Tsunami Runup and Inundation Simulation in Malaysia Including the Role of Mangroves

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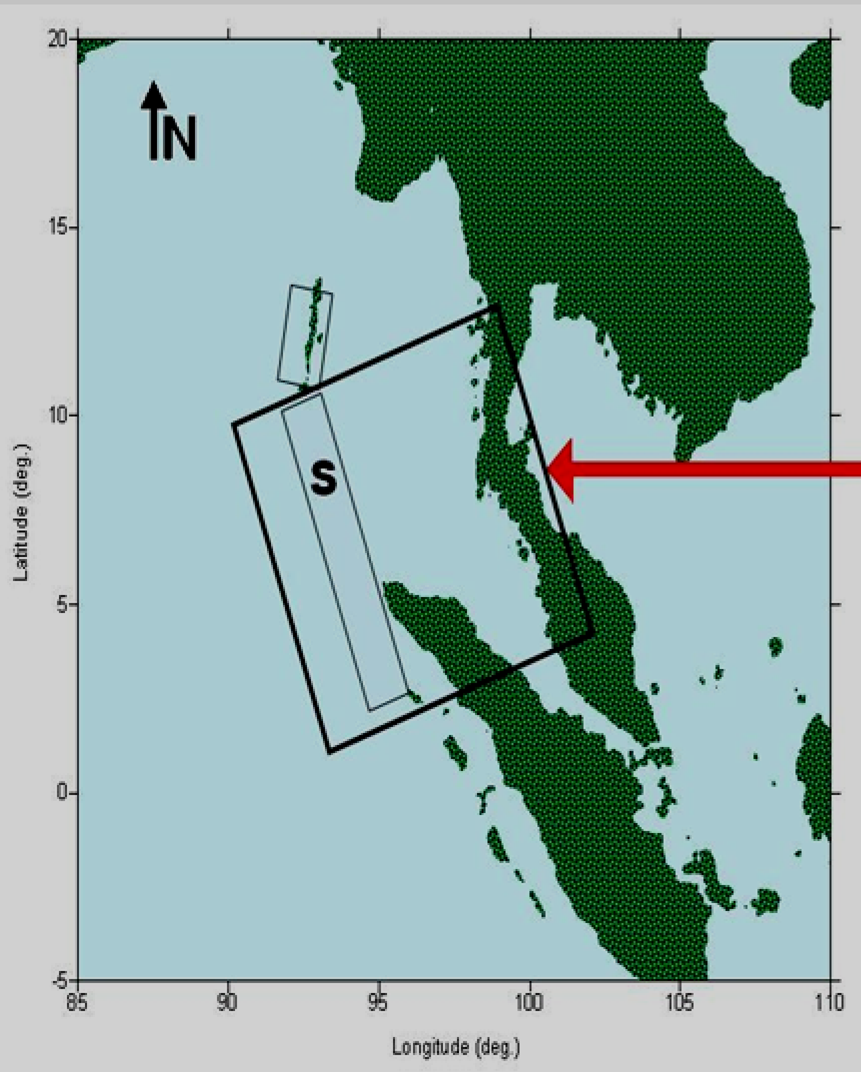
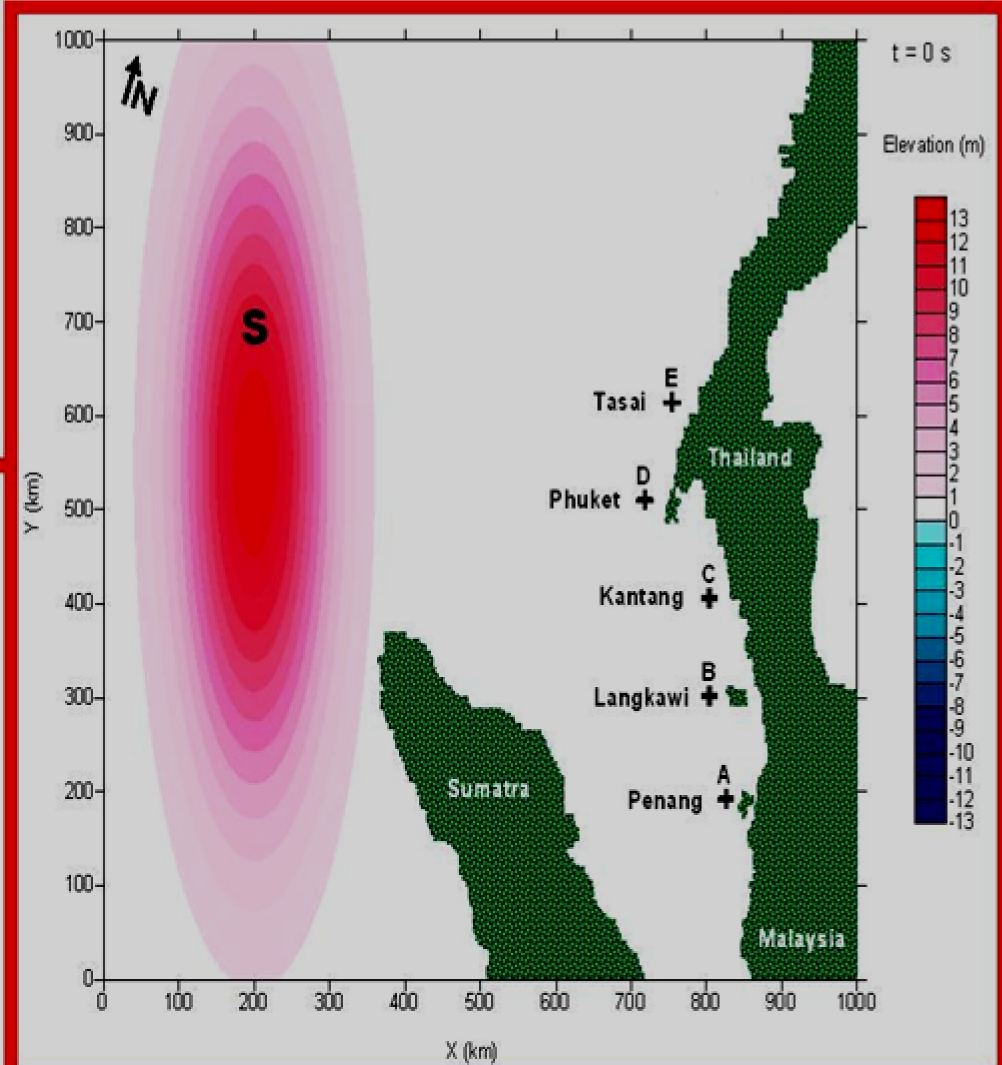
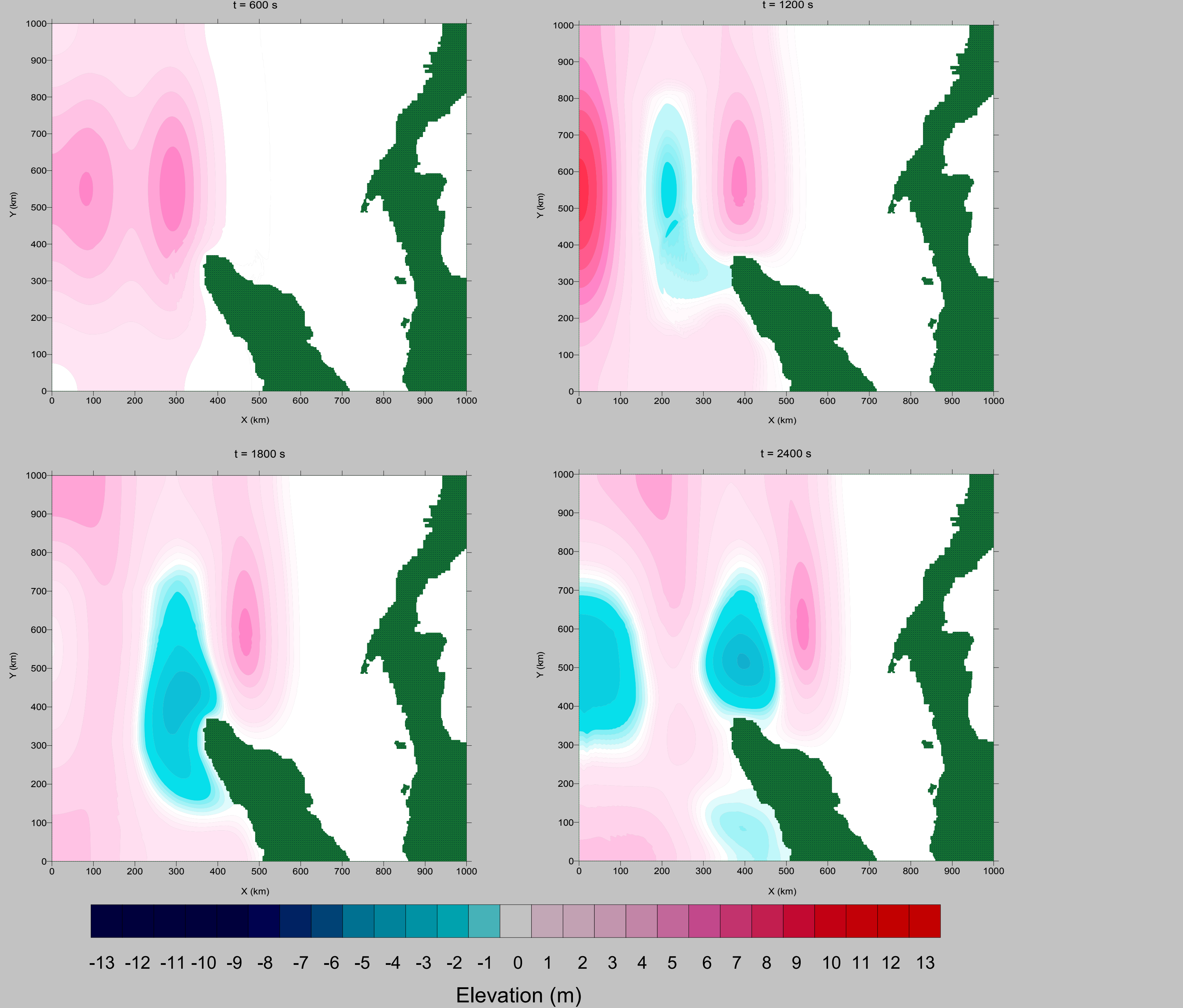
26 December 2004 Tsunami

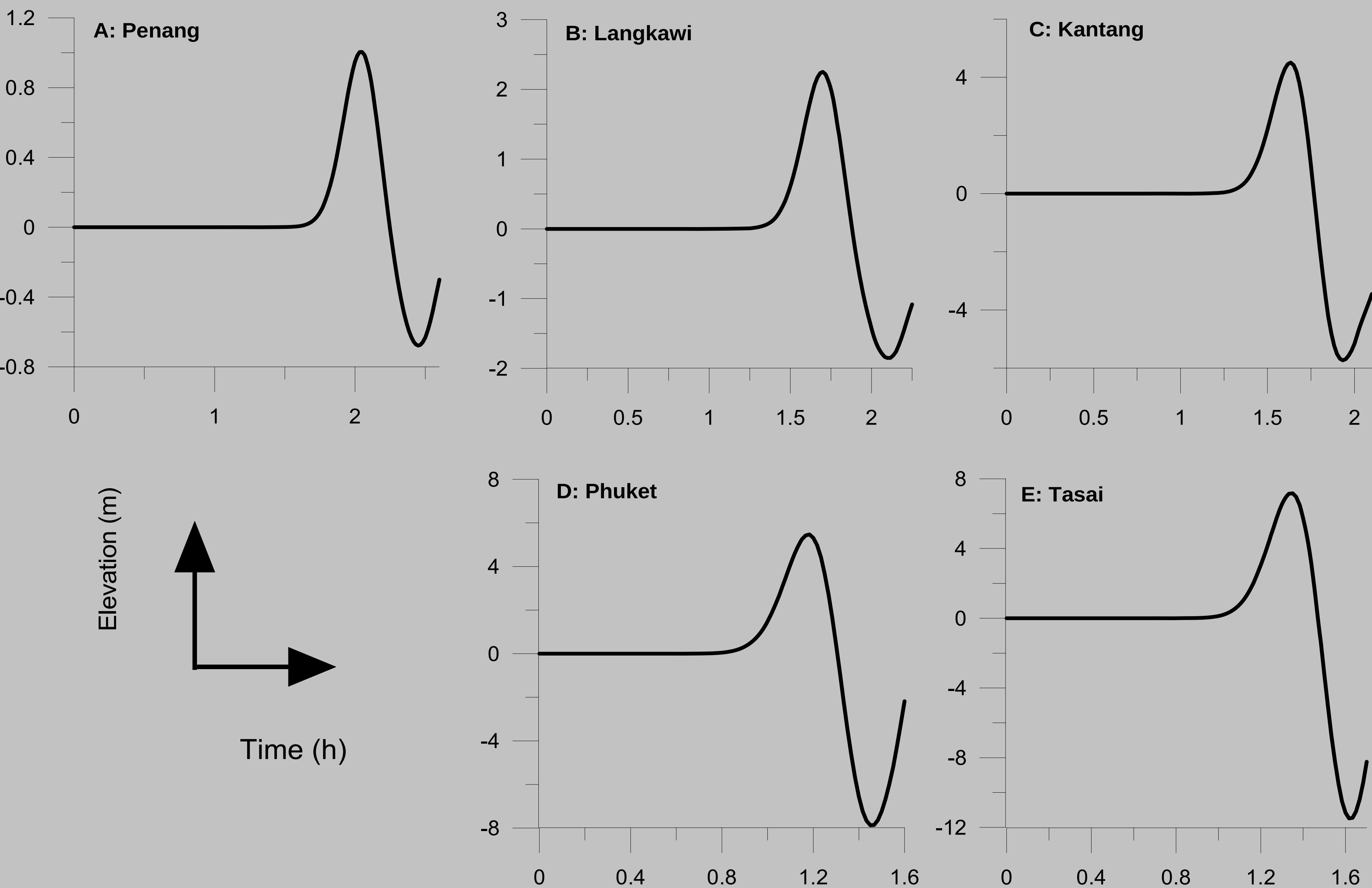






t = 600 s
t = 1200 s
t = 1800 s
t = 2400 s
X (km)
Y (km)
0
100
200
300
400
500
600
700
800
900
1000
-13 -12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13
Elevation (m)

Simulated Tsunami Wave Heights




22 2:09PM


22 2:38PM


22 4:34PM


22 4:50PM


23 8:33AM

Survey runup heights for the December 26 2004 tsunami

Location Name	Date (2005)	Lat. (N)		Long. (E)		Runup Height (m)	Distance to Shore (m)
		°	Min.	°	Min.		
B. Ferringhi (Teluk Bayu)	20/4	5	28.3	100	14.6	3.460	19.200
B. Ferringhi (Miami Beach)	20/4	5	28.7	100	16.1	4.000	25.600
Tanjung Tokong	20/4	5	27.6	100	18.5	3.650	35.800
Tanjung Tokong	20/4	5	27.6	100	18.4	N/A	190.000
Tanjung Tokong	20/4	5	27.7	100	18.5	2.610	18.300
Tanjung Bungah	21/4	5	28.2	100	16.7	2.310	18.380
Tanjung Bungah	21/4	5	28.2	100	16.7	2.940	36.200

Location Name	Date (2005)	Lat. (N)		Long. (E)		Runup Height (m)	Distance to Shore (m)
		°	Min.	°	Min.		
Kuala Kedah	22/8	6	6.00	100	26.0	0.900	N/A
Yan (Kg. K.S. Limau)	22/8	5	53.0	100	21.0	1.227	12.900
Sg udang	22/8	5	48.0	100	22.0	1.500	N/A
Tanjung Dawai	22/8	5	40.0	100	21.0	0.385	75.319
Kota K. Muda	22/8	5	34.0	100	20.0	3.800	100.524
Kuala Kurau	23/8	5	0.0	100	25.0	1.930	N/A
Pantai Acheh	23/8	5	24.0	100	11.0	2.505	13.400
Pantai Tengah (Lanai Hotel)	24/8	6	15.0	99	43.0	3.660	44.500
Pantai Chenang (Pelangi Hotel)	24/8	6	17.0	99	43.0	3.749	54.720
Kuala Teriang	24/8	6	21.0	99	42.0	3.091	27.038
Pantai Kok (Mutiara Beach Resort)	24/8	6	21.0	99	40.0	2.246	50.840
Pantai Kok (Berjaya Hotel)	24/8	6	21.0	99	40.0	2.983	34.879

1-D Runup Model

$$\frac{\partial \eta}{\partial t} + \frac{\partial \left(u \left(\eta + H \right) \right)}{\partial x} = 0$$

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

U = velocity [m/s]

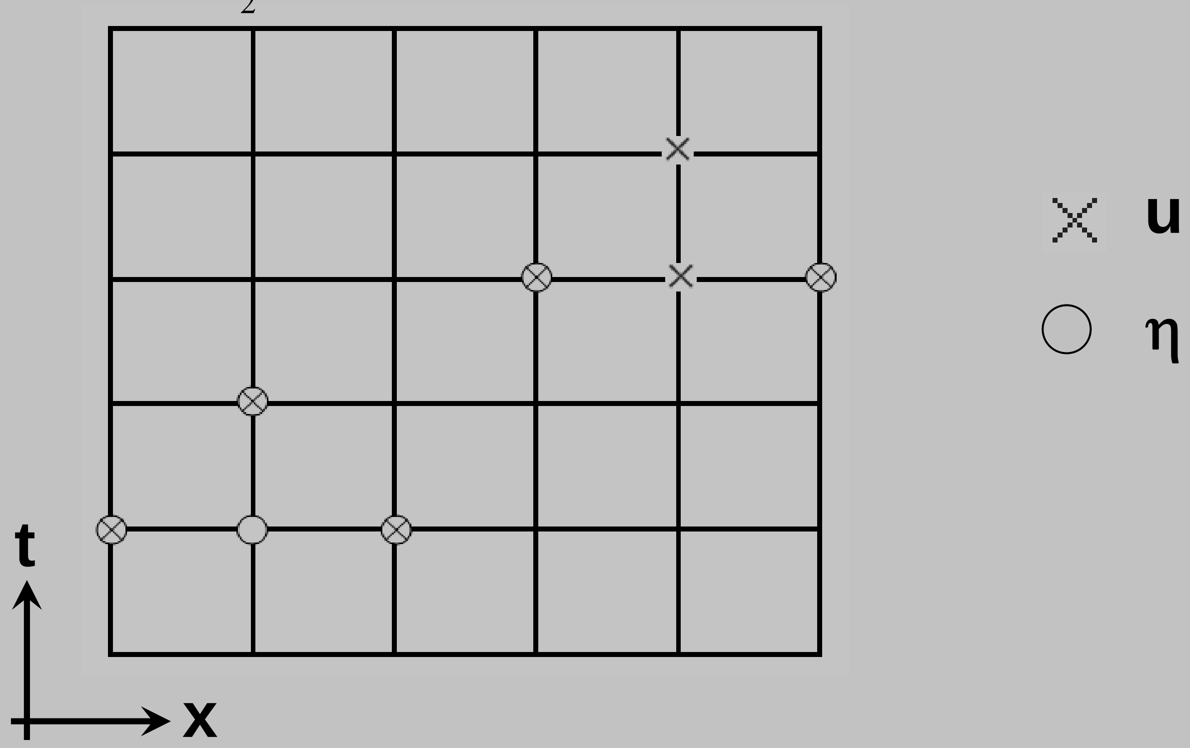
η **= surface elevation [m]**

H = depth [m];

Staggered Scheme

$$\frac{\eta_i^{n+1}-\eta_i^{n}}{\Delta t}+\left(H_i+\eta_i^{n}\right)\frac{u_{i+\frac{1}{2}}^{n+\frac{1}{2}}-u_{i-\frac{1}{2}}^{n+\frac{1}{2}}}{\Delta x}+u_{i+\frac{1}{2}}^{n+\frac{1}{2}}\frac{H_{i+1}+\eta_{i+1}^{n}-H_i-\eta_i^{n}}{\Delta x}=0$$

$$\frac{u_{i+\frac{1}{2}}^{n+\frac{1}{2}}-u_{i+\frac{1}{2}}^{n-\frac{1}{2}}}{\Delta t}+u_{i+\frac{1}{2}}^{n-\frac{1}{2}}\frac{\left(u_{i+\frac{1}{2}}^{n-\frac{1}{2}}-u_{i-\frac{1}{2}}^{n-\frac{1}{2}}\right)}{\Delta x}+g\frac{\left(\eta_{i+1}^{n+1}-\eta_i^{n+1}\right)}{\Delta x}=0$$

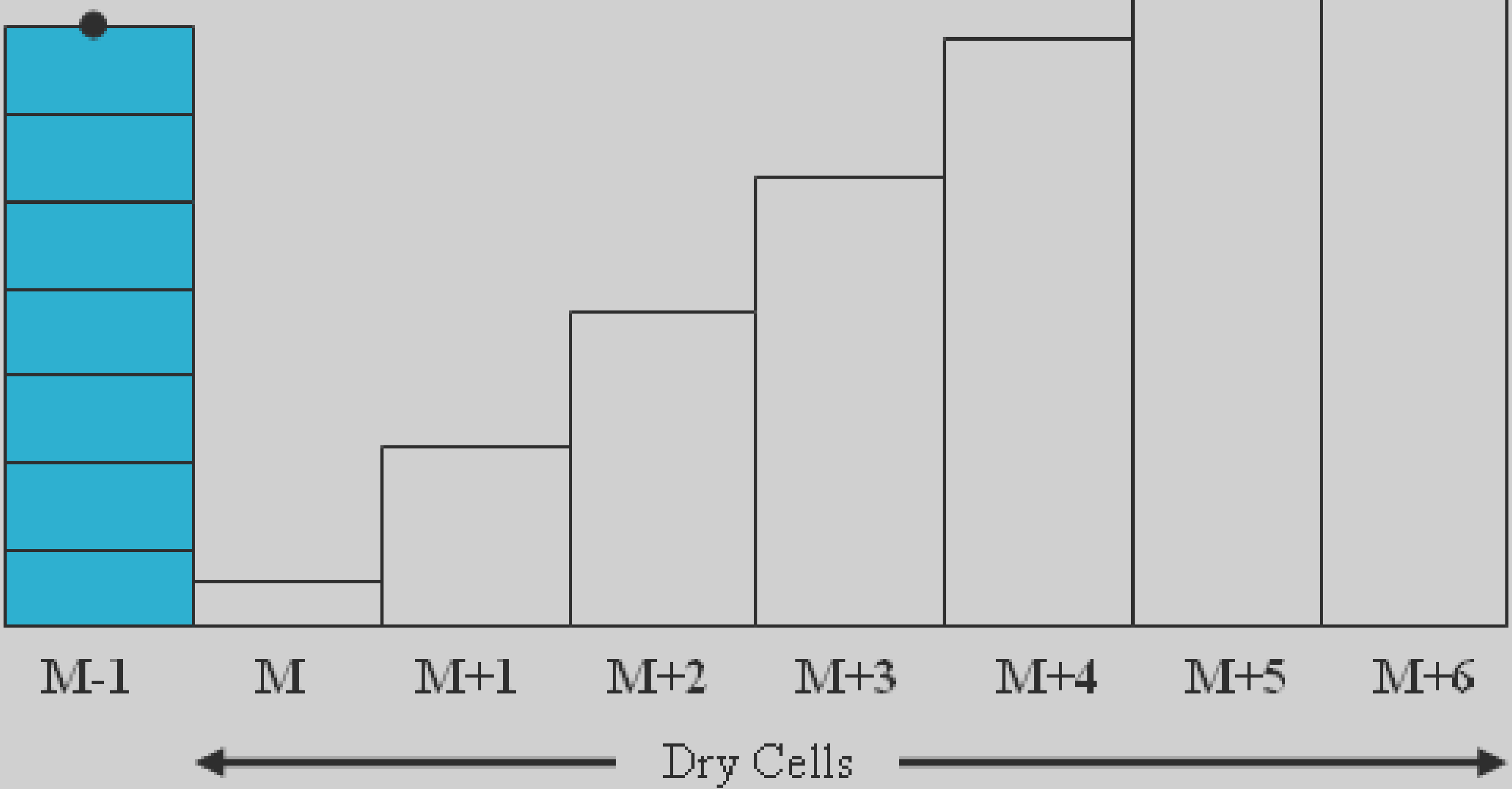


$$E_{kin\,M-1} = 0.5 \times m \times \left(u_{M-1}^{k}\right)$$

$$E_{pot\,M-1} = m \times g \times h_{max}$$

$$h_{max} = \frac{0.5 \times \left(u_{M-1}^{k}\right)^{2}}{g}$$

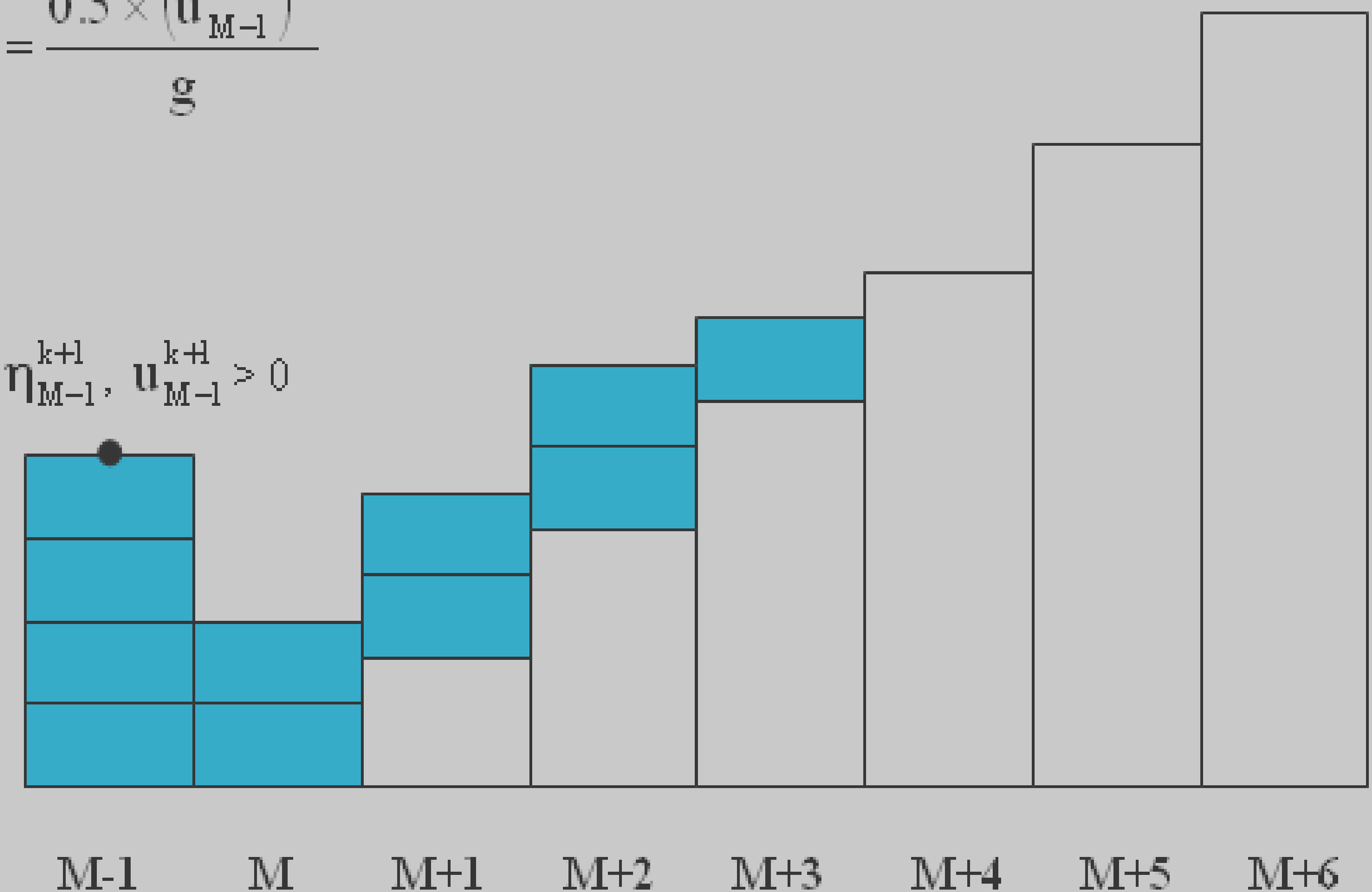
$\eta_{M-1}^{k},\ u_{M-1}^{k} > 0$



$$E_{kin\,M-1} = 0.5 \times m \times \left(u_{M-1}^{k+1}\right)$$

$$E_{pot\,M-1} = m \times g \times h_{max}$$

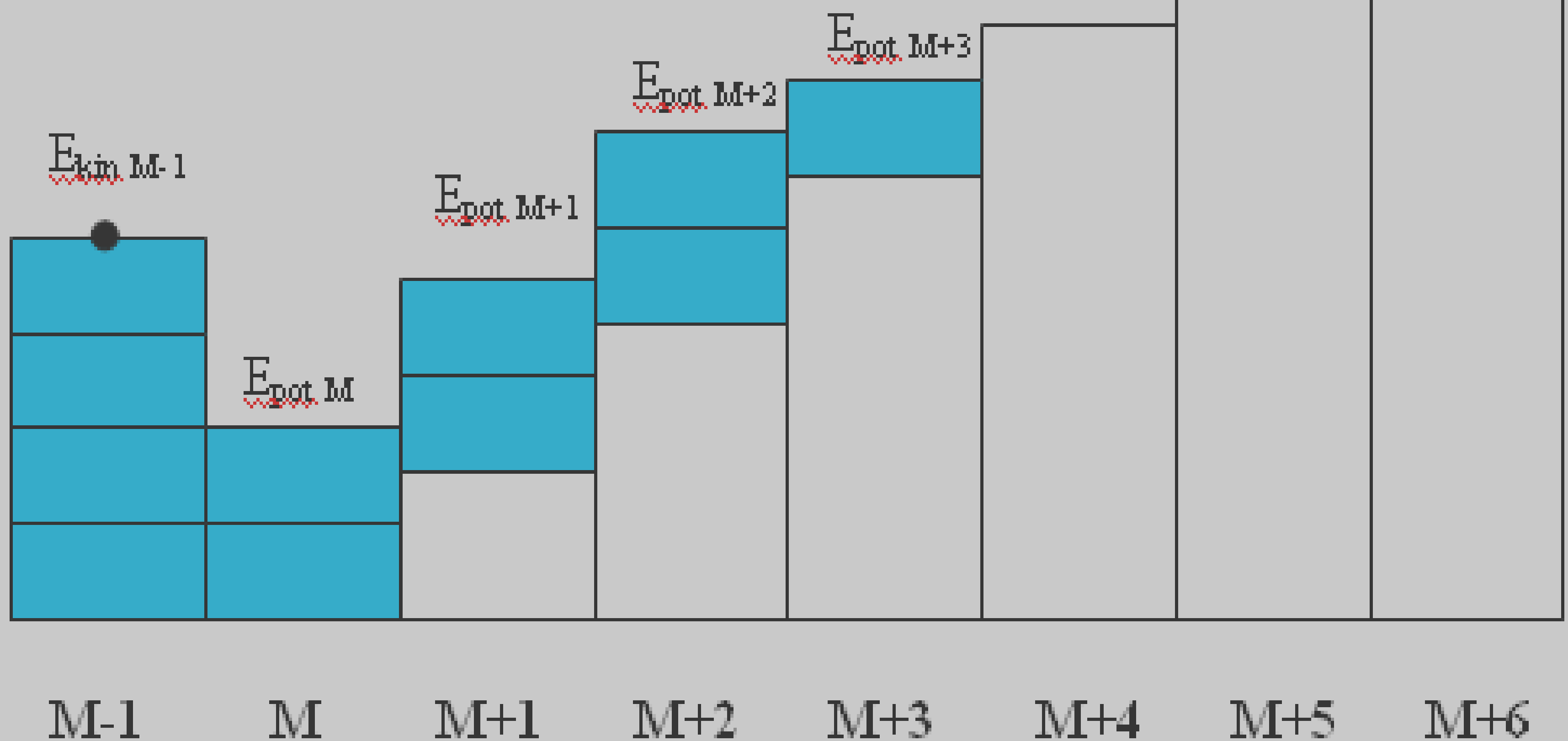
$$h_{max} = \frac{0.5 \times \left(u_{M-1}^{k+1}\right)^2}{g}$$



$$E_{kin\,M-1} = 0.5 \times m \times \left(u_{M-1}^{k+1}\right)$$

$$E_{pot\,M-1} = m \times g \times h_{max}$$

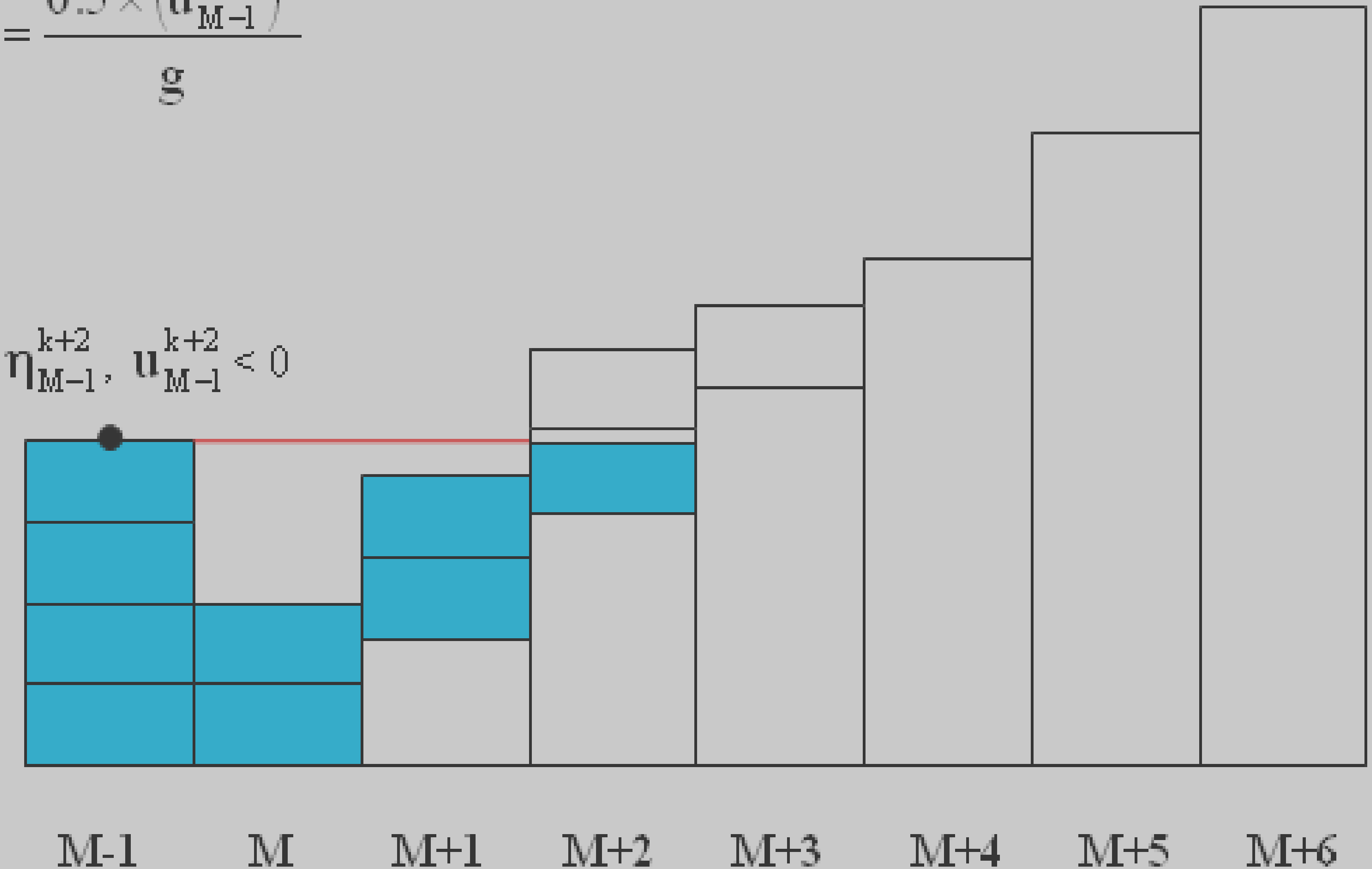
$$h_{max} = \frac{0.5 \times \left(u_{M-1}^{k+1}\right)^2}{g}$$



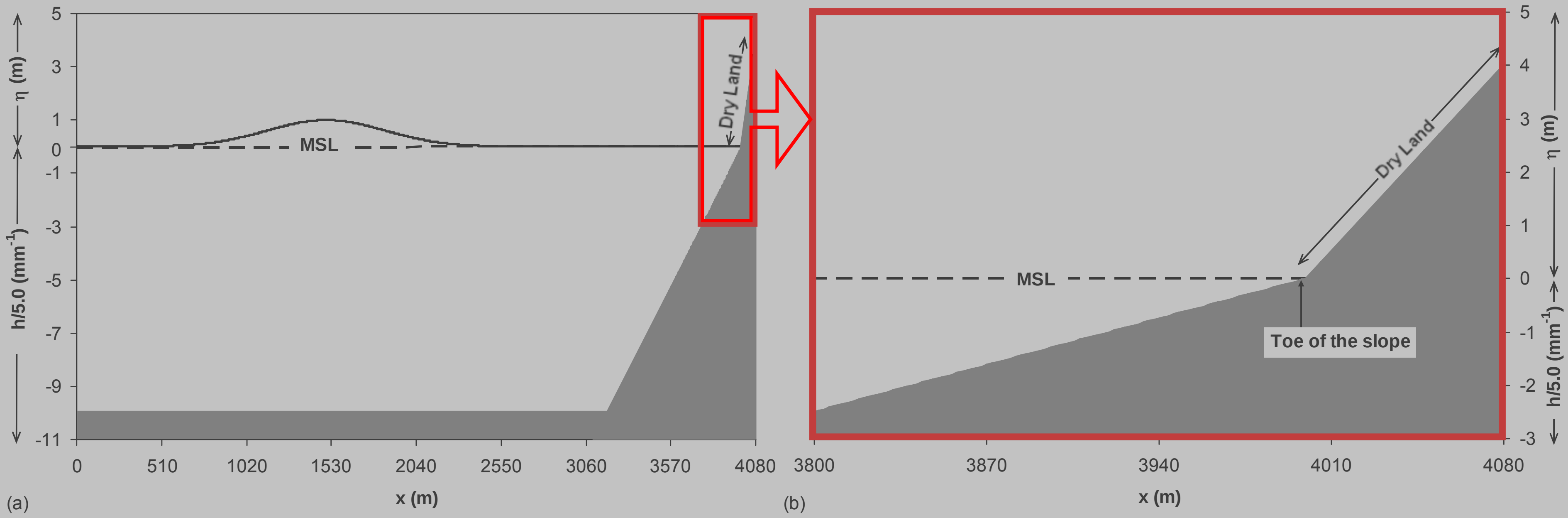
$$E_{kin\,M-1} = 0.5 \times m \times \left(u_{M-1}^{k+2}\right)$$

$$E_{pot\,M-1} = m \times g \times h_{max}$$

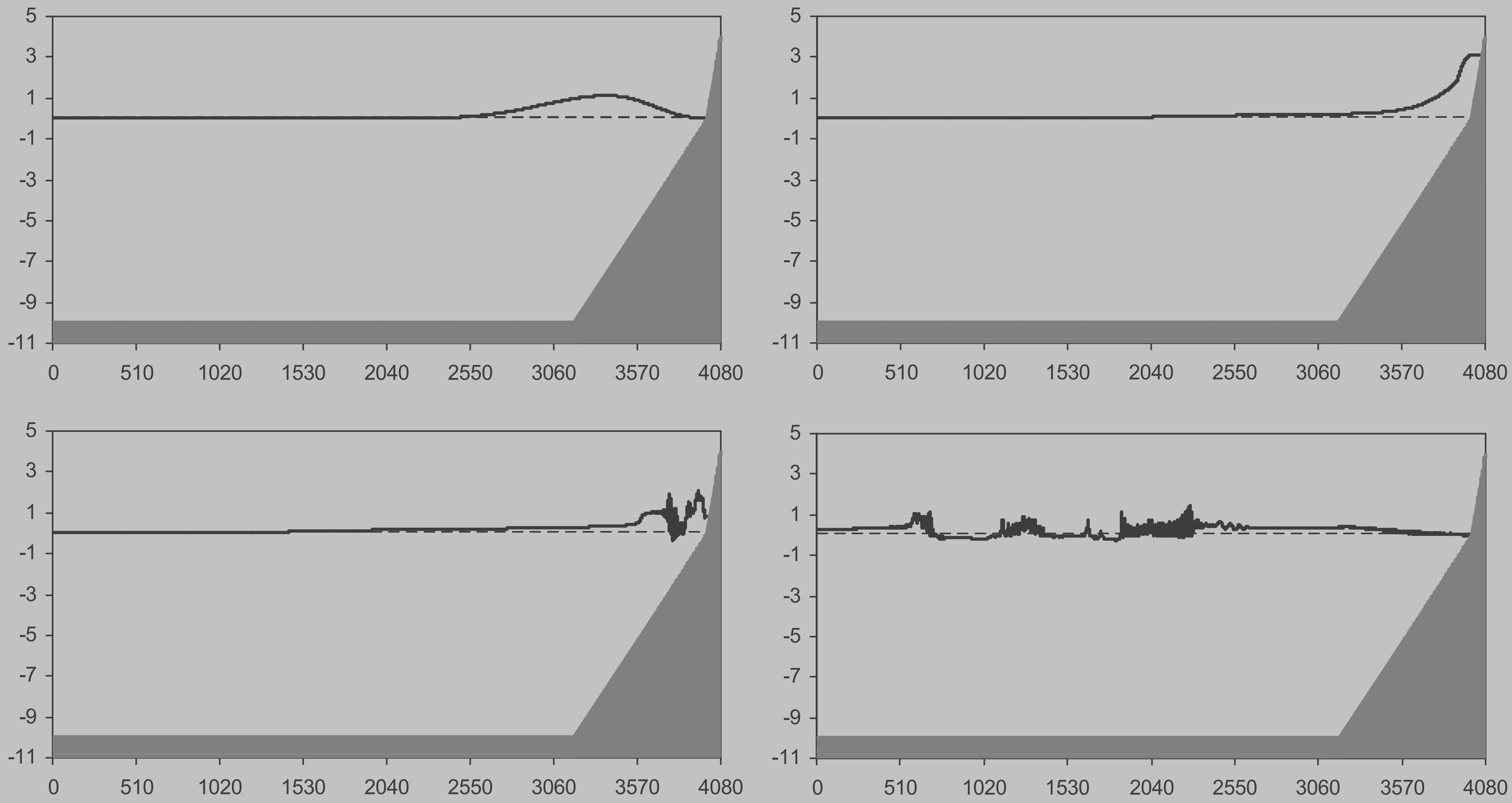
$$h_{max} = \frac{0.5 \times \left(u_{M-1}^{k+2}\right)^2}{g}$$



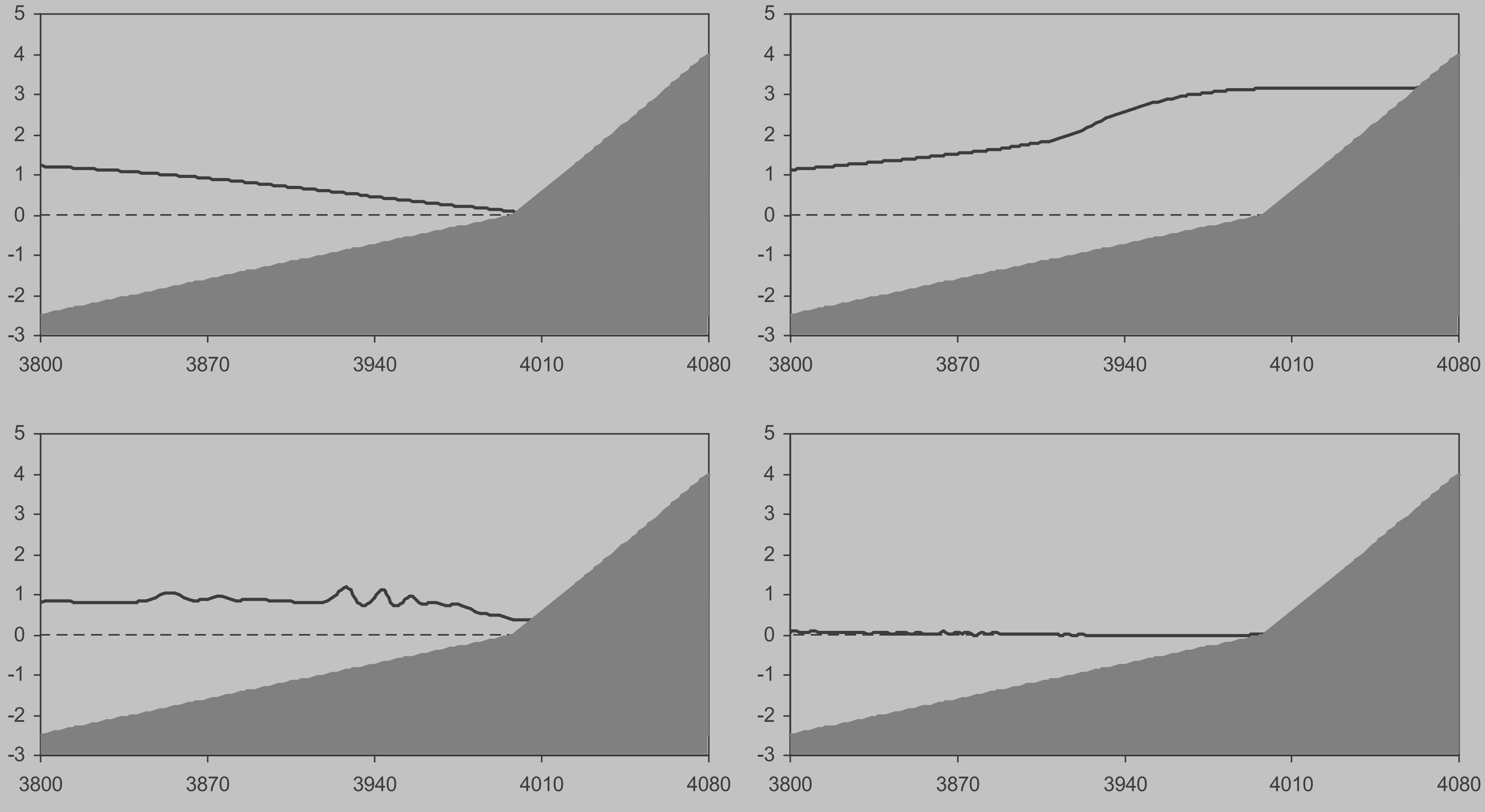
MBC: Study domain



Runup Onto Dry Land

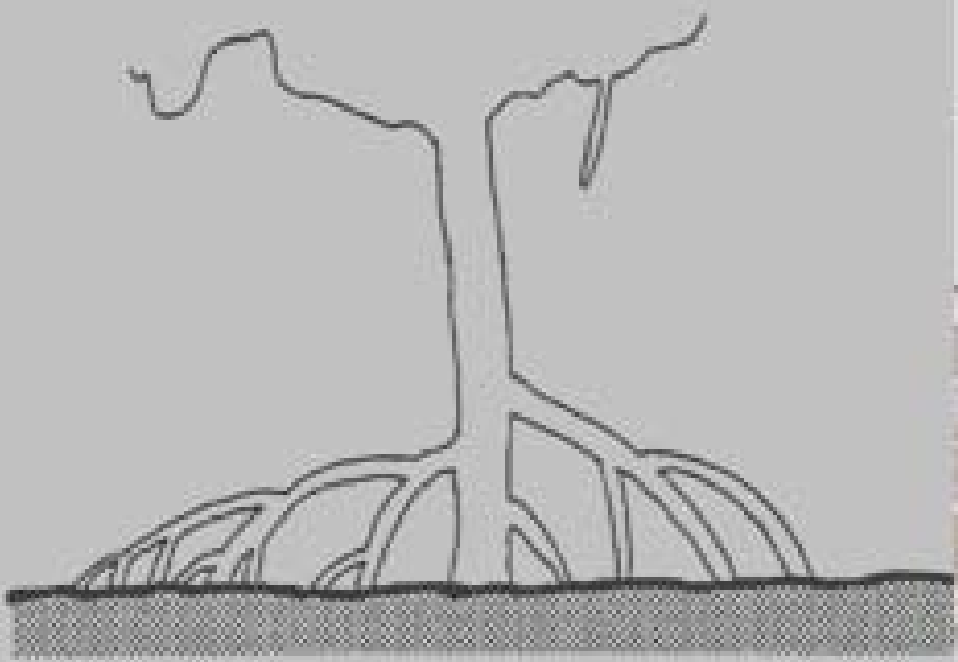


Enlarged Runup Frames

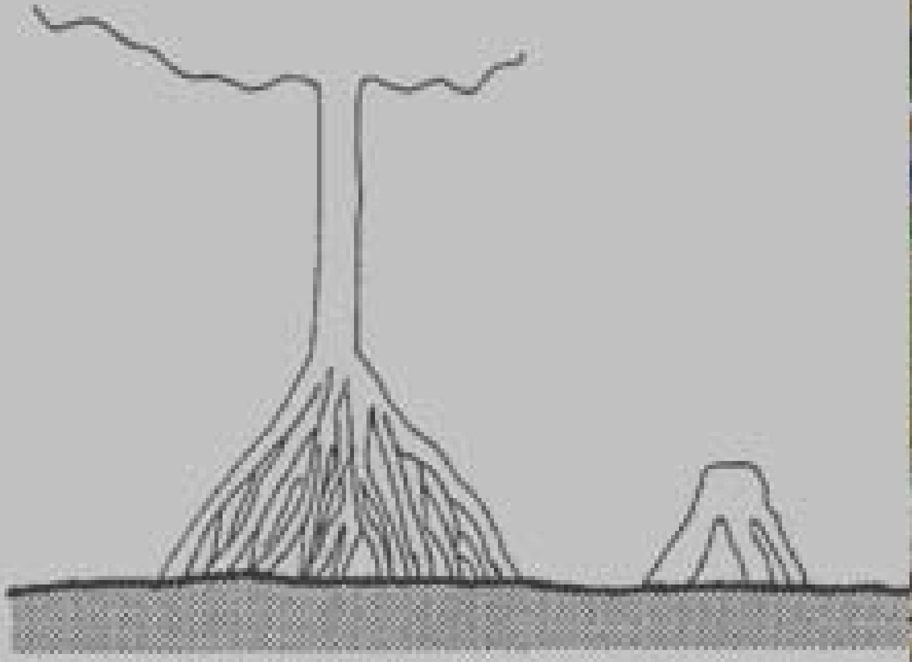


Effects of
Coastal Vegetation

Rhizophora stylosa



Bruguiera gymnorrhiza



Morison Equation

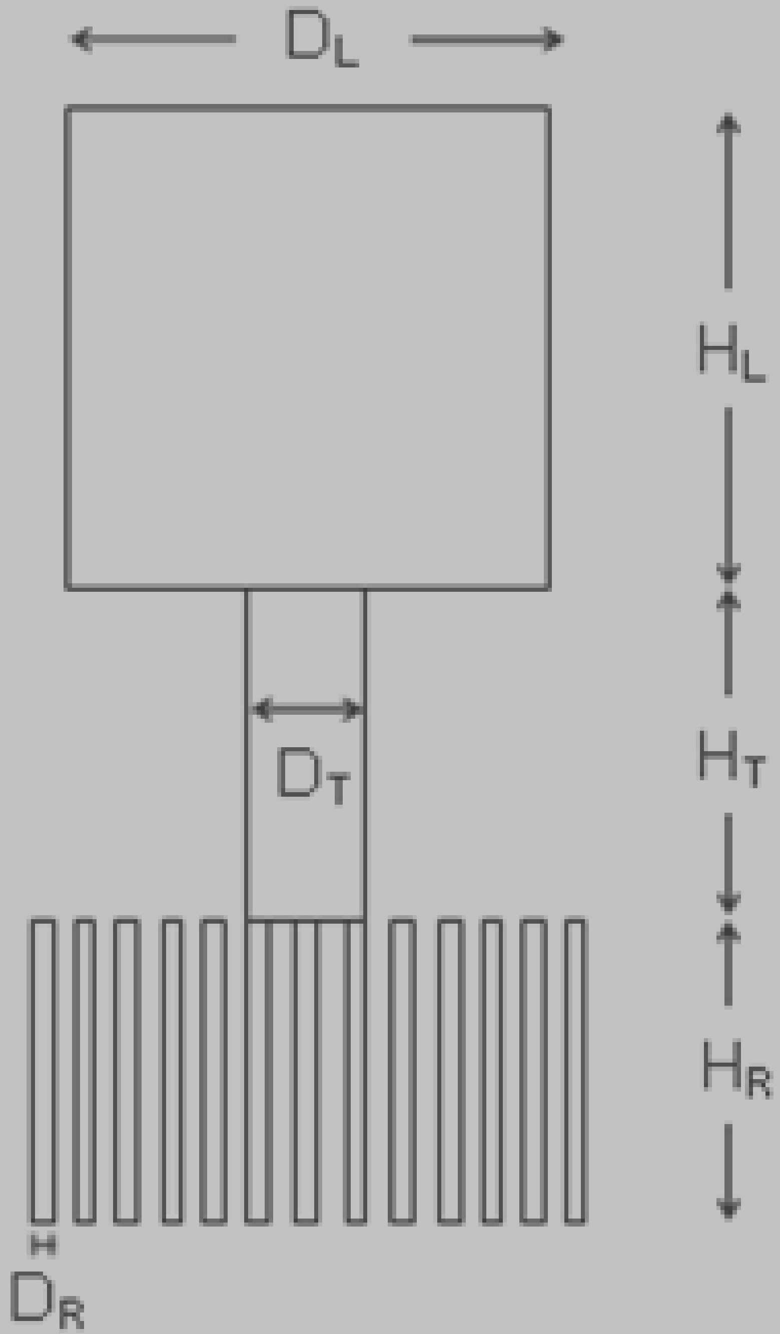
$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + gD\frac{\partial \eta}{\partial x} + \frac{gn^2 M|M|}{D^{7/3}} + \frac{C_D}{2}A_0\frac{M|M|}{D^2} = 0$$

M = flow flux, m^2/s; $D = (\eta + h)$ = total water depth, m;
h = still water depth, m; n = Manning coefficient;
g = gravitational acceleration, m/s^2; C_D = drag coefficient;
A_0 = projected area of trees under water surface, per 100 m^2.

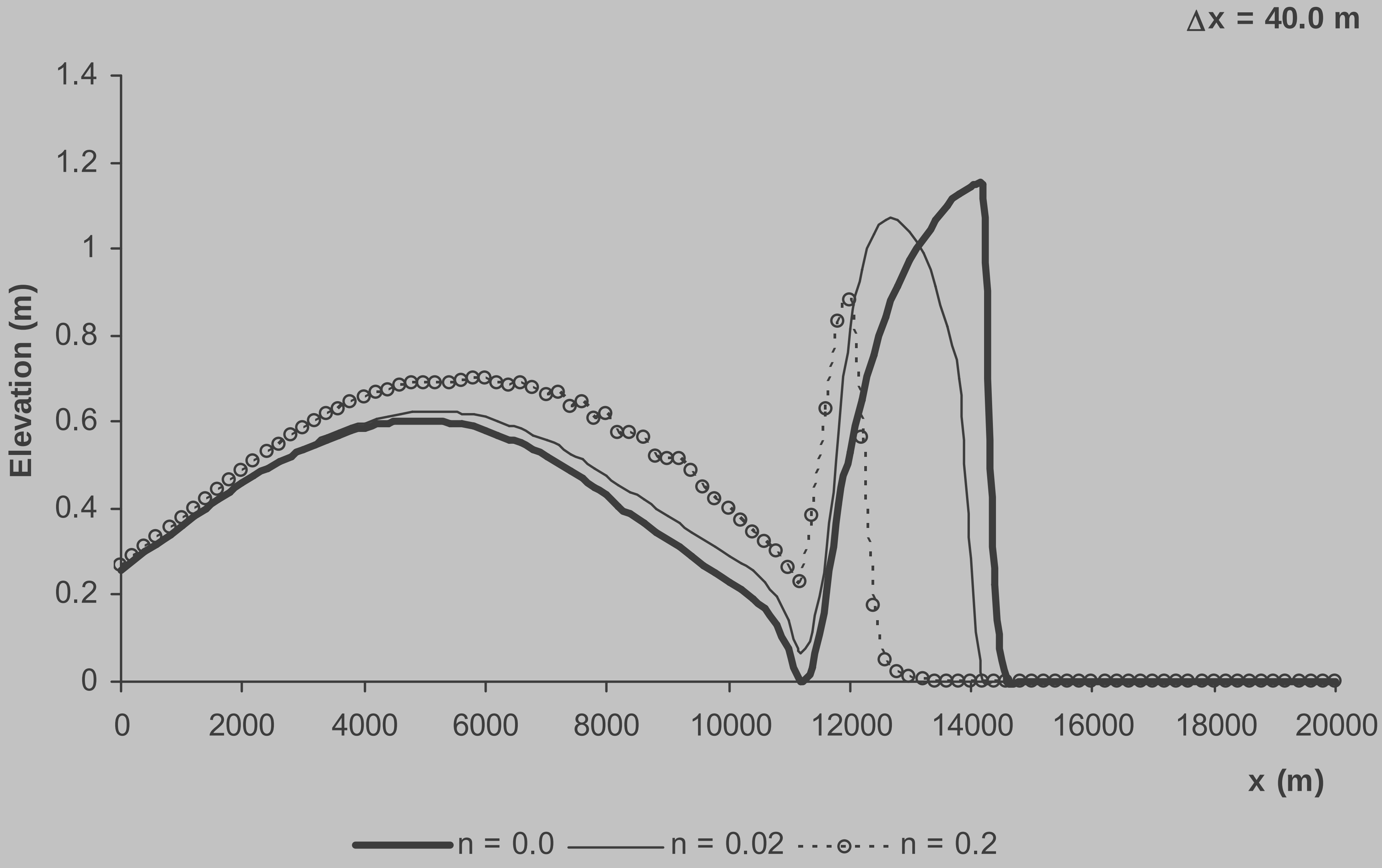
Drag Coefficient

$$C_D = 8.4\frac{V_0}{V} + 0.66 \qquad \left(0.01 \le \frac{V_0}{V} \le 0.07\right)$$

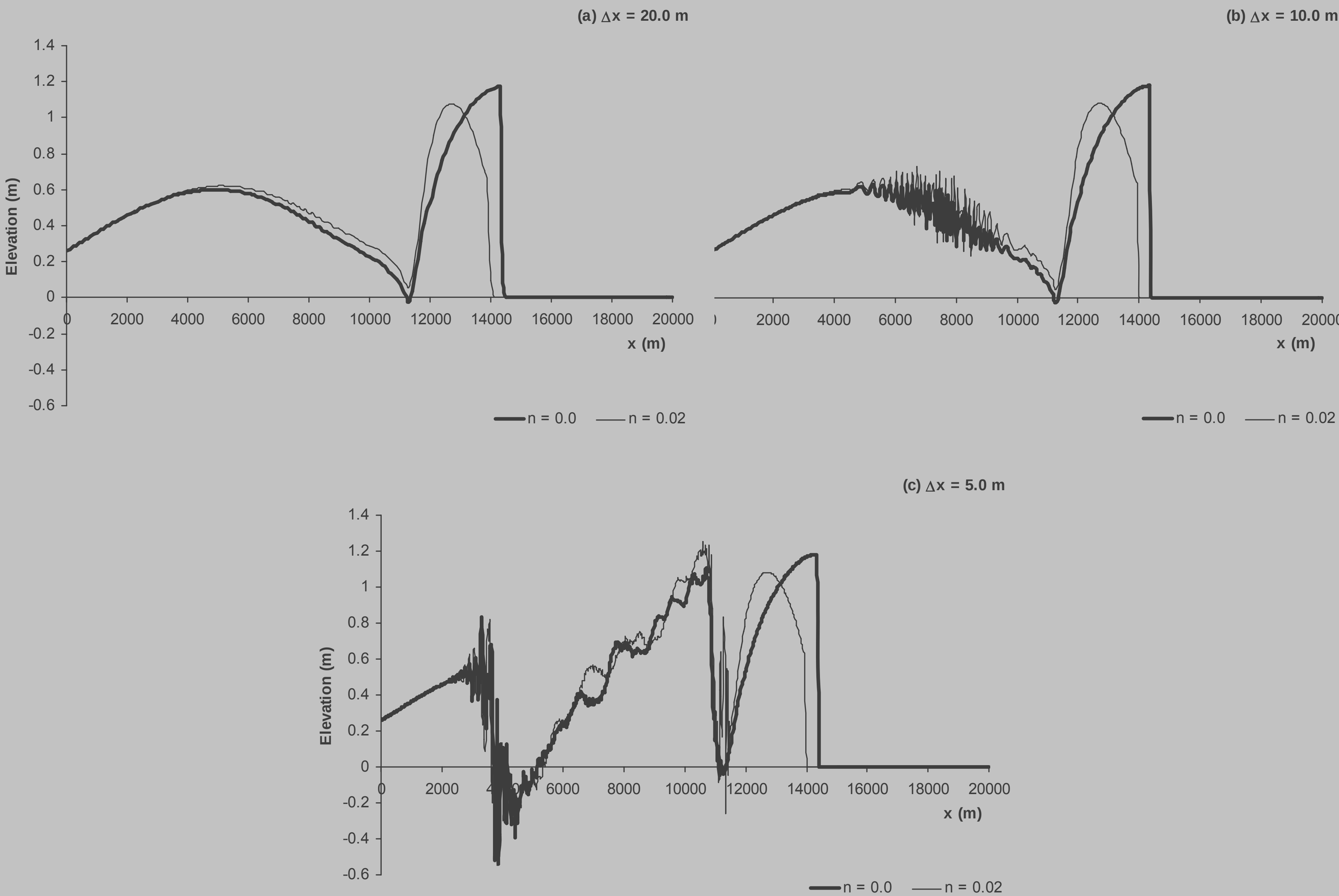
V_0 = total volume of obstacles (m^3);
V = control volume (m^3);

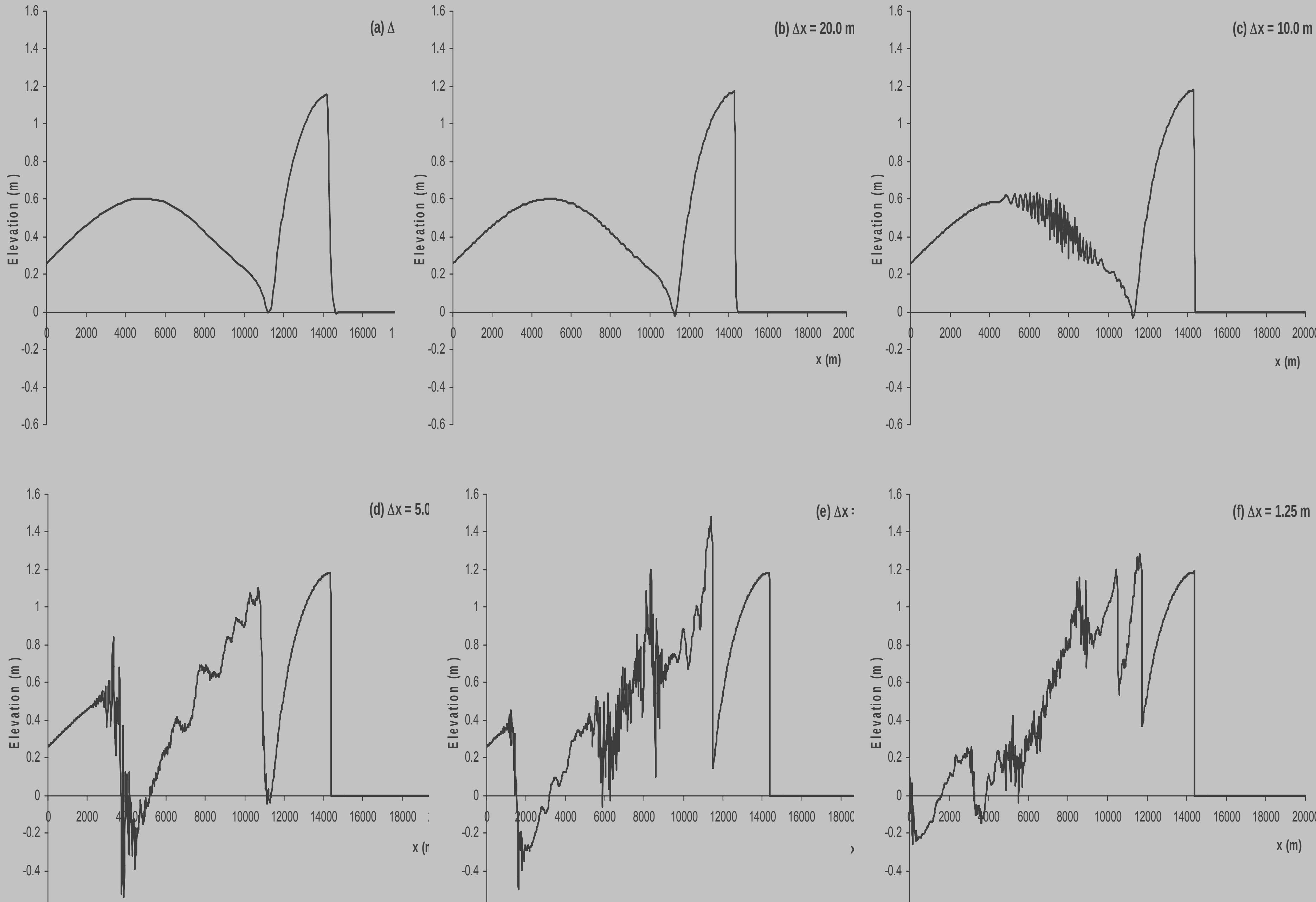


P_L = leaf porosity;
N_T = number of trees per 100 m^2;
N_R = number of prop roots per tree;
D_T = diameter of stem, m;
D_R = diameter of each prop root, m;
D_L = diameter of leaf part, m;
H_R = height of root part, m;
H_T = height of stem part, m;
H_L = height of leaf part, m.



Δx = 40.0 m
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Elevation (m)
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
x (m)
n = 0.0
n = 0.02
n = 0.2


(a) ∆x = 20.0 m
Elevation (m)
x (m)
n = 0.0
n = 0.02
(b) ∆x = 10.0 m
x (m)
n = 0.0
n = 0.02
(c) ∆x = 5.0 m
Elevation (m)
x (m)
n = 0.0
n = 0.02


(a) Δ
(b) Δx = 20.0 m
(c) Δx = 10.0 m
(d) Δx = 5.
(e) Δx =
(f) Δx = 1.25 m
Elevation (m)
x (m)

Linear Approximation

$$\frac{\partial \eta}{\partial t} = -h\frac{\partial u}{\partial x} \qquad \frac{\partial u}{\partial t} = -g\frac{\partial \eta}{\partial x} - \frac{\gamma}{h}u|u|$$

$$-\frac{\gamma}{h}u|u| \approx -R_f u = -\frac{gn^2}{h^{4/3}}u|u|$$

Analytical Solution

$$u = ae^{-\beta x}\sin(\sigma t - kx + \alpha) \qquad \eta = abe^{-\beta x}\sin(\sigma t - kx)$$

$$u \approx u_0 e^{-\beta x} \qquad \eta \approx \eta_0 e^{-\beta x}$$

$$R_f = \left(\frac{\gamma}{h} v_0 \frac{2}{\pi} \right) \qquad \gamma = \frac{gn^2}{h^{1/3}}$$

$$R_f = \left(\frac{gn^2}{h^{1/3} \cdot h} v_0 \frac{2}{\pi} \right) = \frac{gn^2}{h^{4/3}} v_0 \frac{2}{\pi}$$

$$k^2 = \frac{\sigma^2}{gh} \left\{ \frac{1}{2} + \frac{1}{2} \sqrt{1 + \frac{R_f^{\ 2}}{\sigma^2}} \right\}$$

$$\beta = \frac{R_f \sigma}{2gHk} m^{-1}$$

Case (a)

$$\left(\frac{R_f}{\sigma}\right) << 1$$

β = decay number, m^{-1};
n = Manning coefficient, $sm^{-1/3}$;
h = water depth, m;
T = wave period, s;
v_0 = wave maximum velocity, ms^{-1};
x = half distance, m.

$$\frac{R_f^{\ 2}}{\sigma^2} \approx 0 \qquad k = \frac{\sigma}{\sqrt{gh}}$$

Case (b)

$$\left(\frac{R_f}{\sigma}\right) >> 1 \qquad \frac{R_f^{\ 2}}{\sigma^2} >> 1$$

$$k^2 = \frac{\sigma^2}{gh}\frac{R_f}{2\sigma} = \frac{\sigma R_f}{2gh} \qquad k = \sqrt{\frac{\sigma R_f}{2gh}}$$

$$\beta = \frac{R_f \sigma}{2ghk} = \frac{R_f \sigma}{2gh}\sqrt{\frac{2gh}{\sigma R_f}} = \sqrt{\frac{R_f \sigma}{2gh}} = k$$

$$\beta = \frac{n}{h}\sqrt{\frac{2v_0}{Th^{1/3}}} \qquad \hat{x} = -\frac{1}{\beta}\ln(0.5)$$

Decay number β (n,T)

T (min)	n ($sm^{-1/3}$)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
10	3.64	7.27	10.91	14.55	18.19	21.82	25.46
20	2.57	5.14	7.72	10.29	12.86	15.43	18.00
30	2.10	4.20	6.30	8.40	10.50	12.60	14.70
40	1.82	3.64	5.46	7.27	9.09	10.91	12.73
50	1.63	3.25	4.88	6.51	8.13	9.76	11.39
60	1.48	2.97	4.45	5.94	7.42	8.91	10.39

Half distance x(n,T)

T (min)	n ($sm^{-1/3}$)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
10	190.58	95.29	63.53	47.64	38.12	31.76	27.23
20	269.52	134.76	89.84	67.38	53.90	44.92	38.50
30	330.09	165.05	110.03	82.52	66.02	55.02	47.16
40	381.16	190.58	127.05	95.29	76.23	63.53	54.45
50	426.15	213.07	142.05	106.54	85.23	71.02	60.88
60	466.82	233.41	155.61	116.70	93.36	77.80	66.69

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} = 0$$

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + gD\frac{\partial \eta}{\partial x} + \frac{gn^2 M|M|}{D^{7/3}} + \frac{C_D}{2} A_0 \frac{M|M|}{D^2} = 0$$

η = elevation, m;
M = flow flux, m^2/s;
H = still water depth, m;
D = (η+h) = total water depth, m;
n = Manning coefficient;
g = gravitational acceleration, m/s^2;
CD = drag coefficient;
A0 = projected area of trees under water surface, m^2;
Δx, Δy = spatial grid size, m.

$$n = \sqrt{\frac{0.5 * C_D A_0 D_f^{1/3}}{g\Delta x\Delta y}}$$

Leaf porosity PL = 0.03

Number of trees per 100 m^2 NT = 30

Number of prop roots per tree NR = 100

Diameter of stem DT = 0.15 m

Diameter of each prop root DR = 0.035 m

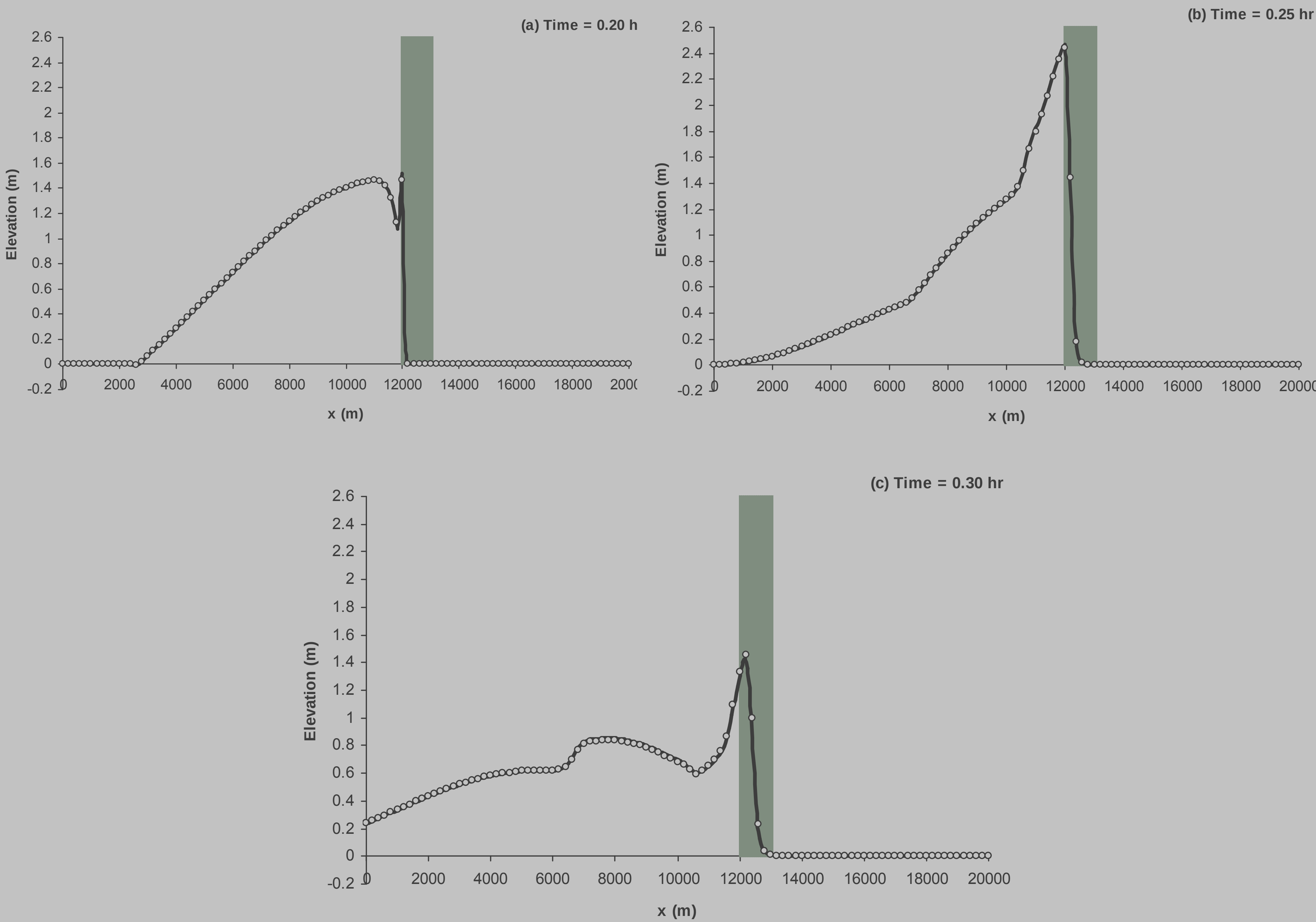
Diameter of leaf part DL = 2 m

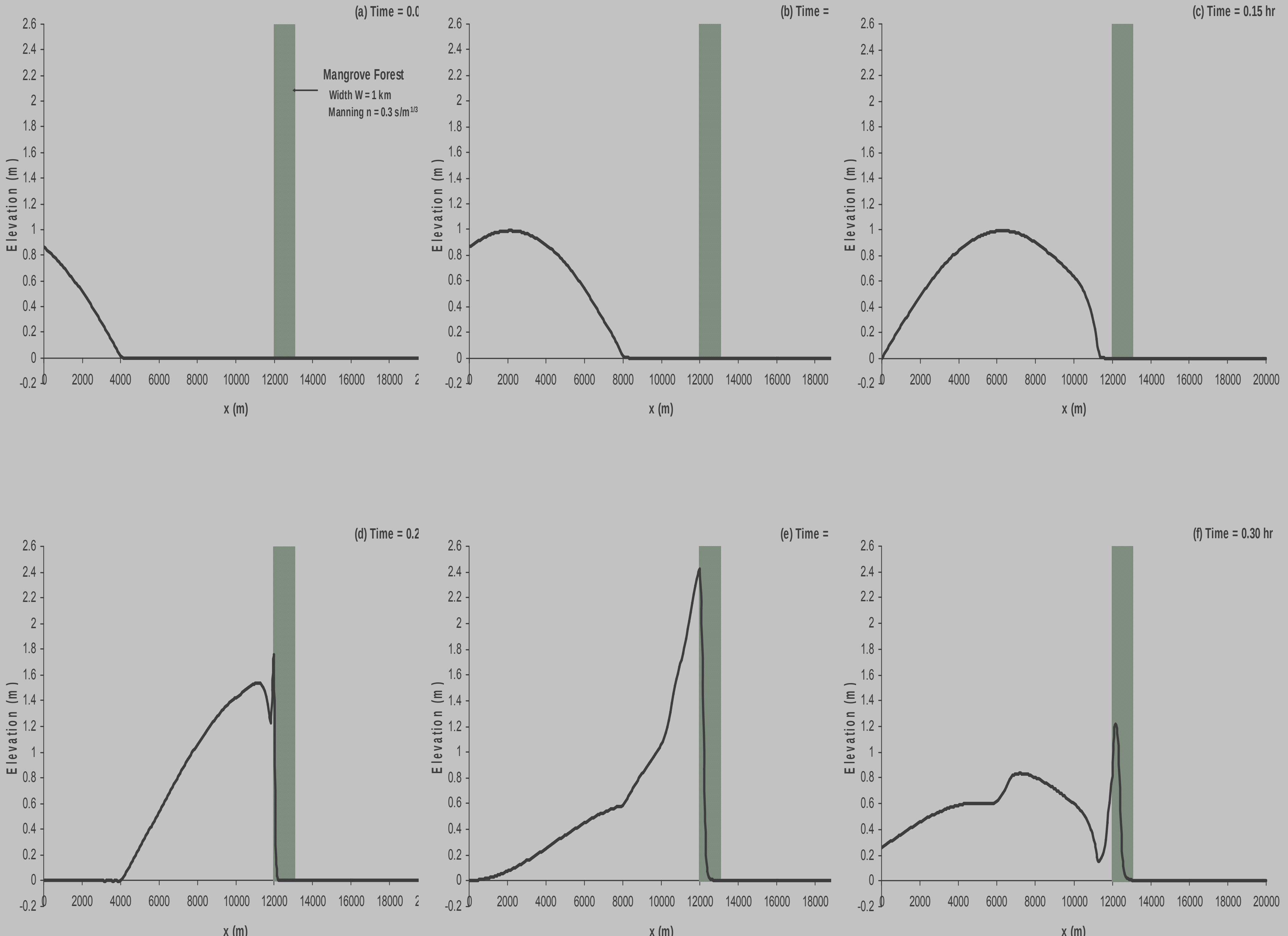
Height of root part HR = 1 m

Height of stem part HT = 2 m

Height of leaf part HL = 8 m

Forest width W = 1000 m


(a) Time = 0.20 h
Elevation (m)
x (m)
(b) Time = 0.25 hr
Elevation (m)
x (m)
(c) Time = 0.30 hr
Elevation (m)
x (m)



(a) Time = 0.0
Mangrove Forest
Width W = 1 km
Manning n = 0.3 s/m1/3
(b) Time =
(c) Time = 0.15 hr
(d) Time = 0.2
(e) Time =
(f) Time = 0.30 hr
Elevation (m)
x (m)

Reduction Ratio

$$r_\eta = \frac{\eta_{for\,max}}{\eta_{max}} \qquad r_u = \frac{u_{for\,max}}{u_{max}}$$

r_η = reduction ratio of elevation;

η_{formax} = maximum elevation with mangrove forest;

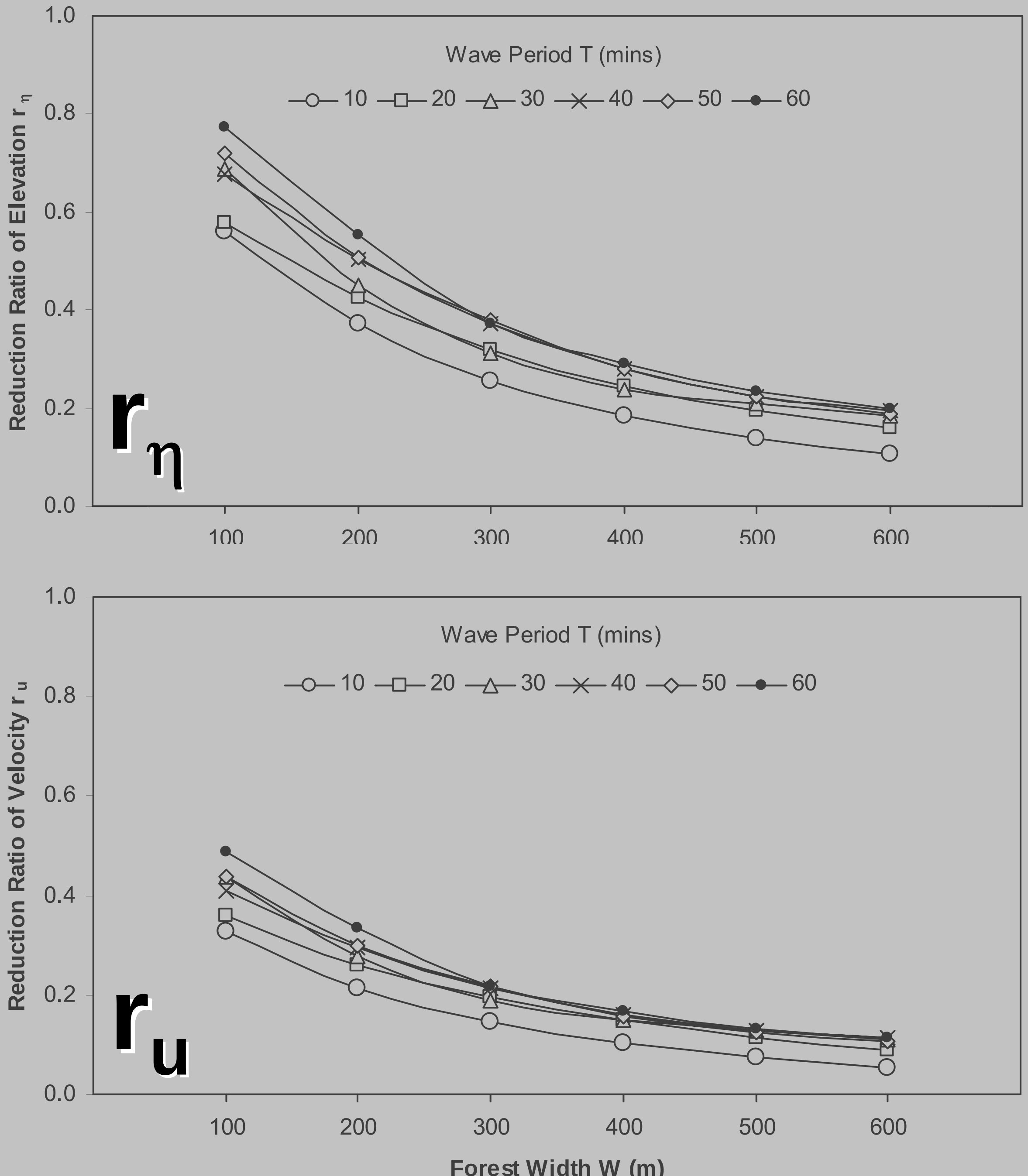
η_{max} = maximum elevation without mangrove forest;

r_u = reduction ratio of velocity;

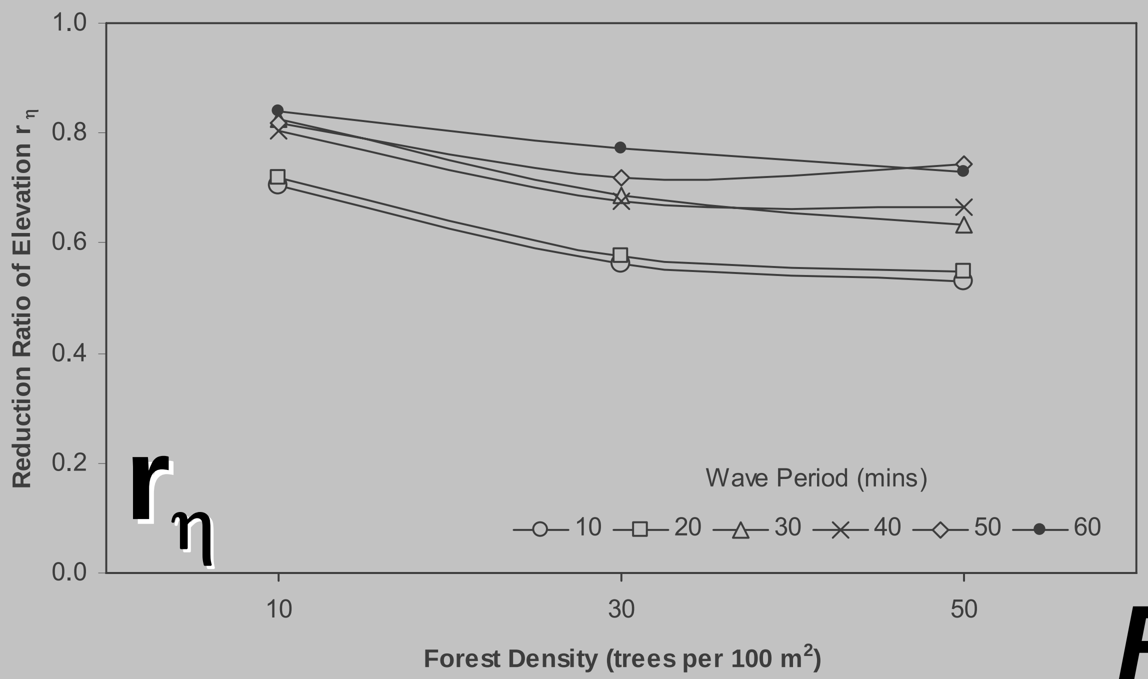
u_{formax} = maximum velocity with mangrove forest;

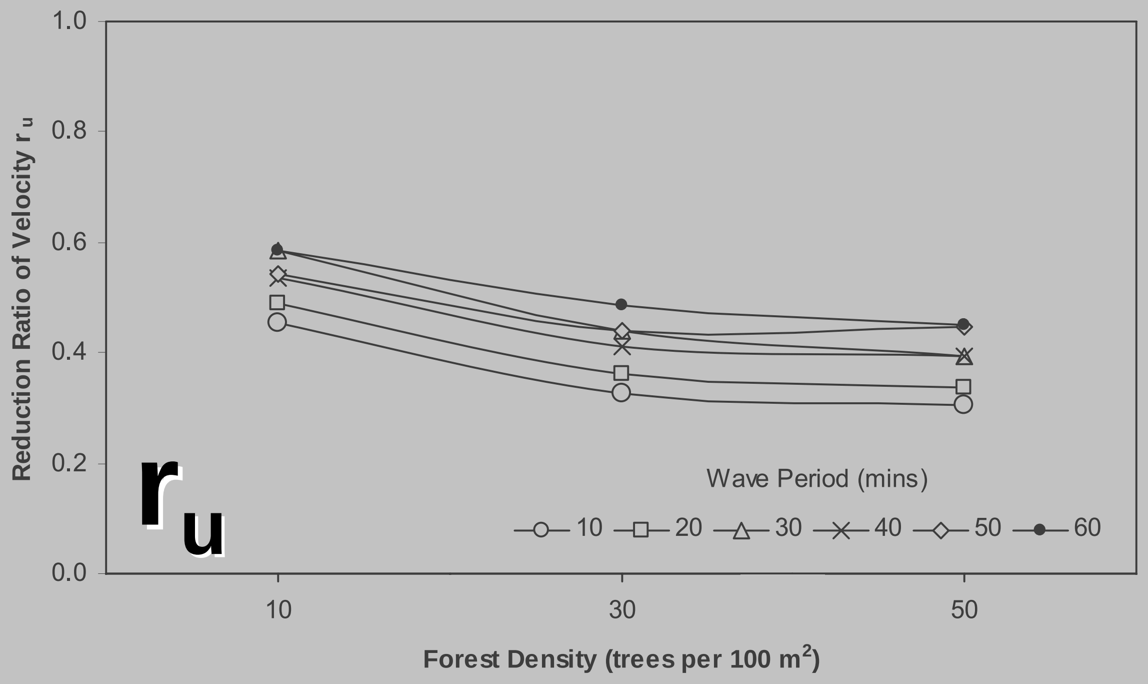
u_{max} = maximum velocity without mangrove forest.

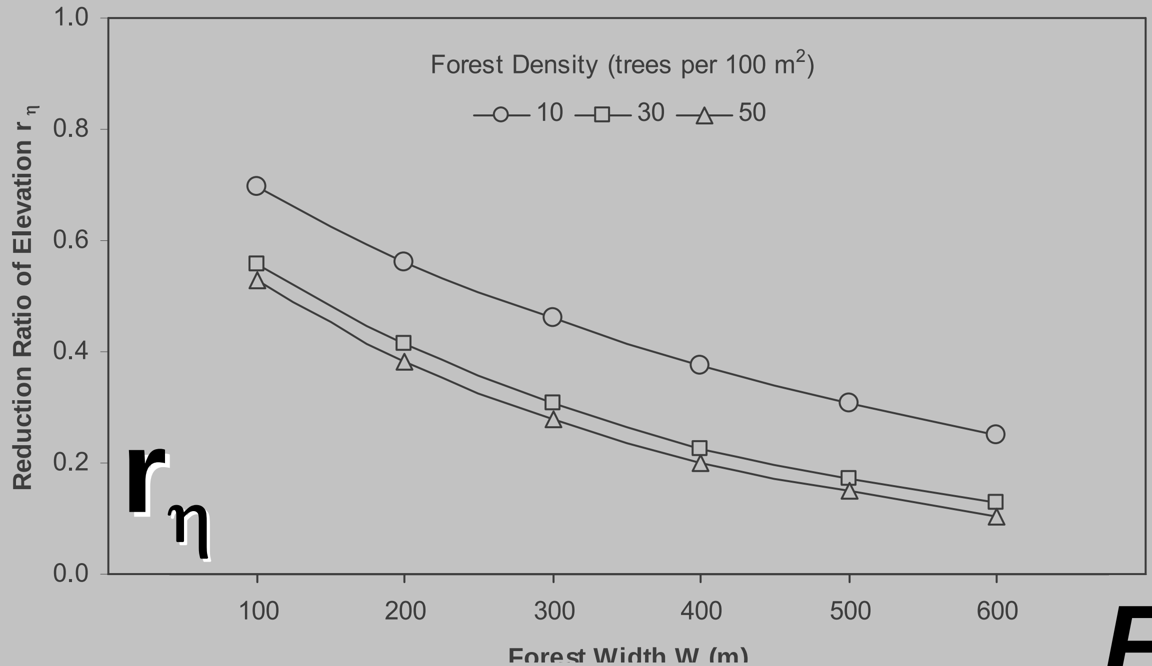
Wave Period vs. Forest Width

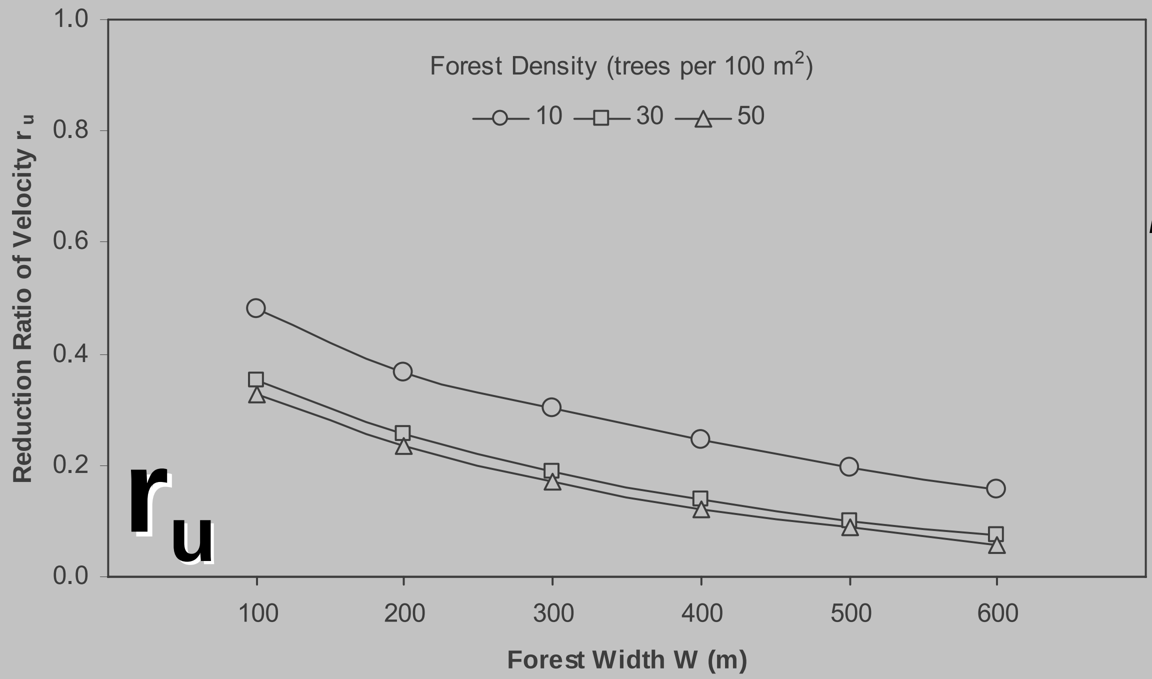


Wave Period vs. Forest Density



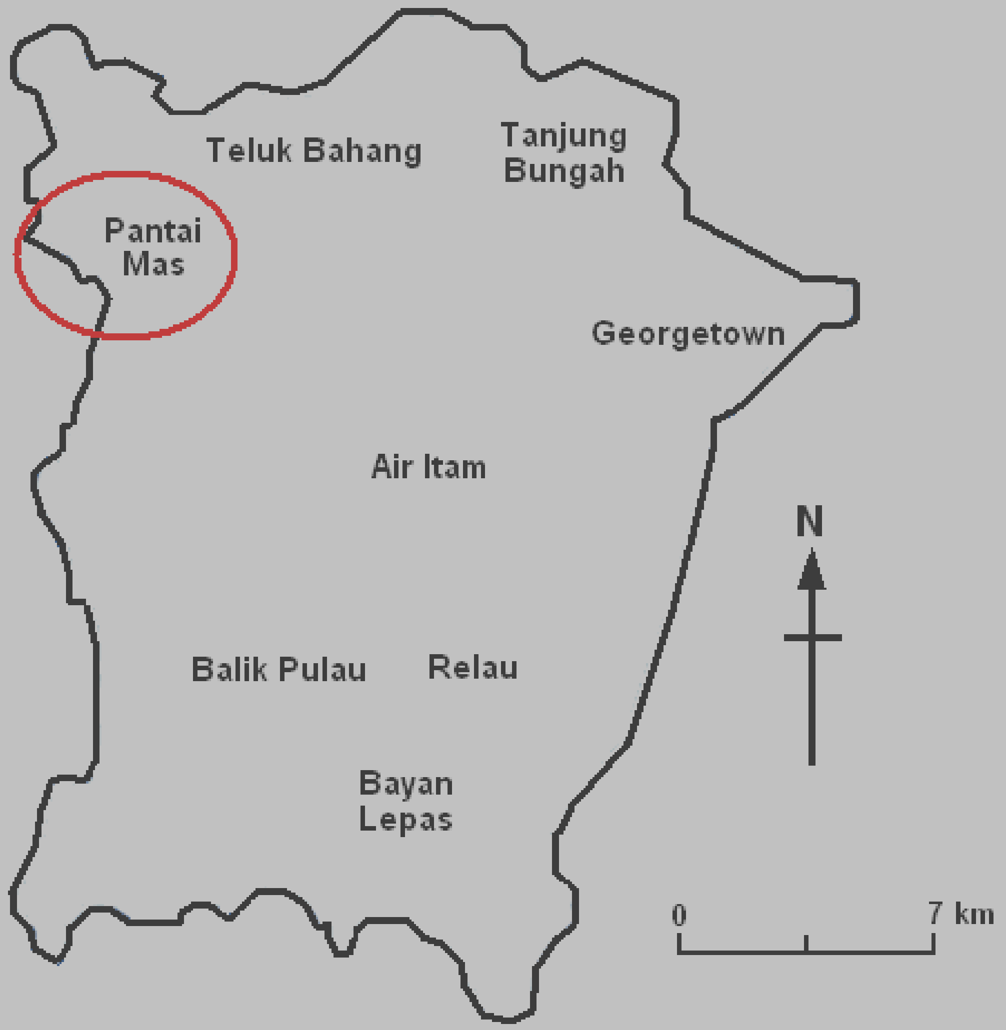






Forest Density vs. Forest Width

Penang Case Study

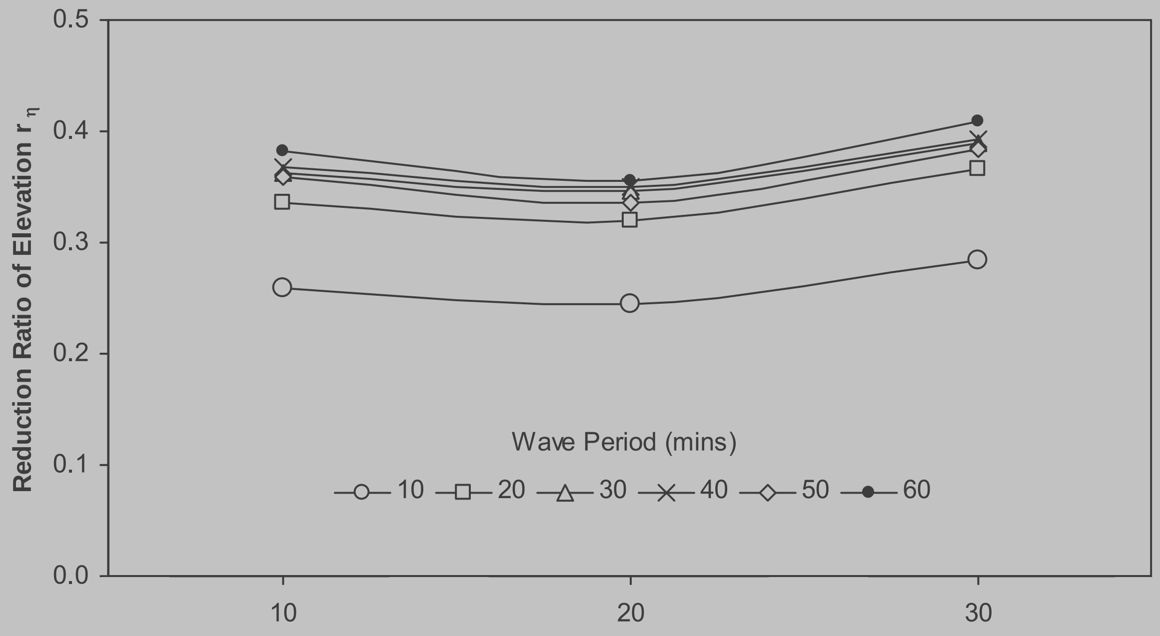



07

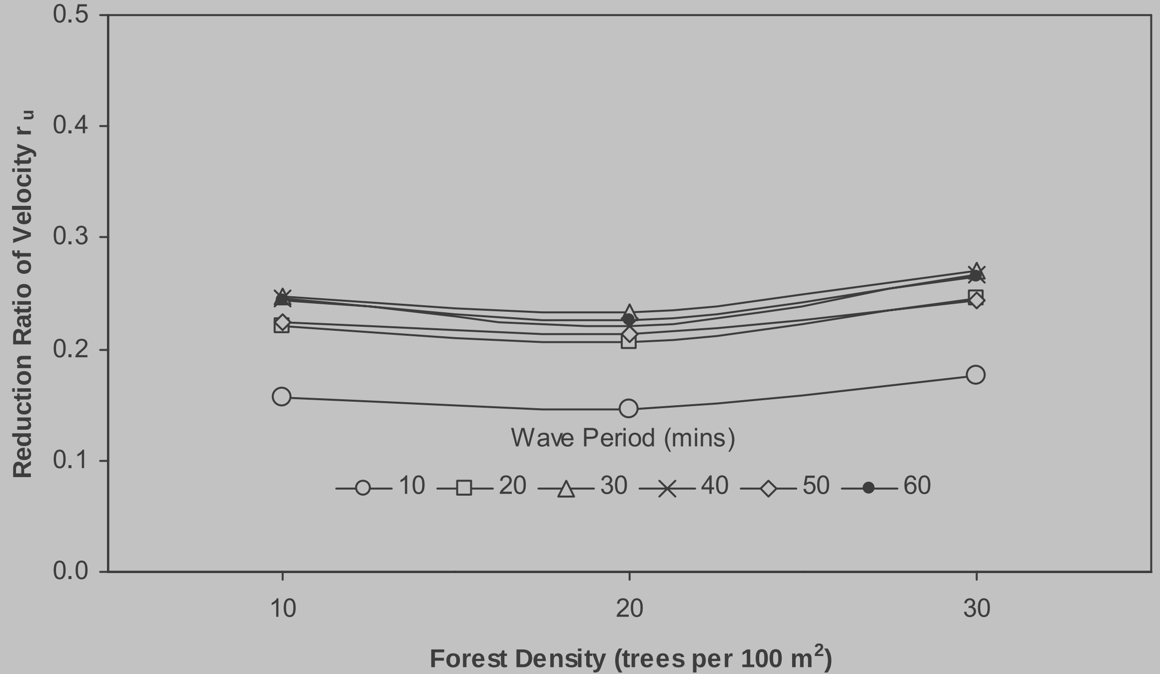
Pantai Mas Mangrove Forest

Parameter values	Forest Density (trees per 100 m^2)		
	10	20	30
P_L	0.03	0.03	0.03
N_T (trees per 100 m^2)	10	20	30
N_R (roots per 100 m^2)	6,000	6,000	6,000
D_L (m)	4.0	3.0	2.0
D_T (m)	0.28	0.18	0.07
D_R (m)	0.008	0.008	0.008
H_L (m)	4.0	3.0	2.0
H_T (m)	6.0	5.5	5.0
H_R (m)	0.18	0.18	0.18

Forest Width = 1000 m

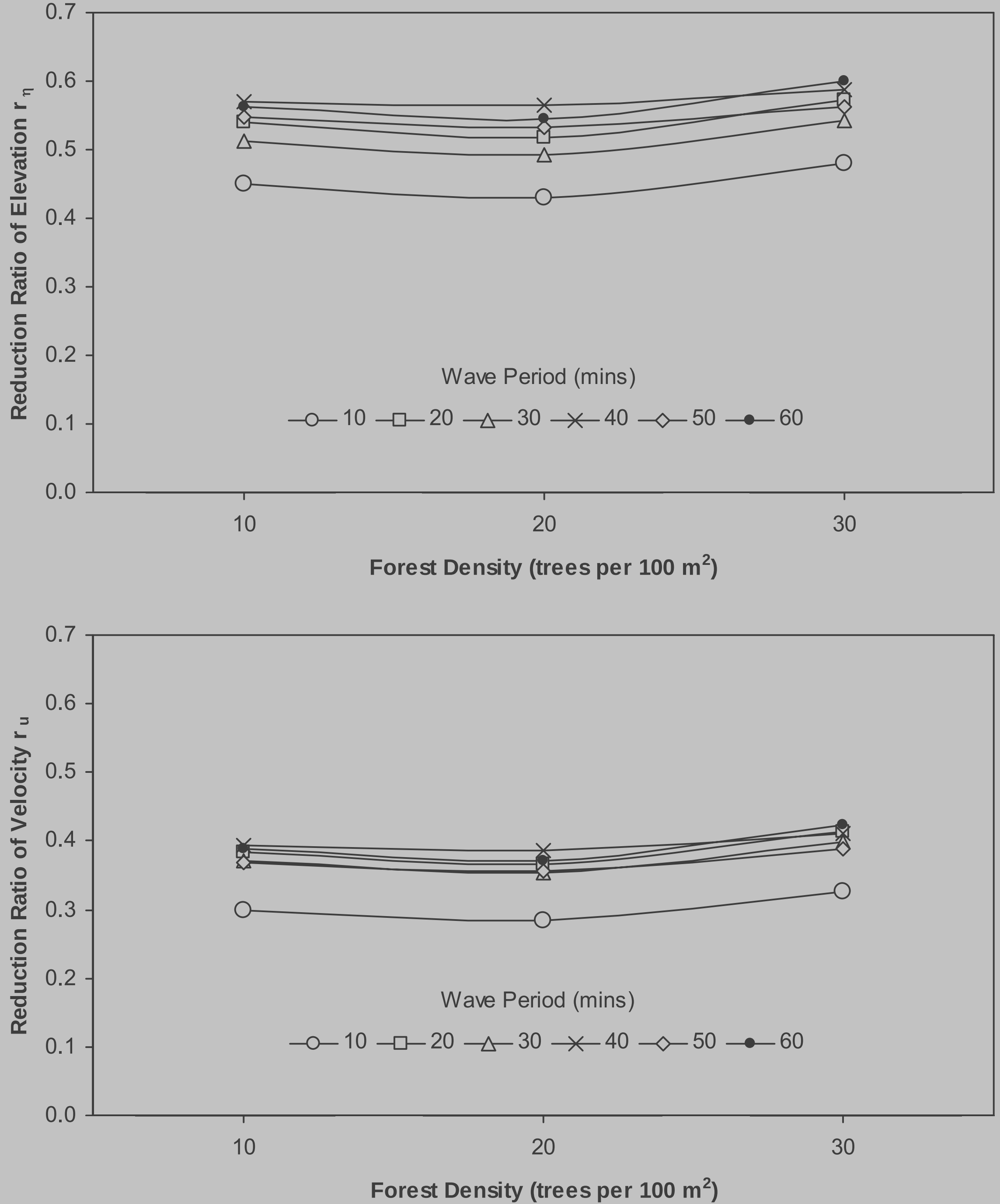


r_η



r_u

Forest Width = 500 m



r_η

r_u


Thank you