

# Engineering Hydrology

**Week-6**

## **CHAPTER -3 FLOOD ROUTING**

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# Lecture contents of the last weeks (Week-3-5)

## **CHAPTER -2 Rainfall-runoff Relationships**

2.1 Hydrological Models

2.2 Rational Method

2.3 Rainfall intensity and Time of Concentration

2.4 SCS Curve Number and Time-Area Methods

2.5 Stream Flow Hydrograph

2.6 The Unit Hydrograph (UH)

2.7 Applications of Unit Hydrograph

2.8 Synthetic Unit Hydrographs

2.9 Hydrology of Ungauged Catchment



# Home assignment:

I hope you are sure you area able to exercise on:

- **Hydrological modeling:** definition, importance and classification
- **Rainfall:** Intensity, duration, frequency, effective rainfall and time of concentration
- **Rational method:** symbols, units and problem analysis
- **SCS-CN methods:** symbols, units and problem analysis
  - Compare and contrast rainfall, effective rainfall and direct runoff.
    - Relate parameters under these methods
    - Try to solve mathematical expression and problem solving on these methods for effective rainfall
- **Baseflow separation:** definitions and methods
  - What does baseflow mean?
  - Why it is important?
  - Compare and contrast baseflow separation methods graphically.
- **Hydrograph:** Factors affecting, UH., SUH
- **Data transfer for ungauged watersheds**



# Lecture contents of the week

## **HAPTER -3 FLOOD ROUTING**

3.1 General

3.2 Simple non-storage routing

3.3 Reservoir or Level Pool Routing

3.4 Channel Routing



# Lecture Learning Outcomes

**Course Learning Outcomes:** After completion of this Lecture, you will be able to:

**CLO-1:** Apply measurement techniques of the components of the hydrologic cycle, water balance and filling of missed data;

**CLO-2:** Examine rainfall-runoff relationship and hydrograph;

- Apply flood routing

**CLO-3:** Examine the probability of occurrence;

**CLO-4:** Analyze the water movement in to, over, and through the soil surface;

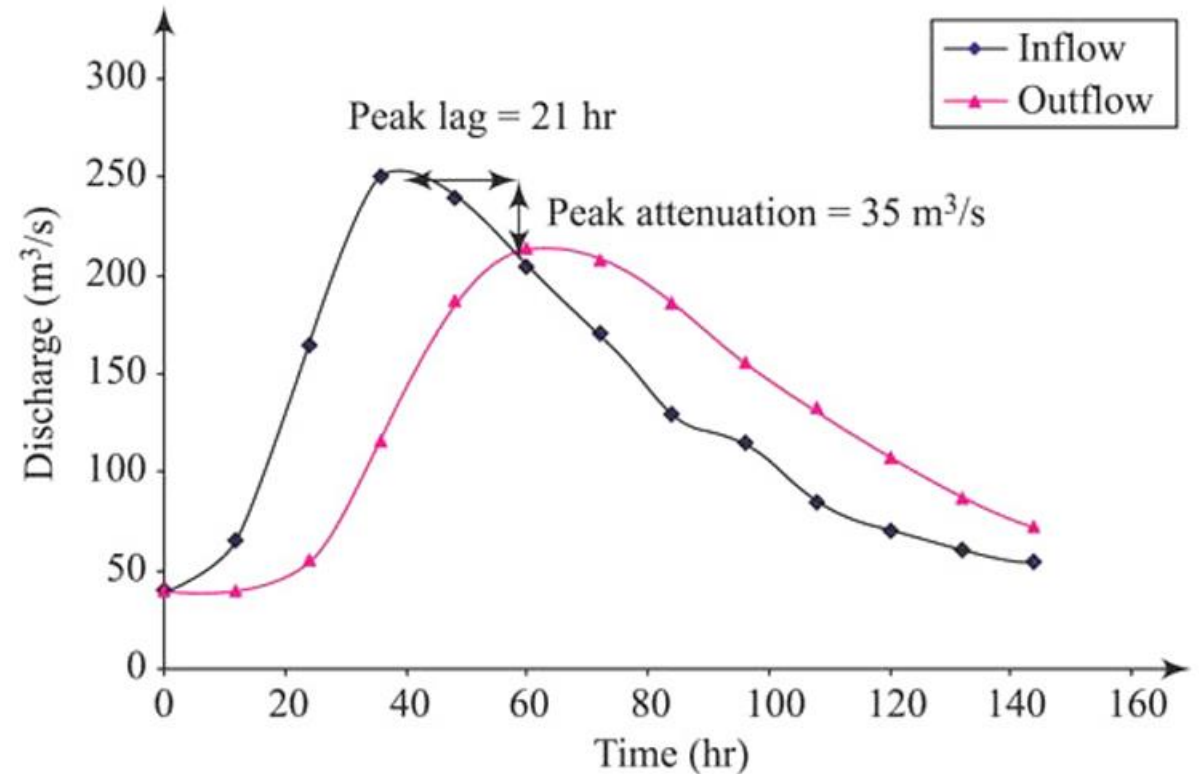
**CLO-5:** Design capacity of reservoir;

**CLO-6:** Design runoff volume and time of distribution of the runoff hydrograph from urbanization effect.



### 3. FLOOD ROUTING: General

- **Flood routing** is a 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**.
- The two broad categories of routing:
  - **reservoir** routing and **channel** routing.
- The difference between these two are:
  - in the reservoir routing, the water **surface slope is zero**;
  - while in channel routing, it is a non-zero value.



**Source:** Textbook, (Ojha et al, 2008)



### 3. FLOOD ROUTING

- Flood routing is the 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.
- when a flood wave passes through a reservoir, its peak is **attenuated** and the **time base is enlarged** (translated) due to the effect of storage.
- Flood waves passing down a river have their peaks **attenuated** due to friction if there is no lateral inflow.



## 3. FLOOD ROUTING

- The hydrologic analysis of problems such as flood forecasting, flood protection, reservoir and spillway design invariably include **flood routing**.
- Flood Routing helps to fix the capacity of the **spillway** of reservoirs, **water control** structures, and **forecasting** of floods

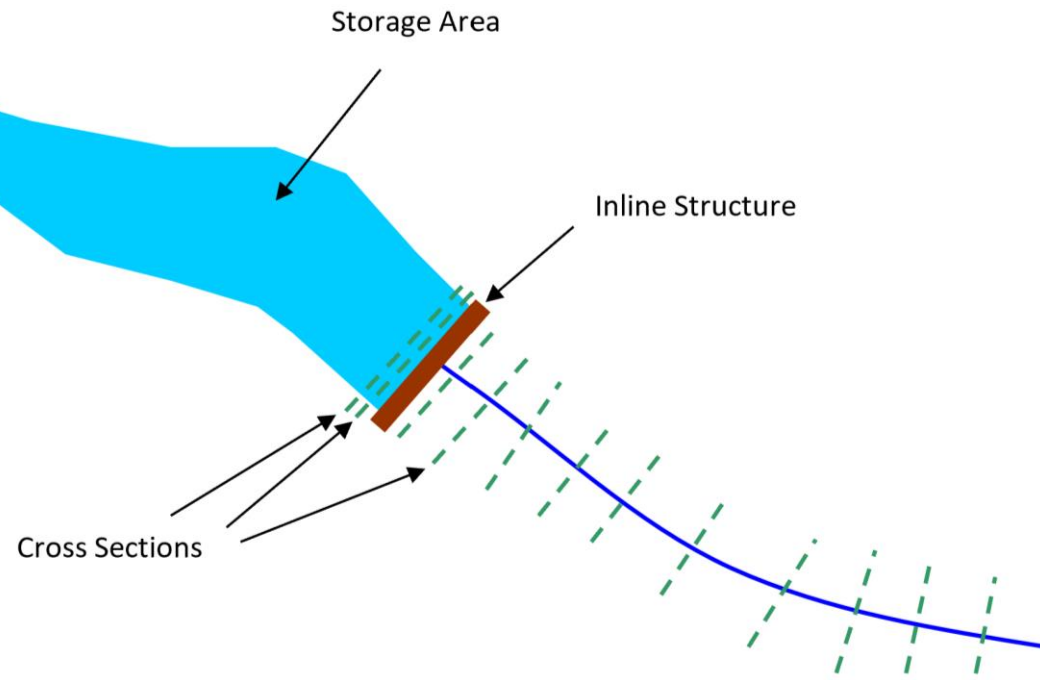


### 3. FLOOD ROUTING: Applications

- The effect of a flood wave entering the reservoir is studied to predict the **variation of reservoir elevation** and out flow discharge with time.
- This form of routing is essential to:
  - (i) In the design of the **capacity of spillways** and other reservoir outlet structures
  - (ii) In the **location** and **sizing** of the capacity of reservoirs to meet specific requirements.



### 3. FLOOD ROUTING: Applications



(iii) For conducting **river basin watershed studies** for watersheds where one or more storage facilities exist.

<https://www.hec.usace.army.mil/confluence/rasdocs/ras1dtechref/files/6.0/43816671/54661880/1/1616797276420/Figure+13-3.png>



### 3. FLOOD ROUTING: Channel routing

- In channel routing the changes in the shape of a hydrograph as it travels **down a channel** is studied.
- By considering a channel reach and an **input** hydrograph at the **upstream end**, this form of routing aims to predict the flood hydrograph at a **various sections** of the reach.
- The flood hydrograph at various sections of the reach is predicted by considering a channel reach and an input hydrograph at the upstream end.



# Methods of flood routing

## Techniques of flood routing:

- Hydraulic Routing and Hydrologic Routing.
- **Hydrologic routing methods** employ essentially the equation of **continuity** and **a storage function**, indicated as **lumped routing**.
- **Hydraulic methods**, on the other hand, employ the **continuity equation** together with the equation of **motion of unsteady flow**.

**Home assignment: Read about**  
**1. Flow types**  
**2. Continuity equation**



# Methods of flood routing

## Data requirement

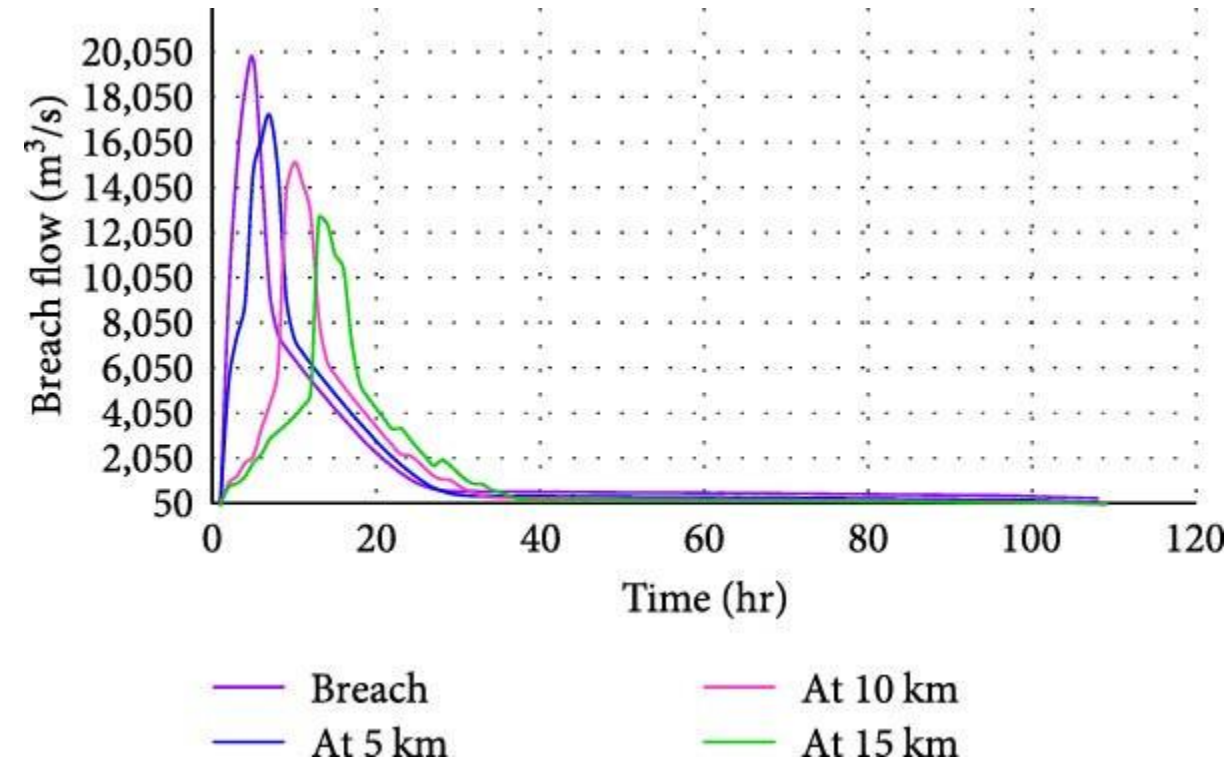
- Consider the variation of ***I*** (Inflow), ***S*** (storage), ***h*** (Water level), and ***Q*** (outflow) with time.
- Storage ***volume*** vs ***elevation*** for the reservoir (**capacity curve**)
- Water-surface ***elevation*** Vs ***outflow*** (**Rating curve**)
- Storage Vs outflow discharge (***S-Q***)
- Inflow hydrograph  **$I = I(t)$**
- Initial values of ***S***, ***I***, and ***Q*** at time  $t =$



# Methods of flood routing

**Dam Breach Modeling, *Gumara*,  
Ethiopia  
(Beza et al., 2023)**

Chainage	Peak flow (m <sup>3</sup> /s)	Velocity (m/s)	Flood height	Time to peak (hr)
At dam	25,128.1	11.88	15	4
5 km	21,254.68	10.54	14.5	6
10 km	15,458.32	8.75	13.57	10
15 km	13,705.96	6.03	11.23	13





**Break:**  
for rehearsal  
on:



**Flood routing, importance, types, techniques**



# Simple non-storage routing

- It is also known as **direct runoff routing**, assumes no water is **stored** within the channel during the routing process.
- It focuses on the **direct flow of water** through the channel reach, ignoring any temporary storage within the reach.
  - E.g a river reach with a straight path and no significant areas for **storage**.
- This approach is often used in situations where the channel reach is **relatively short**, and the storage capacity is **minimal**.
  - Continuity Equation:  $\text{Inflow} = \text{Outflow}$



# Storage Routing (Reservoir or Level Pool Routing)

## Mathematical representations of flood routing

- By the **principle of continuity**, the volume of inflow equals the volume of outflow and change in storage,

$$\text{volume} = \int_0^{T_1} I dt = \int_{T_2}^{T_3} O dt$$

The amount of storage,  $S$ , within the **reach at time  $t = T$**  is given by

$$S = \int_0^T (I - O) dt .$$



# Storage Routing

- The principle of hydrologic flood routings (both reservoir and channel) uses the **continuity equation** in the form of “Inflow minus outflow equals rate of change of storage”.

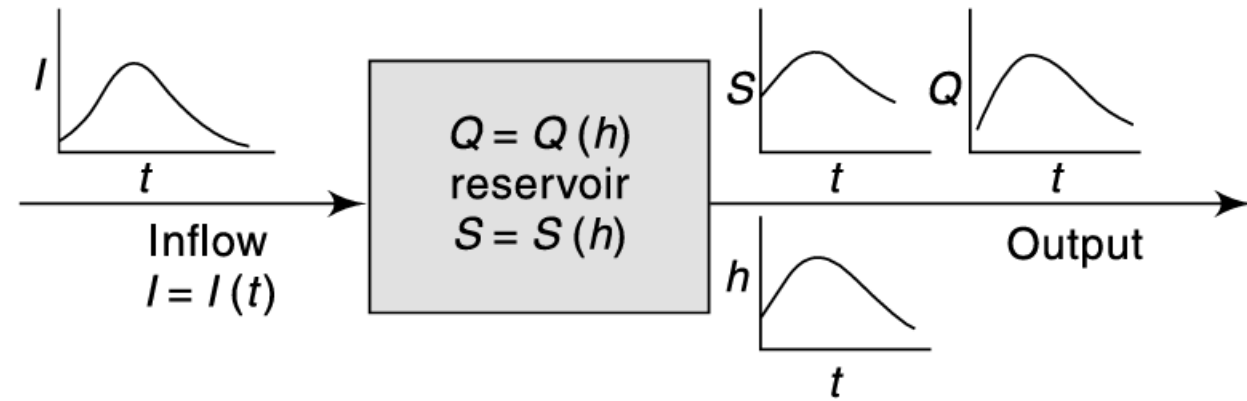
$$\frac{ds}{dt} = I_t - O_t$$

Where:

$I_t$  = Inflow in to the reach

$O_t$  = Outflow from the reach

$d_s/d_t$  = Rate of change of storage within the reach.



**Source:** Textbook, (Ojha et al, 2008)



# Storage Routing

$$\frac{S_{i+1} - S_i}{\Delta t} = \frac{1}{2}(I_{i+1} + I_i) - \frac{1}{2}(O_{i+1} + O_i)$$

$$\bar{I} \Delta t - \bar{O} \Delta t = \Delta S$$

Where,  $\bar{I}$  = average inflow in time  $\Delta t$

$\bar{O}$  = average outflow in time  $\Delta t$

$\Delta S$  = change in storage

$\Delta t$  = routing period.

- The time interval  $\Delta t$  should be sufficiently short so that the inflow and outflow hydrographs can be assumed to be **straight line** in that interval.
- As a rule of thumb  $\Delta t \leq 1/6$  of the time to peak of the inflow hydrograph is required.



# Storage Routing (Level Pool Routing)

For reservoir routing, the **following data** have to be known:

1. **Storage volume versus elevation** for the reservoir
  - For example, the volume of water stored ( $V$ ) *between two successive contours having areas  $A_1$  and  $A_2$*  (planimeter) and the contour interval  $d$ , *is given by*

**Cone formula,**

$$V = d/3(A_1 + A_2 + \sqrt{A_1A_2})$$

**Prismoid formula, more accurate**

$$V = d/6(A_1 + A_2 + 4A_m), A_m = (A_1 + A_2)/2$$



# Storage Routing (Level Pool Routing)

For reservoir routing, the **following data** have to be known:

2. Water surface **elevation versus out flow** and hence **storage versus outflow** discharge
  - The outflow rates are determined by computing the discharge through **the sluices** and the **spillway discharge** for different water surface elevations of the reservoir. (*i.e., pool elevations*)
    - Discharge through **sluices**,  $Q_{sl} = CdA\sqrt{2gh}$
    - Discharge over **spillway crest**,  $Q_{sp} = CLH^{3/2}$
    - Outflow from the **reservoir**  $Q = Q_{sl} + Q_{sp}$



# Storage Routing

## Data .....

3. Inflow hydrograph,  $I = I(t)$ ; and

4. Initial values of S, I and Q at time  $t = 0$

$$I - Q = dS/dt$$

Where H-the head of water above the crest.

- The finite difference form of the continuity equation can be rewritten as:

$$\frac{(I_1 + I_2)\Delta t}{2} - \frac{(O_1 + O_2)\Delta t}{2} = S_2 - S_1$$

Where,  $(I_1 + I_2)/2 = \bar{I}$ ;  $(O_1 + O_2)/2 = \bar{O}$  and  $S_2 - S_1 = \Delta S$  and suffixes 1 and 2 to denote the beginning and end of the time interval  $\Delta t$



# Storage Routing

Rearranging the above Equation to get the unknowns  $S_2$  and  $O_2$  on one side of the equation and to adjust the  $O_1$  term to produce:

1. The **Modified pulse or ISD** (Inflow-storage-discharge) method.

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

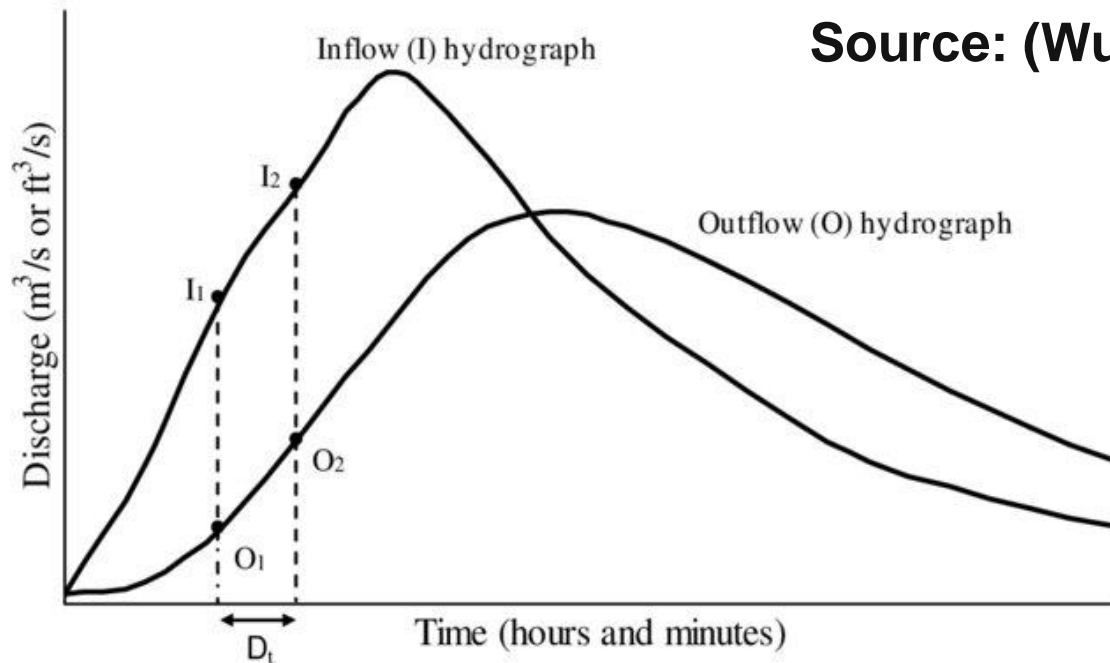
2. **Goodrich** Method.

$$(I_1 + I_2) + (2S_1/\Delta t - Q_1) = 2S_2/\Delta t + Q_2$$



# Storage Routing

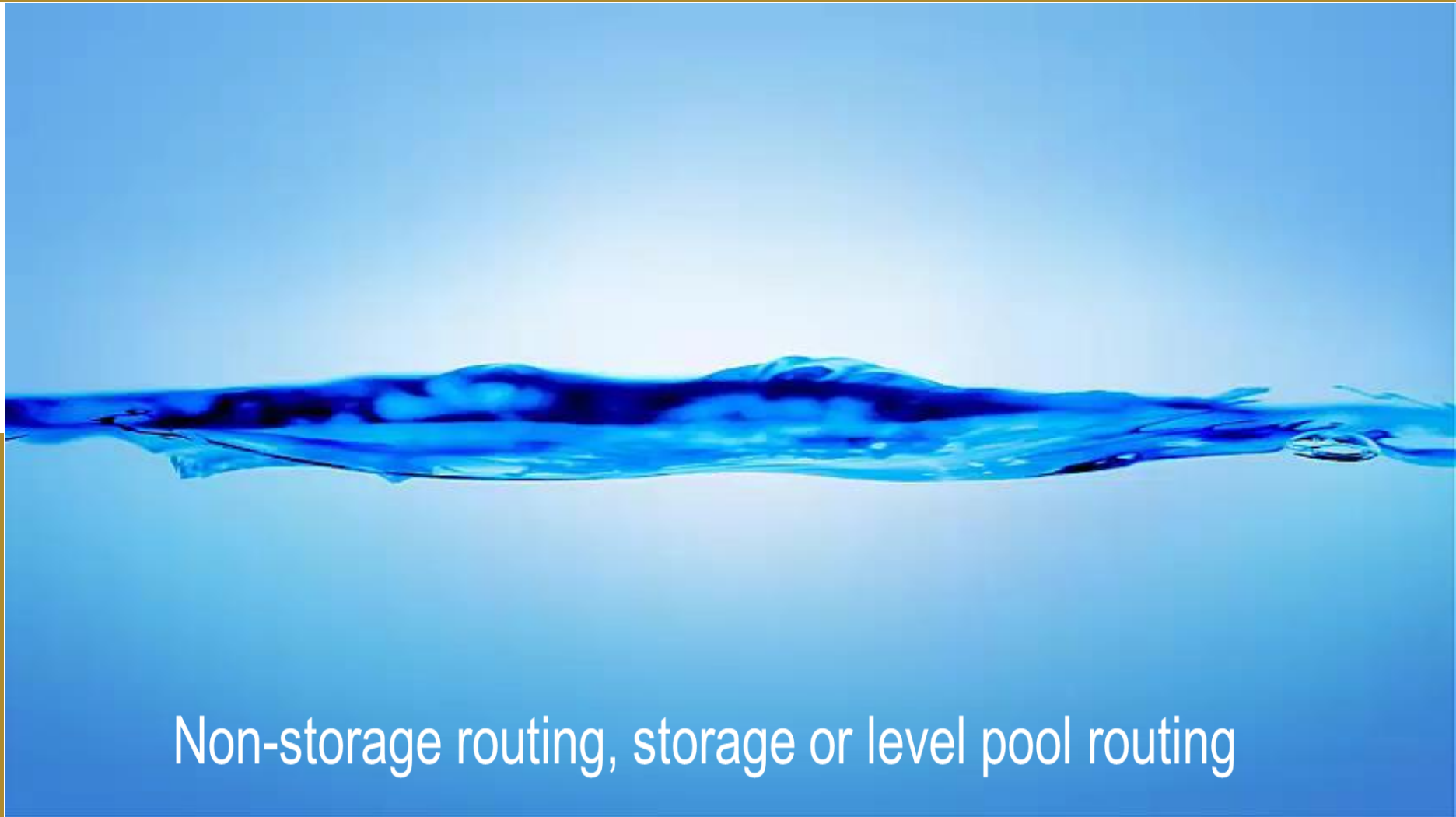
- A useful check on the validity of any level pool routing calculation is that the **peak of the outflow hydrograph** should occur at the intersection of the inflow and out flow hydrograph on the same plot.



**Source: (Wurbs, R.A.. 2005)**



**Break:**  
for rehearsal  
on:



Non-storage routing, storage or level pool routing



# Channel routing

**In channel routing**, the flood hydrograph at various sections of **the reach is predicted** by considering a channel reach and an input hydrograph at the upstream end.

- Information on the **flood-peak attenuation** and the duration of **high-water levels** obtained by channel routing.
  - its utmost importance in **flood- forecasting operations** and **flood-protection works**.
- As the flood wave moves down the river, the shape of the wave gets modified due to various factors:
  - channel storage, resistance, lateral addition or withdrawal of flows, etc.
- storage is a function of both **outflow** and **inflow discharges** and hence a different routing method is needed.



# Channel routing

## Basic Equations:

- The flow in a river during a flood belongs to the category of **gradually varied unsteady flow**.
- the equation of **continuity is used**: the rate of **change of storage** is the difference between the inflow and outflow rate.

$$I - Q = \frac{dS}{dt}$$



# Channel routing

IN a small time interval ( $\Delta t$ ), the difference between the **total inflow** and **total outflow** in a reach is equal to the **change in storage** in that reach.

$$I - Q = \frac{dS}{dt}$$

$$\bar{I} \Delta t - \bar{Q} \Delta t = \Delta S$$

where,  $\bar{I} = (I_1 + I_2)/2$ ,  $\bar{Q} = (Q_1 + Q_2)/2$ , and  $\Delta S = S_2 - S_1$

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

- At must be shorter than the time of transit of the flood wave through the reach.



# Channel routing

- The **equation of continuity** for unsteady flow in a reach with no lateral flow is given by the differential forms:

$$\frac{\partial h}{\partial t} + u \frac{\partial h}{\partial x} + h \frac{\partial u}{\partial x} = 0$$

where,  $u$  = velocity of flow, and  $h$  = depth of flow

- The equation of motion for a flood wave is derived from the application of the **momentum equation** as:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + g \frac{\partial h}{\partial x} - (S_0 - S_f)g = 0$$

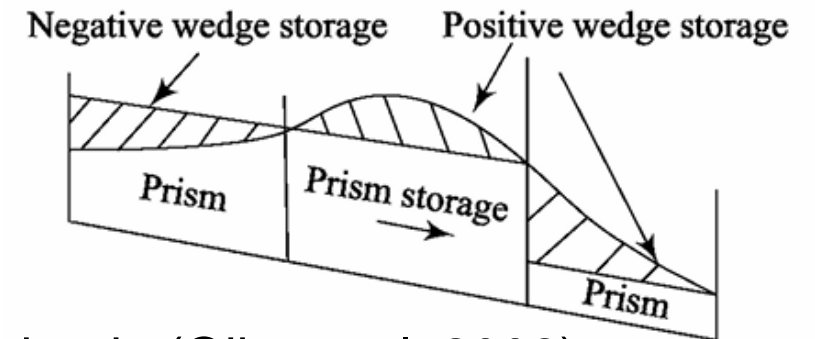
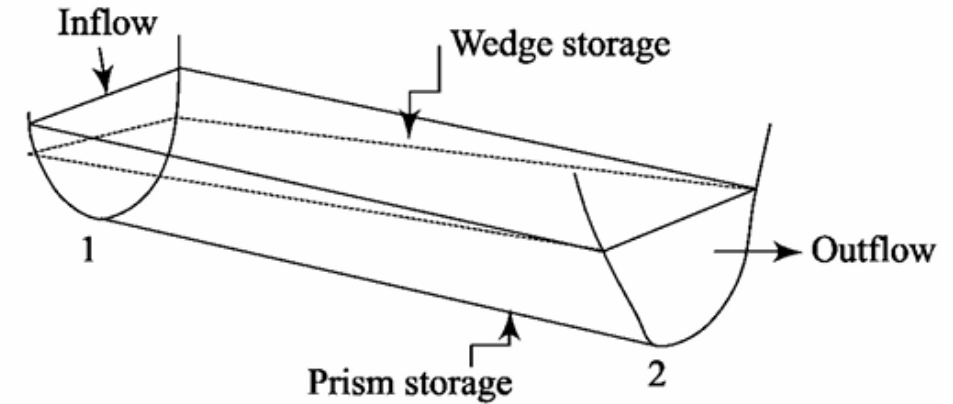
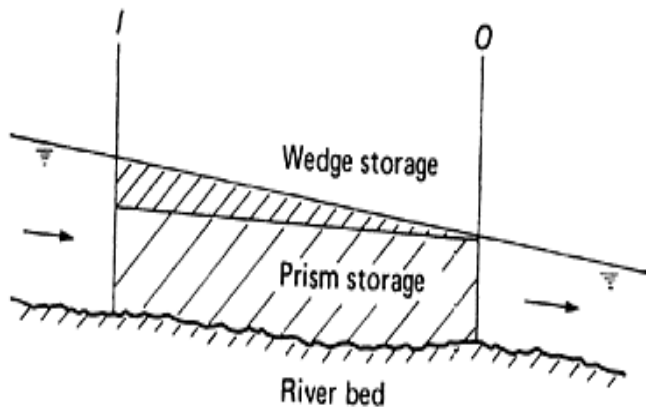
where,  $S_0$  = channel bed slope, and  $S_f$  = slope of the energy line.



# Channel routing

## Storages in the Channel,

- the storage in the reach may be split up in two parts:
  - prism storage**
  - wedge storage**
- the **prism** storage is constant
- the **wedge** storage changes from a **positive** value at an advancing flood to a **negative** value during a receding flood.



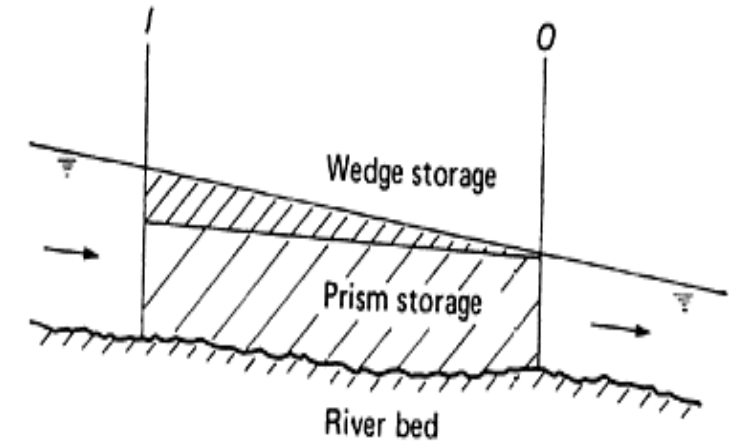
Source: Textbook, (Ojha et al, 2008)



# Channel routing

## Storages in the Channel,

- The prism storage ( $S_p$ ) is similar to a reservoir and can be expressed as a function of the **outflow** discharge,  $S_p = f(Q)$ .
- The **wedge storage** can be accounted for by expressing it as  $S_w = f(I)$ .
- The **total storage** in the channel reach can then be expressed as:
$$S = K [x I^m + (1 - x)Q^m]$$
- where,  $K$  and  $x$  are coefficients, and  $m$  is a constant exponent.
  - the value of  $m$  varies from **0.6** for rectangular channels to about **1.0** for natural channels.





# Channel routing

- The total storage in the channel reach can be generally represented by:

$$\text{Storage in wedge} = KX(I - Q)$$

$$\text{Storage in prism} = KQ$$

$$\text{So, Storage } S = KX(I - Q) + KQ$$

And this can then be expressed as:

$$S = K(xI^m + (1 - x)Q^m)$$

**where**

**K** and **x** are coefficients and **m** is a constant exponent. It has been found that the value of **m** varies from **0.6** for rectangular channels to value of about **1.0** for natural channels.



# Channel routing

- **Muskingum Equation**: is the equation that assumes

Using  $m = 1.0$  in:

$$\text{Then,} \quad S = K(xI + (1 - x)Q)$$

**Where,**

- the parameter  $x$  is known as weighting factor and it takes a value between 0 and 0.5.
- It accounts for the storage portion of the routing.
- When  $x = 0$ , the storage is only the function of discharge and

$$S = KQ$$



# Channel routing

- **Muskingum Equation:**

$$S = KQ$$

A storage with  $x=1$  is known as **linear storage** or ***linear reservoir***.

- when  $x = 0.5$ , both the inflow and the outflow become equally important in determining the storage.
- The coefficient  **$K$**  is known as **storage-time constant** and has the dimensions of time.
- It is a function of the flow and channel characteristics.
- It is approximately equal to **the time of travel** of a flood wave through the channel reach.



# Channel routing

## Estimation of $K$ and $x$

- Using the continuity equation in **finite difference** form, we can write the increment in storage at any time,  $t$ , and time element,  $\Delta t$ , can be calculated:

$$\Delta S = S_2 - S_1 = \{(I_1 + I_2)\Delta t\}/2 - \{(Q_1 + Q_2)\Delta t\}/2$$

- For a given channel reach by selecting a routing interval  $\Delta t$  and using the **Muskingum** equation, the change in storage can be determined.

$$S_1 = K(xI_1 + (1 - x)Q_1)$$

$$S_2 = K(xI_2 + (1 - x)Q_2)$$

- By choosing a trial value of  $x$ , values of  $S$  at any time  $t$  are plotted against corresponding  $[xI + (1 - x)Q]$  values.
- for natural channels, the value of  $x$  lies between 0 and 0.3.



# Channel routing

## Muskingum Method of Routing (1960)

- Substituting the above Muskingum equations in to finite difference equation and after rearrangements gives:

$$S_2 - S_1 = K[x(I_2 - I_1) + (1 - x)(Q_2 - Q_1)]$$

- The continuity equation for the reach is:

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

$$Q_{i+1} = C_1 I_i + C_2 I_{i+1} + C_3 Q_i$$

where,

Note that  $\Sigma C = 1$ , i.e.  $C_1 + C_2 + C_3 = 1$

$$C_1 = \frac{\Delta t + 2Kx}{\Delta t + 2K - 2Kx}$$

$$C_2 = \frac{\Delta t - 2Kx}{\Delta t + 2K - 2Kx}$$

$$C_3 = \frac{-\Delta t + 2k - 2KX}{\Delta t + 2k - 2kx}$$

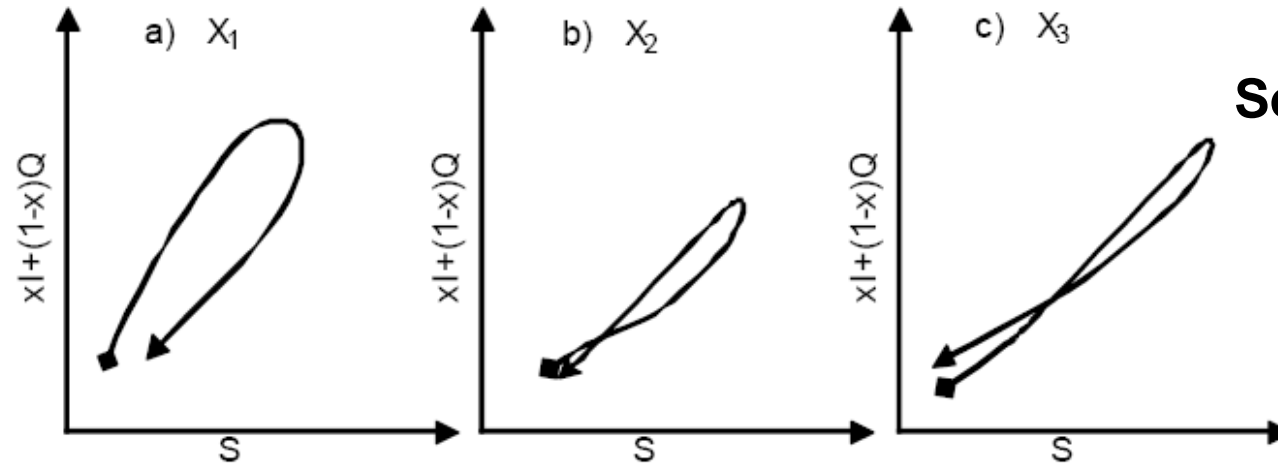


# Channel routing

- It has been found that best results will be obtained when routing interval should be so chosen that;  $\mathbf{K} > \Delta t > 2kx$
- In order to use equation **Muskingum equ.** for  $Q_{i+1}$ , it is necessary to know  $\mathbf{K}$  and  $\mathbf{x}$  for calculating the coefficients  $\mathbf{C}$ . Using **recorded hydrographs** of a flood at the beginning and end of the river reach.



# Channel routing



Source: Textbook, (Ojha et al, 2008)

$x$  and  $k$  can be determined if upstream and downstream hydrographs are available:

1. Compute the **change in storage** for each time interval
2. Compute **cumulative storage** over time
3. Plot **storage vs (  $xI + (1-x)Q$  )** for a range of values of  $x$
4. Select value of  $x$  which produces the narrowest "loop" and calculate  **$K$**  as the best fit slope.

$$\text{i.e } K = \Delta S / \Delta( xI + (1-x)Q )$$



## Home assignment:

**Make sure that you can write, select, compare on the following topics:**

- Flood routing
- Importance of flood routing
- Types of flood routing
- Techniques of flood routing
- Mathematical representation of flood routing



# References

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- Wurbs, R.A.. 2005. Comparative Evaluation of Generalized River/Reservoir System Models, Technical report, TR-282 , Texas Water Resources Institute College Station, Texas.  
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# Thank you very much for your active attendance!!

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