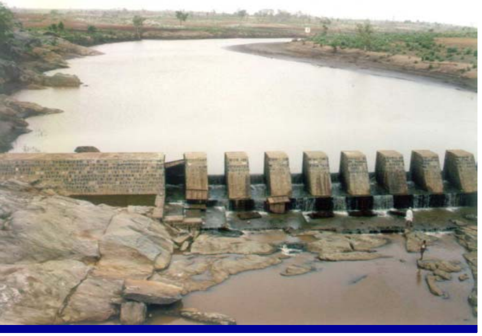
Chow et.al(1988)

Lumped Flow Routing

- Basic equation for hydrologic routing: Continuity equation

$$\frac{dS}{dt} = I(t) - Q(t)$$

- Input I(t), Output Q(t) and storage S(t); Known I(t) & unknowns Q & S
- Second relation (Storage function) needed to relate S, I and Q
- Specific form of storage function depending on nature of system.



Reservoir in main channel

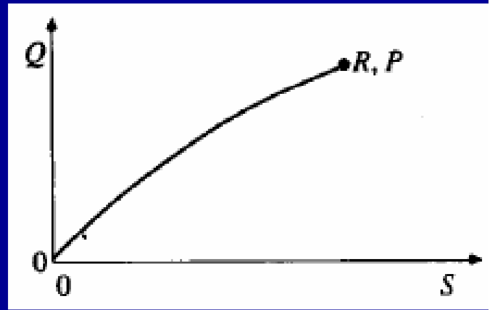
Lumped Flow Routing - Methods

Based on storage function

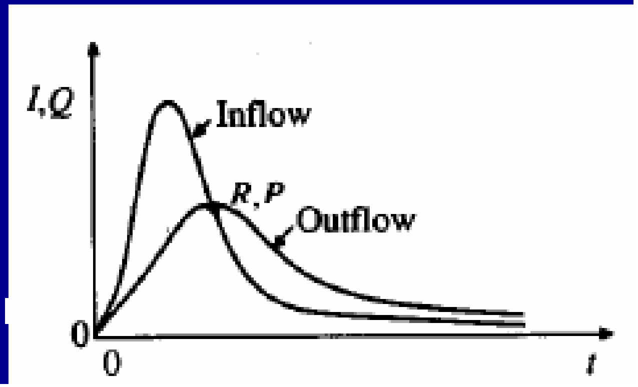
- Level pool reservoir routing - Storage is a nonlinear function of Q only. S = f(Q)
- Muskingum method for flow routing in channels – Storage is linearly related to I & Q
- Linear reservoir models – Storage is a linear function of Q and its time derivatives
- Effect of reservoir storage is to redistribute the hydrograph by shifting the centroid of the inflow hydrograph to the position of that of the outflow hydrograph in time

Lumped Flow Routing - Methods

- **Case 1: Invariable relationship between S & Q**



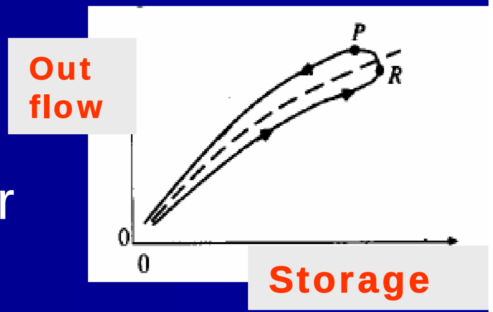
- Storage & outflow are functions of water surface elevation - when reservoir has a horizontal water surface elevation
- S = f (Q) – combination of these two functions
- Peak outflow occurs at intersection of inflow hydrograph and outflow hydrograph



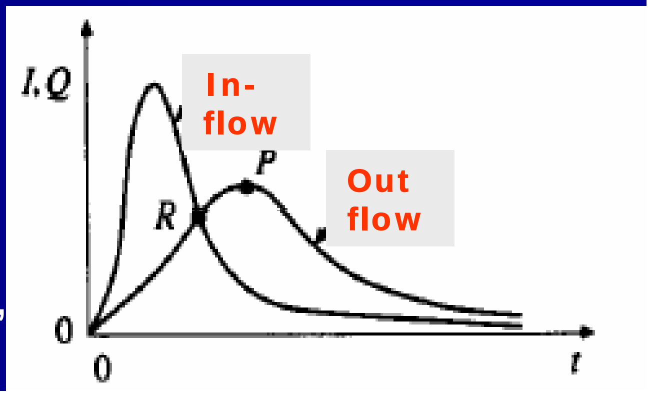
Lumped Flow Routing - Methods

Case 2: Variable relationship between S & Q

- Applies to long, narrow reservoirs & open Channels
- Water surface profile curved due to back water Effects
- Peak outflow occurs later than point of intersection time
- Replacement of loop with dashed line – when back water effect is not significant



Based on Chow et.al(1988)



Reservoir Routing

- Procedure for calculating the outflow hydrograph from a reservoir with a horizontal water surface
- Flow of flood waves from rivers/ streams keeps on changing the head of water in the reservoir h = h(t)
- Required to find variations of S, Q, & h with time for given inflow with time
- In a small interval of time
- Average inflow in time t, Average outflow in time t, Change in storage in t

Reservoir in main channel

$$\bar{I}\,\Delta t - \bar{Q}\,\Delta t = \Delta S \quad (1)$$

$$\left(\frac{I_1 + I_2}{2}\right)\Delta t - \left(\frac{Q_1 + Q_2}{2}\right)\Delta t = S_2 - S_1 \quad (2)$$

Reservoir Routing

For reservoir routing the following data should be known

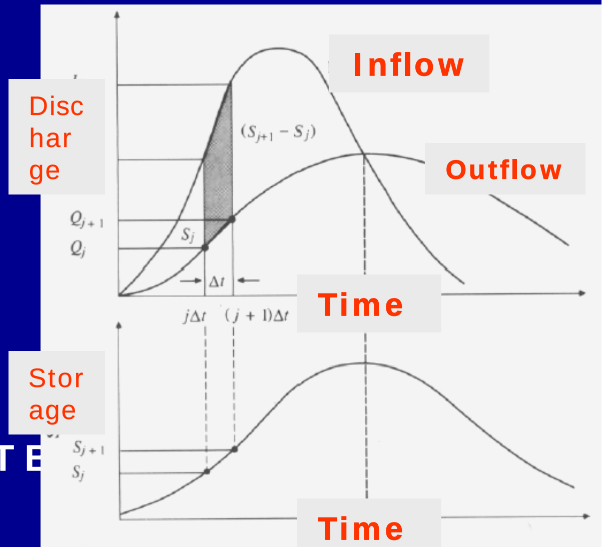
- Elevation vs Storage
- Elevation vs outflow discharge and hence storage vs outflow discharge
- Inflow hydrograph, and
- Initial values of inflow, outflow Q, and storage S at time t = 0.

Δt must be shorter than the time of transit of the flood wave through the reach

Variety of methods- for reservoir routing

Pul's method and Goodrich's method

Based on Chow et.al(1988)



Reservoir Routing – Pul's Method

- Rearrangement of equation (2) as

$$\left(\frac{I_1 + I_2}{2}\right)\Delta t + \left(S_1 - \frac{Q_1 \Delta t}{2}\right) = \left(S_2 + \frac{Q_2 \Delta t}{2}\right)$$

- All terms on the left hand side are known- At the starting of the routing
- RHS is a function of elevation h for a chosen time interval *Δt*
- Preparation of graphs for *h vs Q*, *h vs S* and h versus $\left(S + \frac{Q\,\Delta t}{2}\right)$
- Procedure is repeated for full inflow hydrograph

Reservoir in main channel

Reservoir Routing – Goodrich Method

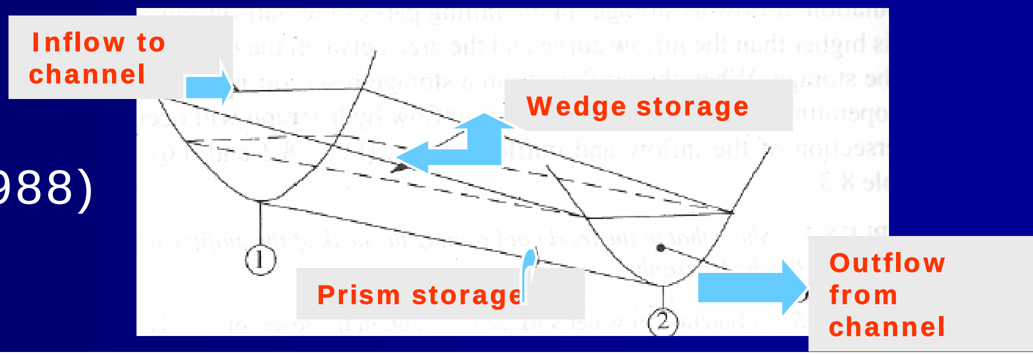
- Rearranged equation is (2) $$\left(I_1 + I_2\right) + \left(\frac{2S_1}{\Delta t} - Q_1\right) = \left(\frac{2S_2}{\Delta t} + Q_2\right)$$
- Preparation of graphs for h vs Q, and h vs S and h versus $\left(\frac{2S}{\Delta t} + Q\right)$
- Flow routing through time interval *Δ*t, all terms on the LHS and hence RHS are known
- Value of outflow Q for $\left(\frac{2S}{\Delta t} + Q\right)$ can be read from the graph
- Value of $\left(\frac{2S}{\Delta t} - Q\right)$ calculated by $\left(\frac{2S}{\Delta t} + Q\right) - 2Q$
  - for next time interval
- Repetition of computations for subsequent routing periods

Reservoir in main channel

Channel Routing- Muskingum Method

- Hydrologic routing method for handling variable discharge – storage relationship.
- Storage is a function of both outflow & inflow discharges
- Water surface in a channel reach is not only parallel to the channel bottom but also varies with time
- Models storage in channel-combination of wedge & prism
- **Prism storage**: Volume that would exist if uniform flow occurred at the downstream depth
- **Wedge storage** : Wedge like volume formed between actual water surface profile & top surface of prism storage

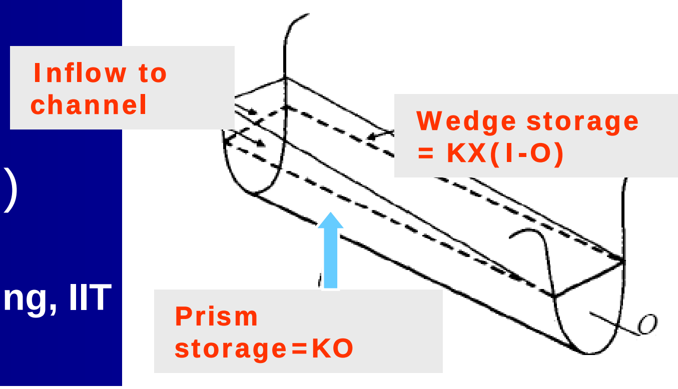
Based on Chow et.al(1988)



Channel Routing- Muskingum Method

- During the advance of flood wave, inflow exceeds outflow – Positive wedge
- During recession, outflow exceeds inflow –Negative wedge
- Assumption: Cross sectional area of the flood flow section is directly proportional to the discharge at the section
- Volume of prism storage is equal to KO
- Volume of the wedge storage is equal to KX(I - O)
- K – proportionality coefficient, X -weighing factor having the range 0 < X < 0.5

Based on Chow et.al(1988)



Channel Routing- Muskingum Method

- Total storage: $S = K\left(XI + (1-X)O\right)$ ---- Muskingum storage equation
- Linear model for routing flow in streams
- Value of X depends on shape of modeled wedge storage
- X = 0 for level pool storage (S = KO); X = 0.5 for a full wedge
- K- Time of travel of flood wave through channel reaches
- Values of storage at time j and j+1 can be written as

$$S_j = K\left(XI_j + (1-X)O_j\right) \text{ and}$$

$$S_{j+1} = K\left(XI_{j+1} + (1-X)O_{j+1}\right)$$

- Change in storage over time interval t is

$$S_{j+1} - S_j = K\left(X\left(I_{j+1} - I_j\right) + (1-X)\left(O_{j+1} - O_j\right)\right)$$

Channel Routing- Muskingum Method

- From the continuity equation $$\left(\frac{I_j + I_{j+1}}{2}\right)\Delta t - \left(\frac{O_j + O_{j+1}}{2}\right)\Delta t = S_{j+1} - S_j$$
- Equating these two equations

$$K\left(X\left(I_{j+1} - I_j\right) + (1-X)\left(O_{j+1} - O_j\right)\right) = \left(\frac{I_j + I_{j+1}}{2}\right)\Delta t - \left(\frac{O_j + O_{j+1}}{2}\right)\Delta t$$

- Simplifying.... $$O_{j+1} = C_1 I_{j+1} + C_2 I_j + C_3 O_j$$ ----- Muskingum's routing equation

Where

$$C_1 = \frac{0.5\Delta t - KX}{K(1-X) + 0.5\Delta t} \qquad C_2 = \frac{0.5\Delta t + KX}{K(1-X) + 0.5\Delta t} \qquad C_3 = \frac{K(1-X) - 0.5\Delta t}{K(1-X) + 0.5\Delta t}$$

Chow et.al(1988) $$C_1 + C_2 + C_3 = 1$$

Channel Routing- Muskingum Method

- Δt should be so chosen that K > t > 2KX ….. For best results
- *If* Δ t < 2KX ……. Coefficient C_1 will be negative

Required input for Muskingum routing

- ✓ Inflow hydrograph through a channel reach,
- ✓ Values of K and X for the reach
- ✓ Value of the outflow Oj from the reach at the start
- ✓ For a given channel reach, K & X are taken as constant
- ✓ K is determined empirically (eg. Clark's method: $K=cL/s^{0.5}$; c – constant; L – length of stream,; s – mean slope of channel) or graphically.
- ✓ X is determined by trial and error procedure

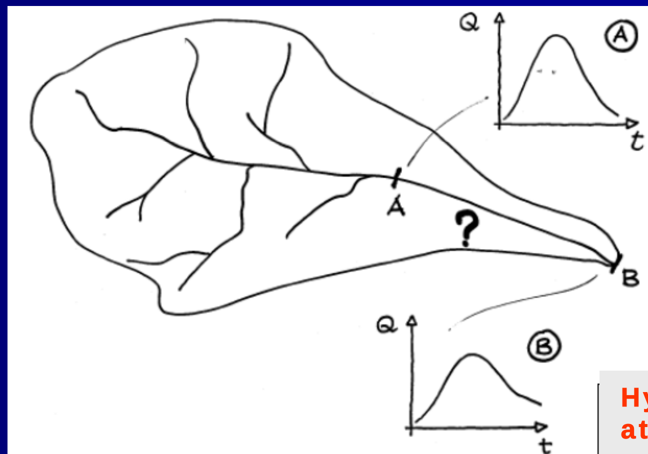
Muskingum Method - Procedure

Routing Procedure:

- Knowing K and X, select an appropriate value of Δt
- Calculate C1, C2, and C3
- Starting from the initial conditions known inflow, outflow, calculate the outflow for the next time step
- Repeat the calculations for the entire inflow hydrograph

Flood Routing by St. Venant Equations

- Physically based theory of flood propagation - from the Saint Venant equations for gradually varying flow in open channels.
- Hydraulic routing method
- Flow as 1 D flow – Gradually varied flow condition
- Conservation of mass- continuity equation
- Conservation of momentum – Dynamic wave equation



Hydrograph at outlet of watershed

Gov. Equation for Flow Routing

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:

$S_0 = S_f$

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

Solution Methodologies

- **Analytical method:** simplified governing equations, boundary conditions & geometry, analytical solutions can be obtained.
- **Computational method:** solution is obtained with the help of some approximate methods using a computer. Commonly, numerical methods (FDM, FEM, FVM) are used to obtain solution in the computational method.
- Finite Element Method:

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

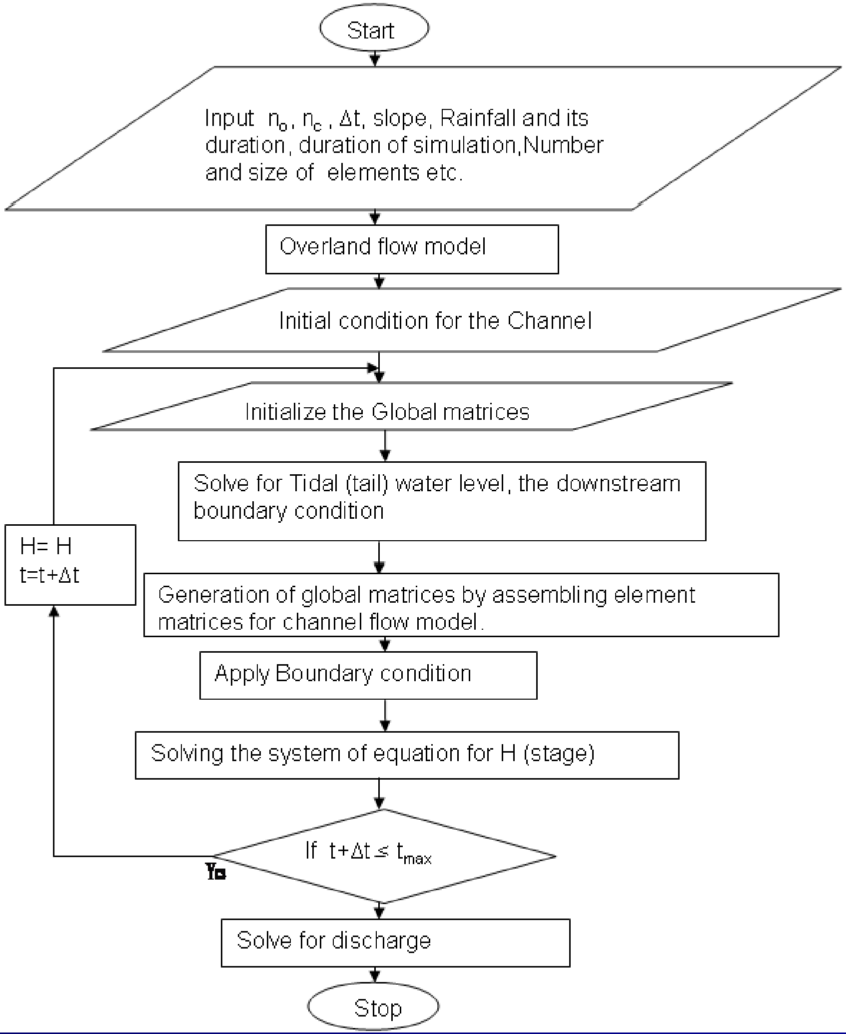
$$\frac{\partial h}{\partial x} = S - S_{f_c}$$

$$Q = \frac{1}{n} R^{(2/3)} S_{f_c}^{(1/2)} A$$

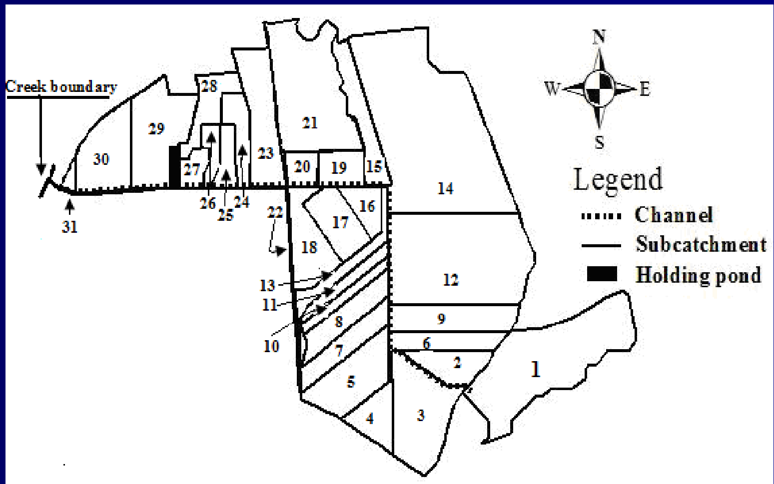
$$(S_{f_c})_i = S_i - \frac{h_k - h_i}{L}$$

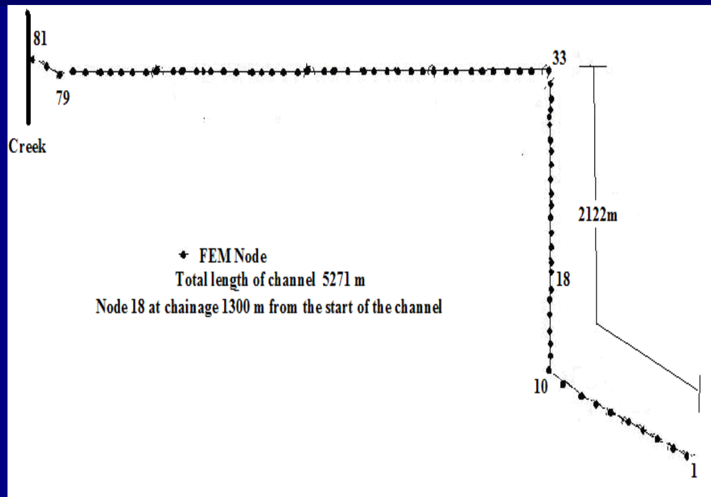
$$[C]\{A\}^{t+\Delta t} = [C]\{A\}^{t} - \Delta t[B]\{(1-\theta)Q^{t} + \theta Q^{t+\Delta t}\} + \Delta t\{f\}((1-\theta)q^{t} + \theta q^{t+\Delta t})$$

FEM Based Flood Routing Model



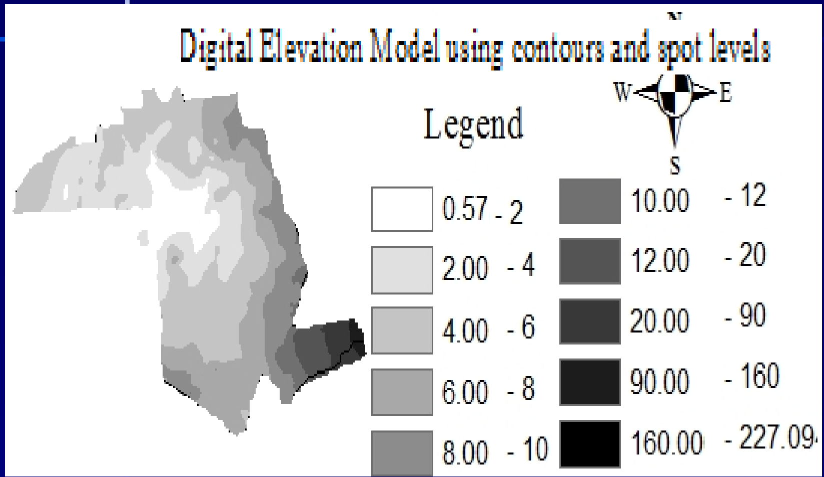
Flood Routing – Case study

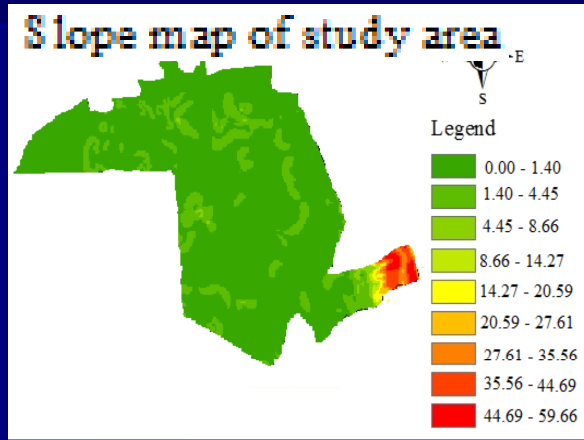


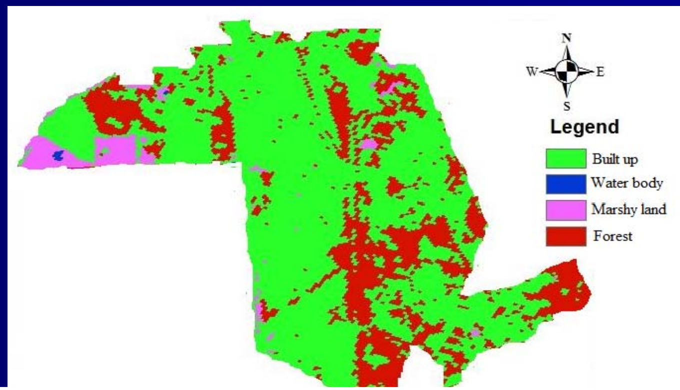


Catchment Area	847.52 Ha
Elevation varies from 0.5 m to 227 m above MSL.	
No of subcatchments	31
Rainfall event	26/07/ 2005; 15/07/2009
Length of channel	5271 m
FEM	Linear 80 Channel elements
Tidal Range	3.25 m to -1.0 m (design)

Case Study: Flood Routing



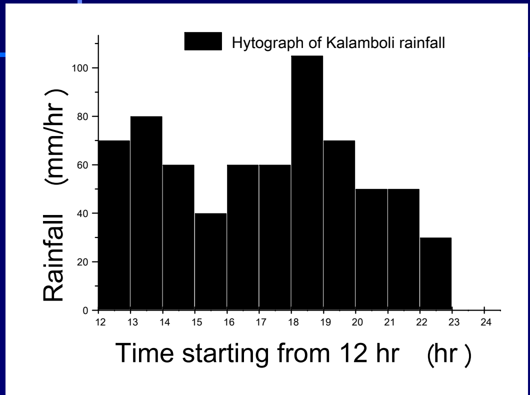


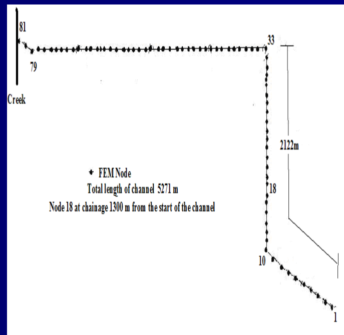


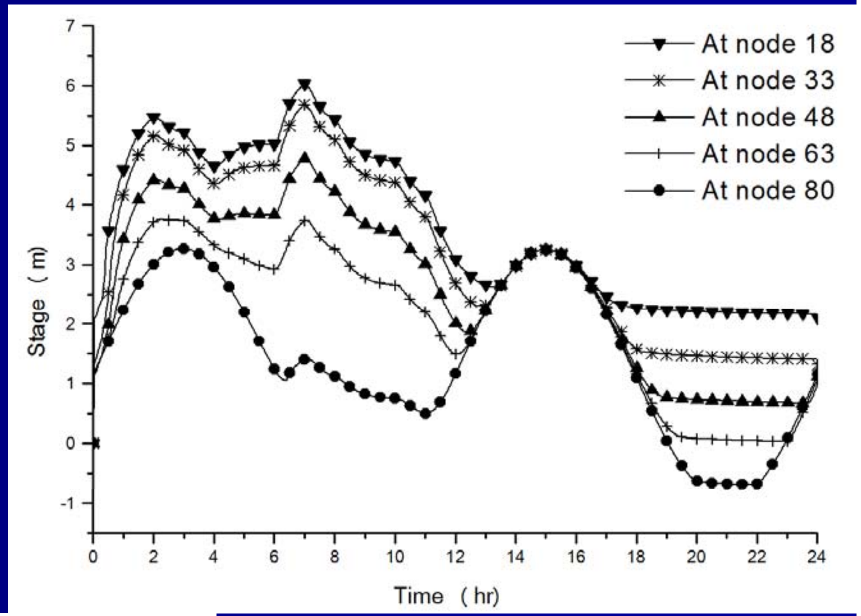
Land use/cover map using satellite imagery

Case Study: Flood Routing

Hyetograph 26/07/2005

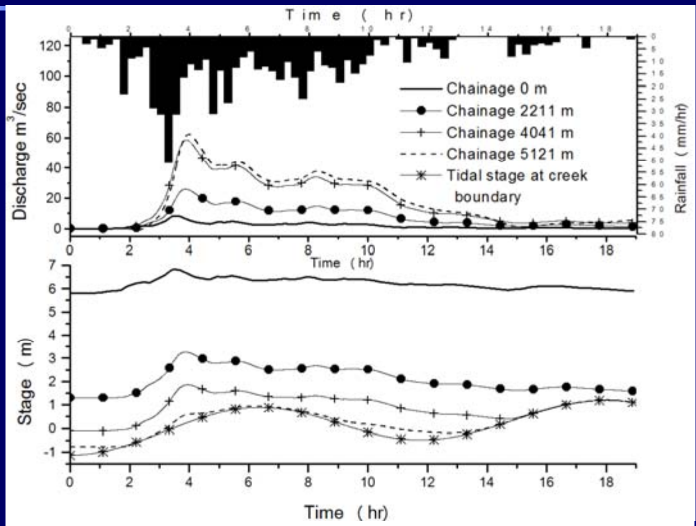


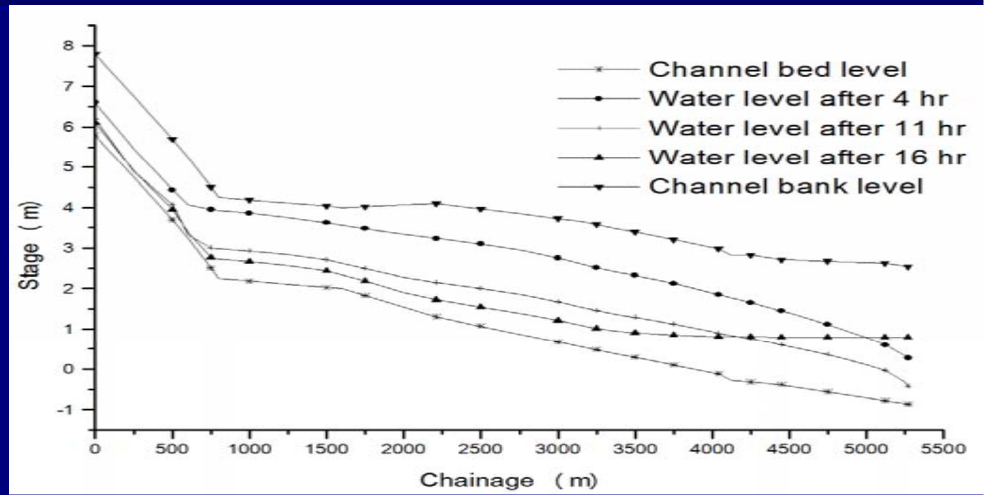




Total rainfall (mm)	Duration (hr)	Start of high tide after rainfall starts (hr)	Critical location node	Flood level developed (m)	Flood depth (m)
675	11	0	18	6.035	-1.941
		3	18	6.102	-2.008
		6	18	6.050	-1.956
		9	18	6.035	-1.941

Case Study: Flood Routing





15July2009

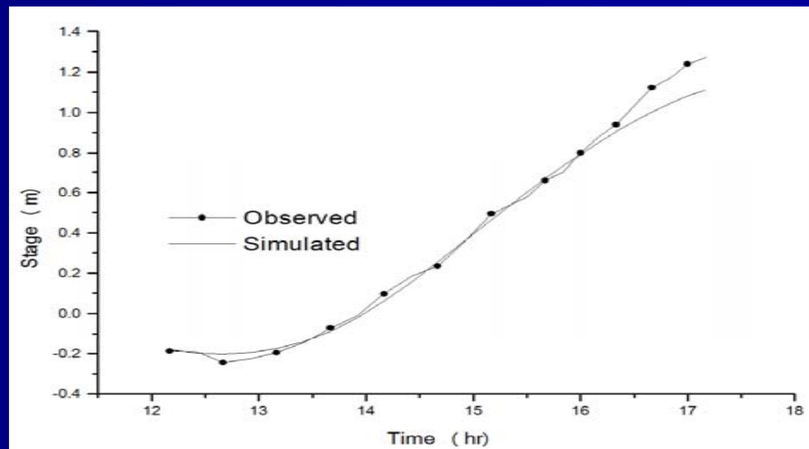


Fig. Comparison of observed and simulated stages at chainage 5121 m on 15th July 2009

References

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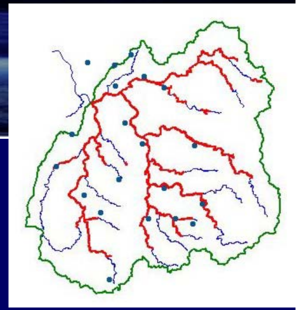
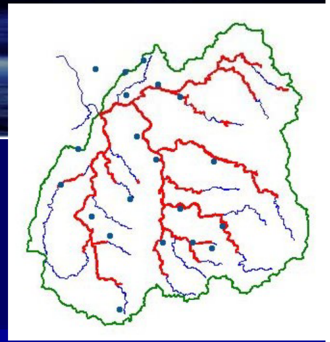


Tutorials - Question!.?.

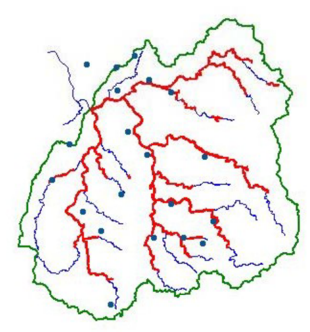
- Study the various flood routing methodologies in details and suggest applications of each.

- What are the software available for flood routing?. (*www.hec.usace.army.mil*) Evaluate the applications for various problems such as reservoir routing/ channel routing.



Self Evaluation - Questions!.

- What is flood routing and where it is used?
- Explain reservoir routing.
- Differentiate between Pul's method & Goodrich method.
- Describe the Muskingum method of flood routing.
- Describe the prism storage & wedge storage in a channel.
- What are the input data required for Muskingum routing?.



Assignment- Questions?.

- What are the motivations for flood routing?.
- Describe different types and advantages of flood routing.
- Illustrate the channel routing procedure.
- Describe the lumped flow routing.
- Discuss physically based flood routing in channels by using St. Venant equations.

THANK YOU

Dr. T. I. Eldho
Professor,
Department of Civil Engineering,
Indian Institute of Technology Bombay,
Mumbai, India, 400 076.
Email: eldho@iitb.ac.in
Phone: (022) – 25767339; Fax: 25767302
http://www.civil.iitb.ac.in