Flood routing

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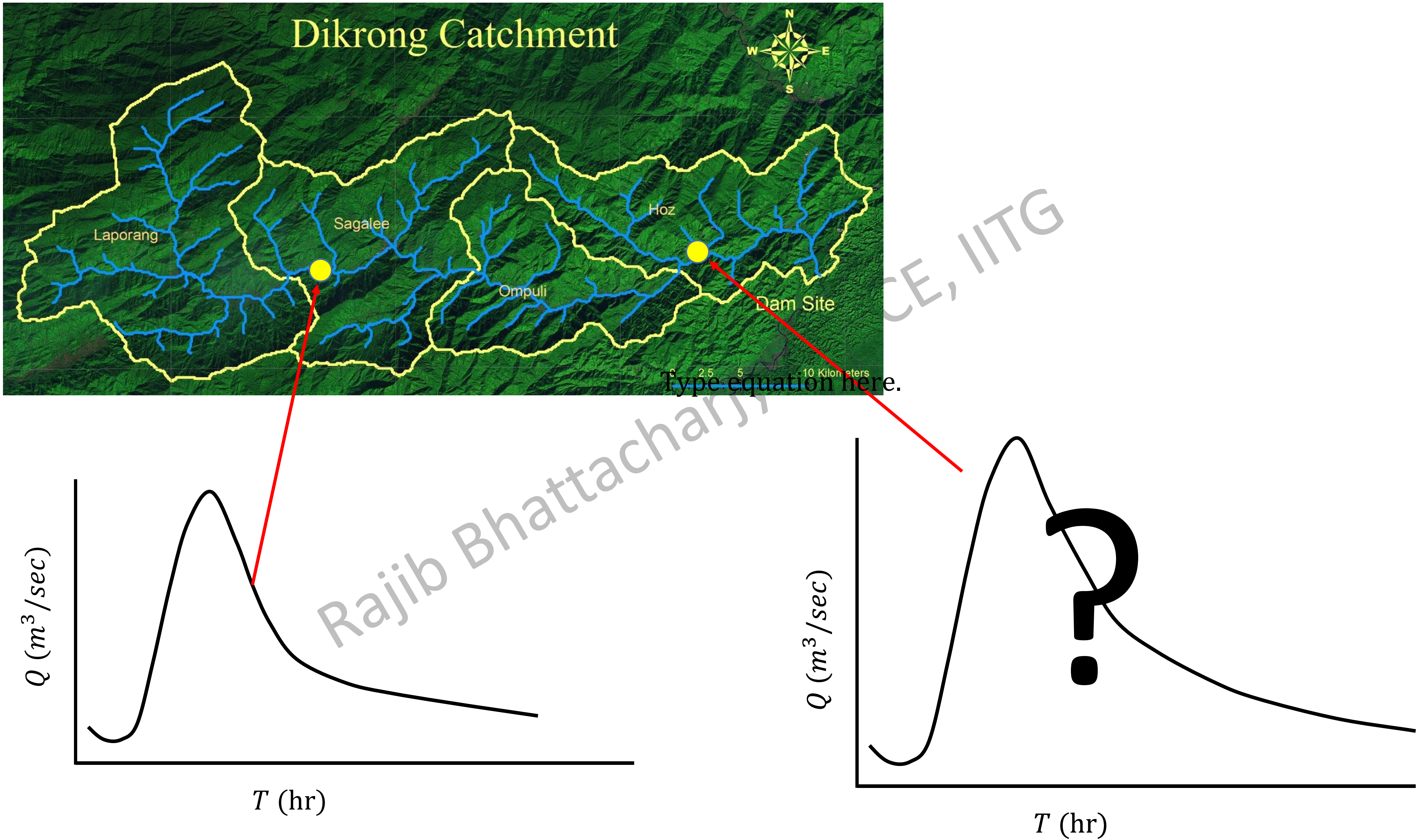


Dikrong Catchment
N
W
E
S
Laporang
Sagalee
Hoz
Ompuli
Dam Site
0 2.5 5 10 Kilometers
Type equation here.
$Q\ (m^3/sec)$
T (hr)
$Q\ (m^3/sec)$
T (hr)
?

Flood routing

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

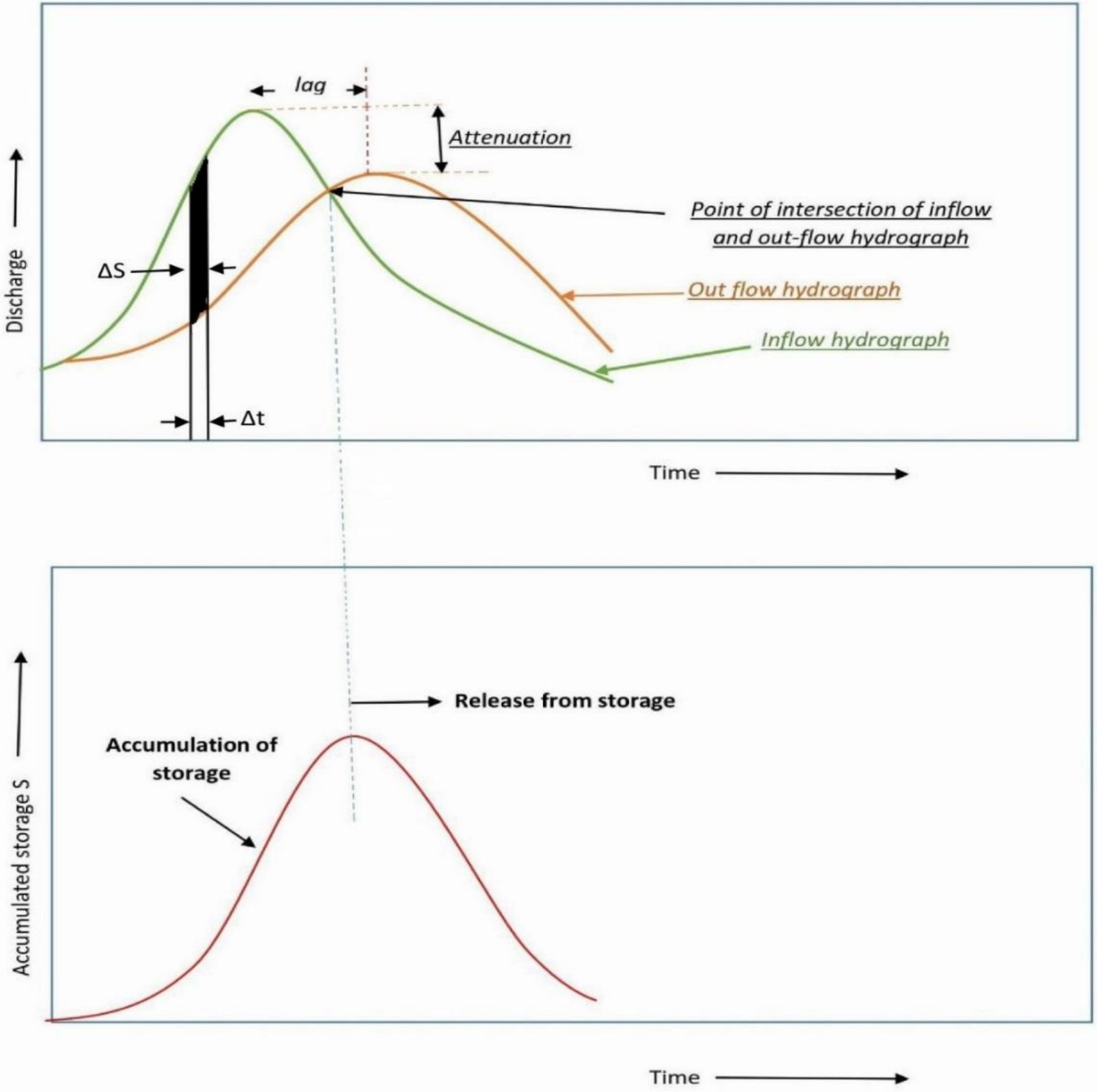
$$S = f\left(I, \frac{dI}{dt}, \frac{d^2I}{dt^2}, \dots, Q, \frac{dQ}{dt}, \frac{d^2Q}{dt^2}, \dots\right)$$

Level pool routing

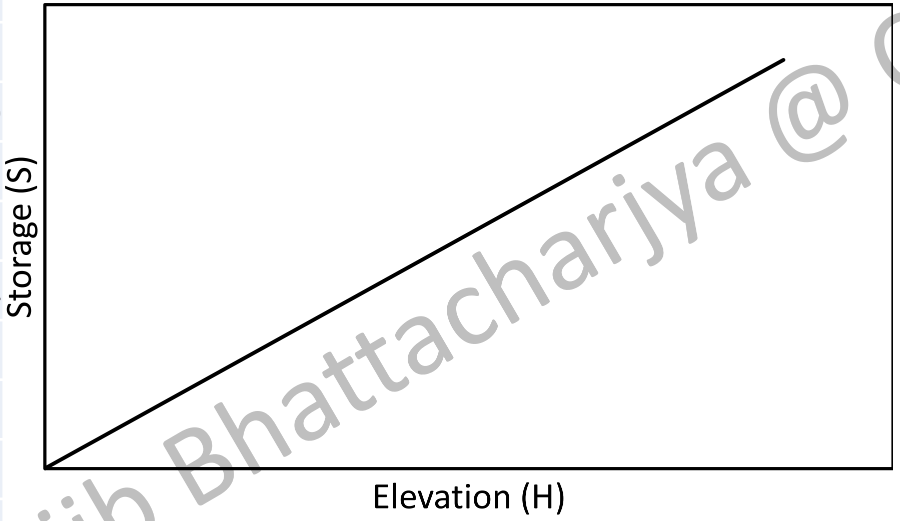
$$\int_{S_j}^{S_{j+1}} dS = \int_{j\Delta t}^{(j+1)\Delta t} I(t)dt - \int_{j\Delta t}^{(j+1)\Delta t} Q(t)dt$$

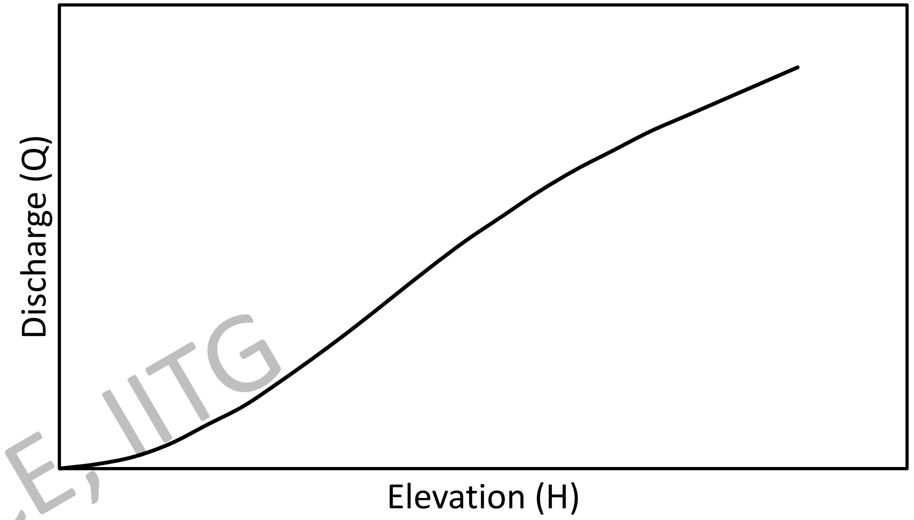
$$S_{j+1} - S_j = \frac{I_j + I_{j+1}}{2}\Delta t - \frac{Q_j + Q_{j+1}}{2}\Delta t$$

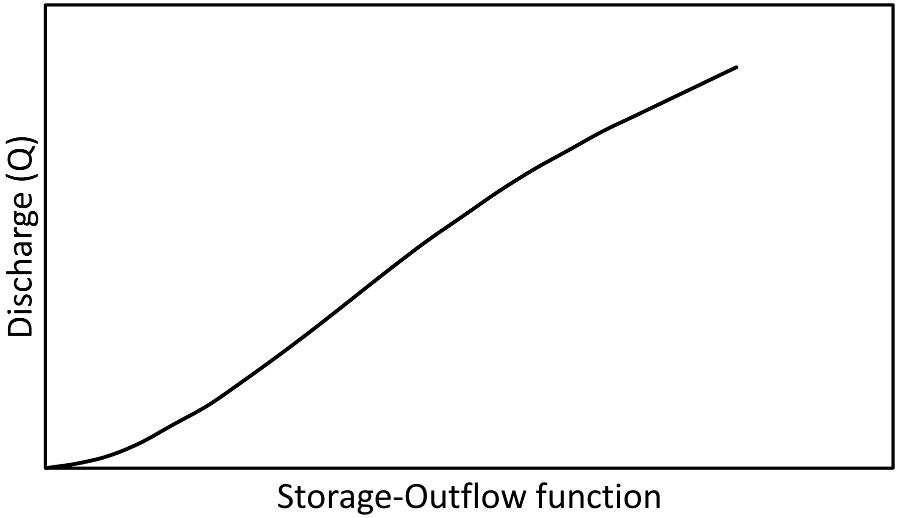
$$\left(\frac{2S_{j+1}}{\Delta t} + Q_{j+1}\right) = I_j + I_{j+1} + \left(\frac{2S_j}{\Delta t} - Q_j\right)$$



H(m)	Q (m^3/s)	S (m^3)	$\frac{2S}{\Delta t}+Q$
0.00	0.00	0.00	0.00
0.15	0.08	616.74	2.14
0.30	0.23	1233.48	4.34
0.46	0.48	1850.22	6.65
0.61	0.85	2466.96	9.07
0.76	1.22	3083.70	11.50
0.91	1.70	3700.45	14.03
1.07	2.21	4317.19	16.60
1.22	2.75	4933.93	19.19
1.37	3.31	5550.67	21.82
1.52	3.88	6167.41	24.44
1.68	4.42	6784.15	27.03
1.83	4.90	7400.89	29.57
1.98	5.38	8017.63	32.11
2.13	5.80	8634.37	34.59
2.29	6.17	9251.11	37.01
2.44	6.54	9867.85	39.43
2.59	6.85	10484.60	41.80
2.74	7.16	11101.34	44.17
2.90	7.48	11718.08	46.54
3.05	7.79	12334.82	48.90







EXAMPLE

Time index	Time (min)	Q (m^3/s)
1	0	0.00
2	10	1.70
3	20	3.40
4	30	5.10
5	40	6.80
6	50	8.50
7	60	10.19
8	70	9.06
9	80	7.93
10	90	6.80
11	100	5.66
12	110	4.53
13	120	3.40
14	130	2.27
15	140	1.13
16	150	0.00

H(m)	Q (m^3/s)	S (m^3)
0.00	0.00	0.00
0.15	0.08	616.74
0.30	0.23	1233.48
0.46	0.48	1850.22
0.61	0.85	2466.96
0.76	1.22	3083.70
0.91	1.70	3700.45
1.07	2.21	4317.19
1.22	2.75	4933.93
1.37	3.31	5550.67
1.52	3.88	6167.41
1.68	4.42	6784.15
1.83	4.90	7400.89
1.98	5.38	8017.63
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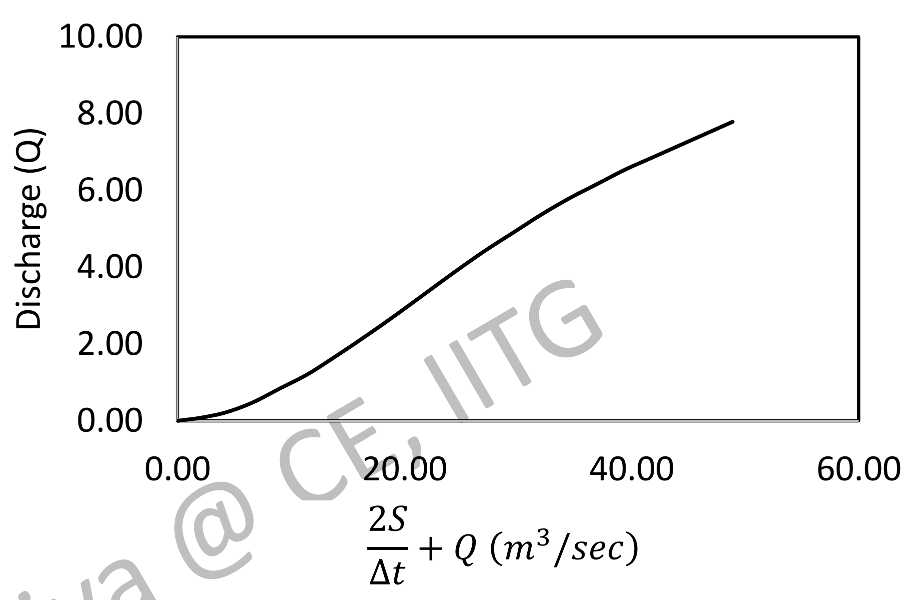
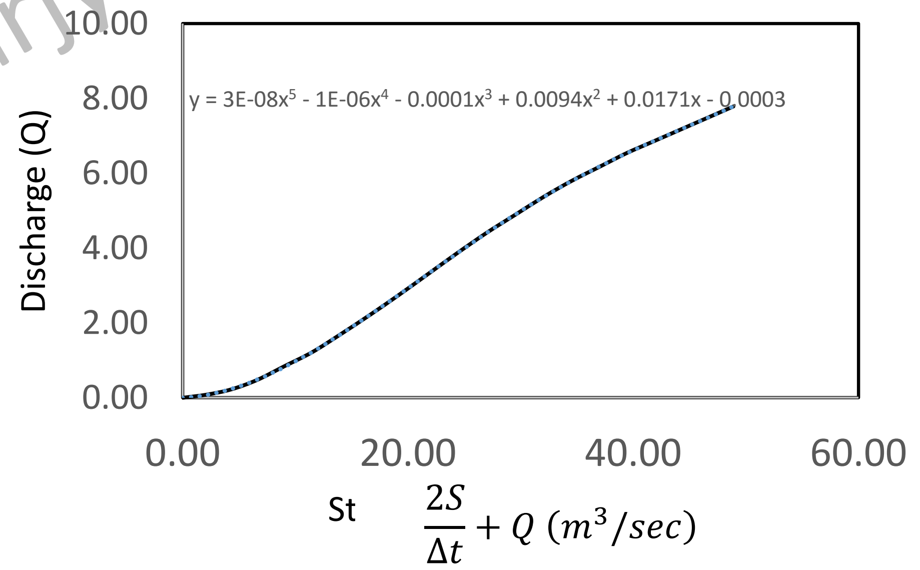
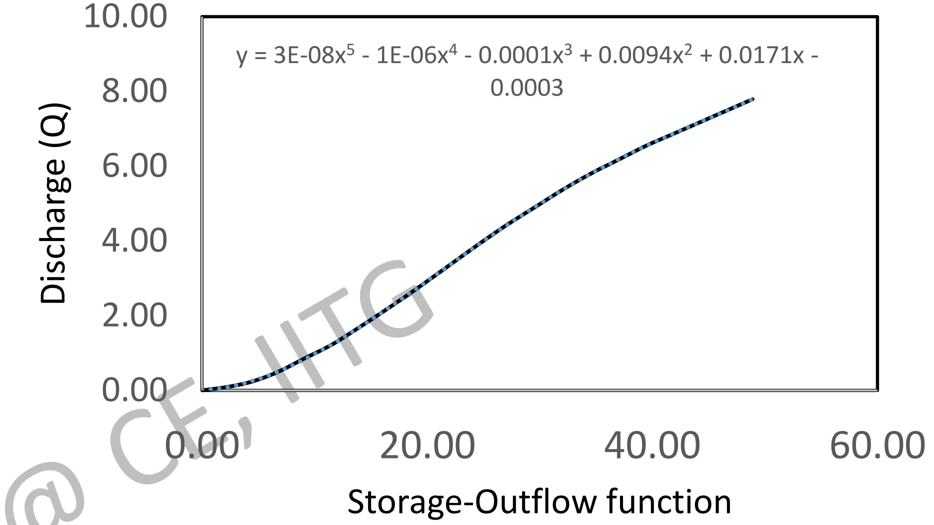
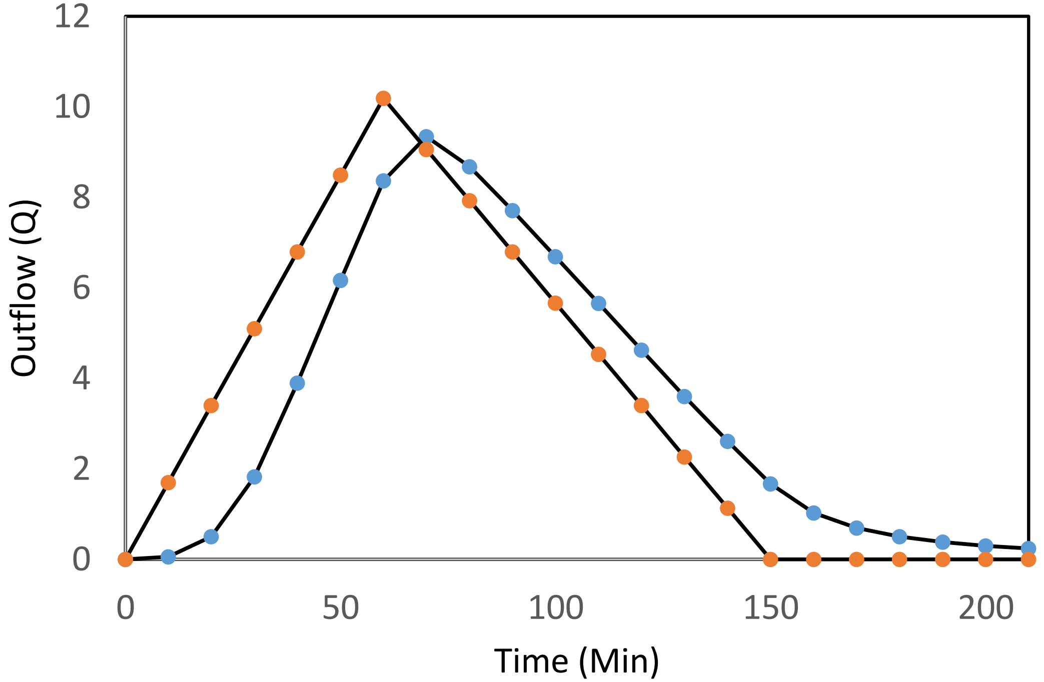




Time index	Time (min)	Inflow (m^3/s)	$I_j + I_{j+1}$	$\frac{2S_j}{\Delta t} - Q_j$	$\frac{2S_{j+1}}{\Delta t} + Q_{j+1}$	Outflow (m^3/s)
1	0	0.00		0		0
2	10	1.70	1.70	1.594	1.70	0.053
3	20	3.40	5.10	5.689	6.69	0.501
4	30	5.10	8.50	10.540	14.18	1.822
5	40	6.80	11.89	14.634	22.43	3.899
6	50	8.50	15.29	17.596	29.93	6.165
7	60	10.19	18.69	19.546	36.28	8.370
8	70	9.06	19.26	20.116	38.80	9.343
9	80	7.93	16.99	19.747	37.11	8.680
10	90	6.80	14.72	19.055	34.47	7.708
11	100	5.66	12.46	18.139	31.51	6.688
12	110	4.53	10.19	17.020	28.33	5.656
13	120	3.40	7.93	15.700	24.95	4.624
14	130	2.27	5.66	14.158	21.36	3.603
15	140	1.13	3.40	12.339	17.56	2.608
16	150	0.00	1.13	10.134	13.47	1.669
17	160	0.00	0.00	8.085	10.13	1.024
18	170	0.00	0.00	6.698	8.09	0.694
19	180	0.00	0.00	5.695	6.70	0.502
20	190	0.00	0.00	4.935	5.69	0.380
21	200	0.00	0.00	4.339	4.93	0.298
22	210	0.00	0.00	3.860	4.34	0.240

$$\left(\frac{2S_{j+1}}{\Delta t} + Q_{j+1}\right) = I_j + I_{j+1} + \left(\frac{2S_j}{\Delta t} - Q_j\right)$$





RUNGA-KUTTA METHOD

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

$$dS = A(H)dH$$

$$\frac{dH}{dt} = \frac{I(t) - Q(H)}{A(H)}$$

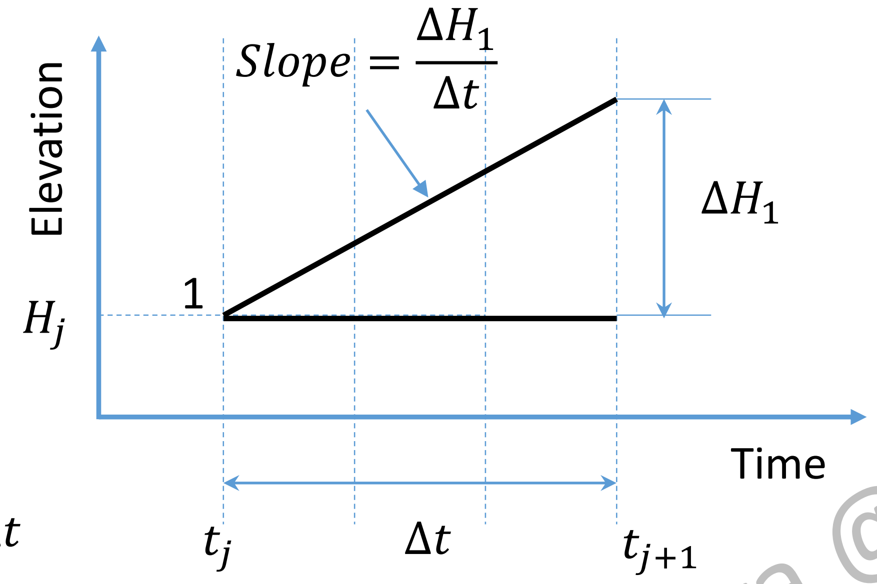
$$\Delta H_1 = \frac{I(t_j) - Q(H_j)}{A(H_j)}\Delta t$$

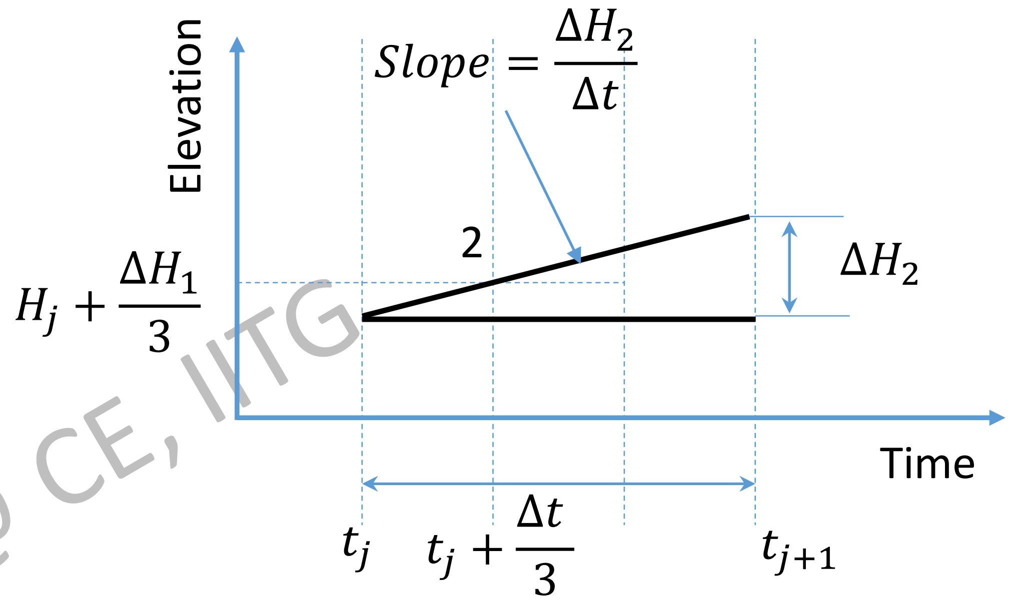
$$\Delta H_2 = \frac{I\left(t_j + \frac{\Delta t}{3}\right) - Q\left(H_j + \frac{2\Delta H_1}{3}\right)}{A\left(H_j + \frac{2\Delta H_1}{3}\right)}\Delta t$$

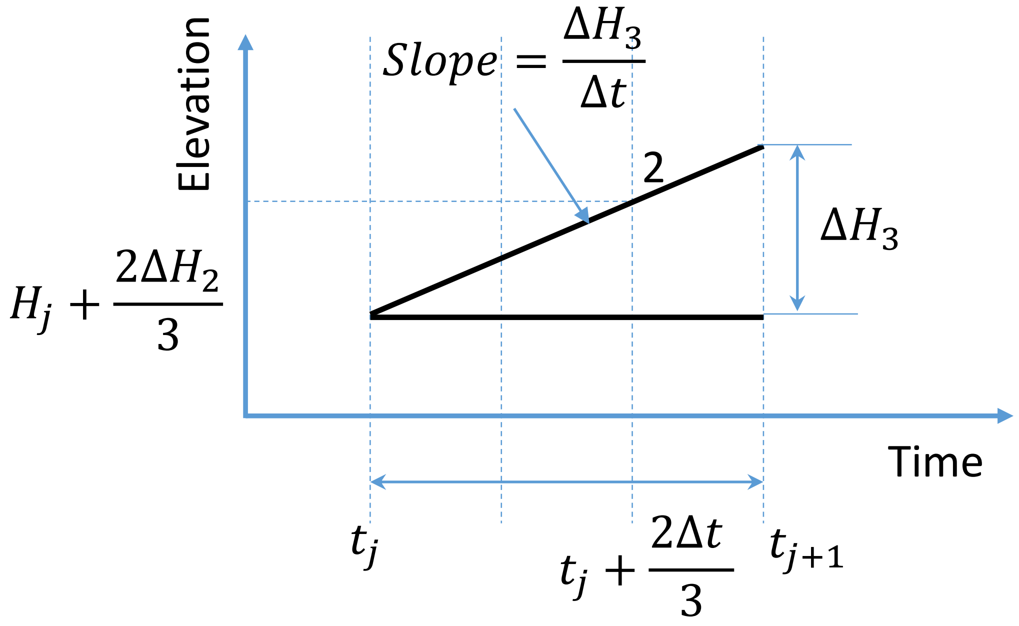
$$\Delta H_3 = \frac{I\left(t_j + \frac{2\Delta t}{3}\right) - Q\left(H_j + \frac{2\Delta H_2}{3}\right)}{A\left(H_j + \frac{2\Delta H_2}{3}\right)}\Delta t$$

$$H_{j+1} = H_j + \Delta H$$

Where $\Delta H = \frac{\Delta H_1}{4} + \frac{3\Delta H_3}{4}$



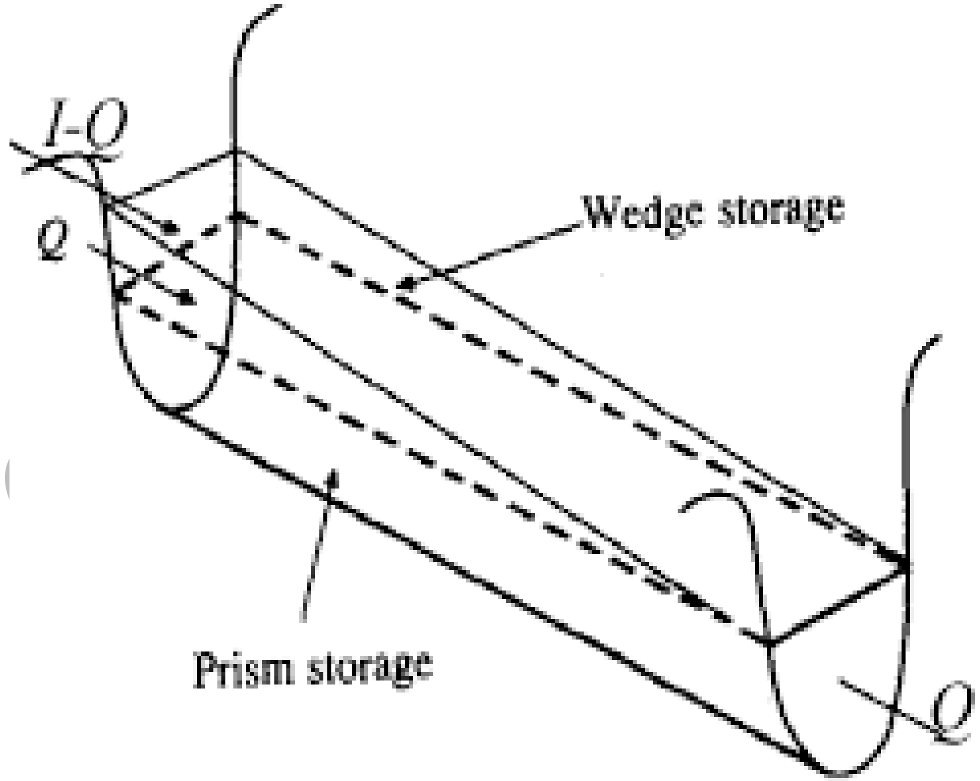




MUSKINGUM METHOD

$S = KQ + KX(I - Q)$

$S = K[XI - (1 - X)Q]$



The value of storage at time j and time $j + 1$

$S_j = K\left[XI_j - (1 - X)Q_j\right]$

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

Combining

$S_{j+1} - S_j = K\left\{\left[XI_{j+1} - (1 - X)Q_{j+1}\right] - \left[XI_j - (1 - X)Q_j\right]\right\}$

Change in storage can also be written as

$$S_{j+1} - S_j = \frac{I_j + I_{j+1}}{2}\Delta t - \frac{Q_j + Q_{j+1}}{2}\Delta t$$

MUSKINGUM METHOD

$$Q_{j+1} = C_1 I_{j+1} + C_2 I_j + C_3 Q_j$$

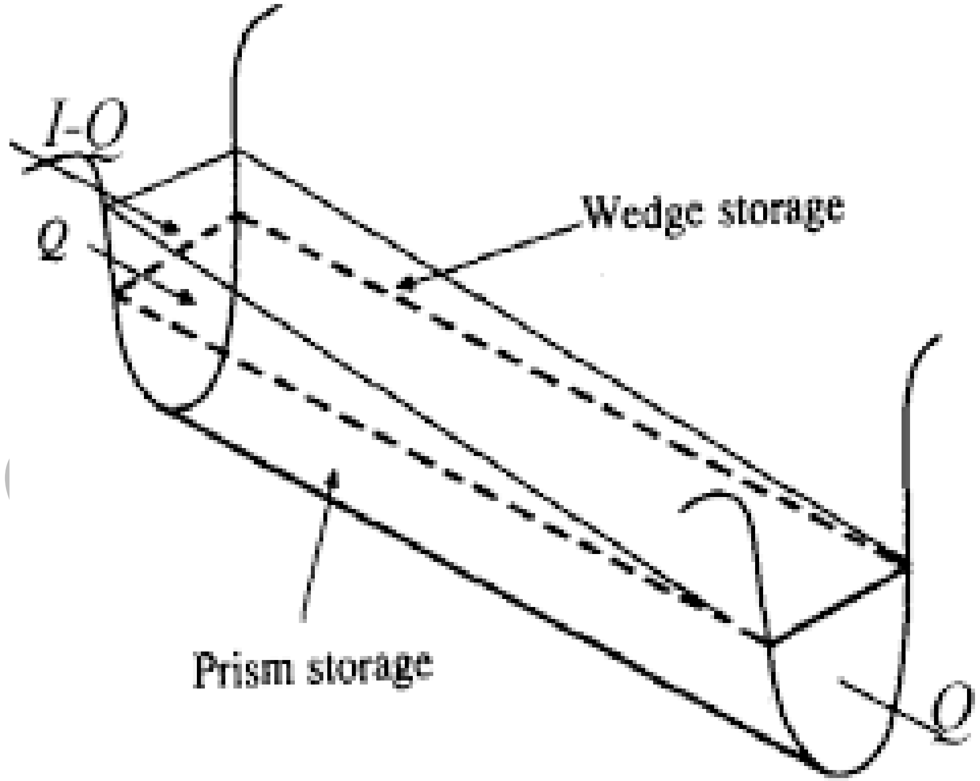
Where

$$C_1 = \frac{\Delta t - 2KX}{2K(1-X) + \Delta t}$$

$$C_2 = \frac{\Delta t + 2KX}{2K(1-X) + \Delta t}$$

$$C_3 = \frac{2K(1-X) - \Delta t}{2K(1-X) + \Delta t}$$

$$C_1 + C_2 + C_3 = 1$$



Saint-Venant equations

Continuity equations

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

Conservation form

$$V\frac{\partial y}{\partial x} + y\frac{\partial V}{\partial x} + \frac{\partial y}{\partial t} = 0$$

Non conservation form

Momentum equations

$$\underbrace{\frac{1}{A}\frac{\partial Q}{\partial t}}_{\text{Local acceleration}} + \underbrace{\frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)}_{\text{Convective acceleration}} + \underbrace{g\frac{\partial y}{\partial x}}_{\text{Pressure force}} - \underbrace{g(S_0}_{\text{Gravity force}} - \underbrace{S_f)}_{\text{Friction force}} = 0$$

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

Kinematic wave

Diffusion wave

Dynamic wave

Kinematic Wave model

Continuity equations $$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q$$

Momentum equations $$S_0 = S_f$$

The momentum equation can also be written as $$A = \alpha Q^{\beta}$$

Manning's equation with $S_0 = S_f$ and $R = A/P$ is

$$Q = \frac{S_o^{1/2}}{nP^{2/3}} A^{5/3}$$

$$A = \left(\frac{nP^{2/3}}{S_o^{1/2}}\right)^{3/5} Q^{3/5}$$

$$\alpha = \left(\frac{nP^{2/3}}{S_o^{1/2}}\right)^{3/5} \qquad \beta = 0.6$$

Kinematic Wave model

$$\frac{\partial A}{\partial t} = \alpha\beta Q^{\beta-1}\left(\frac{\partial Q}{\partial t}\right)$$

Continuity equation

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

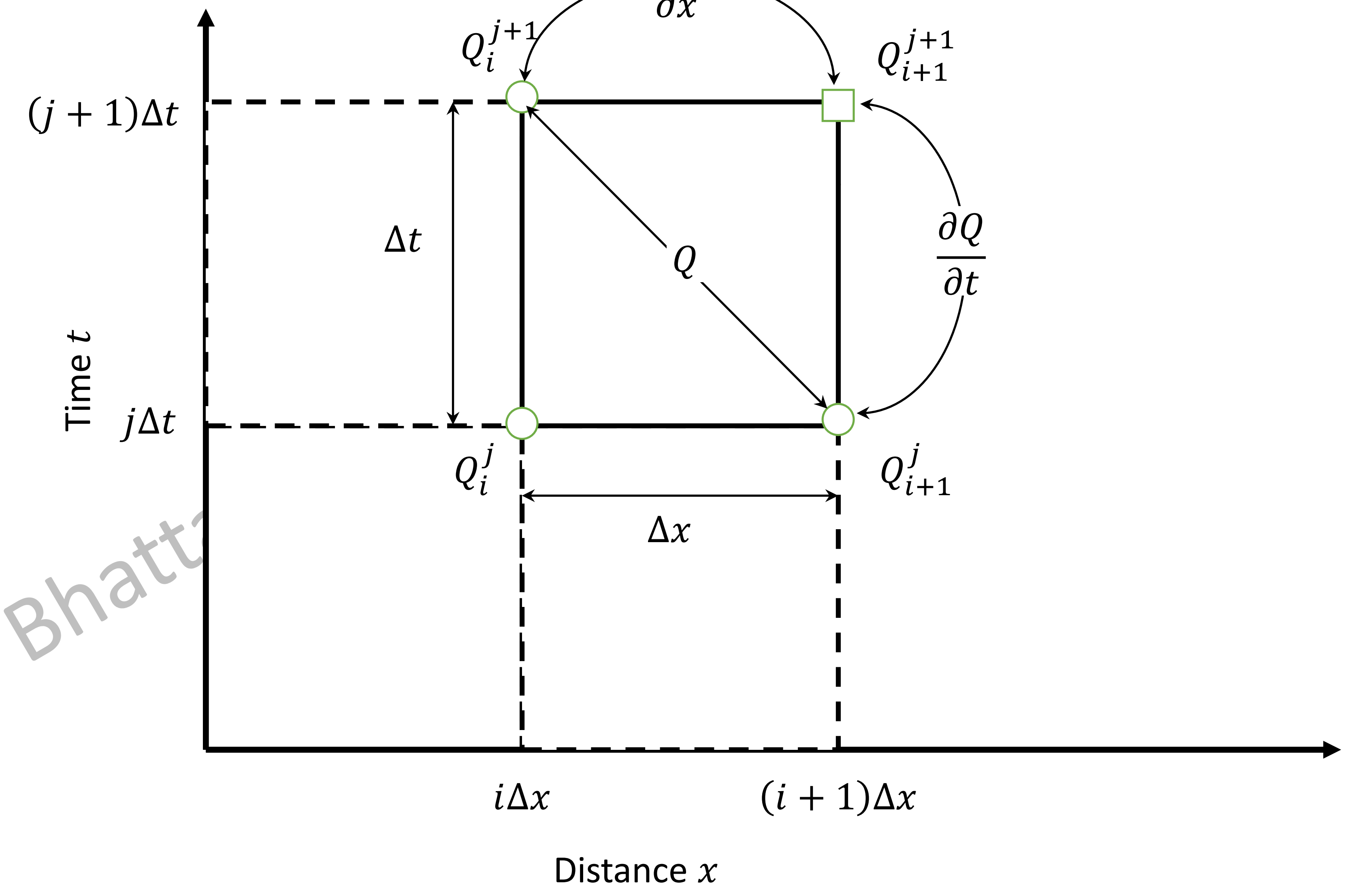
$$\frac{\partial Q}{\partial x} + \alpha\beta Q^{\beta-1}\left(\frac{\partial Q}{\partial t}\right) = q$$

$$\frac{\partial Q}{\partial x} = \frac{Q_{i+1}^{j+1} - Q_i^{j+1}}{\Delta x}$$

$$\frac{\partial Q}{\partial t} = \frac{Q_{i+1}^{j+1} - Q_{i+1}^{j}}{\Delta t}$$

$$Q = \frac{Q_i^{j+1} + Q_{i+1}^{j}}{2}$$

Linear Model



Linear Model

$$\frac{\partial Q}{\partial x} + \alpha\beta Q^{\beta-1}\left(\frac{\partial Q}{\partial t}\right) = q$$

$$\frac{Q_{i+1}^{j+1} - Q_{i}^{j+1}}{\Delta x} + \alpha\beta\left(\frac{Q_{i}^{j+1} - Q_{i+1}^{j}}{2}\right)^{\beta-1}\left(\frac{Q_{i+1}^{j+1} - Q_{i+1}^{j}}{\Delta t}\right) = \frac{q_{i+1}^{j+1} + q_{i+1}^{j}}{2}$$

Solving for Q_{i+1}^{j+1}

$$\boxed{Q_{i+1}^{j+1} = \frac{\left[\frac{\Delta t}{\Delta x} Q_{i}^{j+1} + \alpha\beta\left(\frac{Q_{i}^{j+1} - Q_{i+1}^{j}}{2}\right)^{\beta-1} + \Delta t\left(\frac{q_{i+1}^{j+1} + q_{i+1}^{j}}{2}\right)\right]}{\left[\frac{\Delta t}{\Delta x} + \alpha\beta\left(\frac{Q_{i}^{j+1} - Q_{i+1}^{j}}{2}\right)^{\beta-1}\right]}}$$

$$\frac{\partial Q}{\partial x} = \frac{Q_{i+1}^{j+1} - Q_{i}^{j+1}}{\Delta x}$$

$$\frac{\partial Q}{\partial t} = \frac{Q_{i+1}^{j+1} - Q_{i+1}^{j}}{\Delta t}$$

$$Q = \frac{Q_{i}^{j+1} + Q_{i+1}^{j}}{2}$$

$$q = \frac{q_{i+1}^{j+1} + q_{i+1}^{j}}{2}$$

Nonlinear Model

$$A = \alpha Q^{\beta}$$

$$\frac{\partial Q}{\partial x} = \frac{Q_{i+1}^{j+1} - Q_i^{j+1}}{\Delta x}$$

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

$$A_{i+1}^{j+1} = \alpha\left(Q_{i+1}^{j+1}\right)^{\beta}$$

$$\frac{\partial A}{\partial t} = \frac{A_{i+1}^{j+1} - A_{i+1}^{j}}{\Delta t}$$

$$A_{i+1}^{j} = \alpha\left(Q_{i+1}^{j}\right)^{\beta}$$

$$q = \frac{q_{i+1}^{j+1} + q_{i+1}^{j}}{2}$$

$$\frac{Q_{i+1}^{j+1} - Q_i^{j+1}}{\Delta x} + \frac{A_{i+1}^{j+1} - A_{i+1}^{j}}{\Delta t} = \frac{q_{i+1}^{j+1} + q_{i+1}^{j}}{2}$$

$$\frac{\Delta t}{\Delta x} Q_{i+1}^{j+1} + \alpha\left(Q_{i+1}^{j+1}\right)^{\beta} = \frac{\Delta t}{\Delta x} Q_i^{j+1} + \alpha\left(Q_{i+1}^{j}\right)^{\beta} + \Delta t\left(\frac{q_{i+1}^{j+1} + q_{i+1}^{j}}{2}\right)$$

$$\frac{\Delta t}{\Delta x} Q_{i+1}^{j+1} + \alpha\left(Q_{i+1}^{j+1}\right)^{\beta} = C$$

Residual error

$$f\left(Q_{i+1}^{j+1}\right) = \frac{\Delta t}{\Delta x} Q_{i+1}^{j+1} + \alpha\left(Q_{i+1}^{j+1}\right)^{\beta} - C$$

First Derivative

$$f'\left(Q_{i+1}^{j+1}\right) = \frac{\Delta t}{\Delta x} + \alpha\beta\left(Q_{i+1}^{j+1}\right)^{\beta-1}$$

Nonlinear Model

The objective is to find Q_{i+1}^{j+1} for $f\left(Q_{i+1}^{j+1}\right) = 0$

This can be solved using Newton's method

$$\left(Q_{i+1}^{j+1}\right)_{k+1} = \left(Q_{i+1}^{j+1}\right)_{k} - \frac{f\left(Q_{i+1}^{j+1}\right)_{k}}{f'\left(Q_{i+1}^{j+1}\right)_{k}}$$

Convergence criteria for the iterative processes

$$\left|f\left(Q_{i+1}^{j+1}\right)_{k+1}\right| \le \varepsilon$$

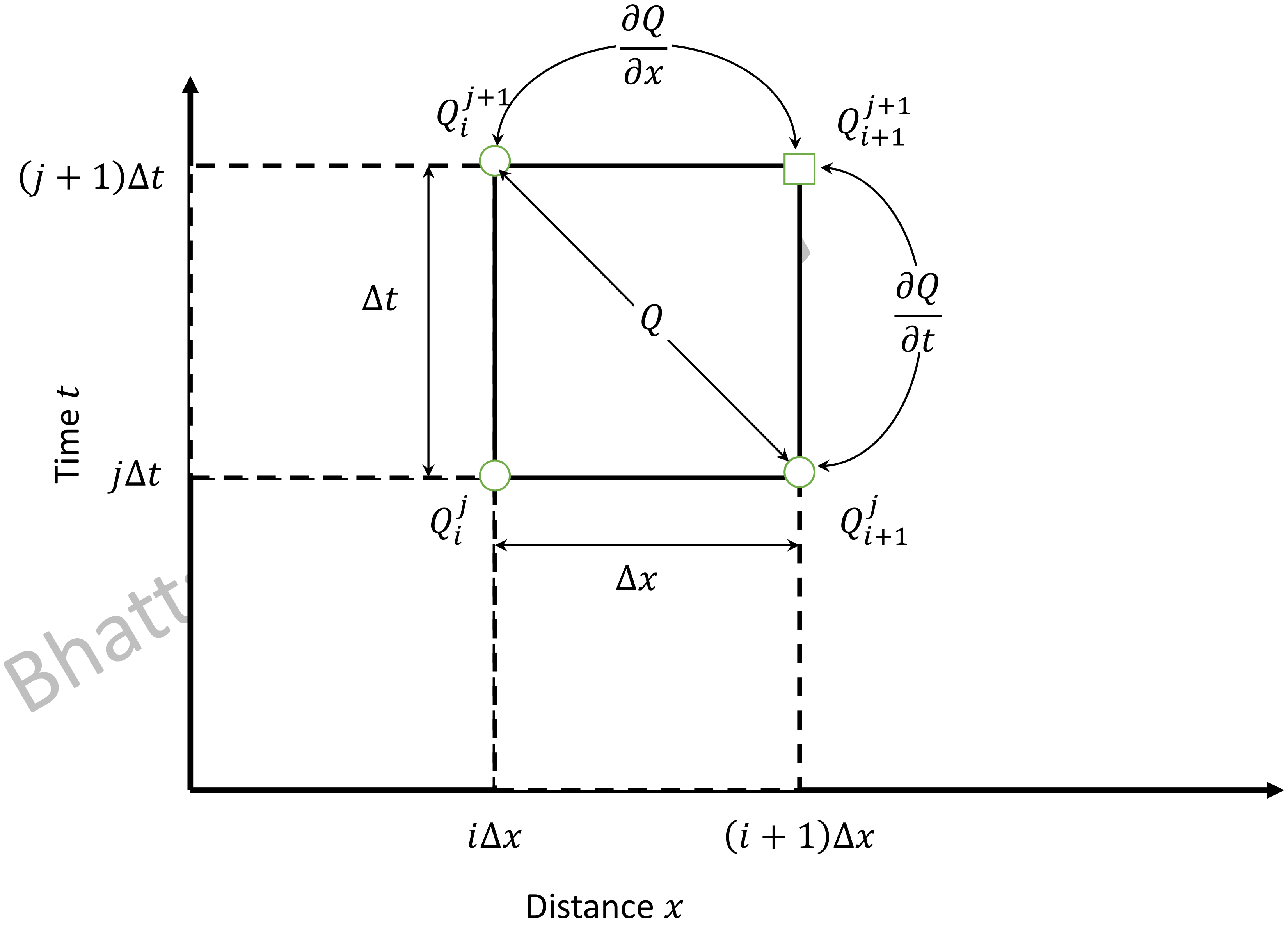
Muskingum Cunge Method

$$Q_{j+1} = C_1 I_{j+1} + C_2 I_j + C_3 Q_j$$

$$Q_{i+1}^{j+1} = C_1 Q_{i+1}^{j} + C_2 Q_i^{j} + C_3 Q_{i+1}^{j}$$

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

$$X = \frac{1}{2}\left(1 - \frac{Q}{B C_k S_o \Delta x}\right)$$



$$Q = \frac{S_o^{1/2}}{nP^{2/3}} A^{5/3}$$

$$Q = \alpha A^m$$ $\alpha = \frac{S_o^{1/2}}{nP^{2/3}}$ and $m = 5/3$

$$\partial Q = \alpha m A^{m-1} \partial A$$

$$\partial Q = \alpha m \frac{A^m}{A} \partial A$$

$$\partial Q = m \frac{Q}{A} \partial A$$

$$\partial Q = mV \partial A$$

$$\frac{\partial Q}{\partial A} = mV = c_k$$

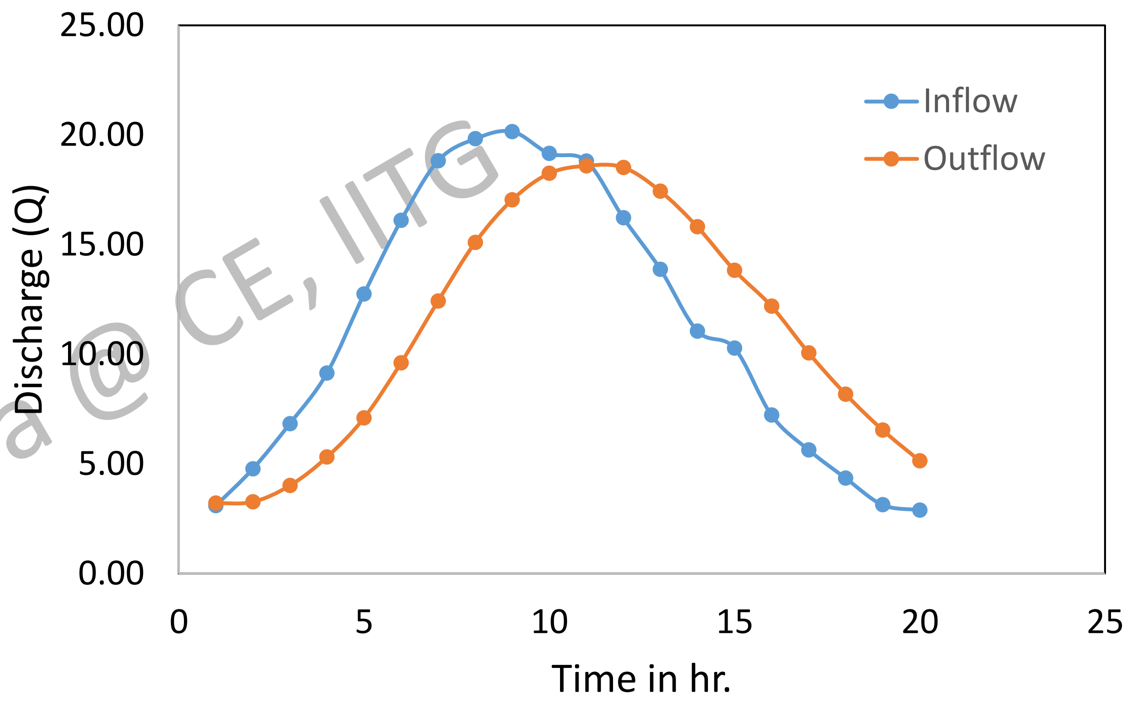
Example problem

$K = 2.3\ h \qquad X = 0.15 \qquad \Delta t = 1\ h \qquad Q_o = 3.21\ m^3/s$

$C_1 = 0.0631 \qquad C_2 = 0.3442 \qquad C_3 = 0.5927$

Routing period (hr.)	Inflow (m^3/s)
1	3.10
2	4.78
3	6.84
4	9.13
5	12.75
6	16.10
7	18.82
8	19.82
9	20.16
10	19.15
11	18.81
12	16.22
13	13.88
14	11.06
15	10.28
16	7.22
17	5.64
18	4.35
19	3.13
20	2.89

Routing period (hr.)	Inflow (m^3/s)	$C_1 I_{j+1}$	$C_2 I_j$	$C_3 Q_j$	Outflow (m^3/s)
1	3.10				3.21
2	4.78	0.30	1.07	1.90	3.27
3	6.84	0.43	1.64	1.94	4.01
4	9.13	0.58	2.35	2.38	5.31
5	12.75	0.80	3.14	3.15	7.10
6	16.10	1.02	4.39	4.21	9.61
7	18.82	1.19	5.54	5.69	12.42
8	19.82	1.25	6.48	7.36	15.09
9	20.16	1.27	6.82	8.95	17.04
10	19.15	1.21	6.94	10.10	18.25
11	18.81	1.19	6.59	10.82	18.60
12	16.22	1.02	6.48	11.02	18.52
13	13.88	0.88	5.58	10.98	17.44
14	11.06	0.70	4.78	10.33	15.81
15	10.28	0.65	3.81	9.37	13.82
16	7.22	0.46	3.54	8.19	12.19
17	5.64	0.36	2.49	7.22	10.07
18	4.35	0.27	1.94	5.97	8.18
19	3.13	0.20	1.50	4.85	6.54
20	2.89	0.18	1.08	3.88	5.14



Example problem

Width = 60.96 m

$\Delta x = 1000$ m

Length = 5000 m

$\Delta t = 3$ min $= 180$ s

Slope = 1%

Initial discharge 56.63 m^3/s

$n = 0.035$

$$\alpha = \left(\frac{nP^{2/3}}{S_o^{1/2}}\right)^{0.6} = \left(\frac{0.035(60.96)^{2/3}}{(0.01)^{1/2}}\right)^{0.6} = 2.75714$$

$$\beta = 0.6$$

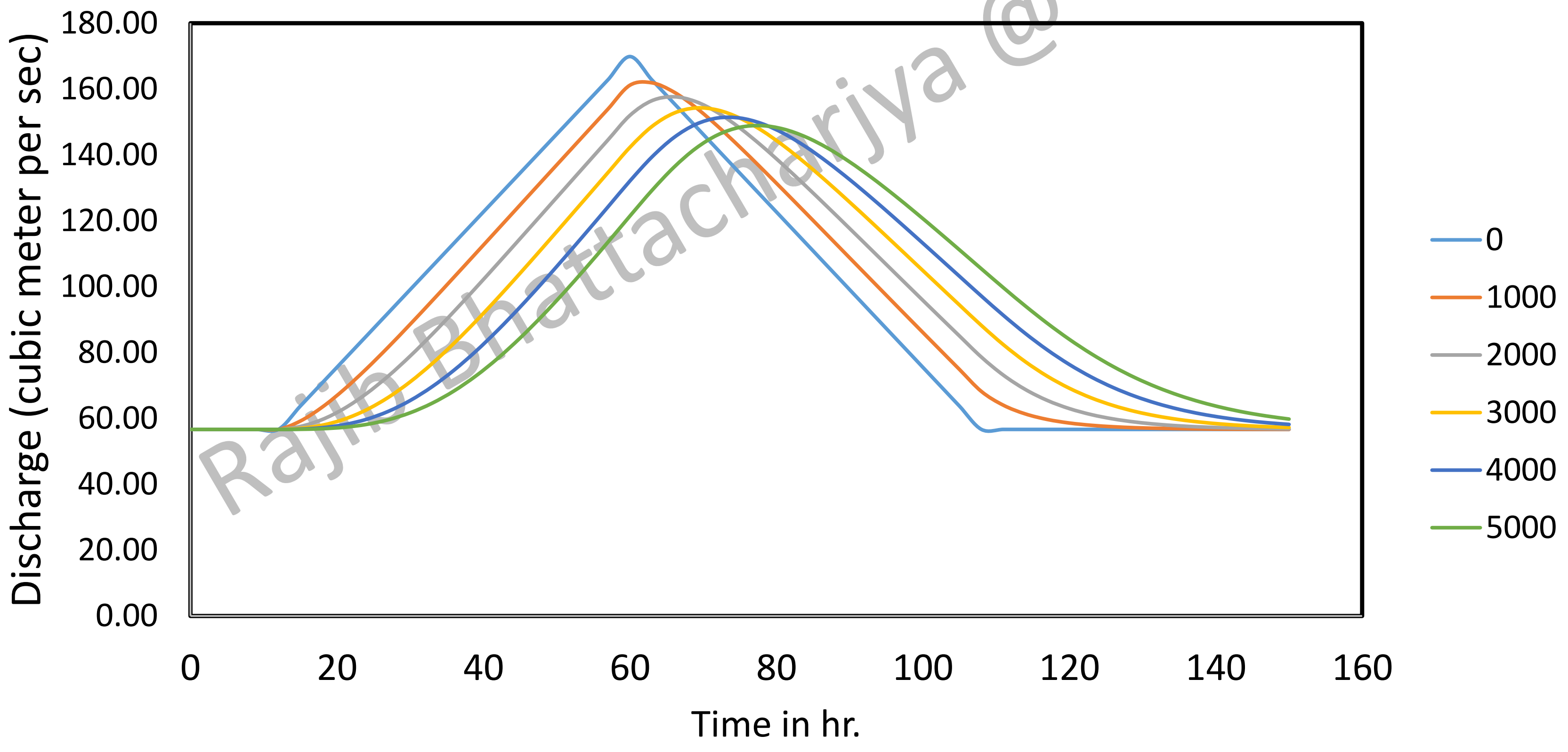
$$Q_{i+1}^{j+1} = \frac{\left[\frac{\Delta t}{\Delta x} Q_i^{j+1} + \alpha\beta\left(\frac{Q_i^{j+1} - Q_{i+1}^{j}}{2}\right)^{\beta-1} + \Delta t\left(\frac{q_{i+1}^{j+1} + q_{i+1}^{j}}{2}\right)\right]}{\left[\frac{\Delta t}{\Delta x} + \alpha\beta\left(\frac{Q_i^{j+1} - Q_{i+1}^{j}}{2}\right)^{\beta-1}\right]}$$

Time index	Time (mm)	Inflow (m^3/s)	Time index	Time (mm)	Inflow (m^3/s)	Time index	Time (mm)	Inflow (m^3/s)
1	0	56.63	24	69	148.66	47	138	56.63
2	3	56.63	25	72	141.58	48	141	56.63
3	6	56.63	26	75	134.51	49	144	56.63
4	9	56.63	27	78	127.43	50	147	56.63
5	12	56.63	28	81	120.35	51	150	56.63
6	15	63.71	29	84	113.27			
7	18	70.79	30	87	106.19			
8	21	77.87	31	90	99.11			
9	24	84.95	32	93	92.03			
10	27	92.03	33	96	84.95			
11	30	99.11	34	99	77.87			
12	33	106.19	35	102	70.79			
13	36	113.27	36	105	63.71			
14	39	120.35	37	108	56.63			
15	42	127.43	38	111	56.63			
16	45	134.51	39	114	56.63			
17	48	141.58	40	117	56.63			
18	51	148.66	41	120	56.63			
19	54	155.74	42	123	56.63			
20	57	162.82	43	126	56.63			
21	60	169.90	44	129	56.63			
22	63	162.82	45	132	56.63			
23	66	155.74	46	135	56.63			

Time index	Time (min)	Distance along channel (m)					
		0	1000	2000	3000	4000	5000
1	0	56.63	56.63	56.63	56.63	56.63	56.63
2	3	56.63	56.63	56.63	56.63	56.63	56.63
3	6	56.63	56.63	56.63	56.63	56.63	56.63
4	9	56.63	56.63	56.63	56.63	56.63	56.63
5	12	56.63	56.63	56.63	56.63	56.63	56.63
6	15	63.71	59.18	57.54	56.95	56.75	56.67
7	18	70.79	63.43	59.66	57.92	57.16	56.85
8	21	77.87	68.83	63.01	59.75	58.08	57.29
9	24	84.95	74.99	67.46	62.56	59.69	58.14
10	27	92.03	81.63	72.83	66.36	62.11	59.57
11	30	99.11	88.58	78.92	71.09	65.42	61.69
12	33	106.19	95.70	85.53	76.63	69.62	64.60
13	36	113.27	102.93	92.51	82.84	74.66	68.35
14	39	120.35	110.20	99.74	89.57	80.45	72.93
15	42	127.43	117.50	107.11	96.68	86.87	78.30
16	45	134.51	124.81	114.57	104.06	93.79	84.38
17	48	141.58	132.10	122.06	111.60	101.08	91.06
18	51	148.66	139.39	129.57	119.24	108.65	98.22
19	54	155.74	146.67	137.07	126.93	116.38	105.73
20	57	162.82	153.94	144.55	134.63	124.21	113.51
21	60	169.90	161.19	152.02	142.32	132.09	121.44
22	63	162.82	161.93	156.49	148.64	139.38	129.21
23	66	155.74	159.13	157.68	152.70	145.29	136.25

Time index	Time (min)	Distance along channel (m)					
		0	1000	2000	3000	4000	5000
24	69	148.66	154.43	156.22	154.28	149.31	142.02
25	72	141.58	148.71	152.85	153.64	151.25	146.12
26	75	134.51	142.44	148.22	151.21	151.23	148.40
27	78	127.43	135.89	142.78	147.46	149.55	148.91
28	81	120.35	129.19	136.84	142.77	146.54	147.86
29	84	113.27	122.41	130.60	137.45	142.53	145.49
30	87	106.19	115.60	124.19	131.70	137.79	142.09
31	90	99.11	108.77	117.68	125.70	132.54	137.91
32	93	92.03	101.95	111.14	119.53	126.95	133.15
33	96	84.95	95.14	104.58	113.28	121.14	127.98
34	99	77.87	88.35	98.03	106.99	115.20	122.54
35	102	70.79	81.59	91.51	100.70	109.19	116.91
36	105	63.71	74.86	85.02	94.43	103.16	111.18
37	108	56.63	68.16	78.59	88.20	97.13	105.41
38	111	56.63	63.98	73.11	82.37	91.28	99.68
39	114	56.63	61.34	68.77	77.20	85.78	94.12
40	117	56.63	59.66	65.44	72.79	80.78	88.86
41	120	56.63	58.58	62.96	69.15	76.36	84.00
42	123	56.63	57.89	61.14	66.21	72.56	79.61
43	126	56.63	57.45	59.82	63.89	69.35	75.72
44	129	56.63	57.16	58.87	62.08	66.68	72.33
45	132	56.63	56.97	58.19	60.68	64.49	69.42
46	135	56.63	56.85	57.72	59.62	62.73	66.96

Time index	Time (min)	Distance along channel (m)					
		0	1000	2000	3000	4000	5000
47	138	56.63	56.78	57.38	58.82	61.32	64.90
48	141	56.63	56.73	57.15	58.23	60.21	63.20
49	144	56.63	56.69	56.99	57.79	59.35	61.81
50	147	56.63	56.67	56.88	57.47	58.68	60.69
51	150	56.63	56.66	56.80	57.23	58.16	59.78



Example: Apply the Muskingum-Cunge method to route the following inflow hydrograph. The peak flow is 680 cfs. The area of cross section of the river the peak flow is 95 sq. ft. and the width is 20 ft. The channel has a bottom slope of 0.0001 and the reach length is 25 mi. Take $\Delta t = 12\ h$.

Time	I	Q
12	100	100
24	300	222
36	680	573
	500	626
	400	373
	310	359
	230	235
	180	197
	100	122
	50	58

Sol.

$\Delta x = 25\ mi$=132000 ft.

$\Delta t - 2KX$

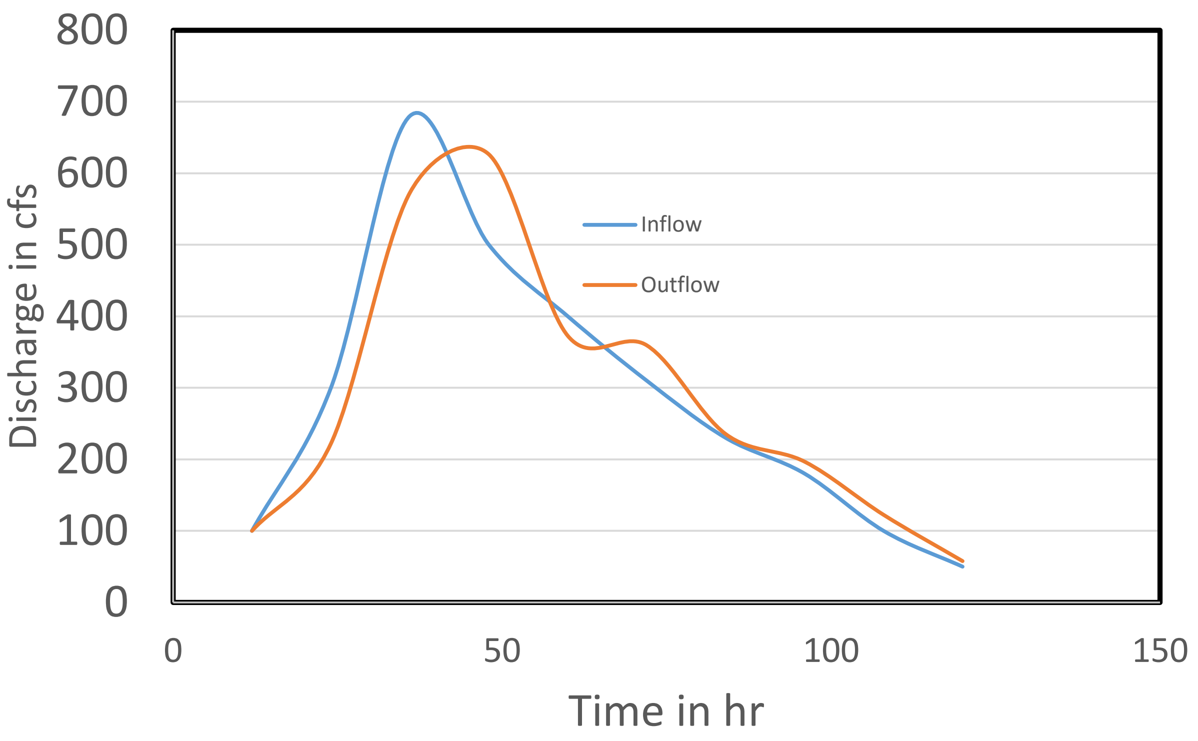
$C = \quad = 0.61$

$$V = \frac{Q_p}{A} = \frac{680}{95} = 7.1$$

$$c_k = mV = \frac{5}{3} \times 7.16$$

$$X = \frac{1}{2}\left(1 - \frac{Q}{BC_kS_o\Delta x}\right.$$

$$K = \frac{\Delta x}{c_k} = 11064.5\ s$$



Example: By the Muskingum-Cunge method, route the following hydrograph. The peak flow rate is 220 m^3/sec. The area of cross section of the river the peak flow is 183 m^2. and the width is 35 m. The channel has a bottom slope of 0.001 and the reach length is 6 km.Take $\Delta t = 12\ h$.

Time (hr)	I (m3/s)
0	15
1	27
2	75
3	160
4	220
5	200
6	160
7	88
8	50
9	25
10	12