Hydrology of Catchments, Rivers and Delta's

FLOOD SURVEYS & FLOOD PROPAGATION

Thom Bogaard - T.A.Bogaard@tudelft.nl

Hillslope and landslide hydrology

Specialization:

Catchment hydrology, field measurements & experiments

Land degradation & Hydrology, Effect vegetation on landslide, Risk assessment

Responsible for CIE 5580: Ecology and Geomorphology

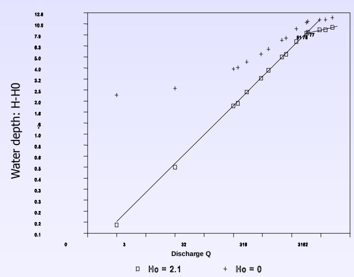
FLOOD SURVEYS & FLOOD PROPAGATION

- Occurrence of floods
- Hydrological routing vs hydraulic routing
- Reservoir routing
- Flood routing in natural channels

Rating curve; stage discharge relationship

Hydrology of Catchments, Rivers and Delta's

$$Q = a(H-H_0)^b$$



Rating curve in Limpopo river at Sicacate

Occurrence of floods

Hydrology of Catchments, Rivers and Delta's

Murphy's law:

Extreme floods occur:

- at night
- on public holidays
- when communication lines are broken
- when roads are blocked
- when the car is in repair
- when the Director of Water Affairs is on holiday

Occurrence of floods

Hydrology of Catchments, Rivers and Delta's

Problems:

- Communication lines destroyed
- The pen of the recorder stopped, or the housing of the water level recorder submerged by the flood
- The reservoir of the raingauge overtopped, or the raingauge washed away by the flood
- The rating weir completely destroyed by the flood
- The bridge on which the recorder was installed blocked by debris
- While trying to measure the velocity, the current meter was caught by debris and lost

Occurrence of floods

Hydrology of Catchments, Rivers and Delta's

Occurrence of floods

Occurrence of floods

Occurrence of floods

Occurrence of floods

Flood surveys

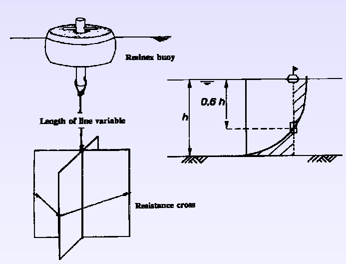
Flood surveys:

- discharge measurement using floats } during flood
- flood mark survey
- slope area method
- simplified slope area method
- interviews

(flood mark survey, slope area method, simplified slope area method: morning after; simplified slope area method, interviews: historic floods)

Flood surveys - floats

Floats

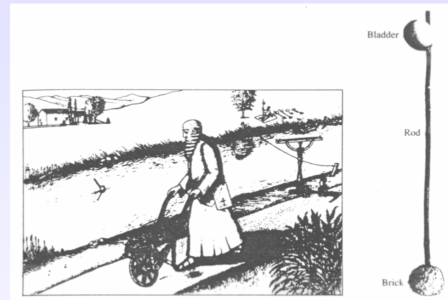


Flood surveys - floats


Cheap floats

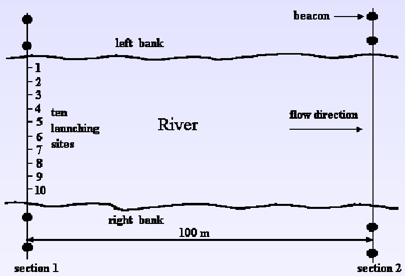
Flood surveys - floats

Float measurement



Flood surveys - floats

Float measurement



Flood surveys - floats

Advantages floats:

- longitudinal integration
- correct vertical position
- quick survey technique
- floats are cheap
- easy to improvise
- debris no problem

Flood surveys

Flood surveys:

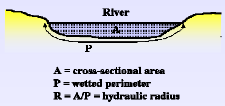
- discharge measurement using floats } during flood
- flood mark survey
- slope area method
- simplified slope area method } morning after
- interviews } historic floods

Flood surveys

Flood survey – slope area method

$$Q = C\,A\,\sqrt{R}\sqrt{S} = C\,K\,\sqrt{S}$$

$$K = \frac{\sum \left(A_i \sqrt{R_i}\right)}{N}$$



Q = discharge [m^3/s]

C = Chezy's coefficient [$m^{1/2}/s$]

A = cross-sectional area [m^2]

R = hydraulic radius [m]

S = longitudinal slope

K = geometric conveyance [$m^{2,5}$]

Hydrology of Catchments, Rivers and Delta's

Flood survey – simplified slope area method

$$\log Q = 0.188 + 1.33 \log A + 0.05 \log S - 0.056 (\log S)^2$$

Riggs (1976)

$$A = \frac{\sum A_i}{N}$$

Q = discharge [m^3/s]

A = cross-sectional area [m^2]

S = longitudinal slope

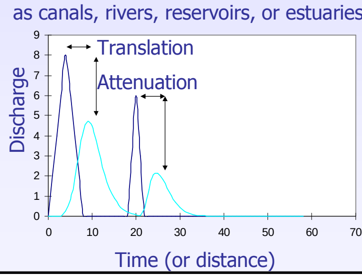
N = number of sections

Hydrology of Catchments, Rivers and Delta's

Routing

Definition

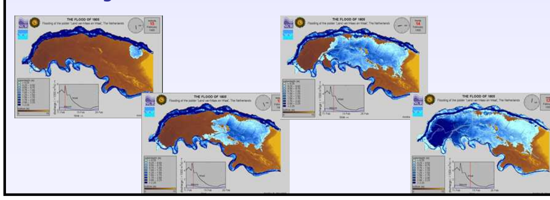
Channel routing is a mathematical method (model) to predict the changing magnitude, speed, and shape of a flood wave as it propagates through waterways such as canals, rivers, reservoirs, or estuaries (Fread, 1985)



Hydrology of Catchments, Rivers and Delta's

Routing

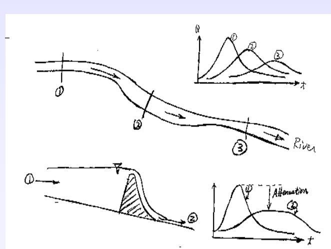
- A technique to compute the effect of system storage and system dynamics on the shape and movement of flow hydrographs along a watercourse.
- When the flow is a flood, then we have flood routing.
- Routing is used to predict the temporal and spatial distribution of flood wave (or hydrograph) as it travel along the channel.



Hydrology of Catchments, Rivers and Delta's

Routing

(a) Flood prediction, warning
(b) Reservoir design
(c) Flood plain delineation
(d) Watershed simulation
(e) ….



Hydrology of Catchments, Rivers and Delta's

Different Routings

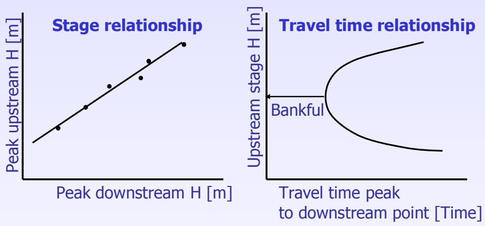
- **By Spatial and Temporal Variation:**
  - (a) Lumped Flow Routing – Flow is calculated as a function of time only at a fixed location in space.
  - (b) Distributed Flow Routing – Flow is calculated as a function of time and space in the system
- **By Governing Equations Used:**
  - (a) Hydrologic Routing [conceptual] - Employs continuity equation, along with an analytical or an assumed relationship between storage and discharge within a system, in the calculation.
  - (b) Hydraulic Routing [physical] – Use both continuity and momentum equations to describe unsteady, non-uniform flow in a flow system.
- **By Watercourse Type**
  - (a) River Flow Routing
  - (b) Reservoir Routing
  - (c) Overland Flow Routing

Hydrology of Catchments, Rivers and Delta's

Hydrologic Routing

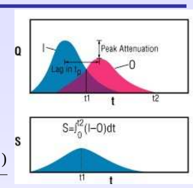
Simple, non-storage routing:
Empirical gauging, Gauging relationships, Regression relationships

Direct relationship based on 'experience' between gauging stations



Storage Routing

Continuity equation



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

$$\frac{\Delta S}{\Delta t} = \frac{S_2 - S_1}{t_2 - t_1} = \bar{I} - \bar{O} = \frac{(I_1 + I_2)}{2} - \frac{(O_1 + O_2)}{2}$$

$$(S_2 + \tfrac{1}{2}O_2 \cdot \Delta t) = (S_1 + \tfrac{1}{2}O_1 \cdot \Delta t) + \tfrac{1}{2}(I_1 + I_2) \cdot \Delta t)$$

1 equation with two unknowns: S_2 and O_2

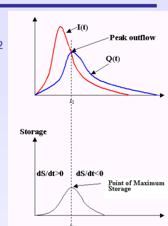
Relationship S-O $O = f(S)$

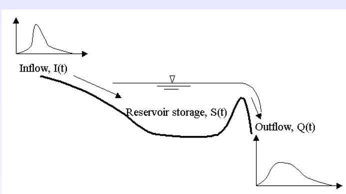
Storage Routing

One equation with two unknowns: S_2 and O_2

Relationship S-O

1) Empirical relationship between S-O
2) Linear reservoir: S = k*Q
3) S = f(O) + f(I-O)





Reservoir Routing

Puls method= Storage routing = Level pool routing = Reservoir routing

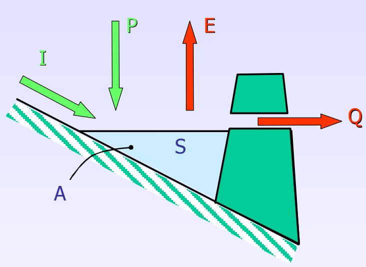
1) Empirical relationship between S-O
2) Linear reservoir: S = k*Q

Incoming water is instantaneously redistributed as a water layer over the reservoir


Three gorges dam: artist impression

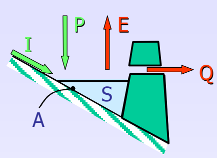

Spirit reservoir dam near Wisconsin river

Reservoir routing



$$\frac{dS}{dt} = I - Q + AP - AE$$

Reservoir routing



$$\frac{dS}{dt} = I - Q + A \cdot (P - E)$$

$$S_1 = S_0 + (I - Q + A(P-E)) * (t_1 - t_0)$$

A = A(H) — $A = A_0 + a(H-H_0)^b$; $A = A_0 \exp(b(H-H_0))$

$$S = \int_{H_0}^{H} A dH$$

$$Q = K(H-H_c)^c$$

Reservoir routing

Short term model, Flood routing:

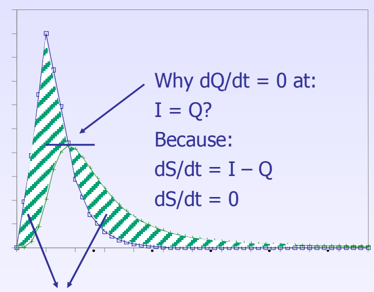
Neglect P-E

Predictor-Corrector:

1. Initial condition: $H_0 = H_c$
2. Predictor: $S_1^* = S_0 + (I - Q(H_0))\Delta t$
3. $H_1^* = H(S_1^*)$ -> $Q^* = K\left(\frac{H_1^* + H_0}{2} - H_c\right)$
4. Corrector: $S_1 = S_0 + (I - Q^*)\Delta t$
5. $H_1 = H(S_1)$
6. Possible iteration
7. Next time step

Reservoir routing

When at t=0 water level is at the spillway crest:



Surfaces are equal

Reservoir routing

What happens when water level is NOT at the spillway crest ?

Reservoir routing

Long term model, Reservoir yield analysis:

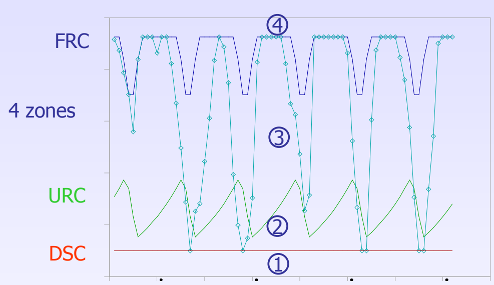
$S_1 = S_0 + (I - Q + A(P-E)) * (t_1 - t_0)$

Q is draft (regulated) and flood discharge (unregulated)

Main questions:

What is the safe yield?

Reservoir routing – yield analysis



FRC = Flood Rule Curve

URC = Utility Rule Curve

DSC = Dead Storage Curve

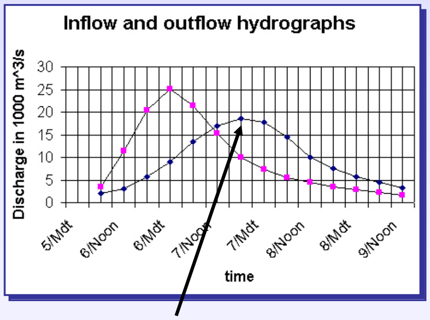
Reservoir routing – yield analysis

$S_1 = S_0 + (I - Q + A(P-E)) * (t_1 - t_0)$

Use operating rules:

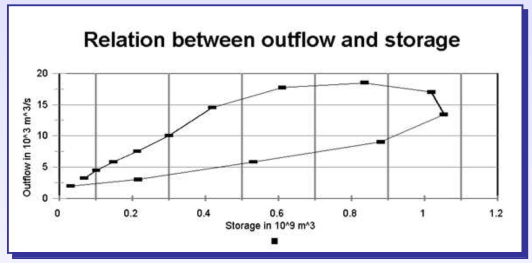
1. Assume Q=D
2. Apply water balance with $A(H_0)$
3. Check rule curves
4. Redo water balance, if rule curves apply
5. Next time step

Flood routing in natural channels



Outflow hydrograph not on recession inflow hydrograph!

Flood routing in natural channels



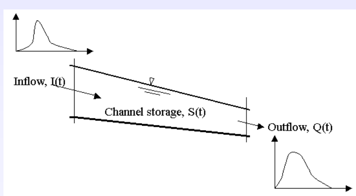
So here there is no unequivocal relation between Q and S

Muskingum Routing

1) Empirical relationship between S-O
2) Linear reservoir: S = k*Q
3) S = f(O) + f(I-O)

In a river the storage is a function of both water upstream and downstream

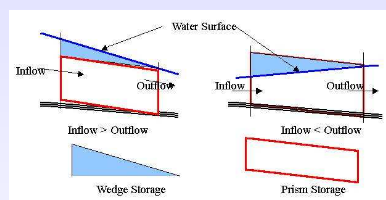
$S = f(H_{up}, H_{down})$



Muskingum Routing

In a river storage is a function of both water up- and downstream

$S = f(H_{up}, H_{down})$



Prism storage = $f(O_t)$ and I=O

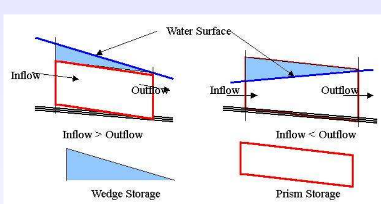
Wedge storage = $f(I_t, O_t)$

$$S = f_1(O) + f_2(I - O)$$

Muskingum Routing

$$S = f_1(O) + f_2(I - O)$$

S_p = K O	Prism Storage
S_w = K (I - O) X	Wedge Storage
S = K [XI + (1-X) O]	**Combined**



Muskingum Routing

Substitute the storage equation

S = K[XI + (1-X)O]

into the continuity equation

$$\frac{S_{n+1} - S_n}{\Delta t} = \frac{I_n + I_{n+1}}{2} - \frac{Q_n + Q_{n+1}}{2}$$

yields

$O_2 = C_0 I_2 + C_1 I_1 + C_2 O_1$

$$C_0 = -\frac{Kx - 0.5\Delta t}{K - Kx + 0.5\Delta t} \quad C_1 = \frac{Kx + 0.5\Delta t}{K - Kx + 0.5\Delta t} \quad C_2 = \frac{K - Kx - 0.5\Delta t}{K - Kx + 0.5\Delta t}$$

and $C_0 + C_1 + C_2 = 1$

Muskingum Routing

Estimating K

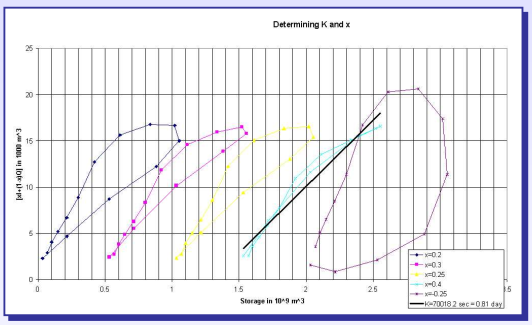
- K can be estimated as the travel time through the reach.
- Estimate the travel time using the average flow and/or peak flow
- The travel time may be estimated using the kinematic travel time or a travel time based on Manning's equation
- Use slope of the XI + (1-X)O vs. S plot, K is slope of plot
- Optimise using fitting procedures

Muskingum Routing

Estimating X

- The parameter X is a weighting coefficient for inflow and outflow.
- The value of X should be between 0.0 and 0.5. Values of X = 0.2 to 0.3 are the most common for natural streams; however, values of 0.4 to 0.5 may be obtained for streams with little or no flood plains or storage effects
- The lower limit of X = 0.0 is indicative of a situation where inflow, I, has little or no effect on the storage
- A value of X = 0.5 represents equal weighting between inflow and outflow and would produce translation with little or no attenuation
- Use slope of the XI + (1-X)O vs. S plot; Best X is least looped
- Optimise using fitting procedures

Flood routing in natural channels



Flood routing in natural channels

Muskingum equation:

S = K[x I+(1-x)Q]

Because dS/dt = I-Q:

$$I - Q = \frac{dS}{dt} = K\left[x\frac{dI}{dt} + (1-x)\frac{dQ}{dt}\right]$$

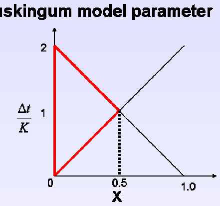
If I = Q, then:

$$x = \frac{dQ/dt}{dQ/dt - dI/dt}$$

Muskingum Routing

Feasible region for Muskingum model parameter

$$\frac{1}{2(1-x)} \le \frac{K}{\Delta t} \le \frac{1}{2x}$$



Muskingum Routing

Conditions:

Courant number

$$C = \frac{c\Delta t}{\Delta x} = \frac{\Delta t}{K} \le 1$$

Physical boundaries of x

$$0 \le x \le 0.5$$

Muskingum Routing

Notes for Muskingum routing

- The method may produce negative flows in the initial portion of the hydrograph
- Additionally, it is recommended that the method be limited to moderate to slow rising hydrographs being routed through mild to steep sloping channels
- The method is not applicable to steeply rising hydrographs such as dam breaks
- Finally, this method also neglects variable backwater effects caused by downstream dams, constrictions, bridges, and tidal influences

Muskingum Example Problem

- A portion of the inflow hydrograph to a reach of channel is given below. If the travel time is **K=1** unit and the weighting factor is **X=0.30**, then find the outflow from the reach for the period shown below:

Time	Inflow	C_0I_2	C_1I_1	C_2O_1	Outflow
0	3				3
1	5				
2	10				
3	8				
4	6				
5	5				

$$C_0 = -\frac{Kx - 0.5\Delta t}{K - Kx + 0.5\Delta t} \qquad C_1 = \frac{Kx + 0.5\Delta t}{K - Kx + 0.5\Delta t} \qquad C_2 = \frac{K - Kx - 0.5\Delta t}{K - Kx + 0.5\Delta t}$$

Muskingum Example Problem

- The first step is to determine the coefficients in this problem
- The calculations for each of the coefficients is given below:

$$C_0 = -\frac{Kx - 0.5\Delta t}{K - Kx + 0.5\Delta t}$$

C_0= - ((1*0.30) - (0.5*1)) / ((1-(1*0.30) + (0.5*1)) = 0.167

$$C_1 = \frac{Kx + 0.5\Delta t}{K - Kx + 0.5\Delta t}$$

C_1= ((1*0.30) + (0.5*1)) / ((1-(1*0.30) + (0.5*1)) = 0.667

$$C_2 = \frac{K - Kx - 0.5\Delta t}{K - Kx + 0.5\Delta t}$$

C_2= (1- (1*0.30) - (0.5*1)) / ((1-(1*0.30) + (0.5*1)) = 0.167

Therefore the coefficients in this problem are:

- C_0 = 0.167
- C_1 = 0.667
- C_2 = 0.167

Muskingum Example Problem

- The three columns now can be calculated.
- C_0I_2 = 0.167 * 5 = 0.835
- C_1I_1 = 0.667 * 3 = 2.00
- C_2O_1 = 0.167 * 3 = 0.501

Time	Inflow	C_0I_2	C_1I_1	C_2O_1	Outflow
0	3	0.835	2.00	0.501	3
1	5	0.835	2.00	0.501	
2	10				
3	8				
4	6				
5	5				

Muskingum Example Problem

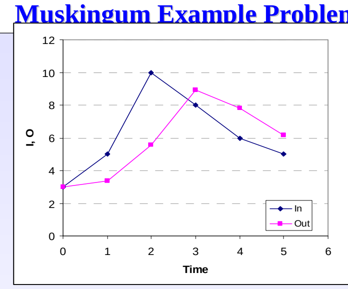
- Next the three columns are added to determine the outflow at time equal 1 hour.
- 0.835 + 2.00 + 0.501 = 3.34

Time	Inflow	C_0I_2	C_1I_1	C_2O_1	Outflow
0	3	0.835	2.00	0.501	3
1	5				3.34
2	10				
3	8				
4	6				
5	5				

- This can be repeated until the table is complete

Time	Inflow	C_0I_2	C_1I_1	C_2O_1	Outflow
0	3	0.835	2.00	0.501	3
1	5	0.835	2.00	0.501	3.34
2	10	1.34	6.67	0.93	5.57
3	8	1.00	5.34	1.49	8.94
4	6	0.835	4.00	1.31	7.83
5	5	0.835	4.00	1.31	6.14

Muskingum Example Problem



Time	Inflow	C_0I_2	C_1I_1	C_2O_1	Outflow
0	3	0.835	2.00	0.501	3
1	5	1.67	3.34	0.557	3.34
2	10	1.34	6.67	0.93	5.57
3	8	1.00	5.34	1.49	8.94
4	6	0.835	4.00	1.31	7.83
5	5		3.34	1.03	6.14

Flood routing in natural channels

Muskingum-Cunge equations:

$$K = \frac{\Delta x}{c}$$

$$c = \frac{dq}{dh} \approx 1.67\bar{v}$$

$$x = 0.5\left(1 - \frac{q}{S_b c \Delta x}\right) \approx 0.5\left(1 - 0.6\frac{h}{S_b \Delta x}\right)$$

Hydrology of Catchments, Rivers and Delta's

Flood routing in natural channels

Muskingum routing equation:

$$Q_2 = c_0 I_2 + c_1 I_1 + c_2 Q_1$$

$$c_0 = -\frac{Kx - 0.5\Delta t}{K - Kx + 0.5\Delta t}$$

$$c_1 = \frac{Kx + 0.5\Delta t}{K - Kx + 0.5\Delta t}$$

$$c_2 = \frac{K - Kx - 0.5\Delta t}{K - Kx + 0.5\Delta t}$$

$$c_0 + c_1 + c_2 = 1$$

Hydrology of Catchments, Rivers and Delta's

Flood routing in natural channels

Date	Hour	I, m^3/s	$c_0 I_2$	$c_1 I_1$	$c_2 O_1$	O, m^3/s
4/9	6 a.m.	1000	...	...	...	1000
	Noon	2400	*-408*	*530*	*640*	*762*
	6 p.m.	3900	*-663*	*1272*	*488*	*1097*
	Midnight	5000	*-850*	*2067*	*702*	*1919*
4/10	6 a.m.	4900	*-833*	*2650*	*1228*	*3045*
	Noon	4000	*-680*	*2597*	*1949*	*3866*

C_0 =-0.17; c_1 = 0.53; c_2 = 0.64

Hydrology of Catchments, Rivers and Delta's

Flood routing in natural channels

Local Inflow:

Four-point method:

$$Q_2 = c_0 I_2 + c_1 I_1 + c_2 Q_1 + c_3 Q_L$$

$$c_3 = \frac{2\Delta t / K}{2(1-x) + \Delta t / K}$$ is sum of c_0 and c_1

Three parameter Muskingum method:

$$\frac{dS}{dt} = I(1+\alpha) - Q$$

$$S = K\left[x(1+\alpha)I + (1-x)Q\right]$$

Hydrology of Catchments, Rivers and Delta's

Hydraulic routing

Hydraulic Routing [physical] – Use both continuity and momentum equations to describe unsteady, non-uniform flow in a flow system.

Momentum equation is the St. Venant equation

$S_f = S_o - \frac{\partial y}{\partial x} - \frac{v}{g}\frac{\partial v}{\partial x} - \frac{1}{g}\frac{\partial v}{\partial t}$ Unsteady - Nonuniform

$S_f = S_o - \frac{\partial y}{\partial x} - \frac{v}{g}\frac{\partial v}{\partial x}$ Steady - Nonuniform

$S_f = S_o - \frac{\partial y}{\partial x}$ Diffusion or non-inertial

$S_f = S_o$ Kinematic

Muskingum – Cunge routing

If you have no data to flood waves to determine K and X, they can be approximated using:

$$K \approx \frac{\Delta x}{c} \approx \frac{\Delta x}{m \cdot v} \qquad X \approx \frac{1}{2}\left(1 - \frac{Q}{BS_0 c\Delta x}\right)$$

Q (discharge), B (width), and c (wave celerity) are best taken as the average values over the Δx reach and Δt time step

m, v are constant throughout the routing trajectory. K, X are constant. $\Delta t < t_p/5$

This is a combination of hydrologic and hydraulic routing.

Channel routing is a mathematical method (model) to predict the changing magnitude, speed, and shape of a flood wave as it propagates through waterways such as canals, rivers, reservoirs, or estuaries (Fread, 1985)

Hydrologic Routing [conceptual] - Employs continuity equation, along with an analytical or an assumed relationship between storage and discharge within a system, in the calculation.

Hydraulic Routing [physical] – Use both continuity and momentum equations to describe unsteady, non-uniform flow in a flow system.

- Kinematic wave – energy equation assuming no pressure and acceleration terms
- Dynamic wave – energy equation assuming no acceleration terms

FLOOD SURVEYS & FLOOD PROPAGATION

- Occurrence of floods
- Hydrological routing vs hydraulic routing
- Reservoir routing
- Flood routing in natural channels