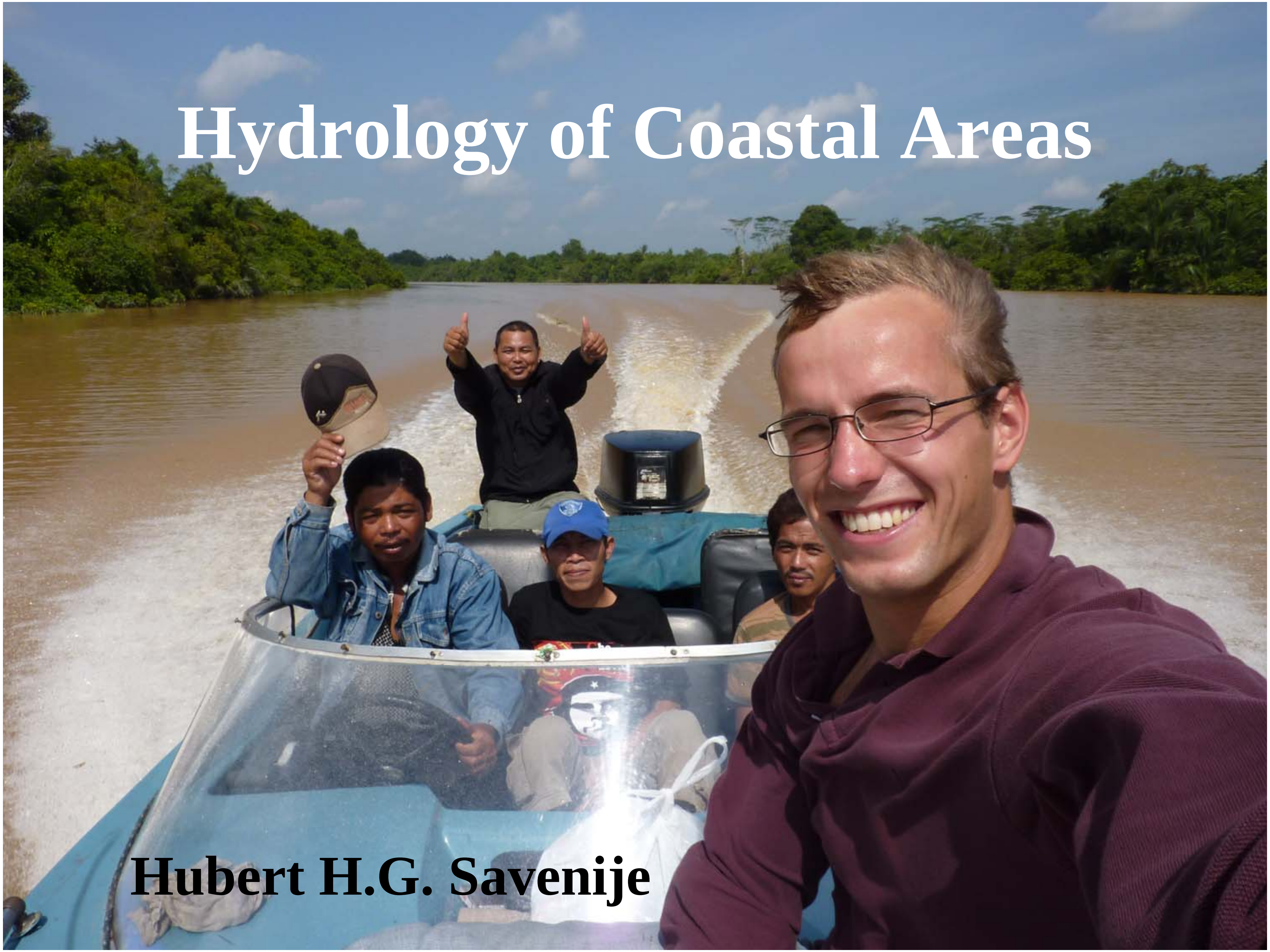
Hydrology of catchments, rivers and deltas (CIE5450)

Prof.dr.ir. Savenije

Lecture ‘Coastal areas’

TU Delft

Hydrology of Coastal Areas

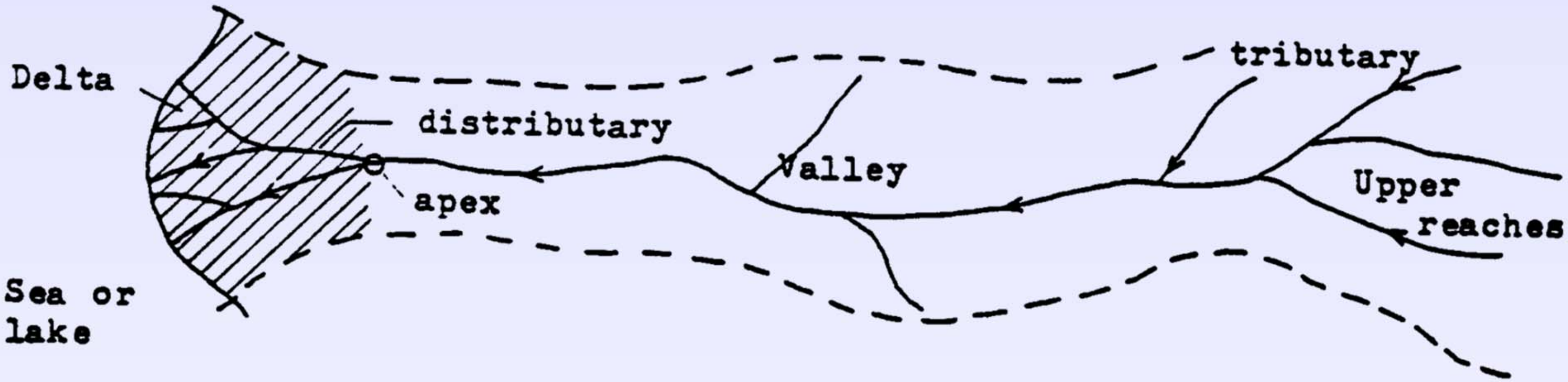


Hubert H.G. Savenije

HYDROLOGY OF COASTAL AREAS

- Introduction
- Astronomical tides and storm surges
- Propagation of astronomical tides and storm surges into estuaries
- Salt water intrusion
- Water control in coastal areas

Introduction



Introduction

	SEA	ESTUARY	RIVER
Shape			
Flow direction			
Salinity			
Wave			
Bottom slope			
Nutrients			

Introduction

	SEA	ESTUARY	RIVER
Shape	Basin	Funnel	Parallel Banks
Flow direction	No dominant direction	Dual direction	Single direction
Salinity	Salt	Brackish	Fresh
Wave	Standing	Mixed	Progressive
Bottom slope	Not relevant	No slope	Downward slope
Nutrients	Nutrient poor	High biodiversity. High biomass prod.	Nutrient rich

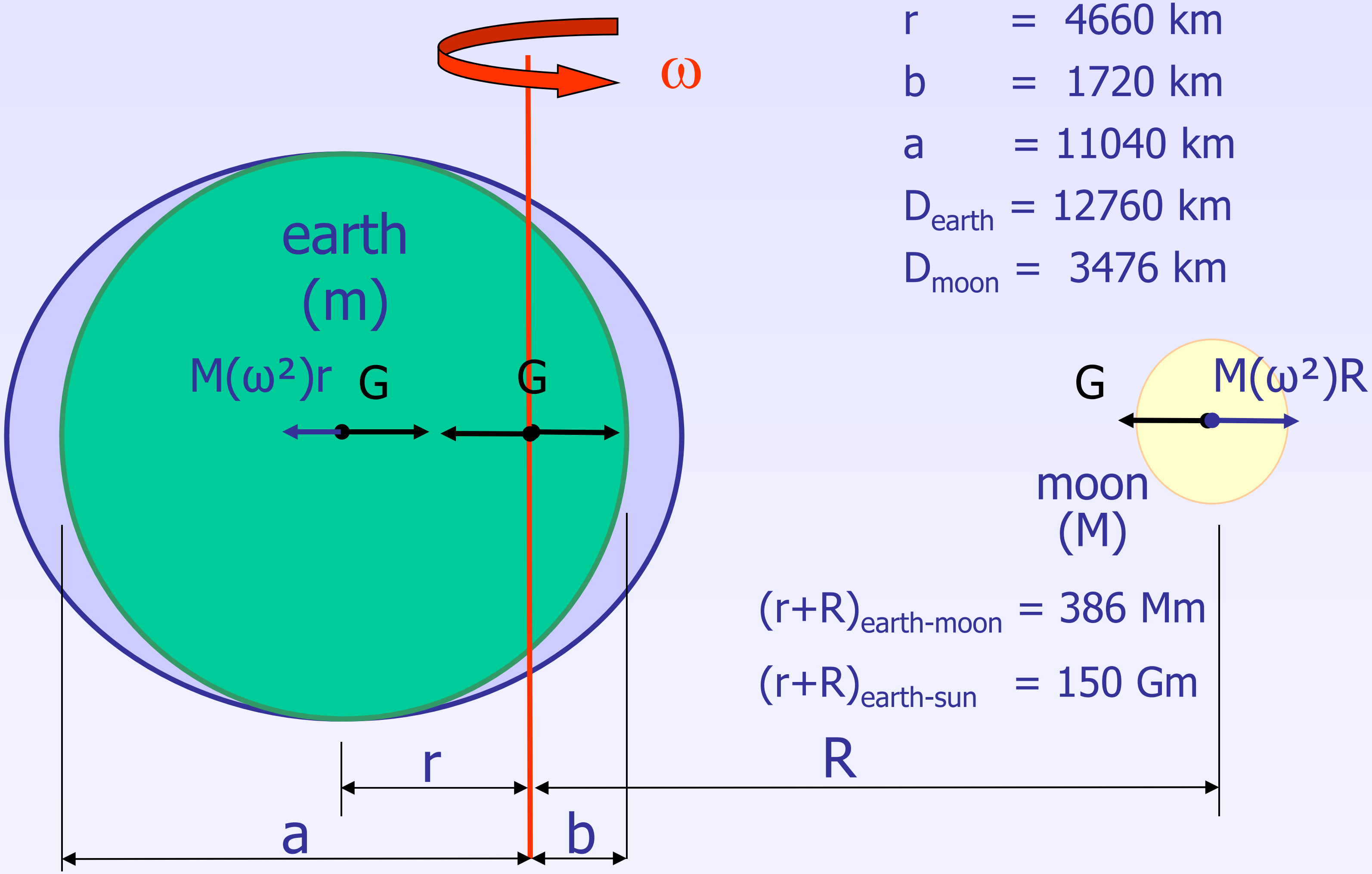
Tides – questions

1. What drives astronomical tides?
2. Why two cycles per day?
3. Why spring tide and neap tide?
4. Why in some places diurnal tides?

Tides

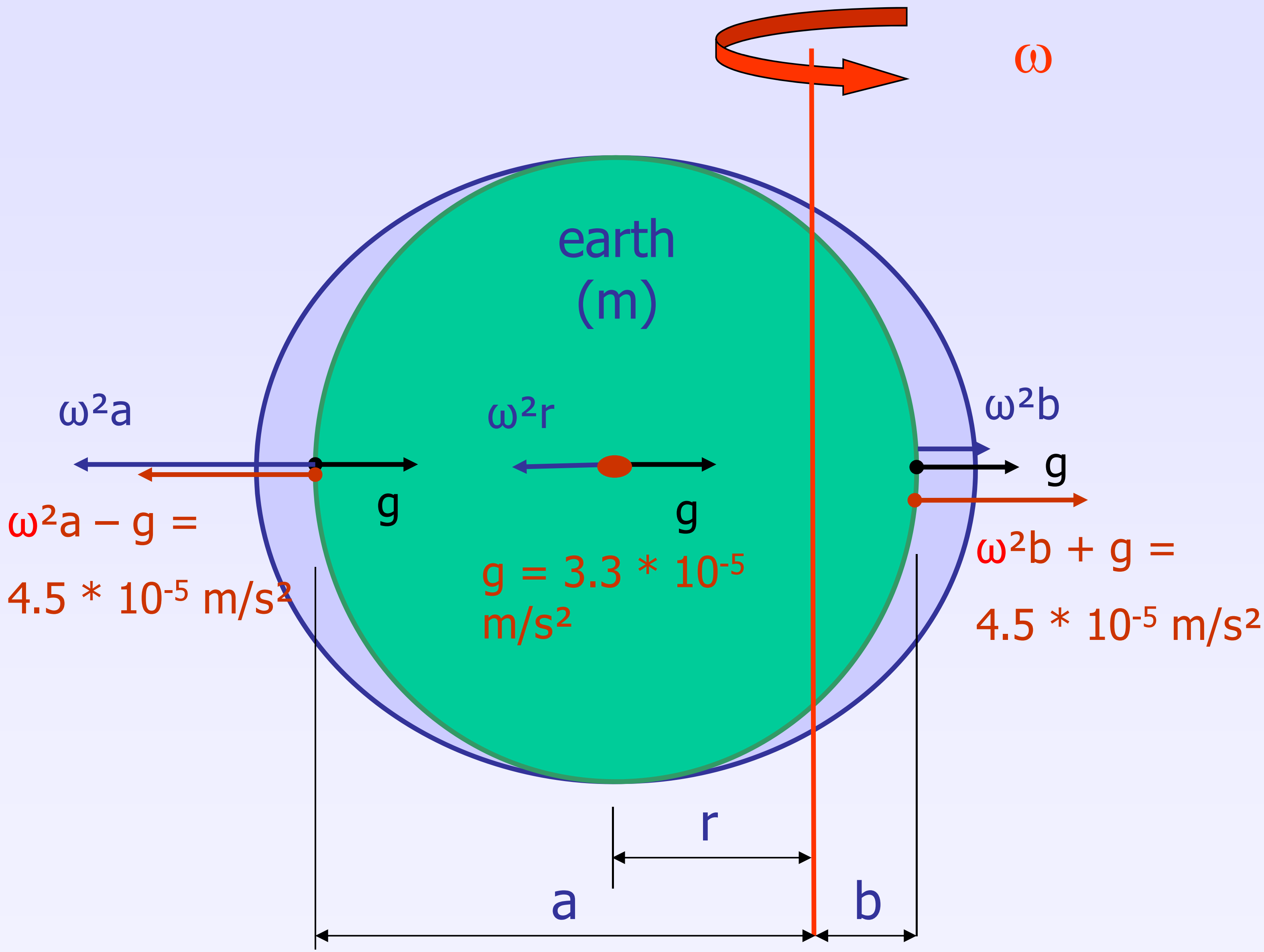
Newton: $G = \gamma \frac{mM}{(r+R)^2} = m \frac{\gamma M}{(r+R)^2} = mg$

$m = 5.97 \times 10^{24}$ kg
$M_{moon} = 7.33 \times 10^{22}$ kg
$M_{son} = 1.96 \times 10^{30}$ kg
r = 4660 km
b = 1720 km
a = 11040 km
D_{earth} = 12760 km
D_{moon} = 3476 km



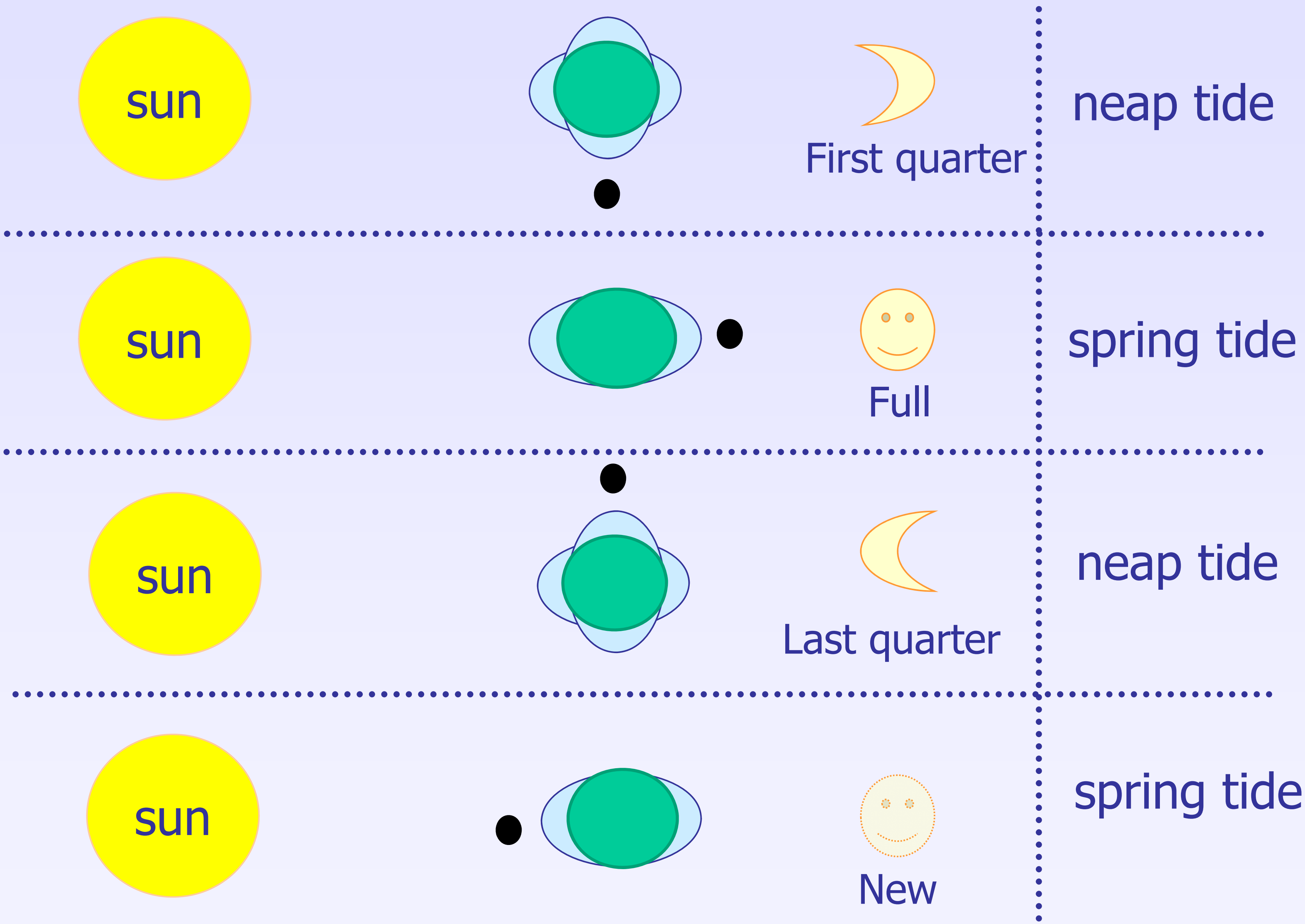
$(r+R)_{earth\text{-}moon}$ = 386 Mm
$(r+R)_{earth\text{-}sun}$ = 150 Gm

Tides - forces



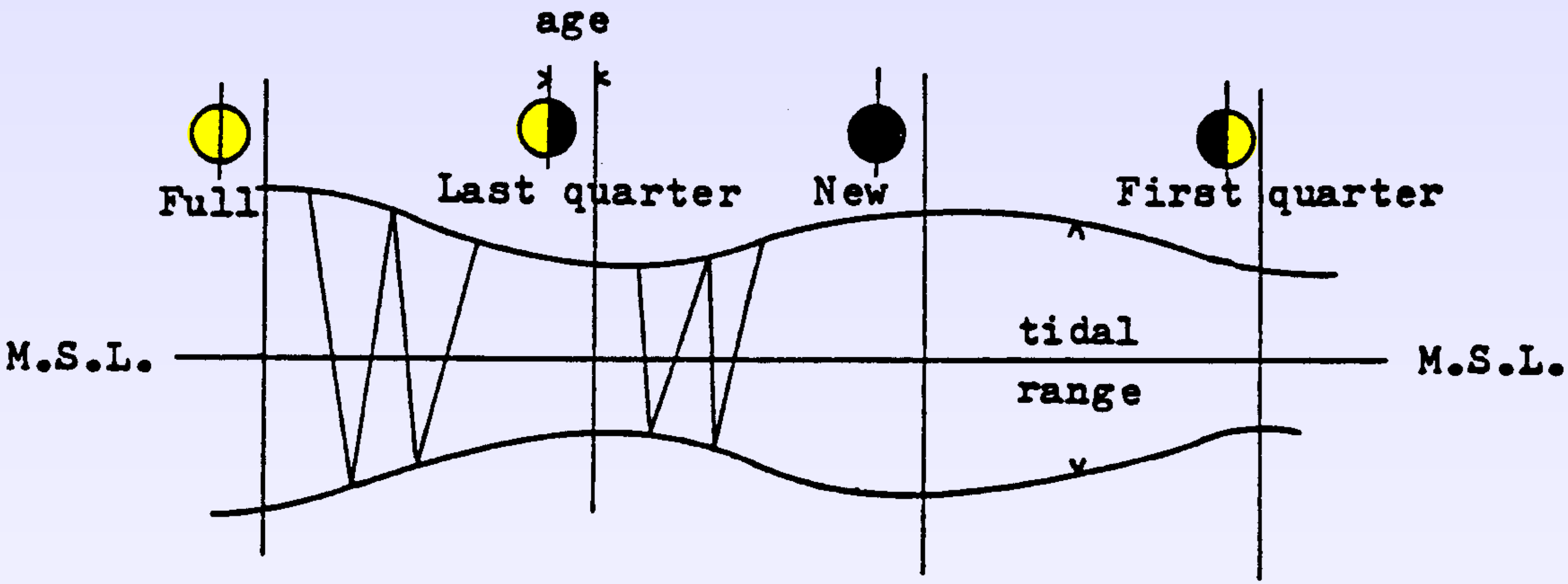
Why Spring Tide and Neap Tide?

Tides - moon phases

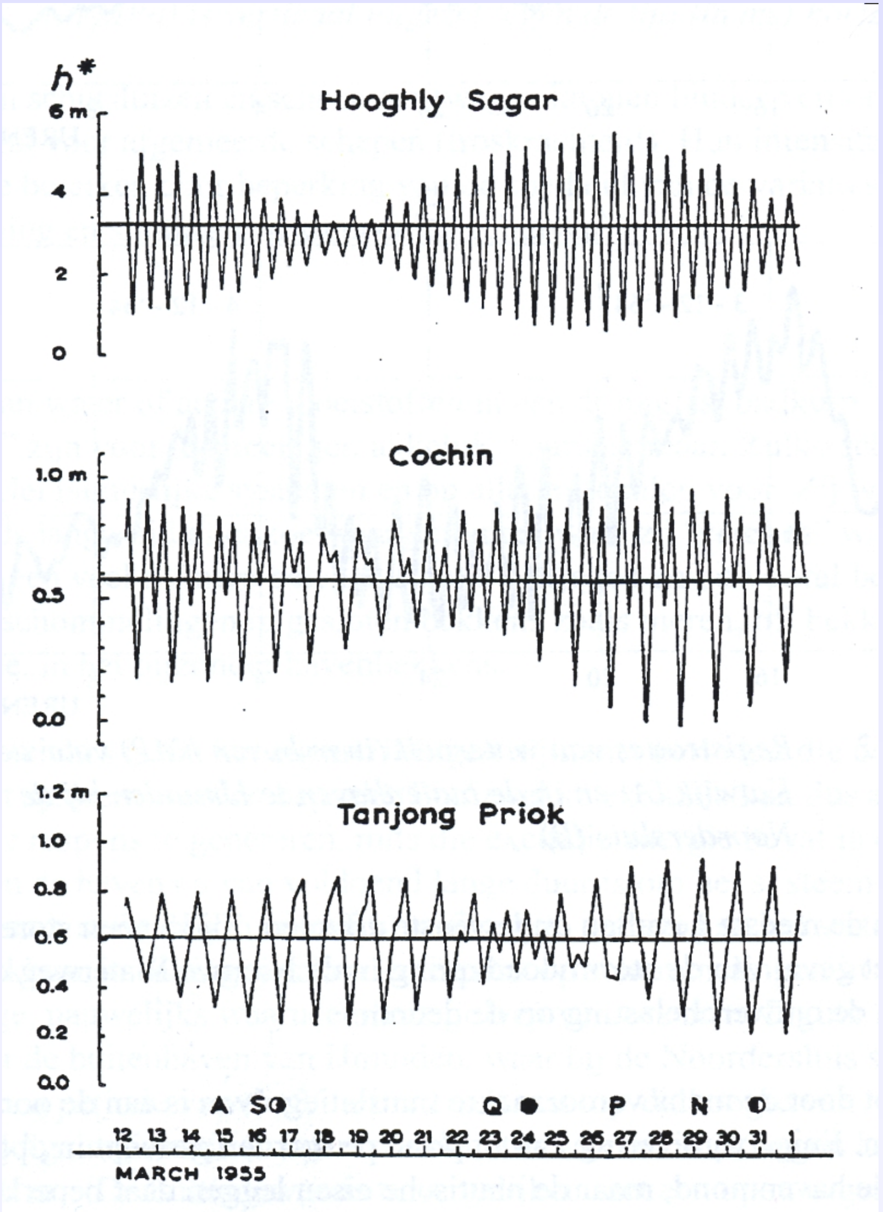


Hydrology of Catchments, Rivers and Delta's

Tides – moon phases



Tides - cycles



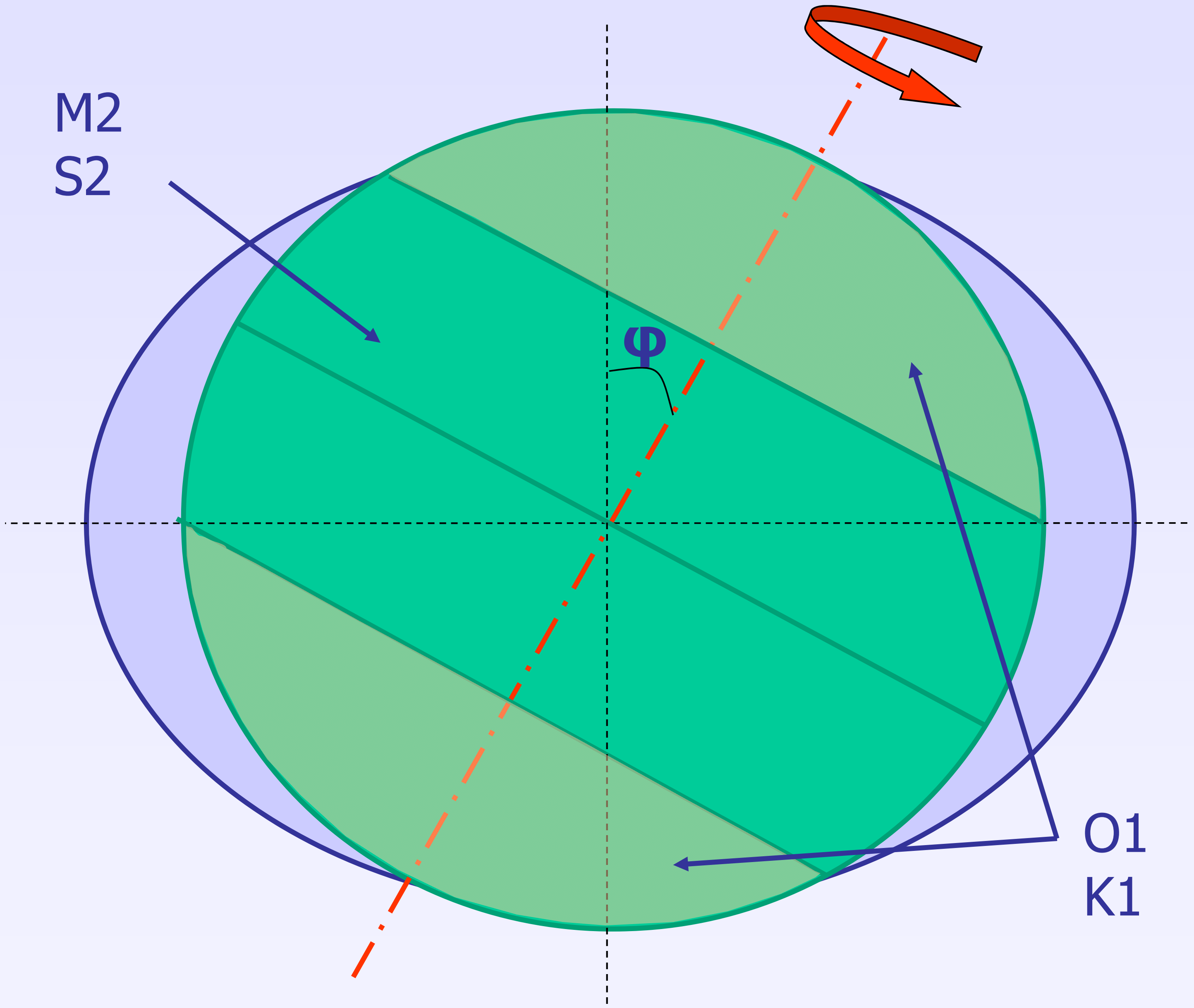
Calcutta

Kerala

Jakarta

Why sometimes Diurnal and sometimes Semi-diurnal Tide?

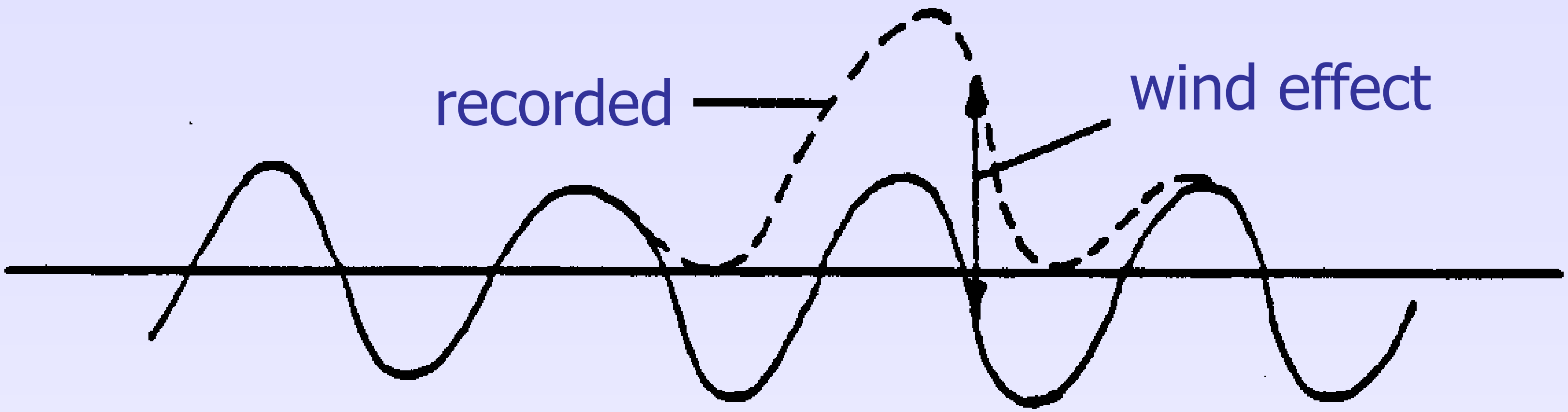
Tides - cycles



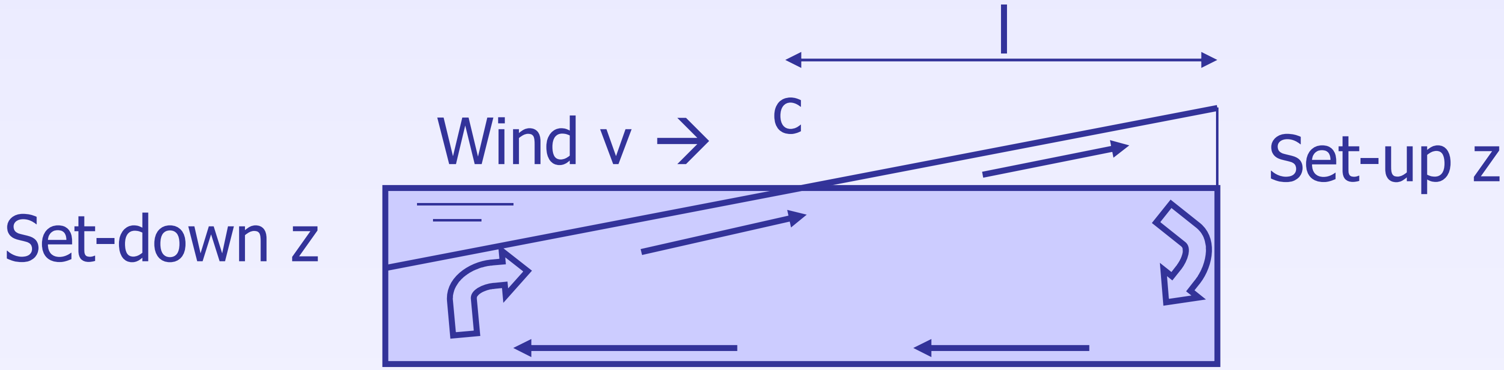
Hydrology of Catchments, Rivers and Delta's

Storm Surges

Storm surges

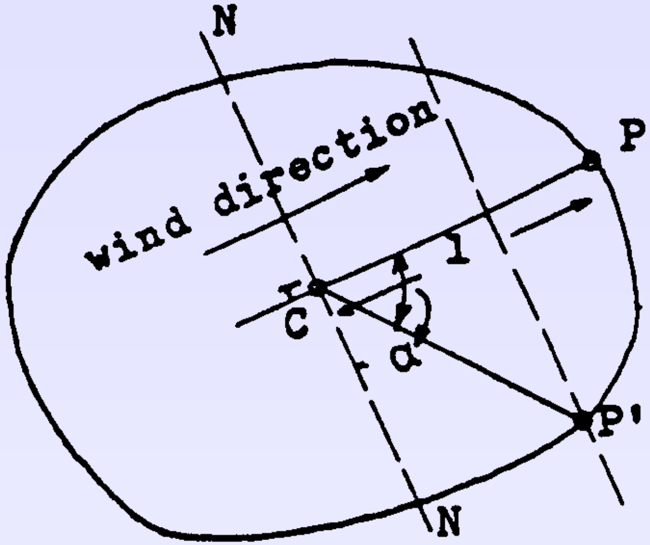


If z << d:



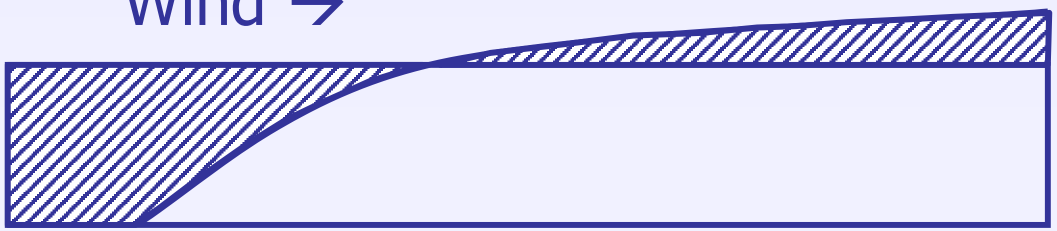
$$z = 3.6 * 10^{-6} \frac{v^2}{gd} * l$$

Storm surges



If z is not << d:

Wind →



Storm surges

After the wind stops,
A standing wave remains which is gradually damped

"Seiche"

Storm surges

How storm surges are generated:

Depressions in the atmosphere:

- Extra-tropical depressions of the temperate zones
- Tropical depressions:
  - cyclones
  - typhoons
  - hurricanes

Other phenomena that can generate abnormally high water levels (Remote effects):

- Differences in barometric pressure
- Tsunamis (Krakatau, 1883; Atjeh, 2004)

Tsunamis

Port (Tsu)

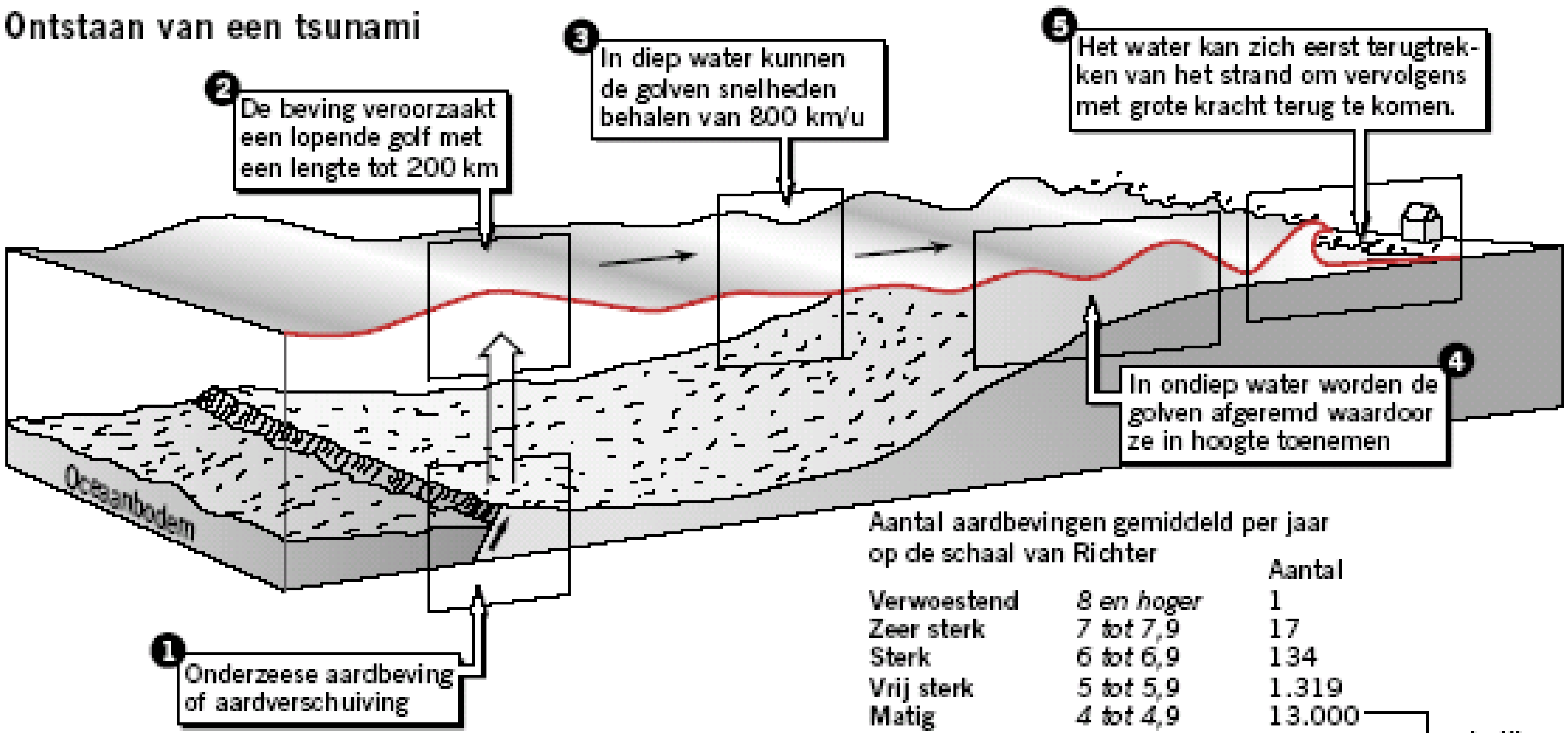
Wave (Nami)

because you
feel the Tsunami only
in the Harbour (Port)


味蔵
宮古店
テレトラック
MIYAKO

Tsunami December 2004

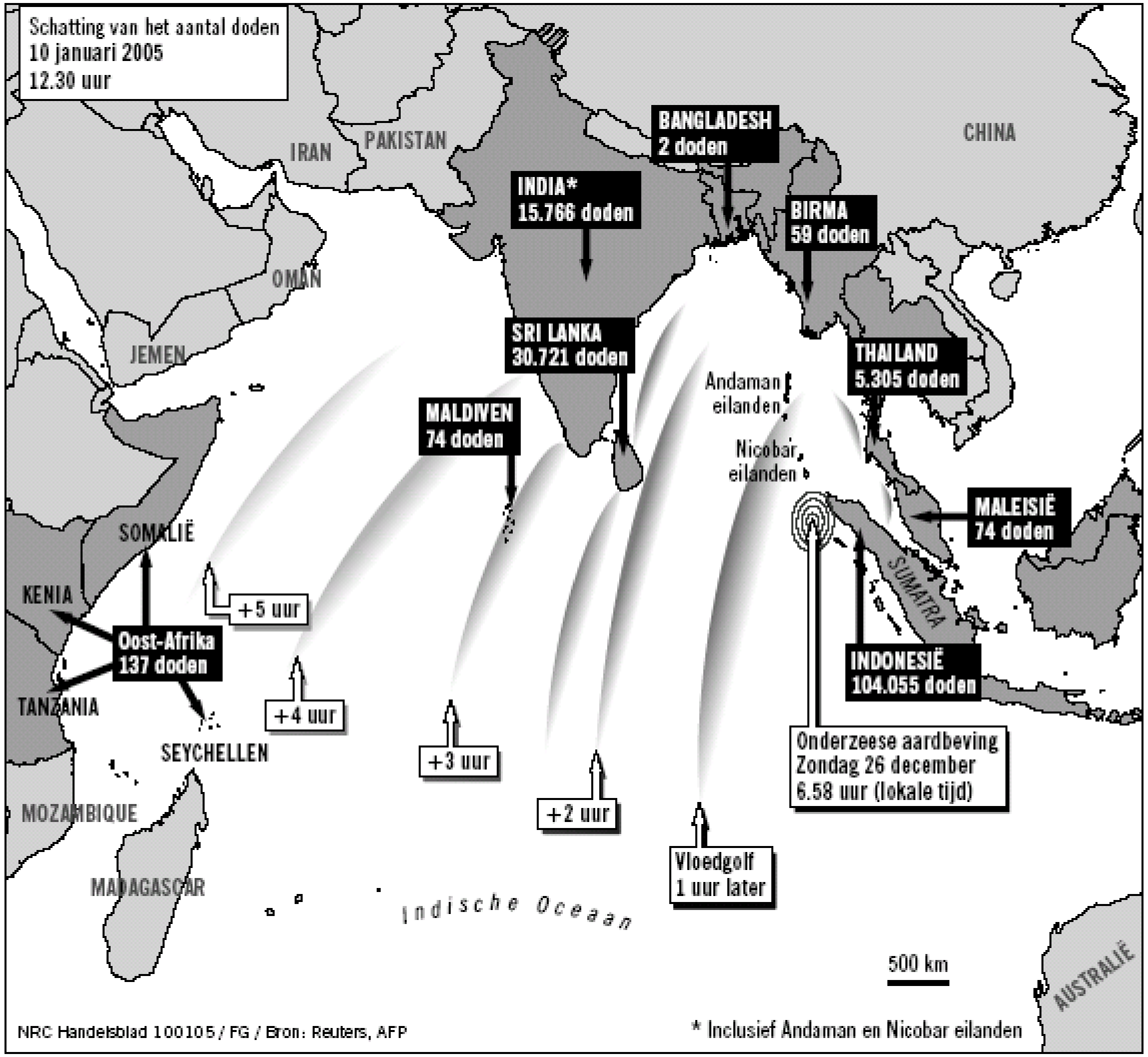
Ontstaan van Tsunami



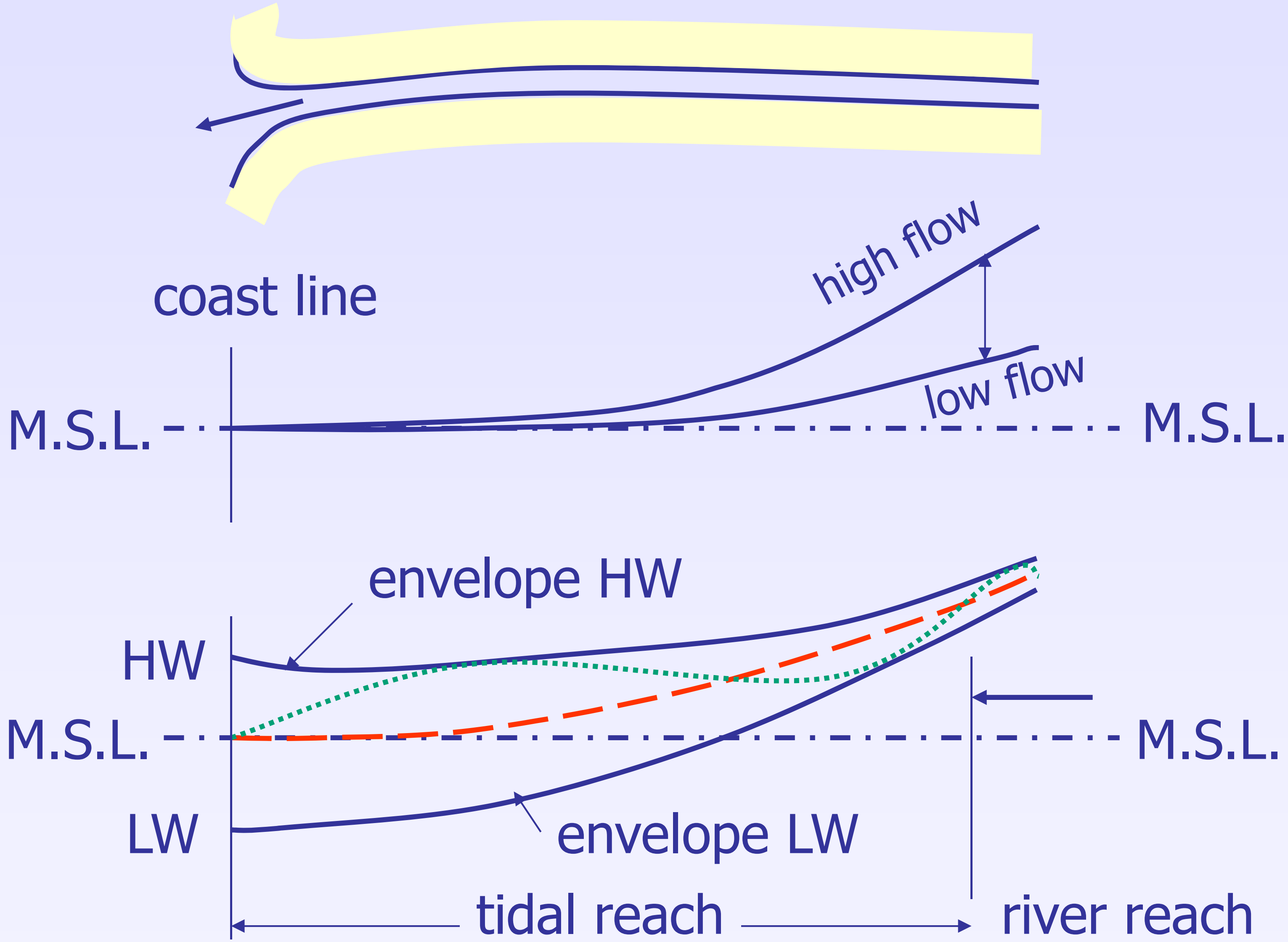
Aantal aardbevingen gemiddeld per jaar op de schaal van Richter

		Aantal	
Verwoestend	*8 en hoger*	1	
Zeer sterk	*7 tot 7,9*	17	
Sterk	*6 tot 6,9*	134	
Vrij sterk	*5 tot 5,9*	1.319	
Matig	*4 tot 4,9*	13.000	schatting
Licht	*3 tot 3,9*	130.000	schatting
Zeer licht	*2 tot 2,9*	1.300.000	schatting

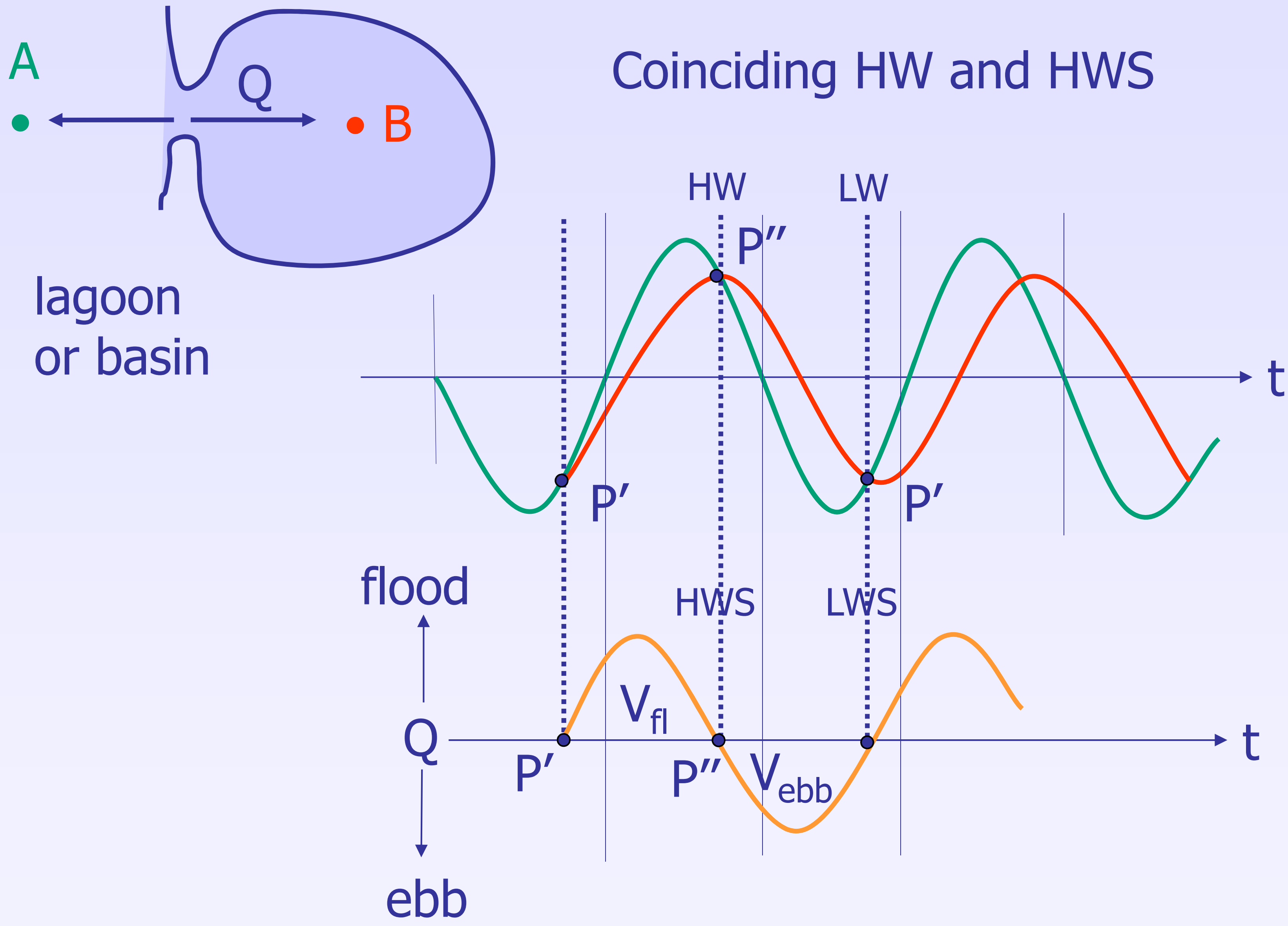
Impact of Tsunami



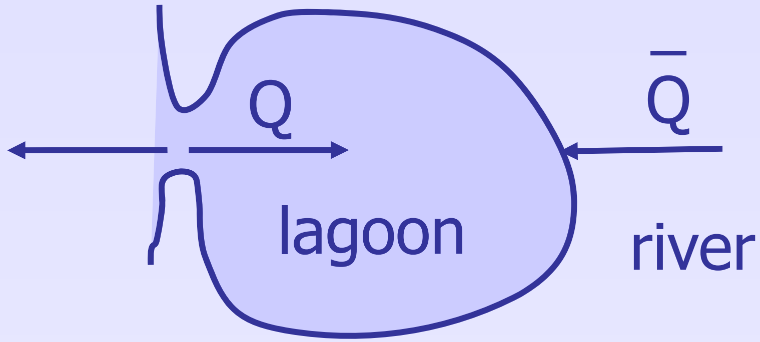
Propagation of astronomical tides



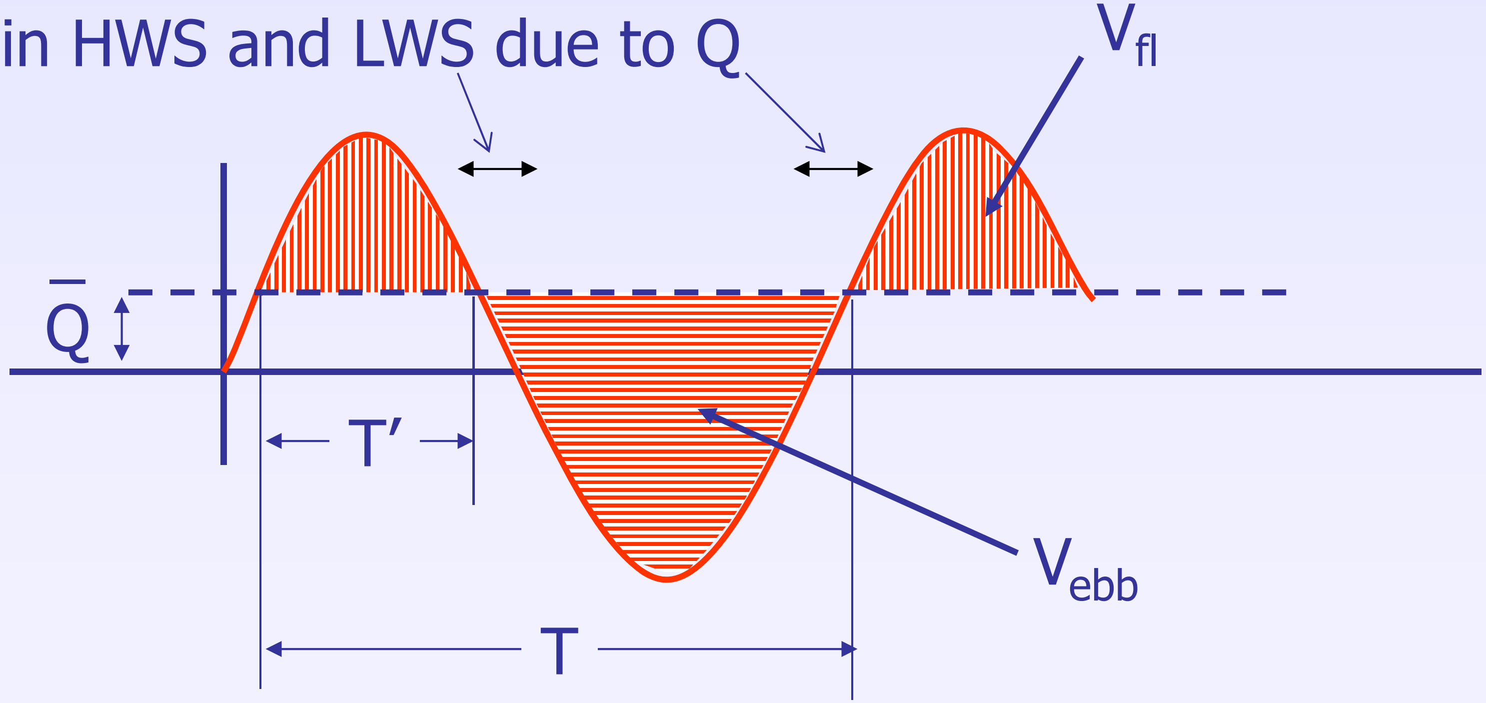
Propagation of astronomical tides



Propagation of astronomical tides



$$V_{ebb} - V_{fl} = \bar{Q} * T$$



Propagation of astronomical tides

Flood number or Canter-Cremers number:

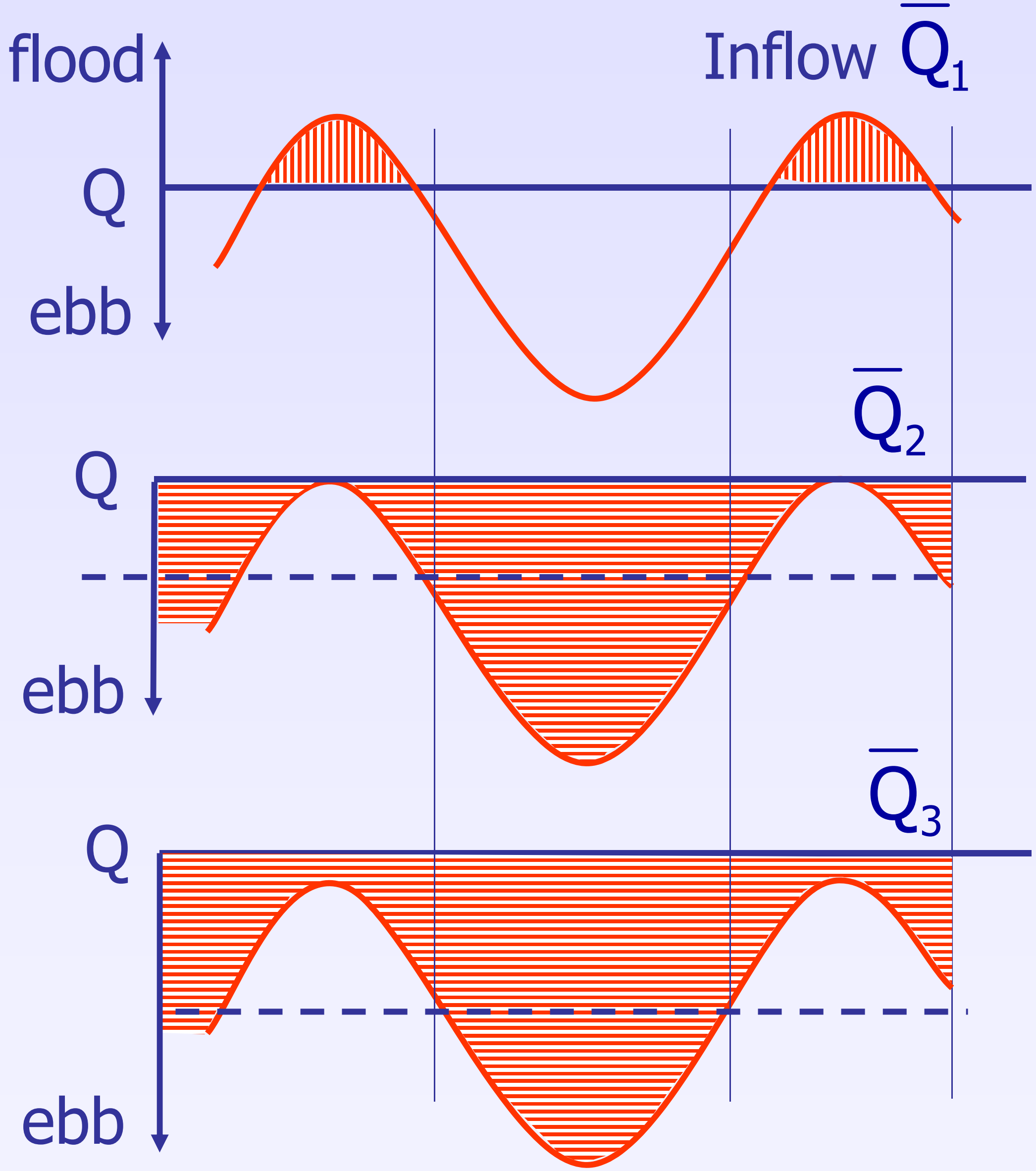
$$N = \frac{\text{volume of upland discharge during tidal period}}{\text{volume of the flood}}$$

$$N = \frac{QT}{V_{fl}}$$

$N = 0$: no river flow

$N \rightarrow \infty$: no tidal influence

Propagation of astronomical tides



Alternating:
2 slacks per
tidal period

1 slacks per
tidal period

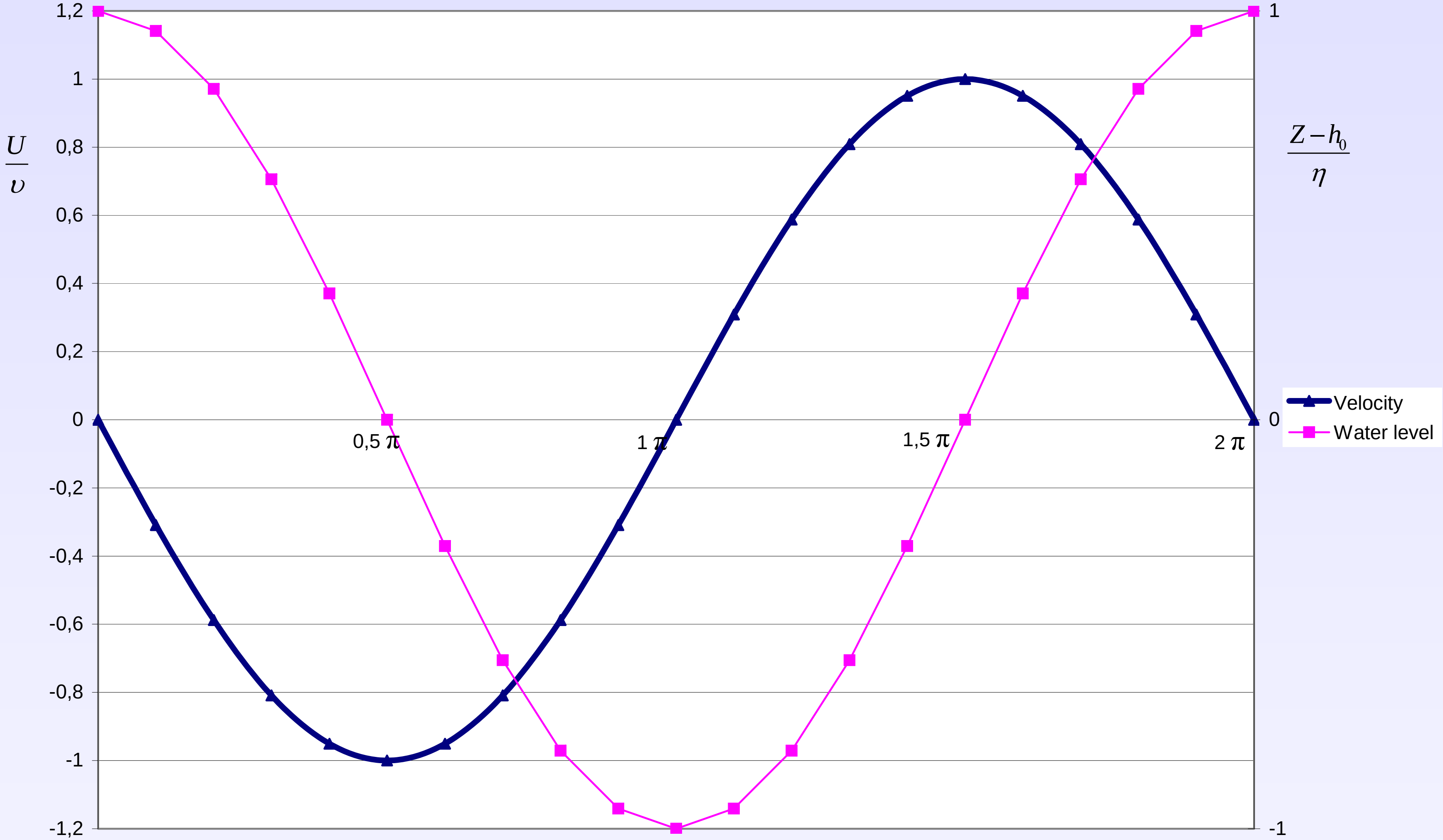
Unidirectional
no slacks

Propagation of astronomical tides

Three types of waves may be distinguished:

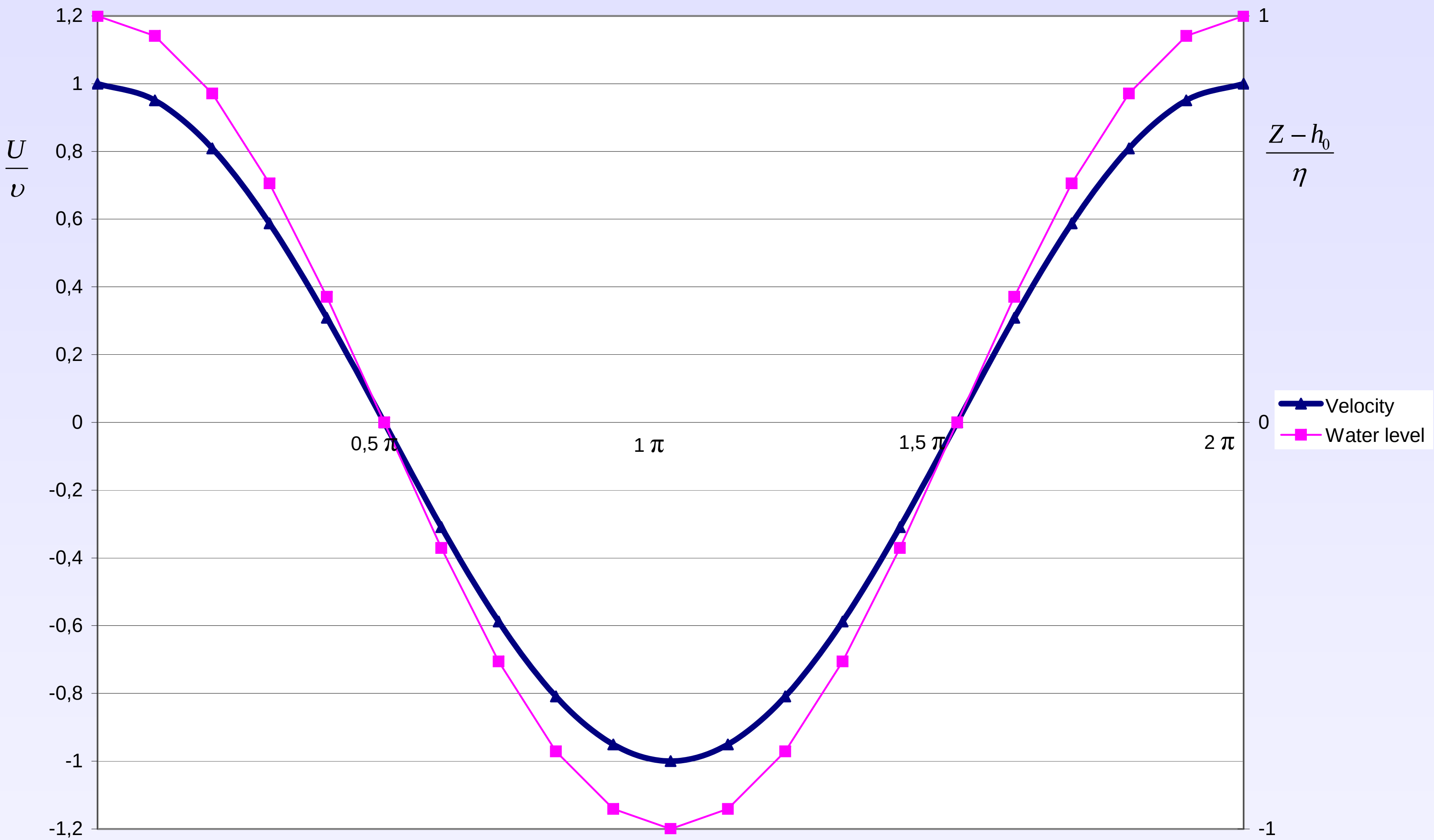
- standing wave (basin, harbour, lagoon)
- progressive wave (river, canal)
- wave of mixed type (natural / alluvial estuary)

Propagation of astronomical tides



Standing wave

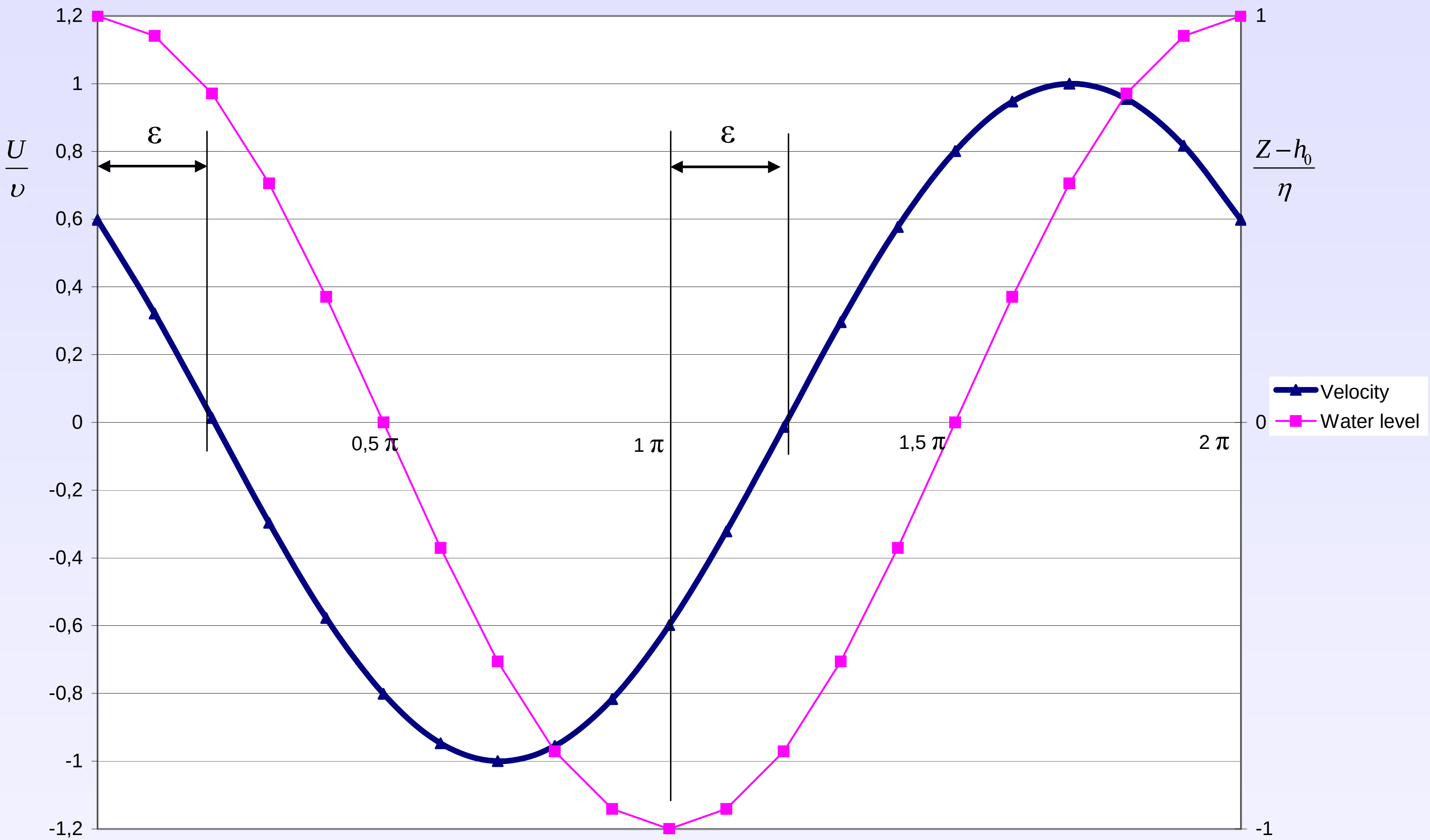
Propagation of astronomical tides



Progressive wave

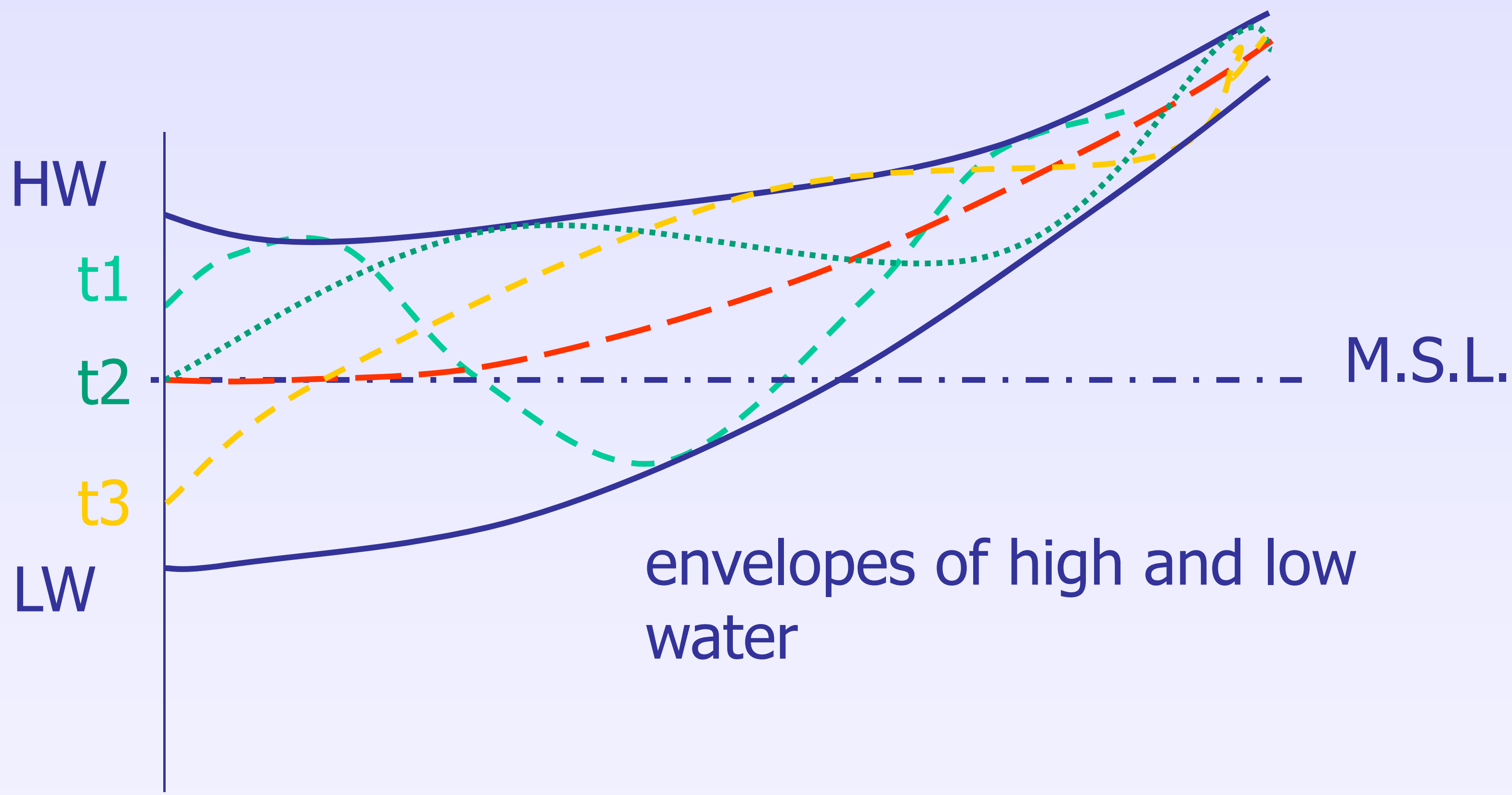
Hydrology of Catchments, Rivers and Delta's

Propagation of astronomical tides



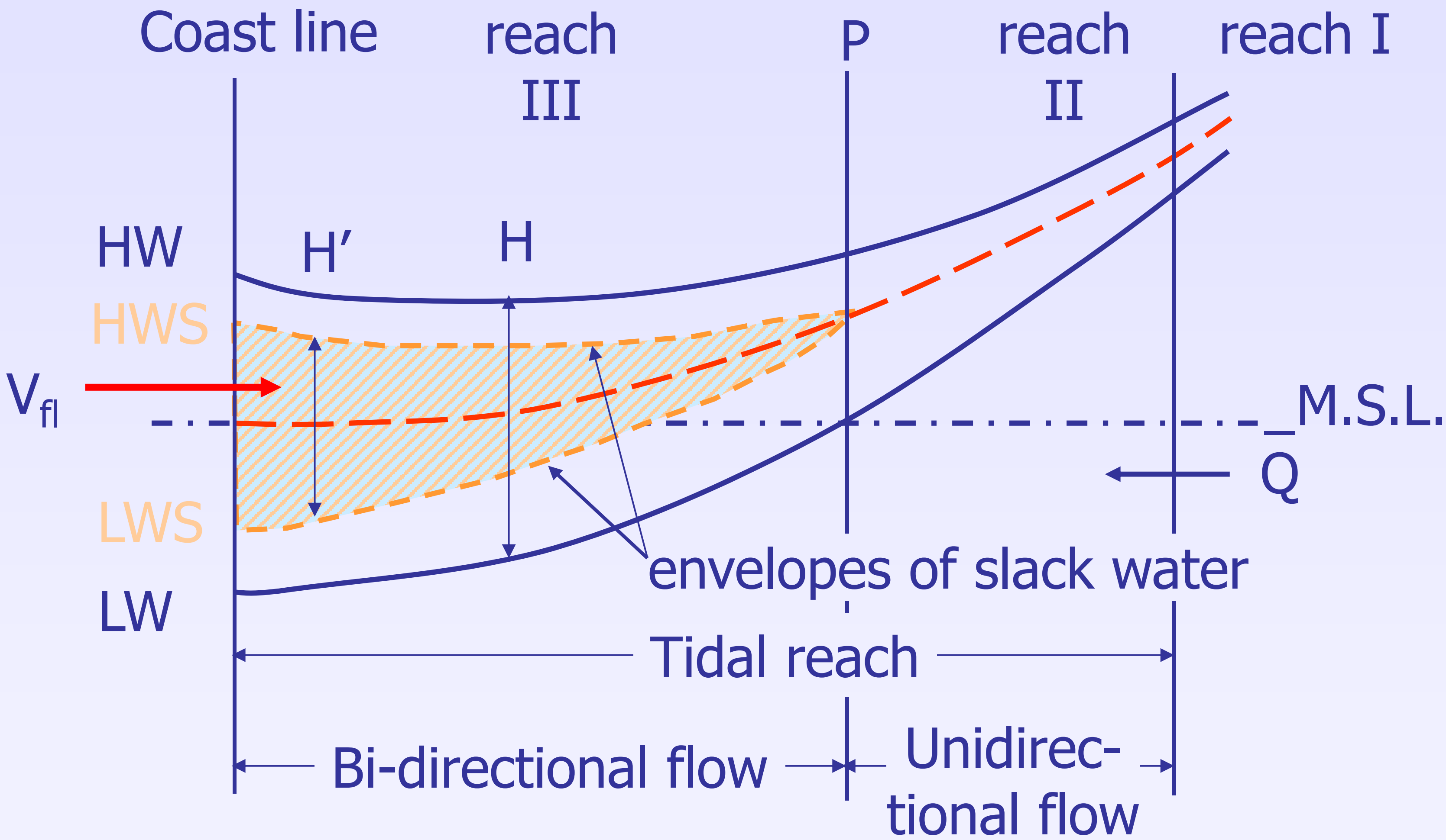
Wave of mixed type

Propagation of astronomical tides

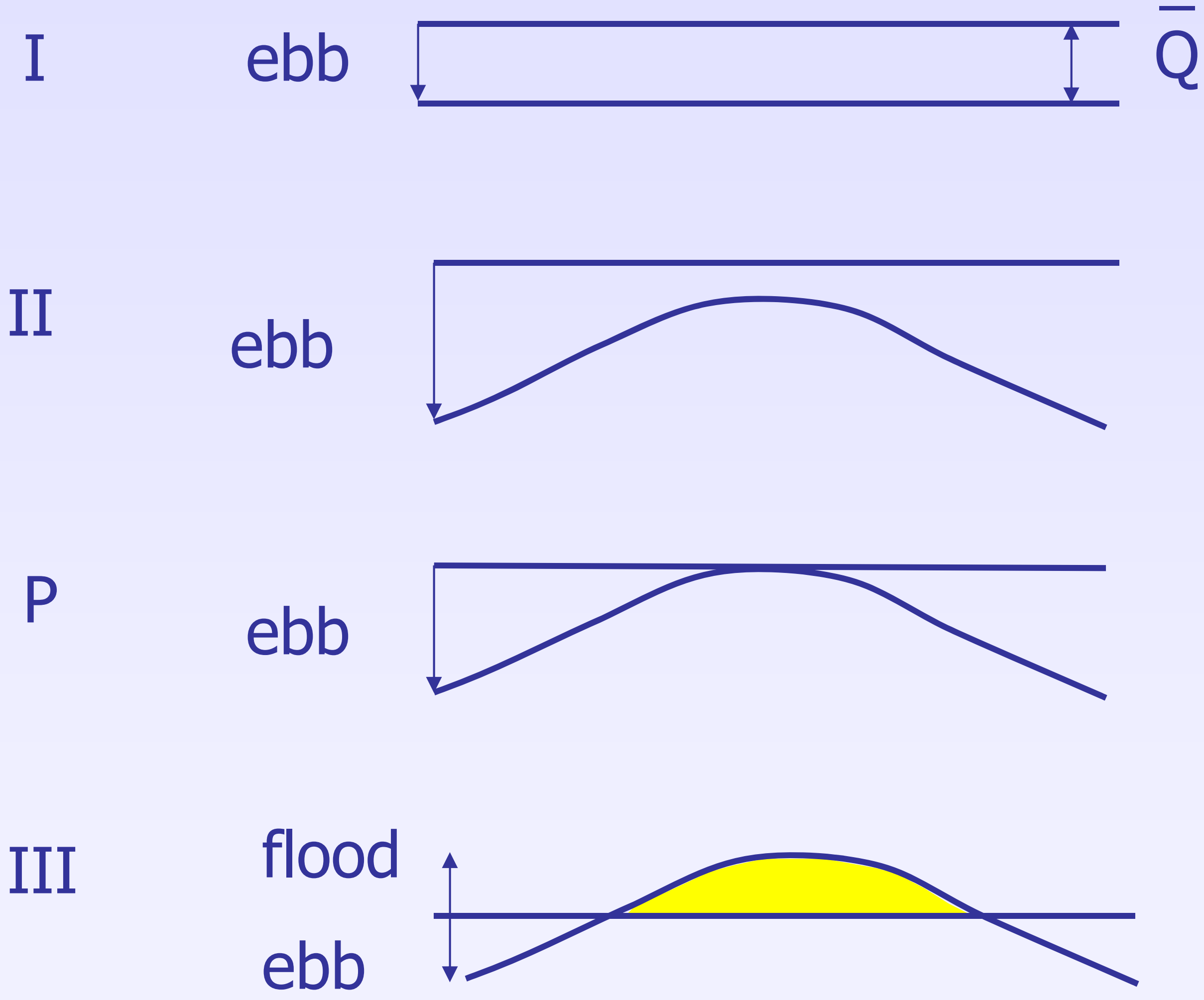


Hydrology of Catchments, Rivers and Delta's

Propagation of astronomical tides



Propagation of astronomical tides



Propagation of astronomical tides

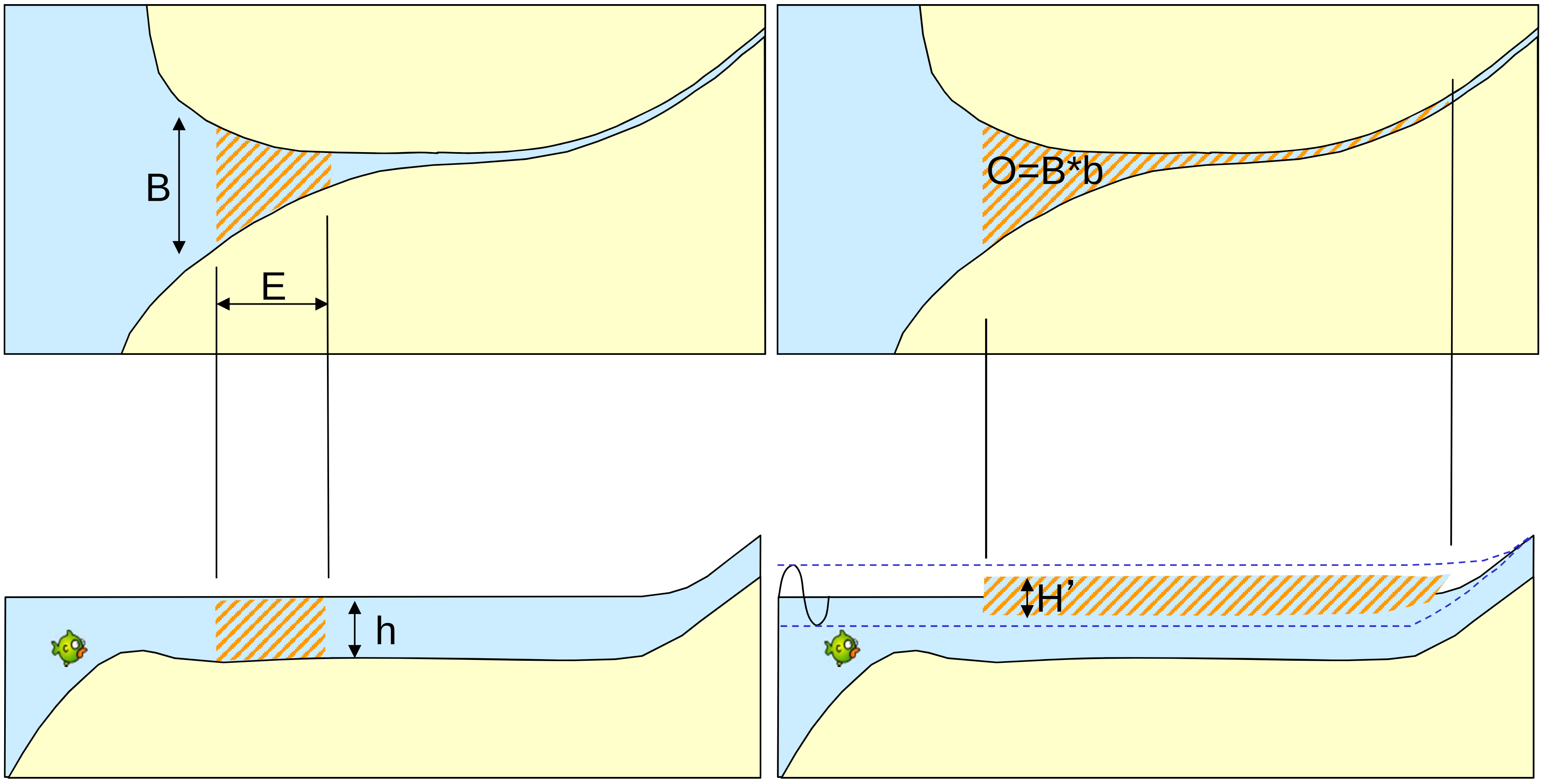
Two methods exist for the determination of V_{fl} :

- From integration of the discharge over the time between LWS and HWS

$$\int_{LWS}^{HWS} Q \, dt = E \, A$$

- From integration of the water levels between HWS and LWS over the area

$$\int_{x}^{\infty} H' B \, \mathrm{d}x = \frac{HBb \cos \varepsilon}{1 - b / \delta}$$



a) b)

Propagation of astronomical tides

$$V_{fl} = \int_{LWS}^{HWS} Q \; dt = E\,A \;\; = \int_{x}^{\infty} H' \, B \; dx = \frac{H\,B\,b\cos\varepsilon}{1 - b/\delta}$$

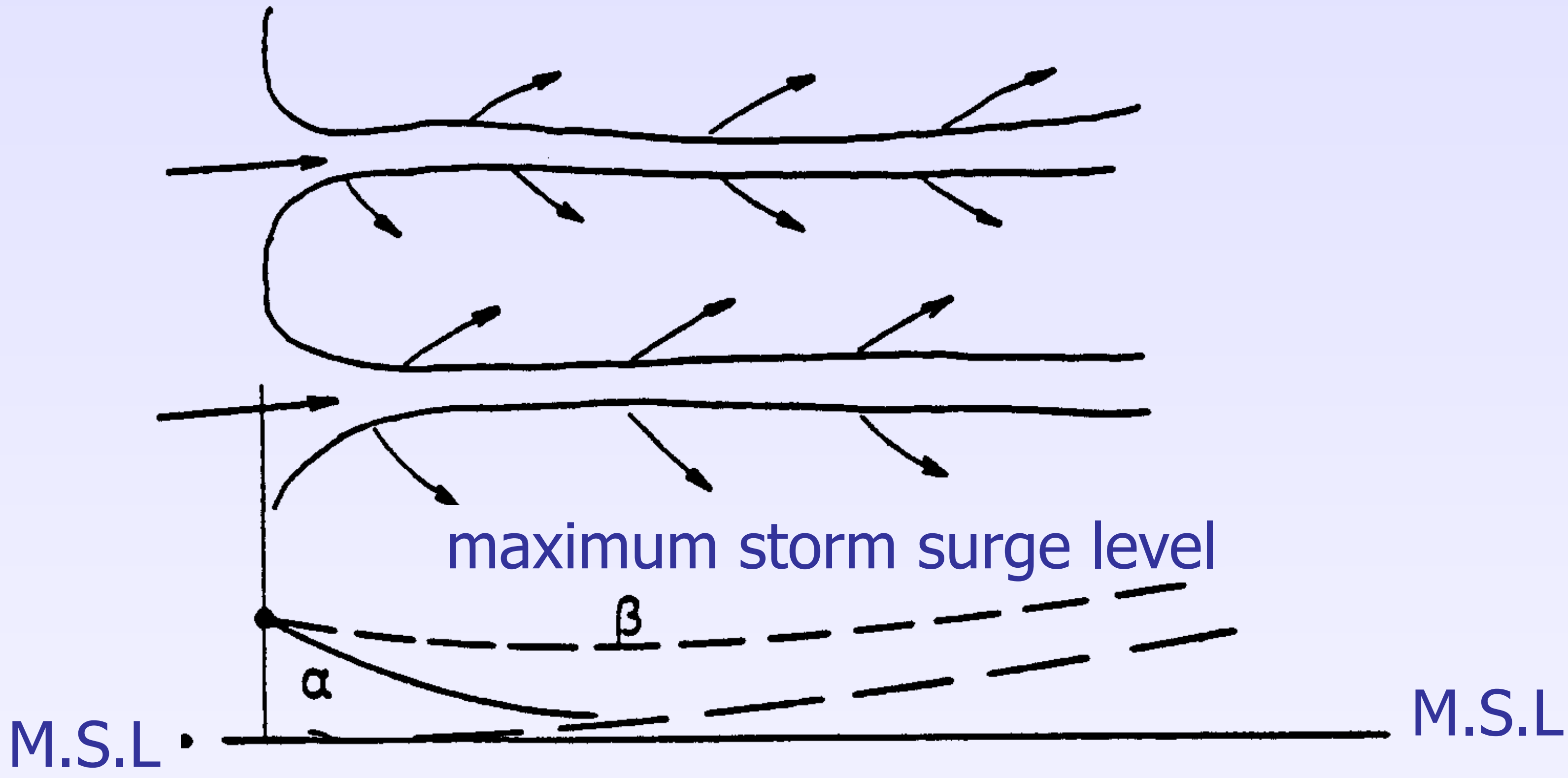
$$E\,h = \frac{H\,b\cos\varepsilon}{1 - b/\delta}$$

$$\boxed{\frac{H}{E} = \frac{h_0}{b}\,\frac{\left(1 - b/\delta\right)}{\cos\varepsilon}}$$

Equation Name	Newly derived equation	"Classical" equation
Phase Lag equation	$\tan\varepsilon = \frac{\omega b}{c(1-\delta b)} = \frac{b}{\lambda}\frac{2\pi}{(1-\delta b)}$	
Geometry-Tide relation	$\frac{H}{E} = \frac{\eta\omega}{\upsilon} = \frac{\bar{h}}{r_S b}\frac{(1-\delta b)}{\cos(\varepsilon)}$	$\frac{\eta\omega}{\upsilon} = \frac{\bar{h}}{r_S b}$
Scaling equation	$r_S\frac{\eta}{\bar{h}} = \frac{\upsilon}{c}\frac{1}{\sin(\varepsilon)}$	$r_S\frac{\eta}{\bar{h}} = \frac{\upsilon}{c}$
Damping equation Green's eq. (1937)	$\frac{\mathrm{d}H}{\mathrm{d}x}\left(1+\frac{g\eta}{c\upsilon\sin\varepsilon}\right) = H\left(\frac{1}{b} - f'\frac{\upsilon\sin\varepsilon}{\bar{h}c}\right)$	$\frac{\mathrm{d}H}{\mathrm{d}x} = H\frac{1}{2b}$
Celerity equation	$c^2 = \frac{1}{r_S}gh/\left[1-\frac{\sin 2\varepsilon}{2(1+\alpha)}\left(\frac{c}{\omega b}-\frac{R'}{\omega}\right)\right]$	$c^2 = \frac{1}{r_S}gh$
Mazure's equation (1837)	$c = \frac{\omega g h \eta}{f\upsilon^2}\cos\varepsilon$	$c = \frac{\omega g h \eta}{f\upsilon^2}$

Equation Name	Assumption made for "Classical" equation	"Classical" equation
Phase Lag equation	either ε=0 or ε=π/2	
Geometry-Tide relation	δ=0 and ε=0	$\frac{\eta\omega}{\upsilon} = \frac{\bar{h}}{r_S b}$
Scaling equation	ε=π/2	$r_S \frac{\eta}{\bar{h}} = \frac{\upsilon}{c}$
Damping equation	ε=π/2 or π/4 and *f'*=0	$\frac{\mathrm{d}H}{\mathrm{d}x} = H \frac{1}{2b}$
Celerity equation	δ=0 or ε=0	$c^2 = \frac{1}{r_S} gh$
Mazure's equation	ε=0	$c = \frac{\omega g h \eta}{f \upsilon^2}$

Propagation of storm surges



a: undiked or short duration
b: diked or long duration

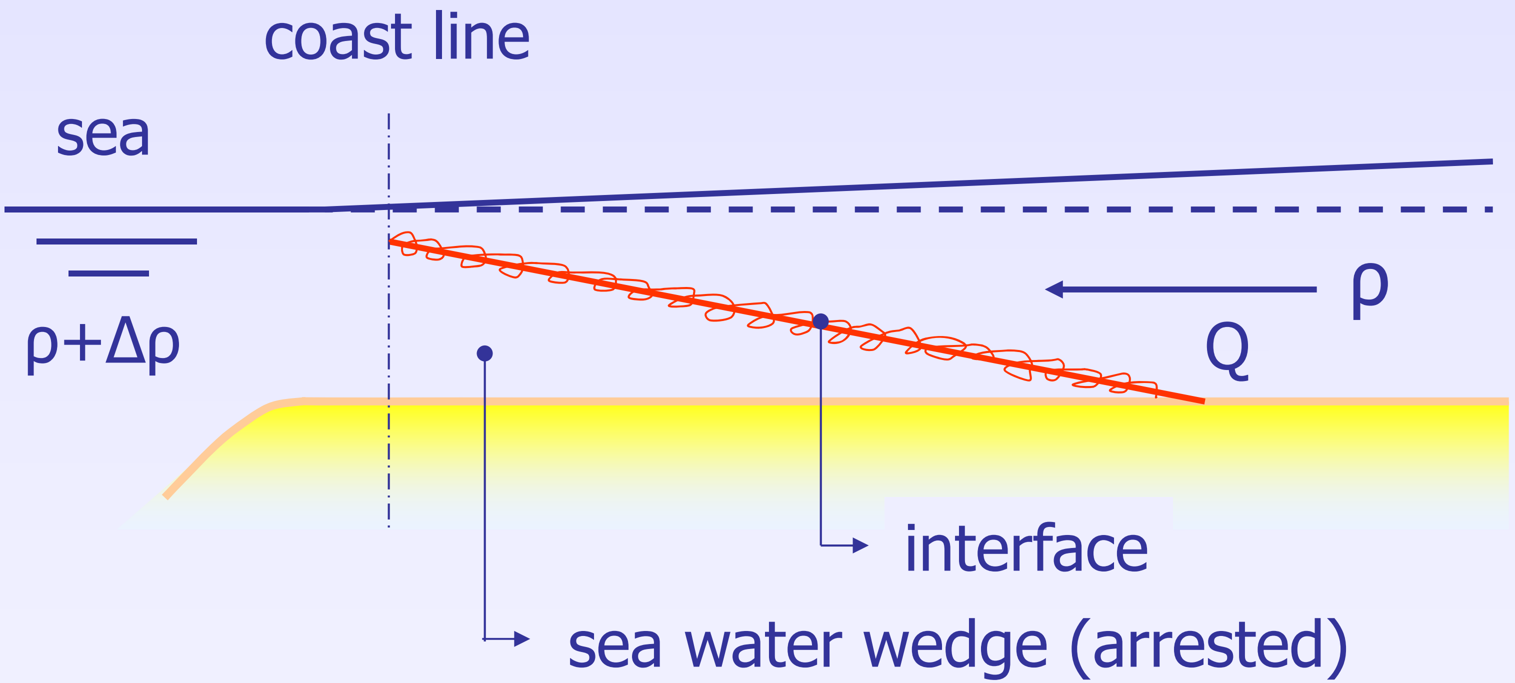
Salt water intrusion

The saline water originates from various sources:

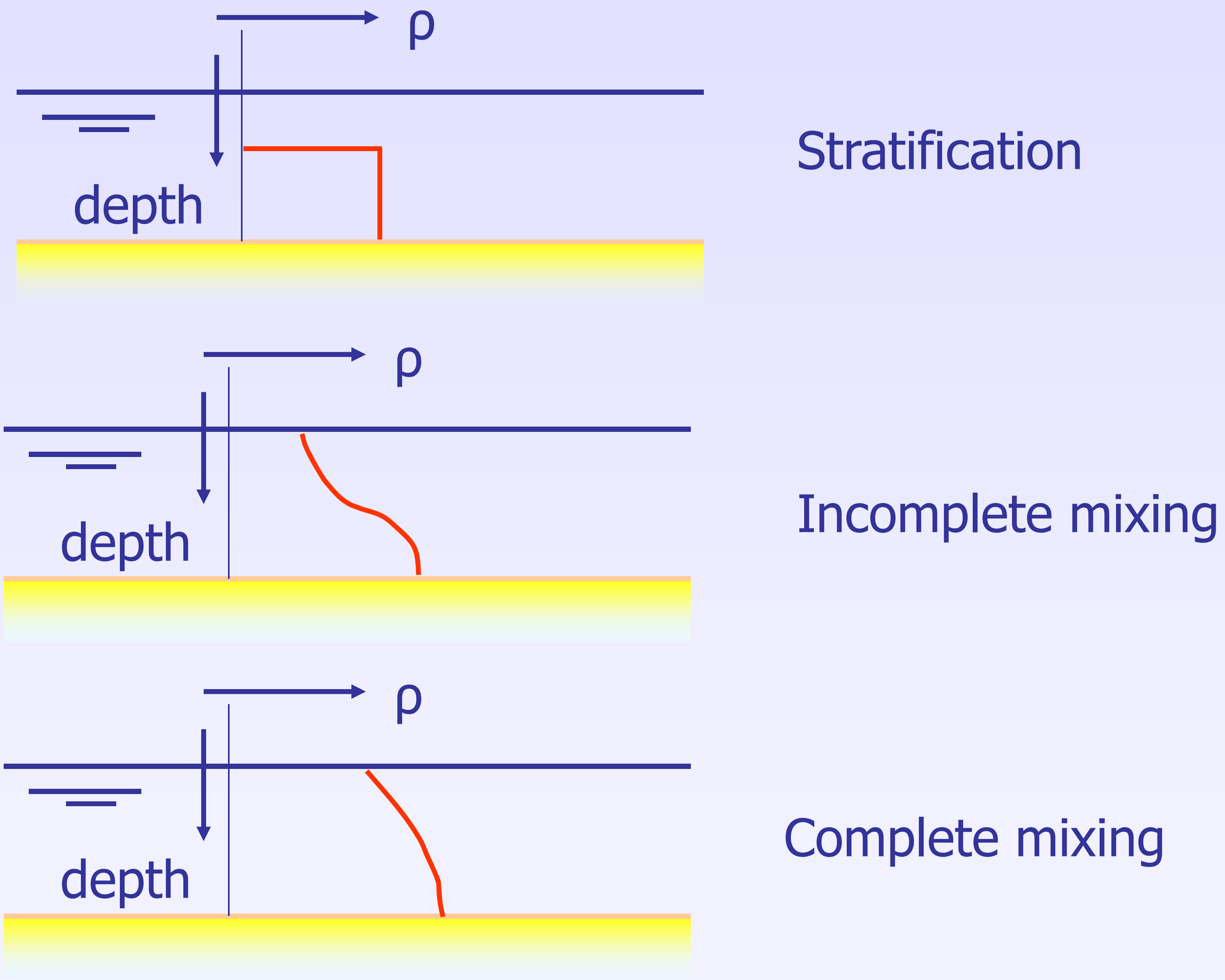
1. Intrusion of sea water into open estuaries.
2. Seepage of brackish or saline ground water; the saline water may originate from old marine deposits.
3. Sea water entering through locks and sluices by leakage and navigation
4. The salt load of a river (natural salinity and brackish effluents from agricultural drainage and industrial wastes).
5. The salt contained in rain water and the saline spray in coastal regions (usually a minor amount).
6. Salinisation due to saline groundwater reaching the surface through irrigation (Iraq) or land clearing (Australia)

Sea water intrusion into open estuaries

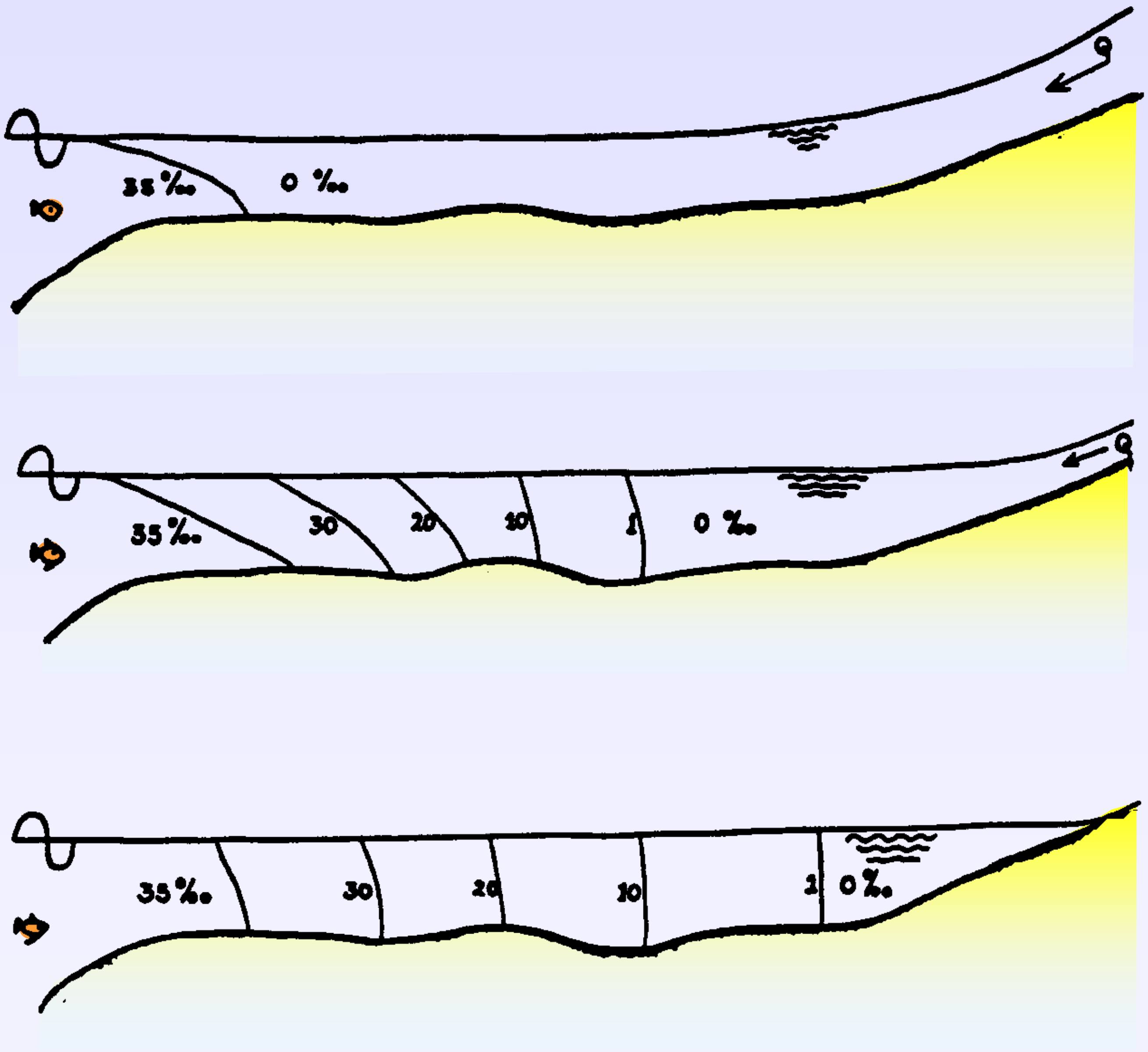
Stratified estuary:



Sea water intrusion into open estuaries



Sea water intrusion into open estuaries



Hydrology of Catchments, Rivers and Delta's

Sea water intrusion into open estuaries

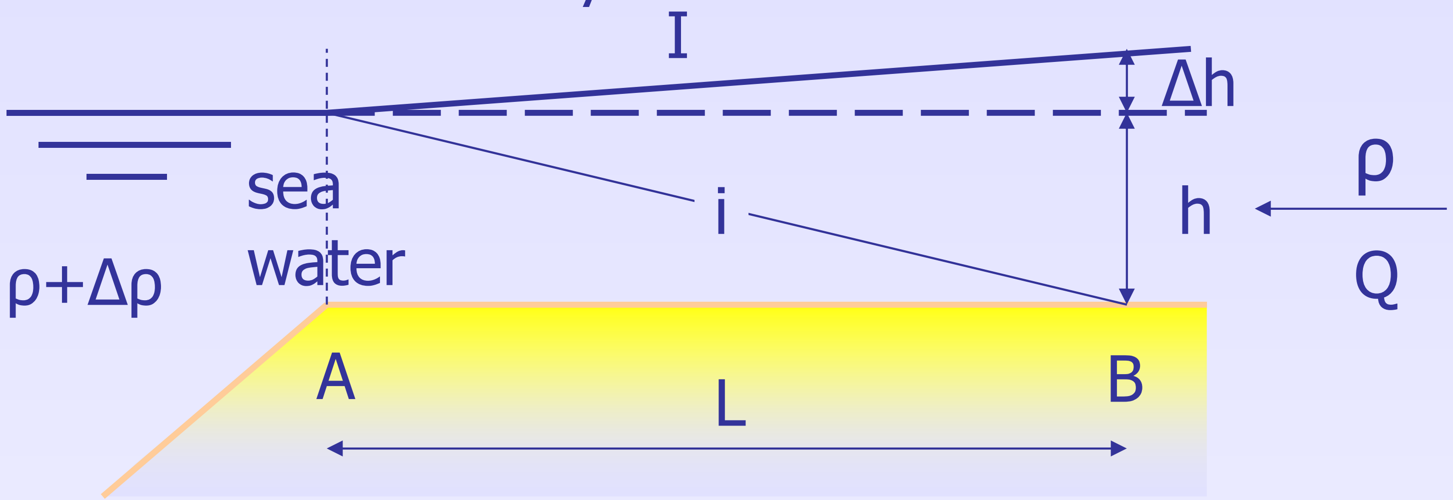
Degree of mixing depends on the flood number:

$$\text{Canter-Cremers number} = N = \frac{QT}{V_{fl}}$$

$N \geq 1{,}0$:	estuary is stratified
$0{,}1 < N < 1{,}0$:	estuary is partly mixed
$0 < N < 0{,}1$:	estuary is well mixed

Balance of forces

Mixed or Stratified estuary:

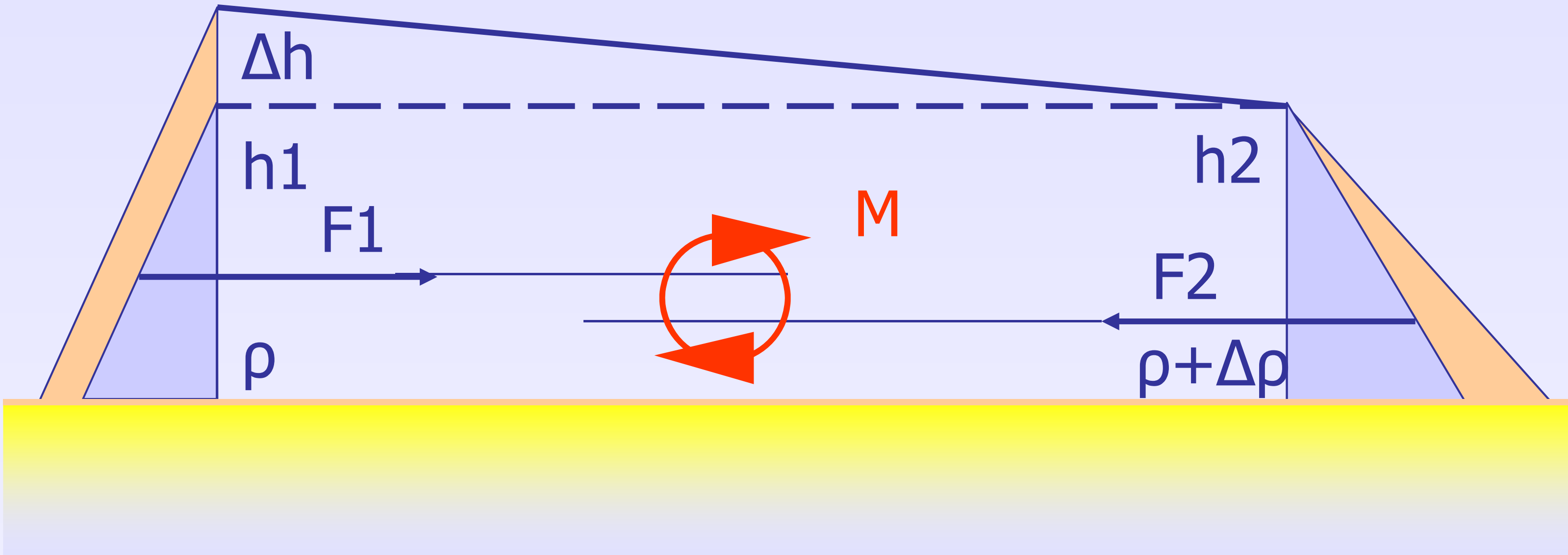


$$\frac{1}{2} g h^2 (\rho + \Delta\rho) = \frac{1}{2} g (h + \Delta h)^2 \rho$$

$$\Delta h = \frac{\Delta\rho}{2\rho} h \quad \text{and} \quad I = \frac{\Delta h}{L} = \frac{\Delta\rho}{2\rho}\frac{h}{L} = \frac{\Delta\rho}{2\rho} i$$

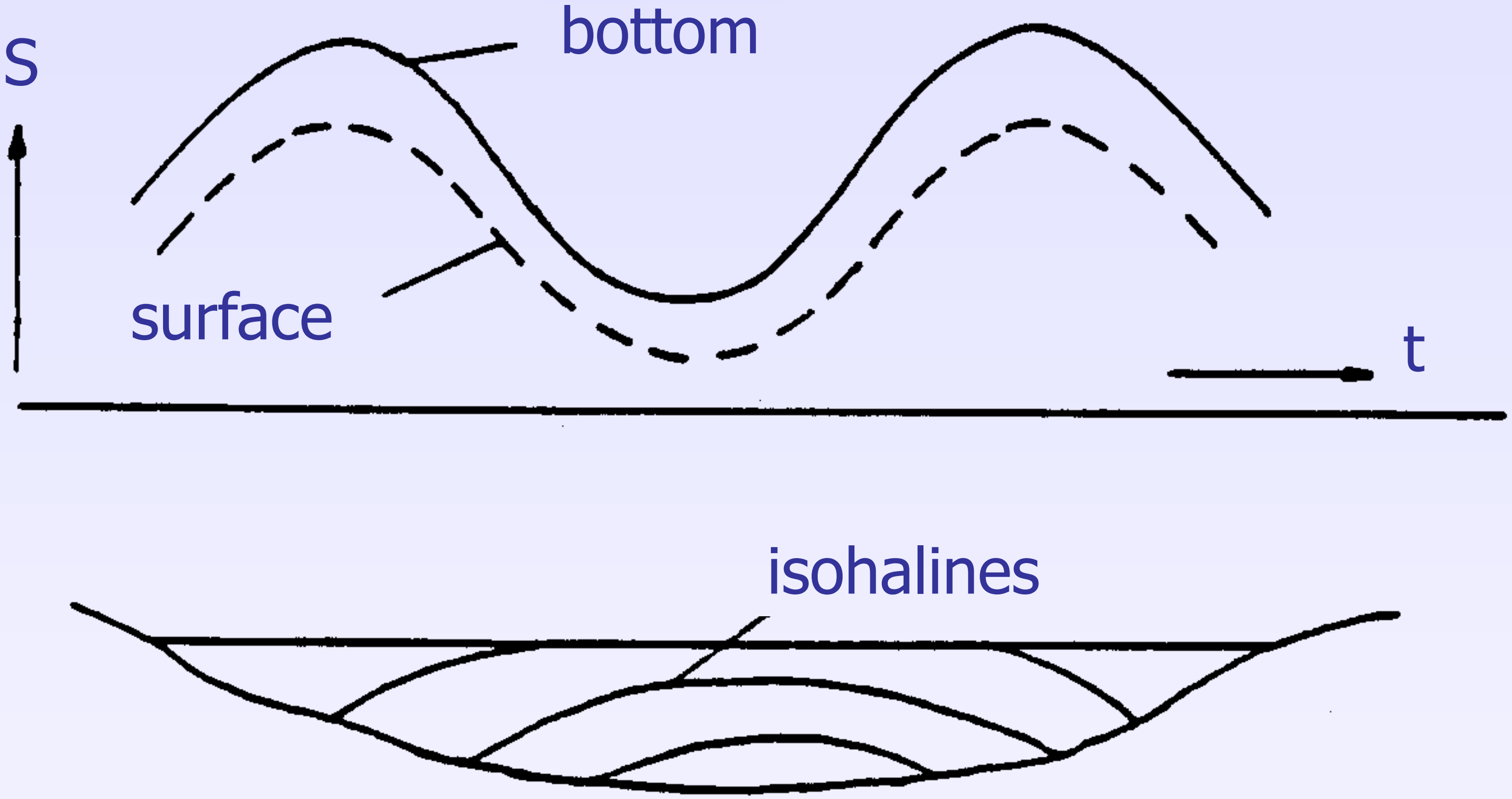
Balance of forces

Mixed or Stratified estuary:



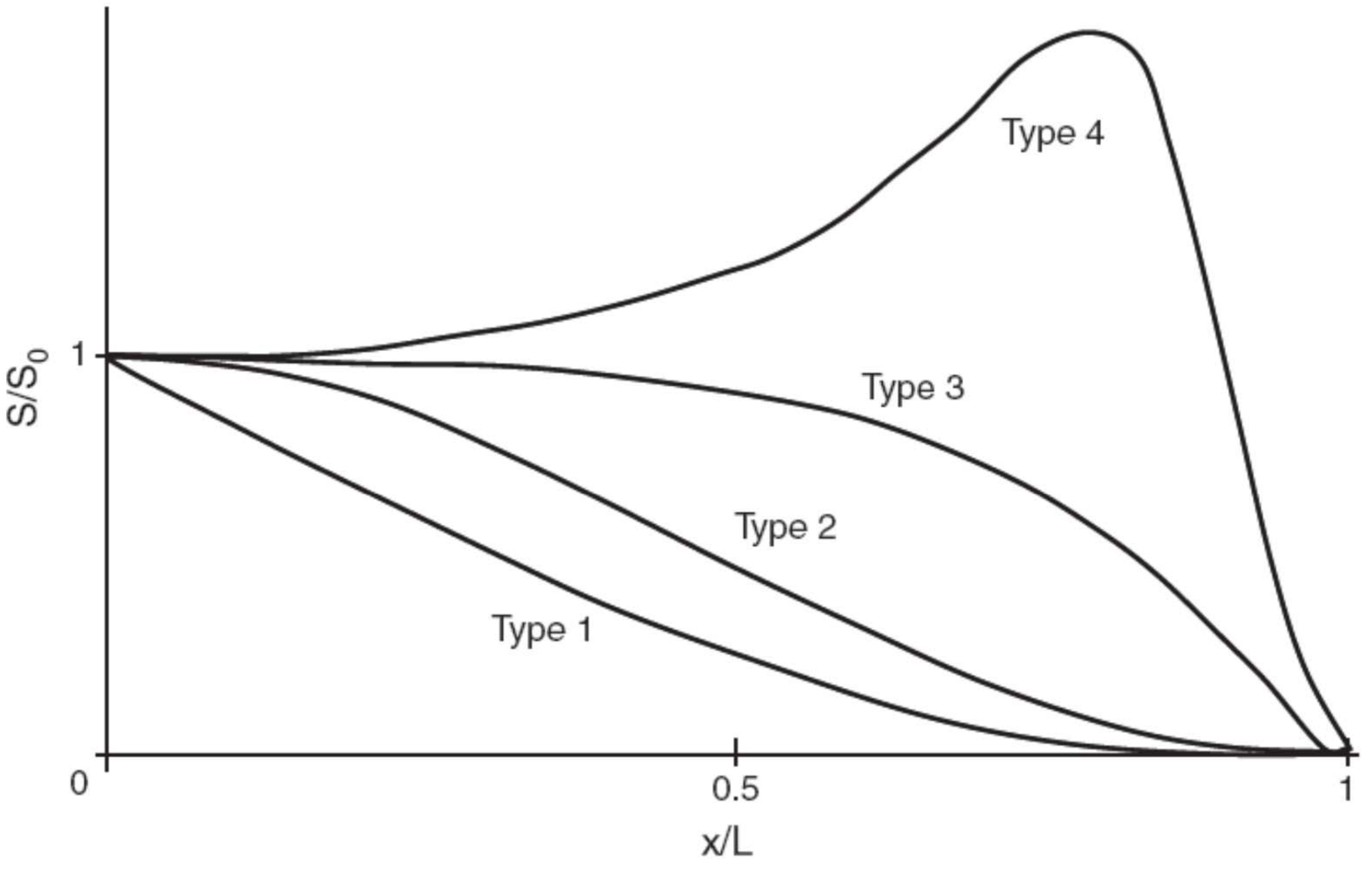
$$M = \frac{1}{2} g h^2 \rho \frac{\Delta\rho}{2\rho} \frac{h}{3} = \frac{1}{12} g \Delta\rho h^3$$

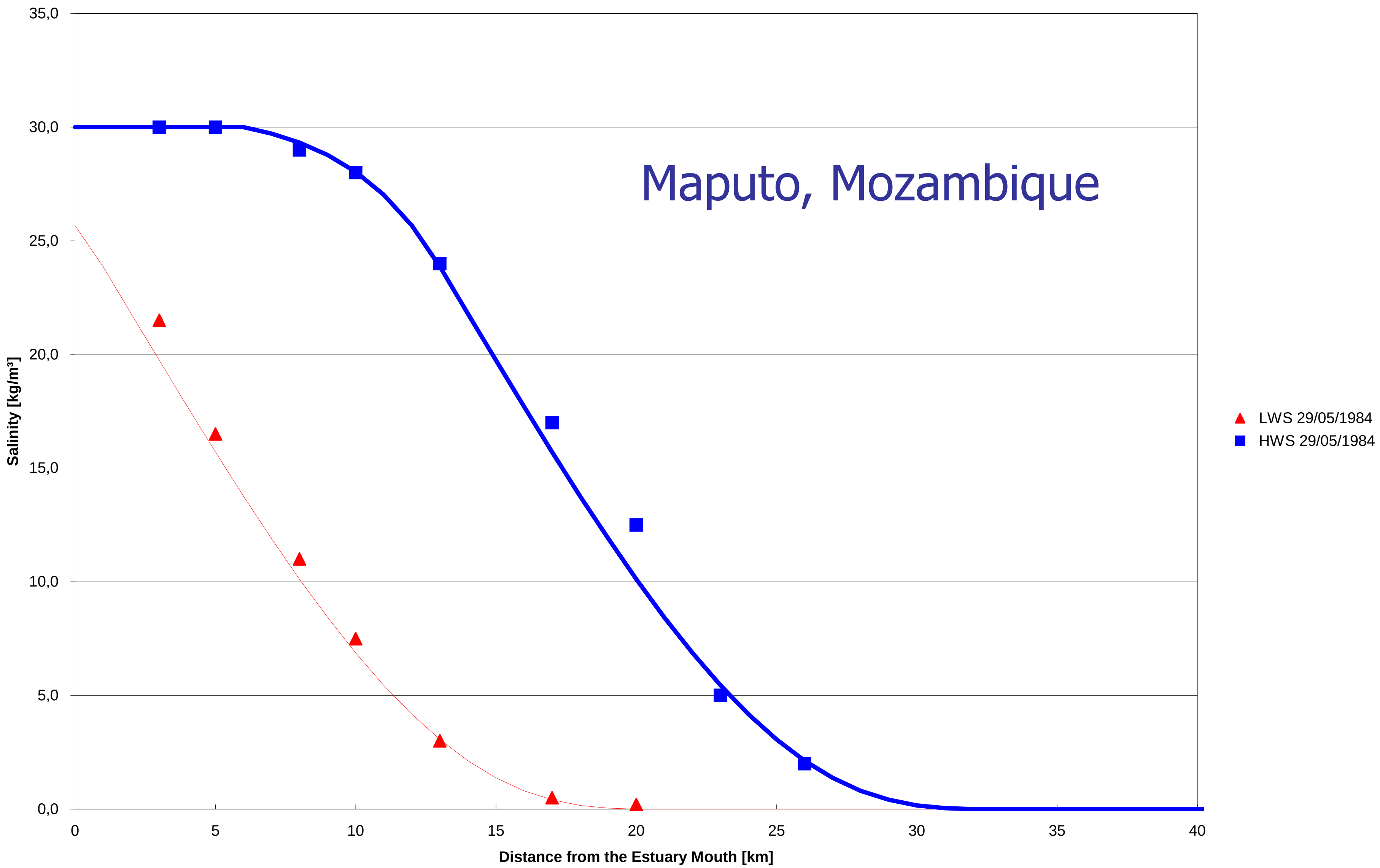
Mixed estuary



Salt intrusion equation

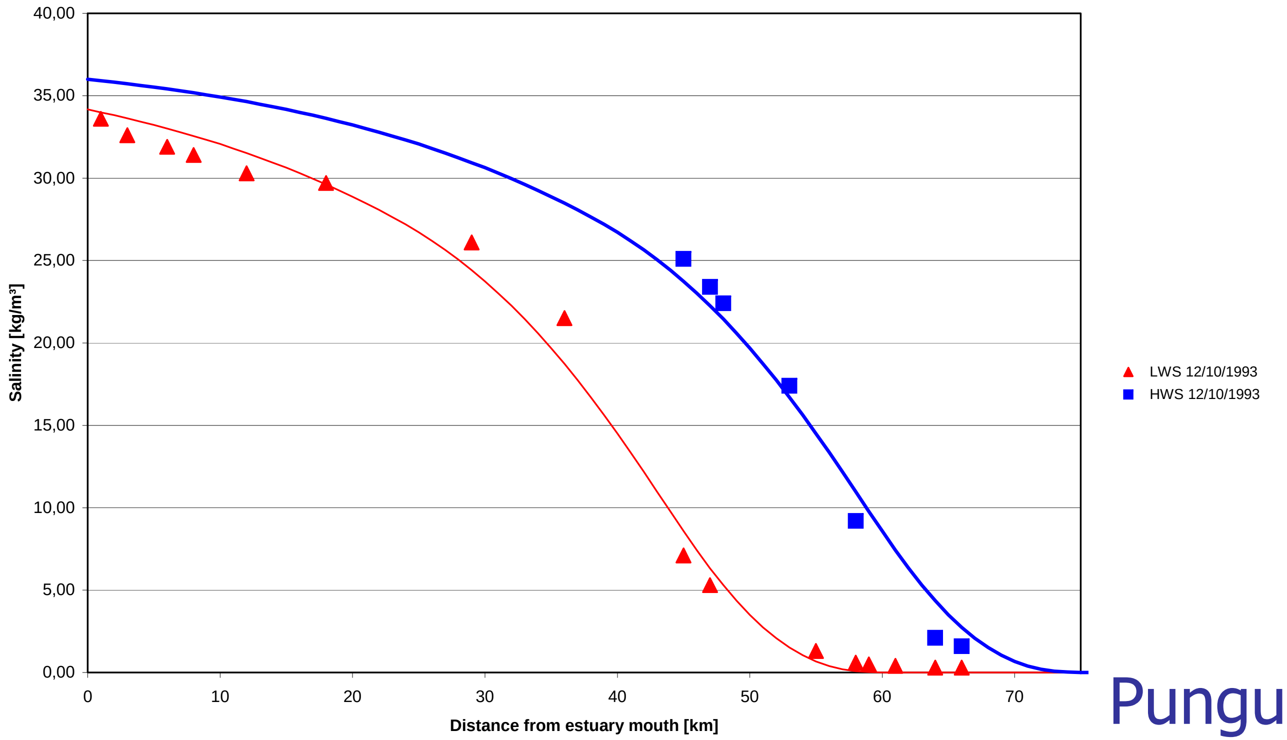
$$r_S A \frac{\partial s}{\partial t} + (Q_t + Q_f)\frac{\partial s}{\partial x} - \frac{\partial}{\partial x}\left(AD\frac{\partial s}{\partial x}\right) = -sR_s \tag{5.7}$$





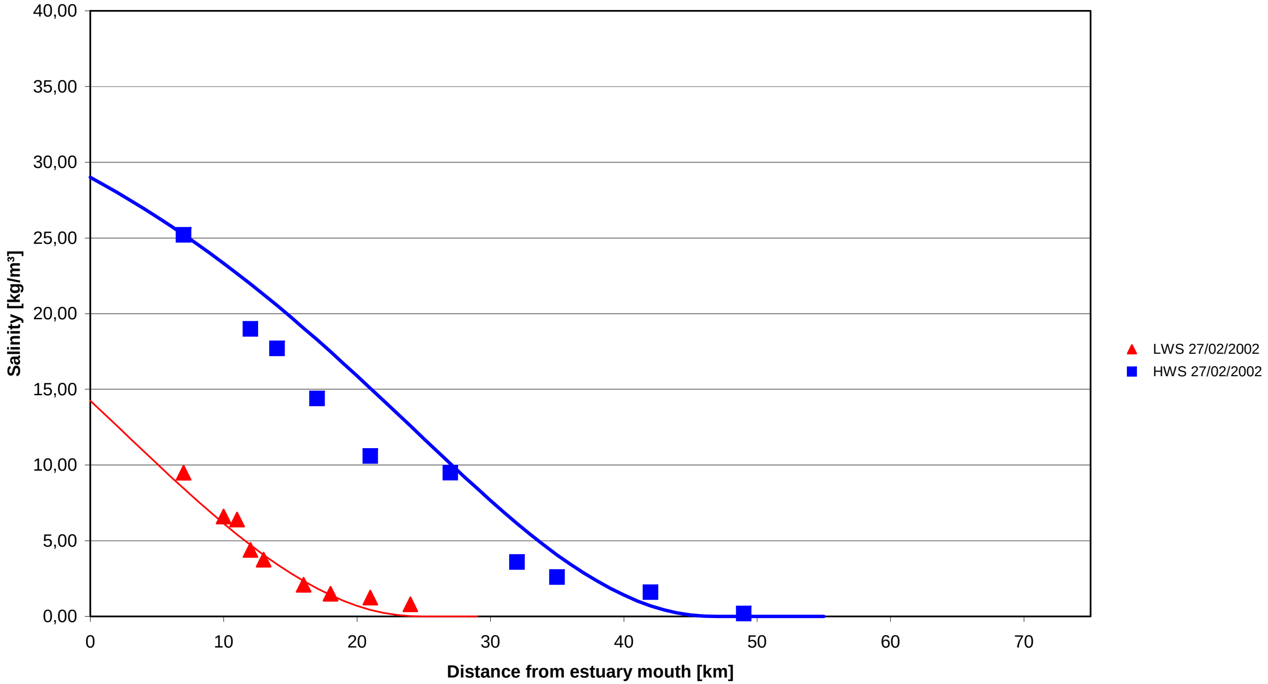
Maputo, Mozambique
Salinity [kg/m³]
35,0
30,0
25,0
20,0
15,0
10,0
5,0
0,0
0
5
10
15
20
25
30
35
40
Distance from the Estuary Mouth [km]
LWS 29/05/1984
HWS 29/05/1984

a)

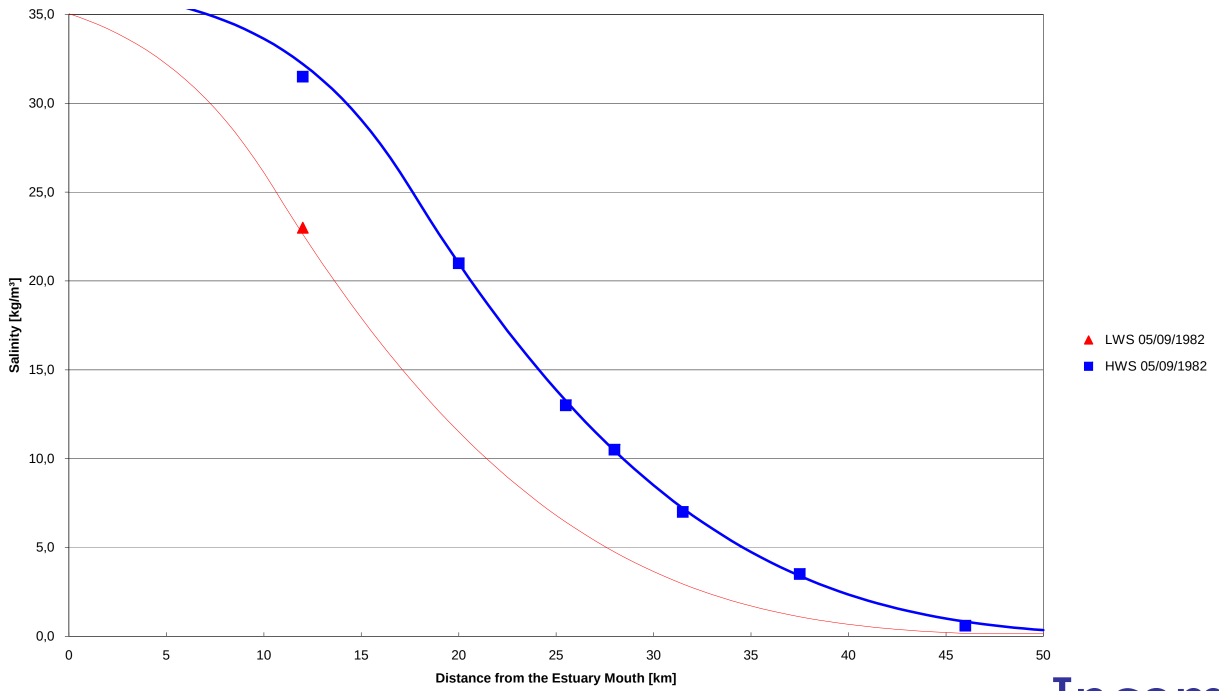


Pungue, Mozambique

b)

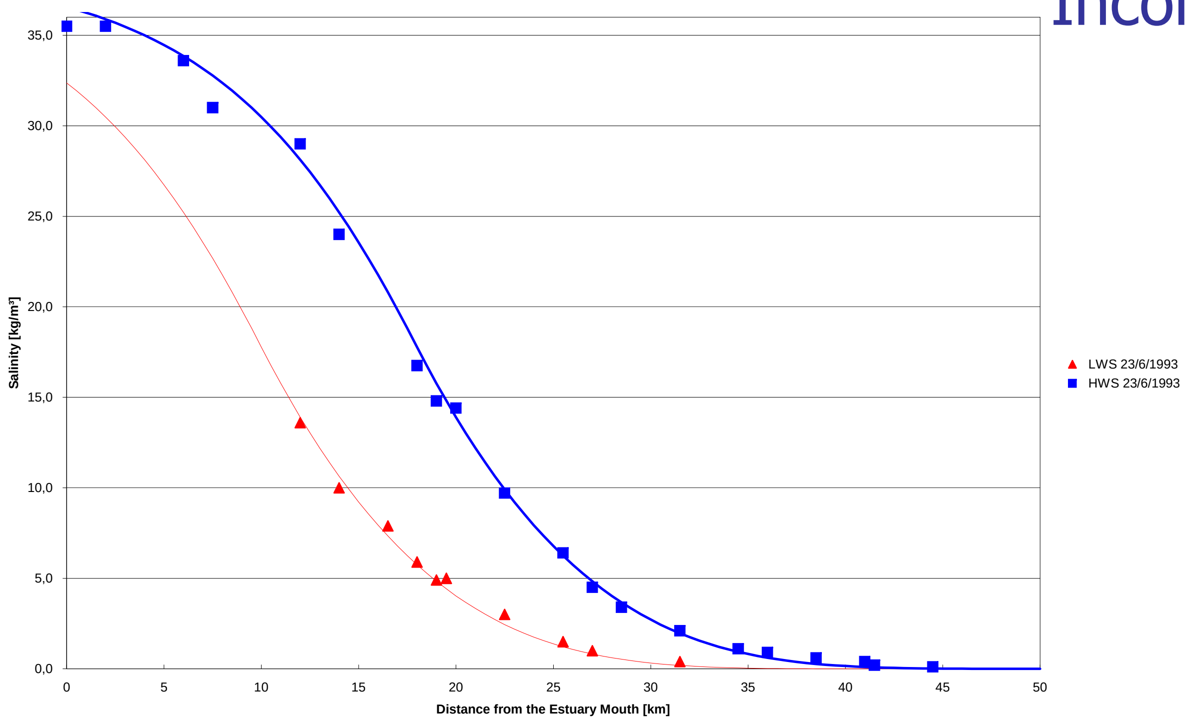


a)

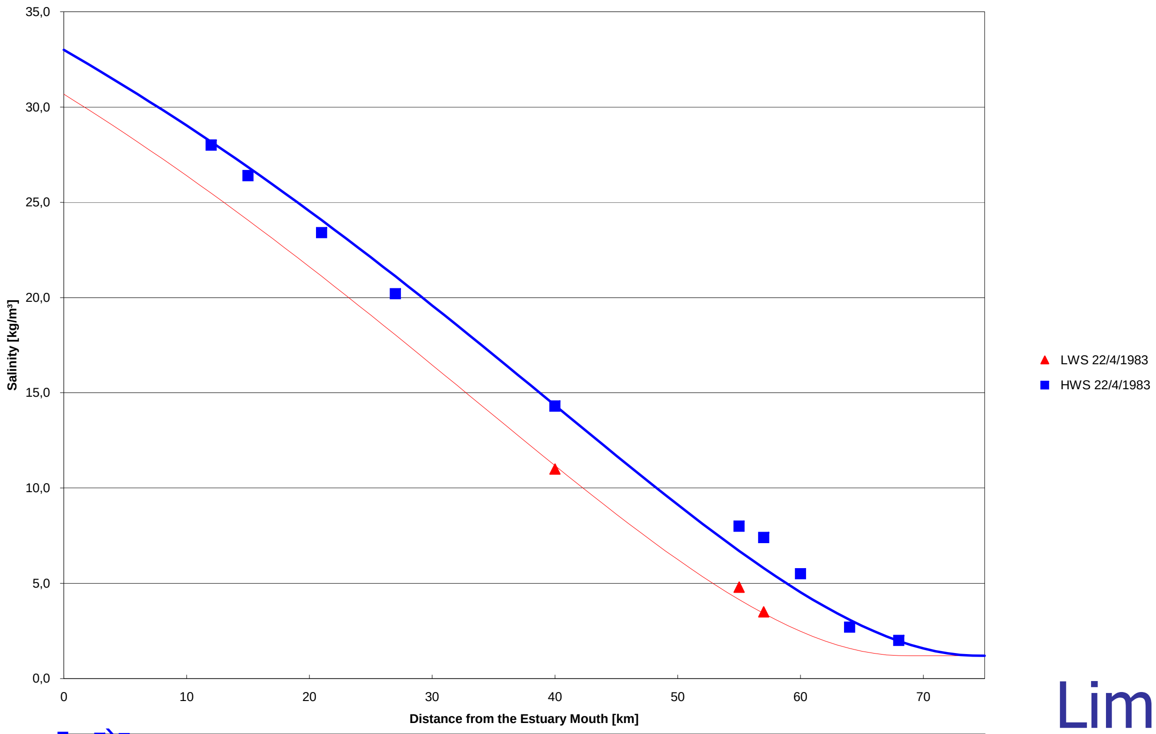


Incomati, Mozambique

b)

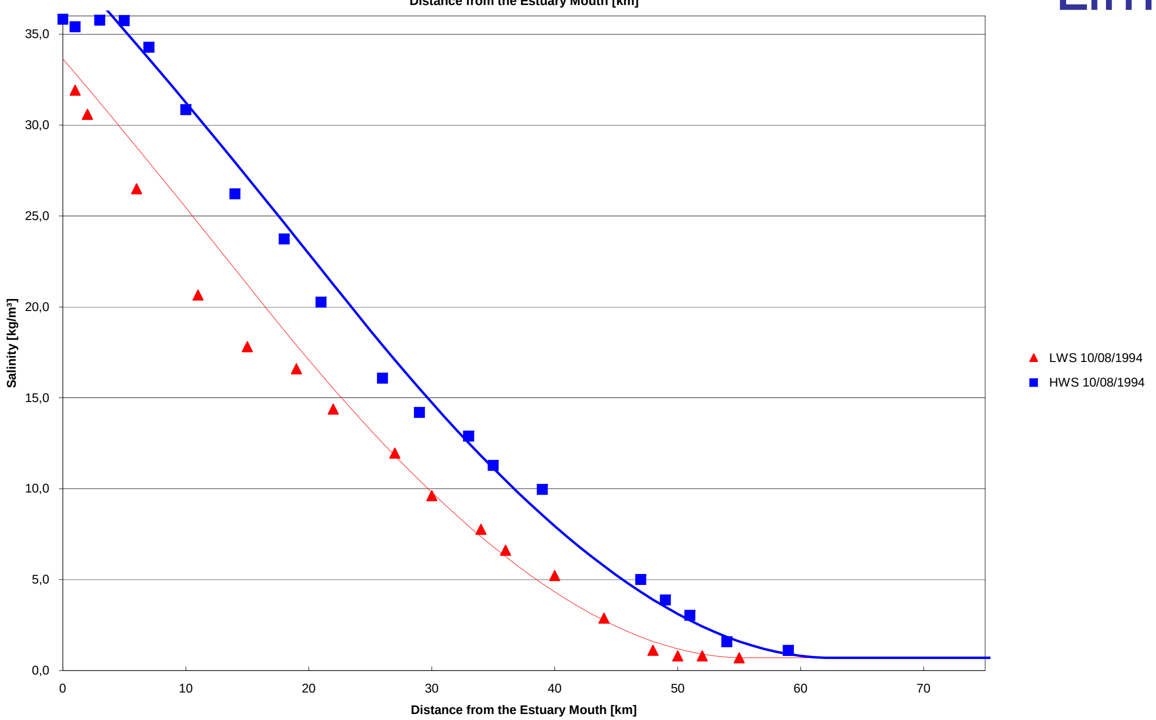


a)

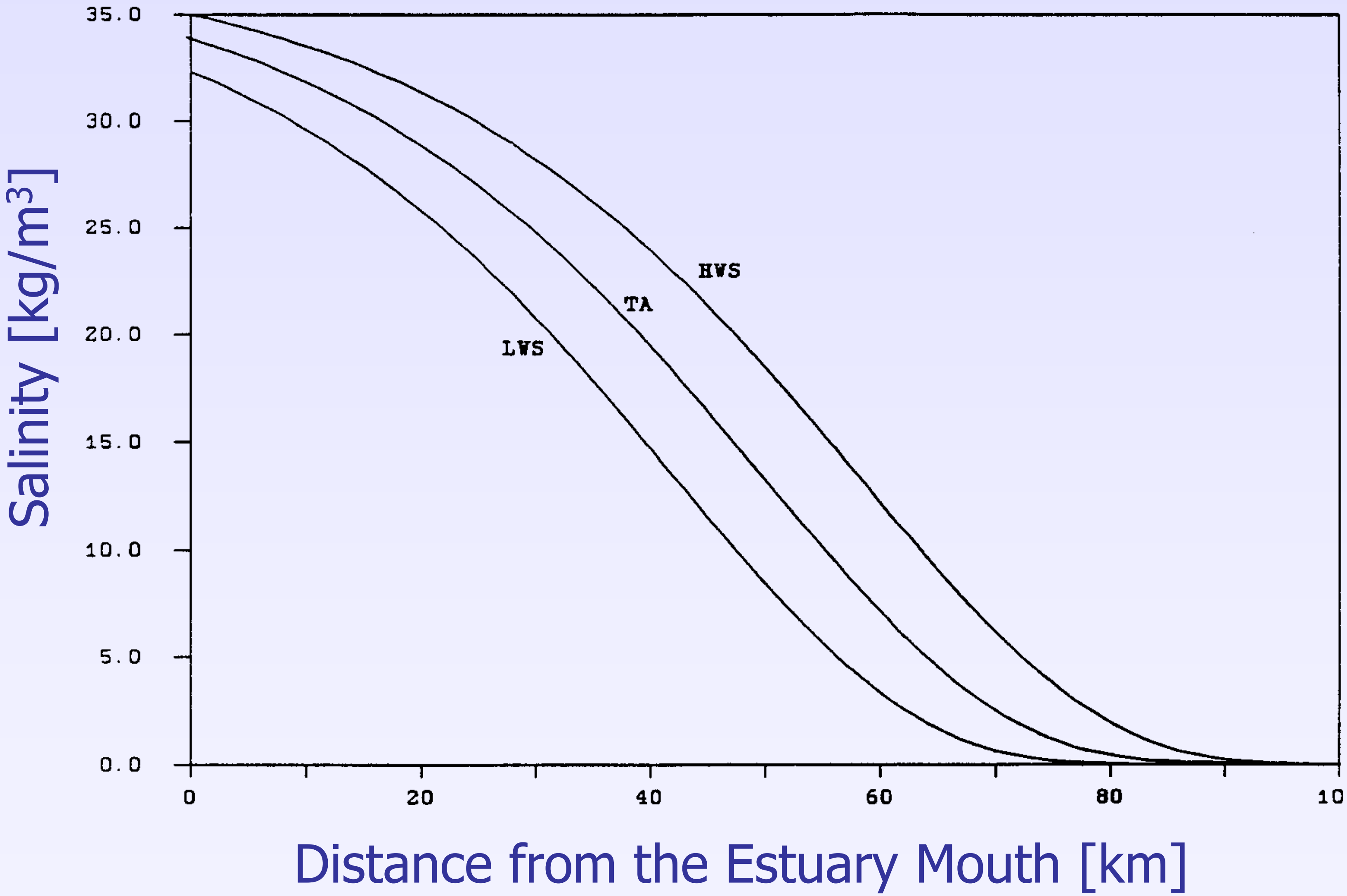


Limpopo, Mozambique

b)



Mixed estuary



Mixed estuary

Best salt intrusion measurement by moving boat at HWS, because:

1. The moment that HWS occurs is easily determined.
2. If the salinity at the downstream boundary is not known, it can easiest be estimated at HWS.
3. At HWS the salt intrusion is at its maximum.
4. A single observer in a small outboard driven boat can travel with the tidal wave and measure the entire salt intrusion curve at HWS or LWS.
5. In a moving boat (at slack) it is easy to measure a full vertical in the center of the stream, which is the best location to measure the salinity.
6. If the intrusion length is not too long, the observe can return to the estuary mouth and repeat the measurement for LWS.

Sea water intrusion into open estuaries

For steady state, there should be an equilibrium in any cross-section between:

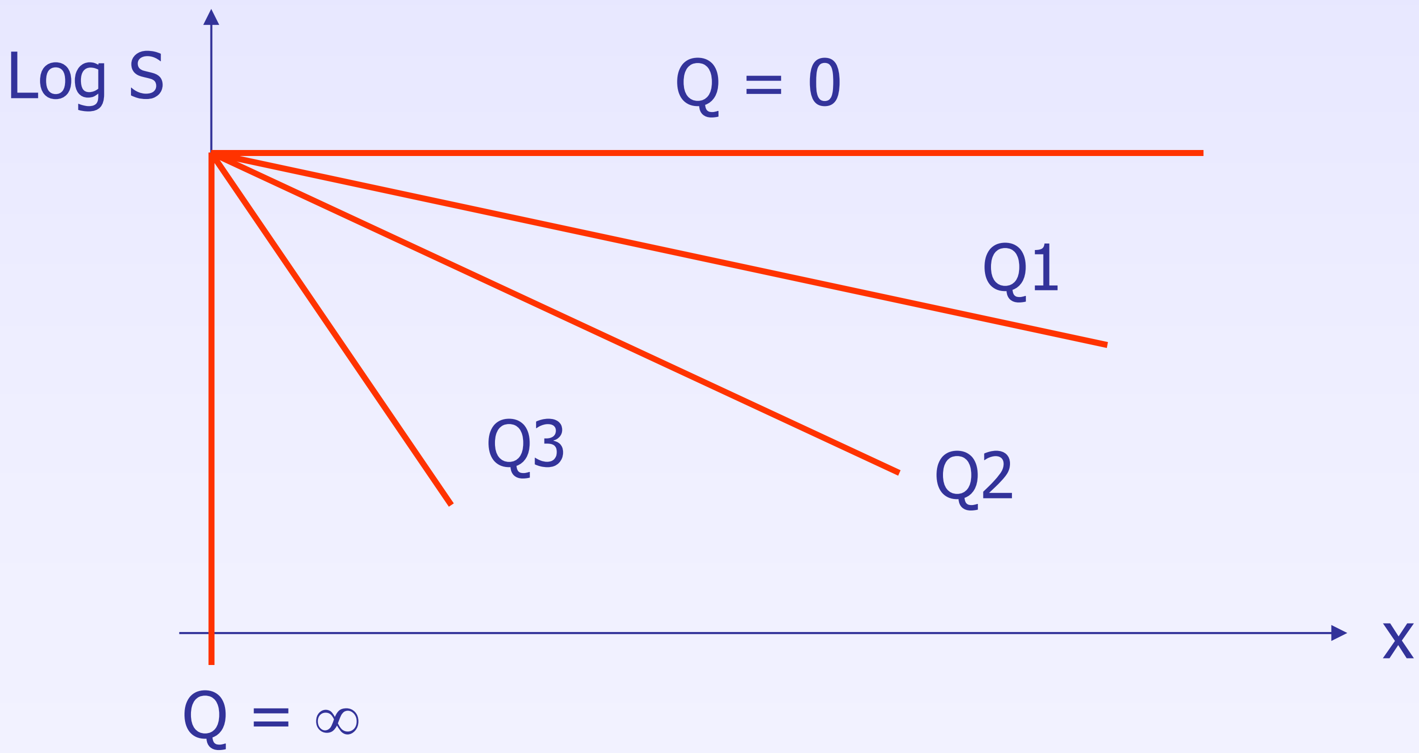
- The *advective transport* of salt by the river flow in downstream direction Q $(S-S_f)$
- The *dispersive transport* of salt in upstream direction under the effect of mixing which is proportional to the concentration gradient dS/dx.

$$\left(S - S_f\right)Q_f = -AD\frac{dS}{dx}$$

Sea water intrusion into open estuaries

If Q/(DA) is constant:

$$S - S_f = (S_0 - S_f)\exp\left(-\frac{Q}{DA}x\right)$$



Sea water intrusion into open estuaries

But it is not that simple, because:

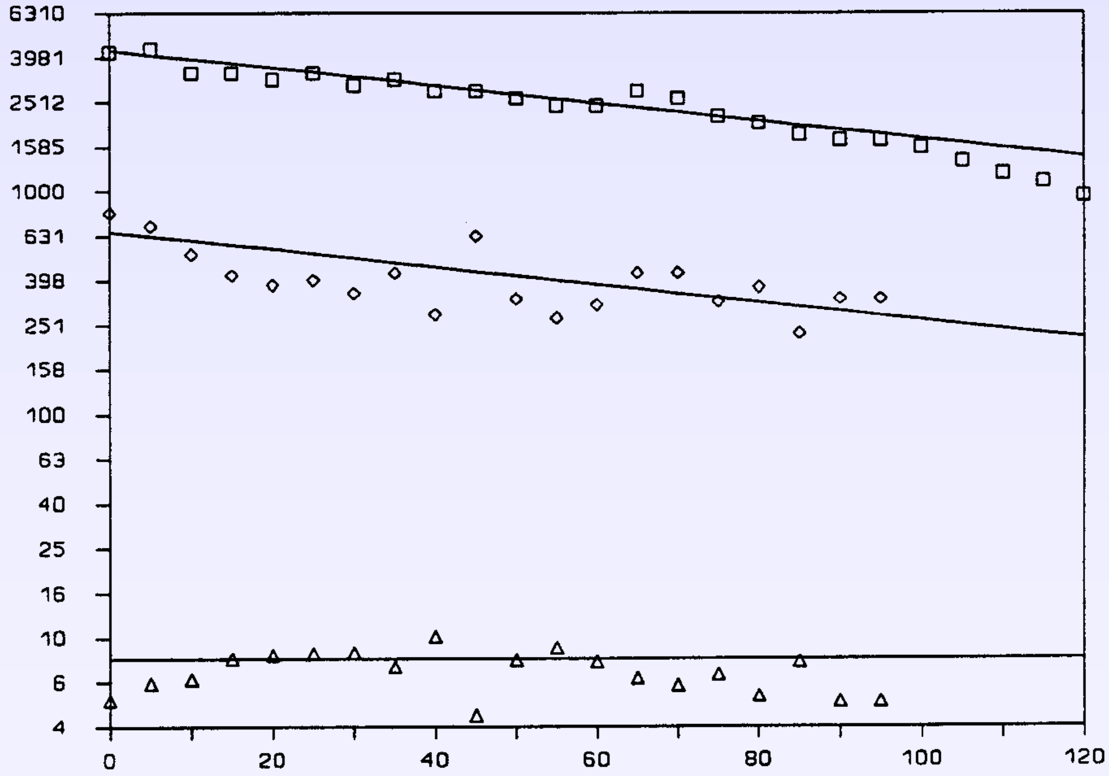
1. The cross-sectional area A is not constant with x;
2. The value of D cannot be easily predicted; it differs from one estuary to another; moreover it varies with x;
3. Actual records show that the lines deviate from straight lines;
4. The concentration for x=0 is not constant but depends on Q;

Sea water intrusion into open estuaries

Cross-sectional area:

$$A(x) = A_0 \exp\left(-\frac{x}{a}\right)$$

Chao Phya Estuary:



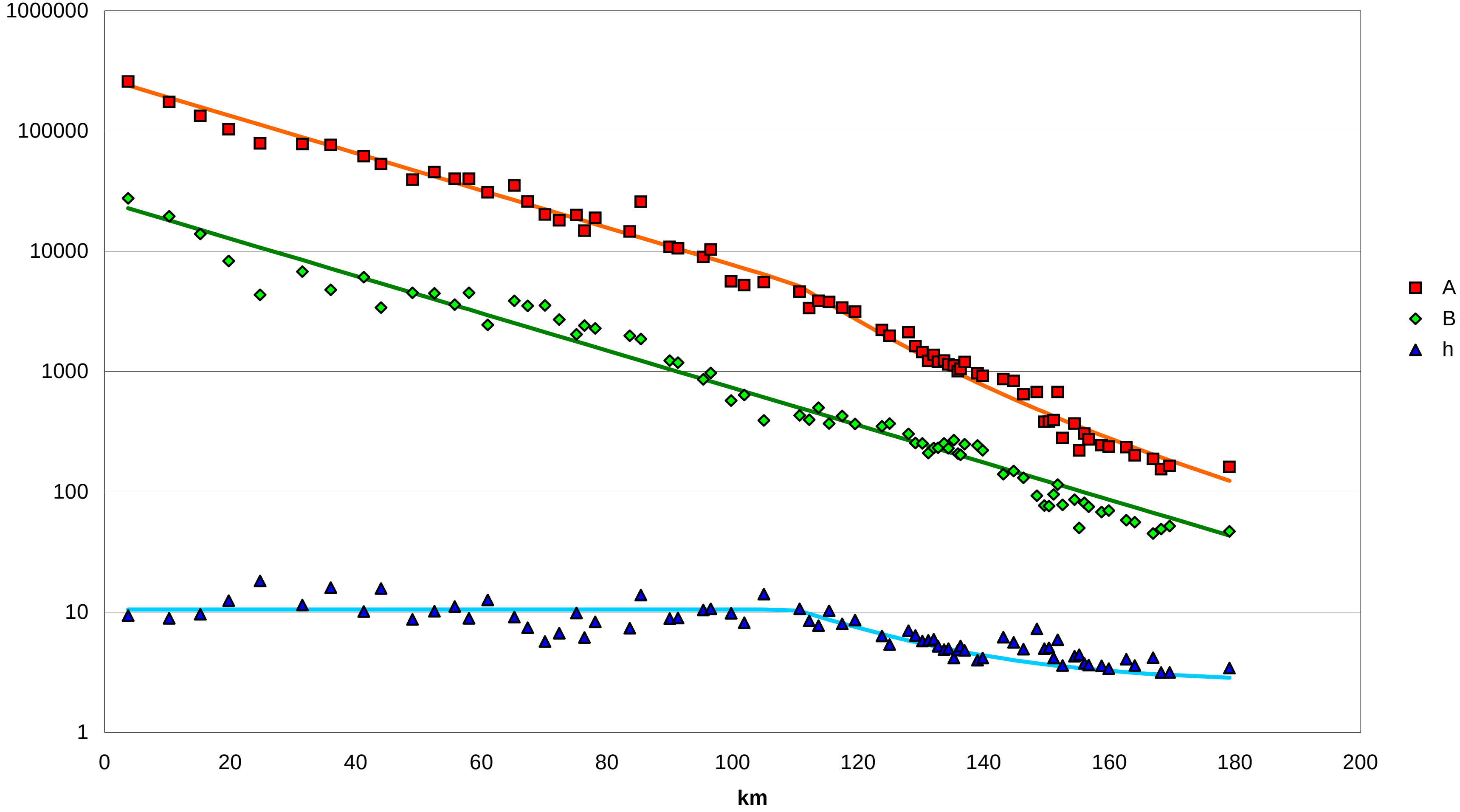
□ Area [m²]

O Width [m]

Δ Depth [m]

Distance for the mouth [km]

Schelde



1000000
100000
10000
1000
100
10
1
0
20
40
60
80
100
120
140
160
180
200
km
A
B
h

Sea water intrusion into open estuaries

Longitudinal dispersion coefficient:

- *Prandle (1981)*

$$\left.\begin{aligned} D &= D_0 \\ D &\propto \frac{\partial S}{\partial x} \\ D &\propto \left(\frac{\partial S}{\partial x}\right)^2 \end{aligned}\right\} \qquad D \propto \left(\frac{\partial S}{\partial x}\right)^k \text{ with } k = 0, 1, 2$$

- *Van der Burgh (1972)*

$$\frac{\partial D}{\partial x} = K \frac{Q_f}{A}$$

- *Savenije (1992)*

$$\frac{D}{D_0} = \left(\frac{S}{S_0}\right)^K$$

Sea water intrusion into open estuaries

$$A\frac{\partial S}{\partial t}+Q\frac{\partial S}{\partial x}-\frac{\partial}{\partial x}\left(AD\frac{\partial S}{\partial x}\right)=0$$

$$Q_f\left(S\text{-}S_f\right) = DA\frac{dS}{dx}$$ and $$\frac{dD}{dx} = K\frac{Q_f}{A} \rightarrow \frac{dD}{K} = \frac{Q_f}{A}dx$$

$$\frac{Q_f}{DA}dx = \frac{dS}{S\text{-}S_f}$$

gives: $$\frac{dD}{D}=K\frac{dS}{S-S_f}$$

Integrated: $$\frac{S\text{-}S_f}{S_0\text{-}S_f} = \left(\frac{D}{D_0}\right)^{\frac{1}{K}}$$

Sea water intrusion into open estuaries

$$\frac{dD}{dx} = K\frac{Q_f}{A} \qquad \text{and} \qquad A(x) = A_0 \exp\left(-\frac{x}{a}\right)$$

$$\frac{dD}{dx} = K\frac{Q_f}{A} = K\frac{Q_f}{A_0\exp\left(-\frac{x}{a}\right)} = \frac{KQ_f}{A_0}\exp\left(\frac{x}{a}\right)$$

Integrated: $$\frac{D}{D_0} = 1 + \frac{KaQ_f}{D_0A_0}\left(\exp\left(\frac{x}{a}\right) - 1\right) = 0$$

At the end of the salt intrusion (x=L): $S=S_f \rightarrow D=0$

$$L = a\ln\left(-\frac{D_0A_0}{KaQ_f} + 1\right)$$

$$\alpha_0 = \frac{D_0}{Q_f}$$

Predicting Do and K using dimless numbers

1. Densimetric Froude number: $$F_d = \frac{\rho}{\Delta\rho}\frac{\upsilon^2}{gh} \approx 40\frac{\upsilon^2}{gh}$$
2. Canter-Cremers number:
   $$N = \frac{QT}{V_{fl}} = \frac{QT}{EA_0}$$
3. Estuarine Richardson number
   $$N_R = \frac{N}{F_d}$$
4. A simpler form of the Canter Cremers number: $$N = \frac{v_f}{\upsilon}$$
5. h/a
6. E/a
7. Coefficient of Van den Burgh K

Sea water intrusion into open estuaries

Empirical formulae for K and α_0

$$K = 0.2 * 10^{-3} \left(\frac{E}{H}\right)^{0.65} \left(\frac{E}{C^2}\right)^{0.39} \left(1 - \delta b\right)^{-2.0} \left(\frac{b}{a}\right)^{0.58} \left(\frac{Ea}{A_0}\right)^{0.14}$$

$$\alpha_0 = 1400 \frac{h_0}{a} \sqrt{\frac{ETgh_0}{-Q_f A_0}} \sqrt{\frac{\Delta\rho}{\rho}}$$

$$\frac{D_0}{\upsilon_0 E_0} = 1400 \frac{h_0}{a} \sqrt{N_R}$$

Sea water intrusion Length

This results in:

$$L_{HWS} = a \ln\left(1 + \frac{1400}{K}\frac{h}{a}\frac{E}{a}\frac{\upsilon}{v_f}\sqrt{N_R}\right)$$

With:

a = convergence length of the cross-sectional area
K = coefficient of Van der Burgh
h = depth
E = tidal excursion
υ = tidal velocity amplitude
v_f = fresh water velocity
N_R = Estuarine Richardson number

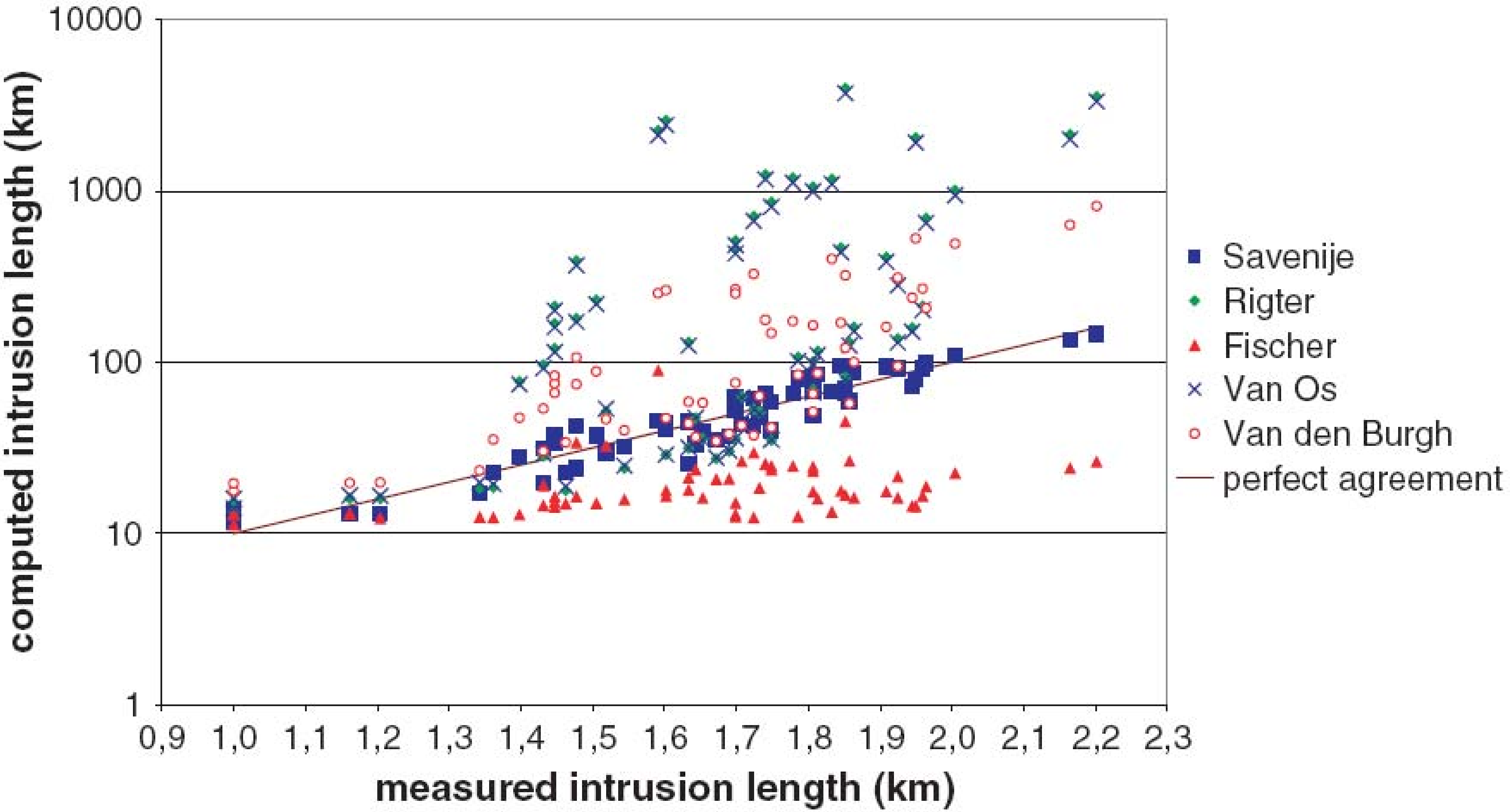
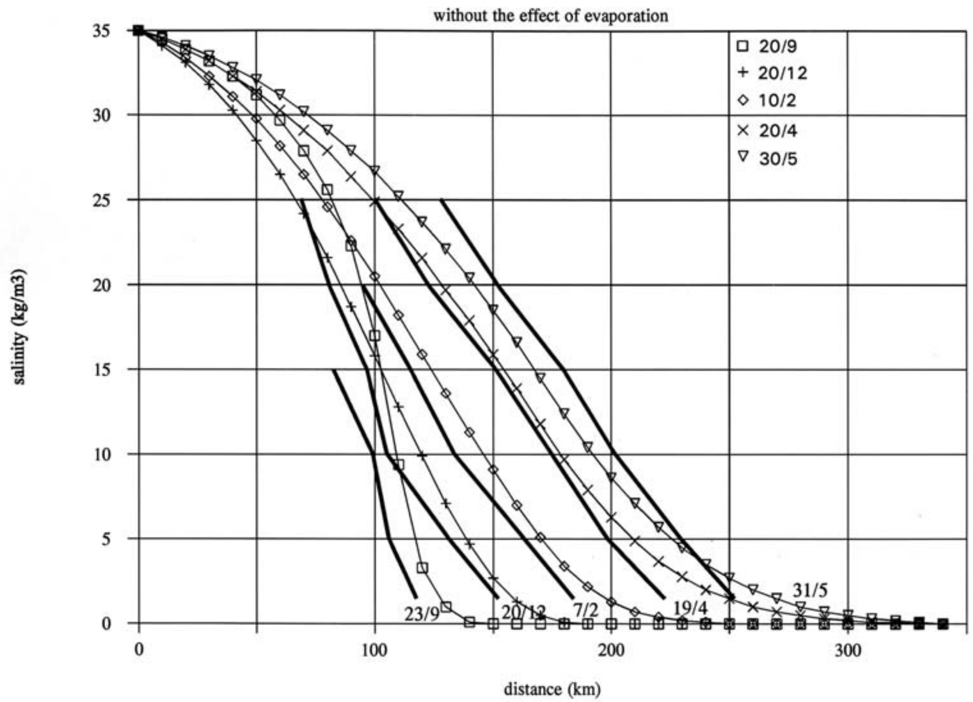
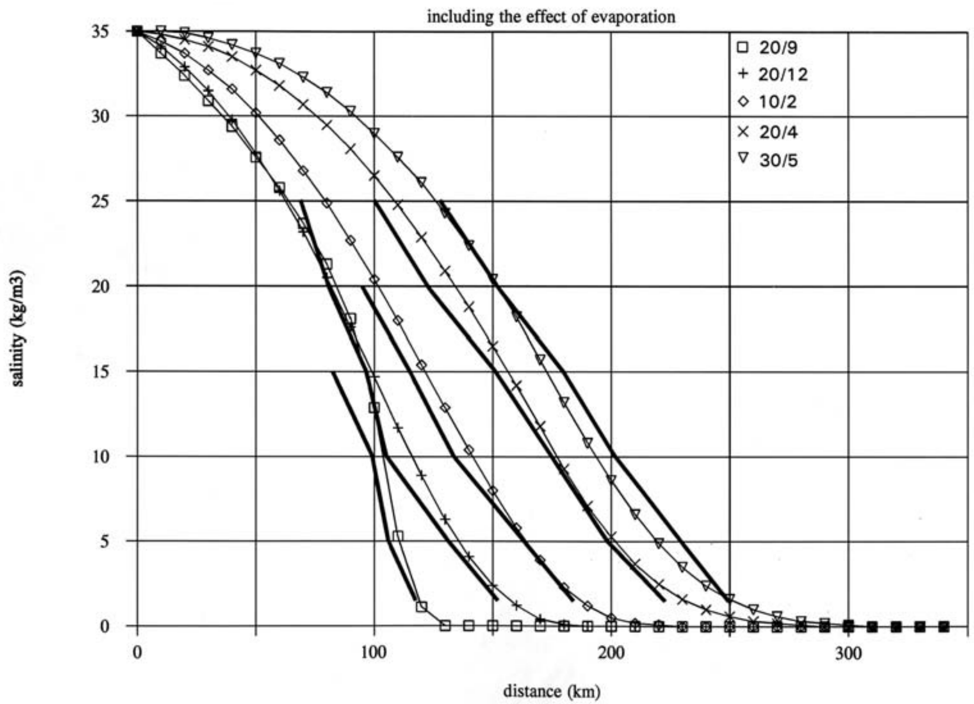


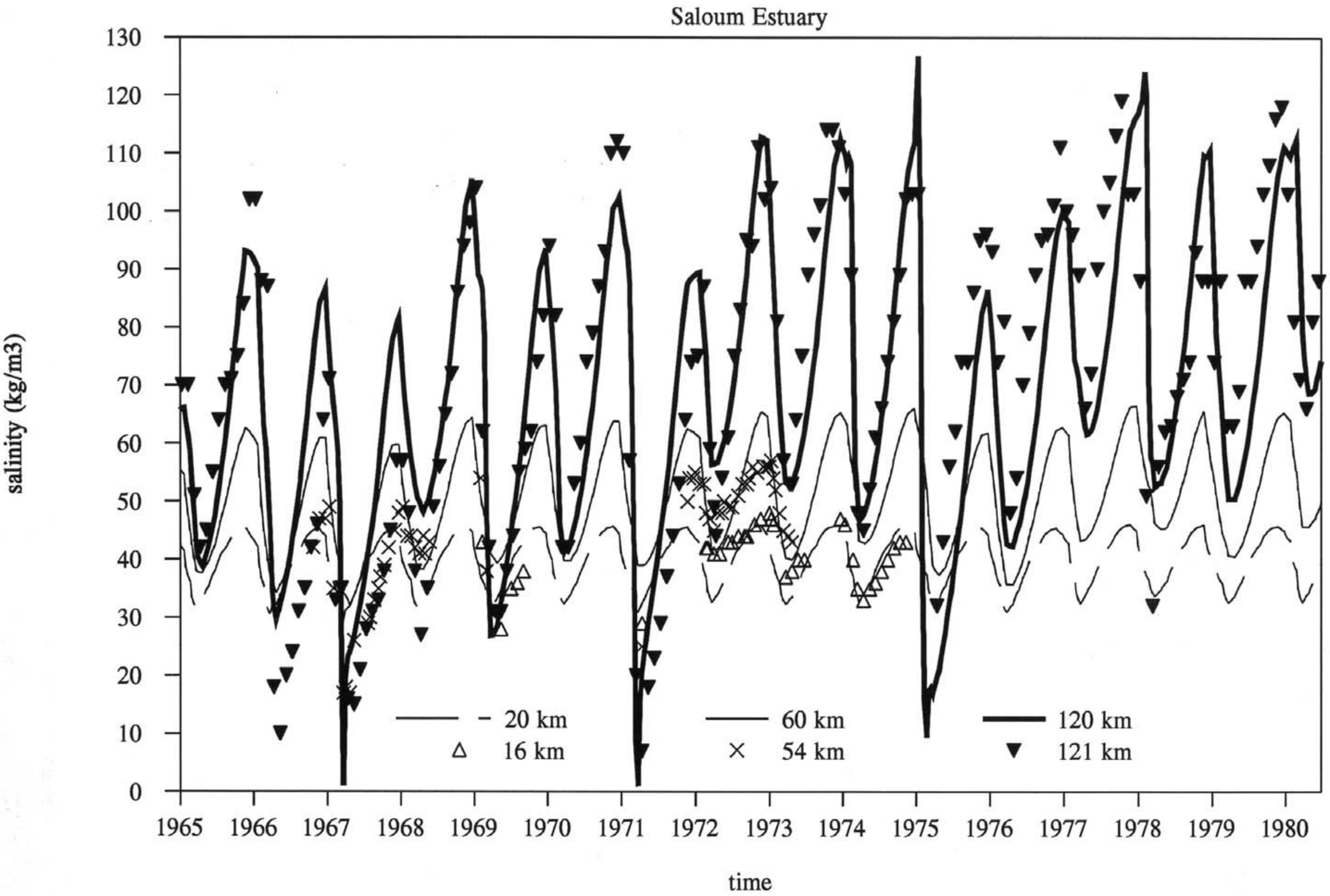
Figure 5.8 Comparison of various predictive models for the salt intrusion length at HWS.

a)

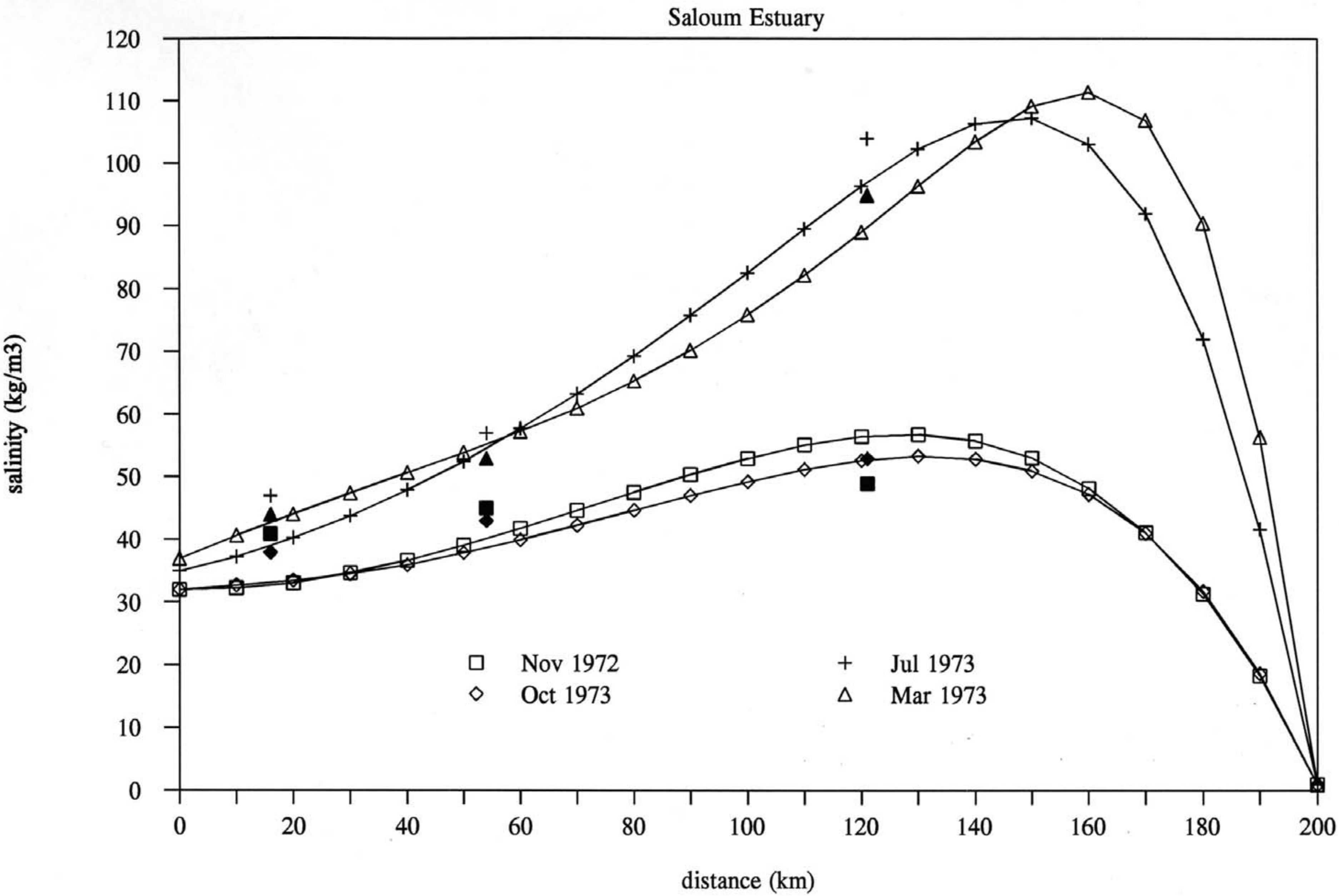

without the effect of evaporation
salinity (kg/m3)
distance (km)
20/9
20/12
10/2
20/4
30/5
23/9
20/12
7/2
19/4
31/5
0
5
10
15
20
25
30
35
0
100
200
300

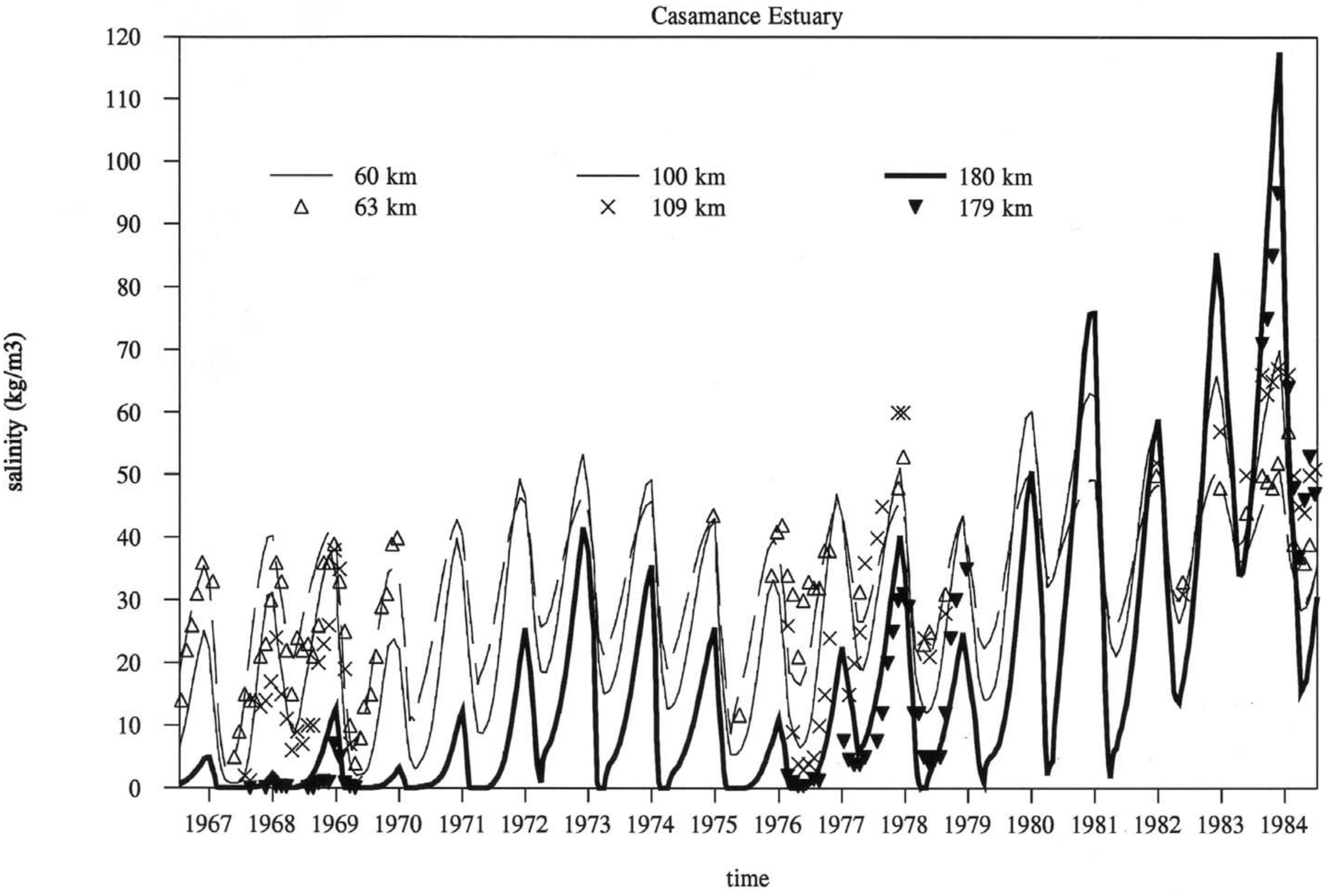
b)


including the effect of evaporation
salinity (kg/m3)
distance (km)
20/9
20/12
10/2
20/4
30/5
0
5
10
15
20
25
30
35
0
100
200
300



Saloum Estuary
salinity (kg/m3)
time
130
120
110
100
90
80
70
60
50
40
30
20
10
0
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
20 km
16 km
60 km
54 km
120 km
121 km

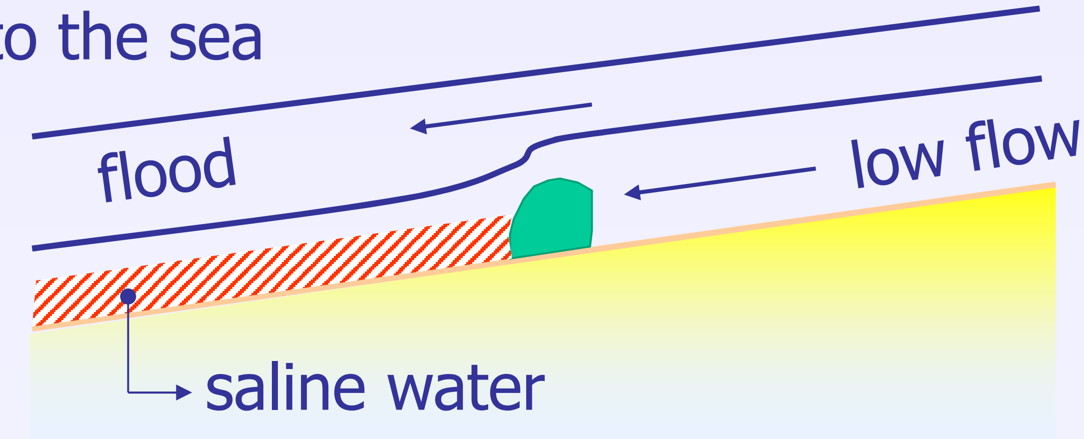

Saloum Estuary
salinity (kg/m3)
distance (km)
120
110
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
120
140
160
180
200
Nov 1972
Oct 1973
Jul 1973
Mar 1973


Casamance Estuary
salinity (kg/m3)
time
60 km
63 km
100 km
109 km
180 km
179 km
120
110
100
90
80
70
60
50
40
30
20
10
0
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984

Sea water intrusion into open estuaries

Preventive measures:

- Increasing the upland discharge
- Decreasing the depth of the estuary
- In case of small tides and a stratified estuary a low submerged sill effectively halts the saline wedge without offering a significant obstacle to flood flows.
- Damming off estuaries by building an enclosing dam equipped with sluices and gates to remove excess water to the sea



Sea water intrusion into open estuaries

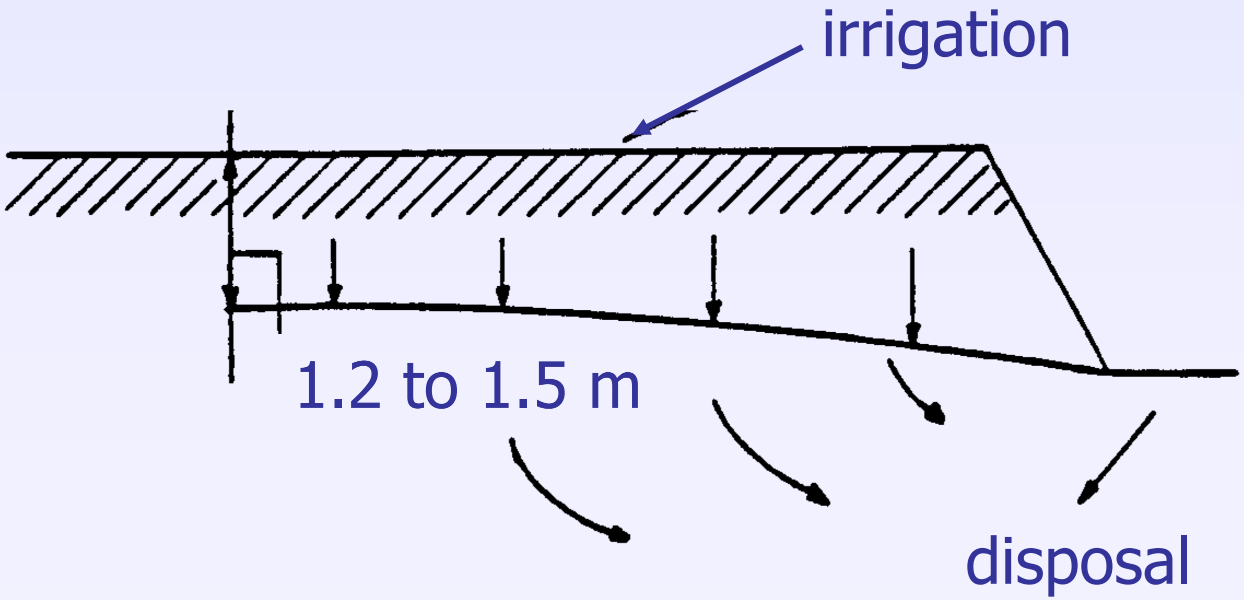
If preventive measures are not feasible:

1. Shifting of intakes of fresh water to points upstream of the saline reach
2. Rinsing or flushing of canals exposed to saline intrusion with fresh water
3. Over-irrigation in combination with adequate drainage to leach the soil

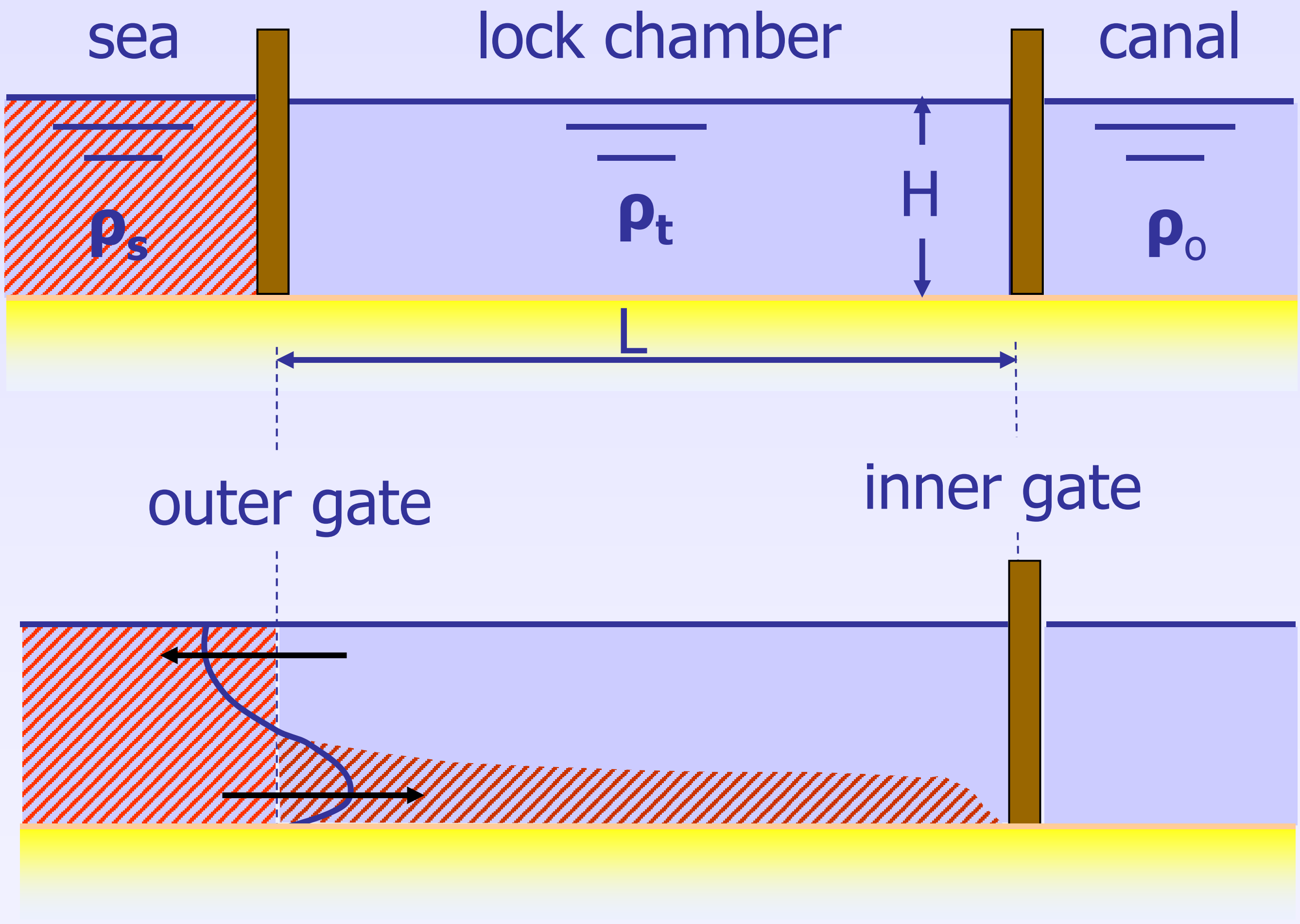
Seepage of brackish ground water

Soil salinization:

- primary soil salinization:
  Use of irrigation water
- secondary soil salinization:
  Capillary forces



Sea water entering at navigation locks



Sea water entering navigation locks

Exchange at time t:

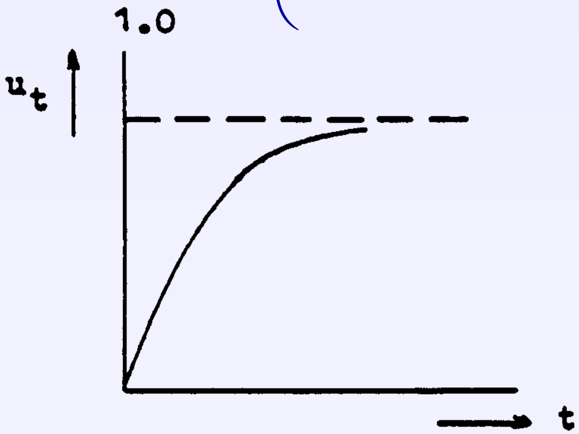
$$u_t = \frac{\rho_t - \rho_0}{\rho_s - \rho_0}$$

if $\rho_t = \rho_s$ $\quad u_t = 1$

$\rho_t = \rho_0$ $\quad u_t = 0$

In the Netherlands (semi-empirical):

$$u_t = \tanh\left(\frac{t}{4L}\left(\frac{\Delta\rho}{\rho_0} gH\right)^{\frac{1}{2}}\right)$$ where $\Delta\rho = \rho_s - \rho_0$

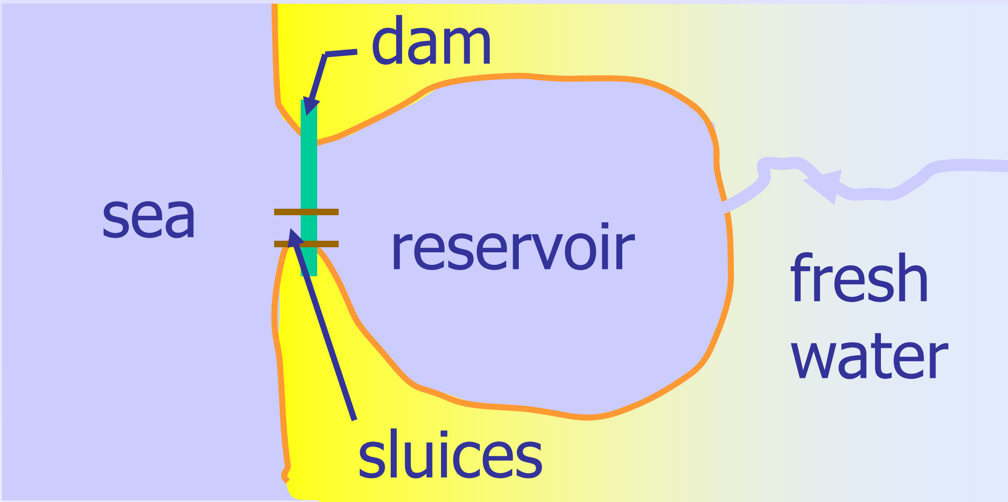


Sea water entering at navigation locks

Preventive measures:

1. Pump back the saline water in the lock chamber to the sea and replace this by fresh water from the canal.
2. Injection of air bubbles during the time that the gates are open.
3. The saline water entered at a lock can be collected in a sump at the canal side of the lock and removed from there by pumping of gravity.
4. Subdivide the lock chamber so that smaller boats can be locked through without using the entire chamber.

Coastal reservoirs – general design



Purposes for reservoirs:

- by shortening the coast line the salt water intrusion is reduced
- fresh water from the river can be stored
- a better defense of the adjacent low-lying areas against storm surges is obtained
- the drainage of these areas can be improved

Coastal reservoirs - general design

Technical feasibility of reservoirs depend on:

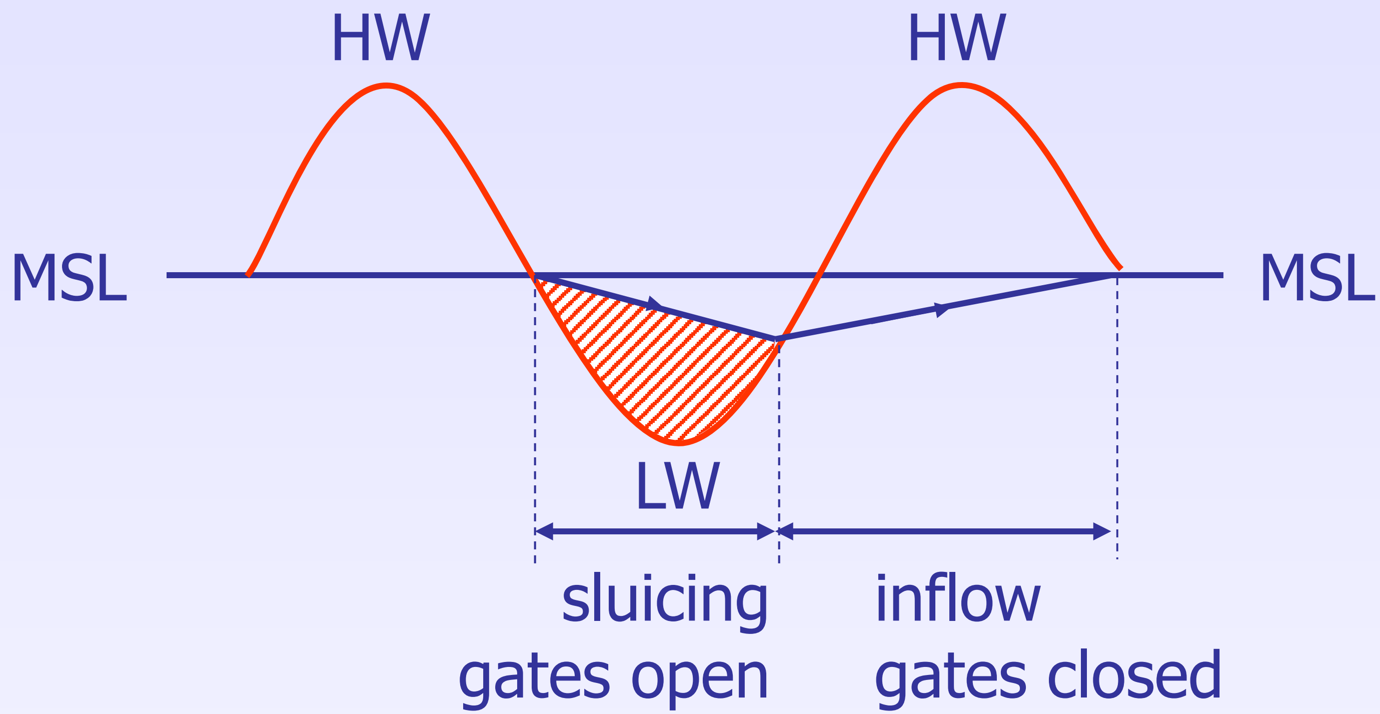
- The length of the period of desalinization
- The ultimate salinity of the water in the reservoir after the desalinization
- The water balance of the reservoir in connection with the regulation of the normal operational level

Coastal reservoirs – water balance

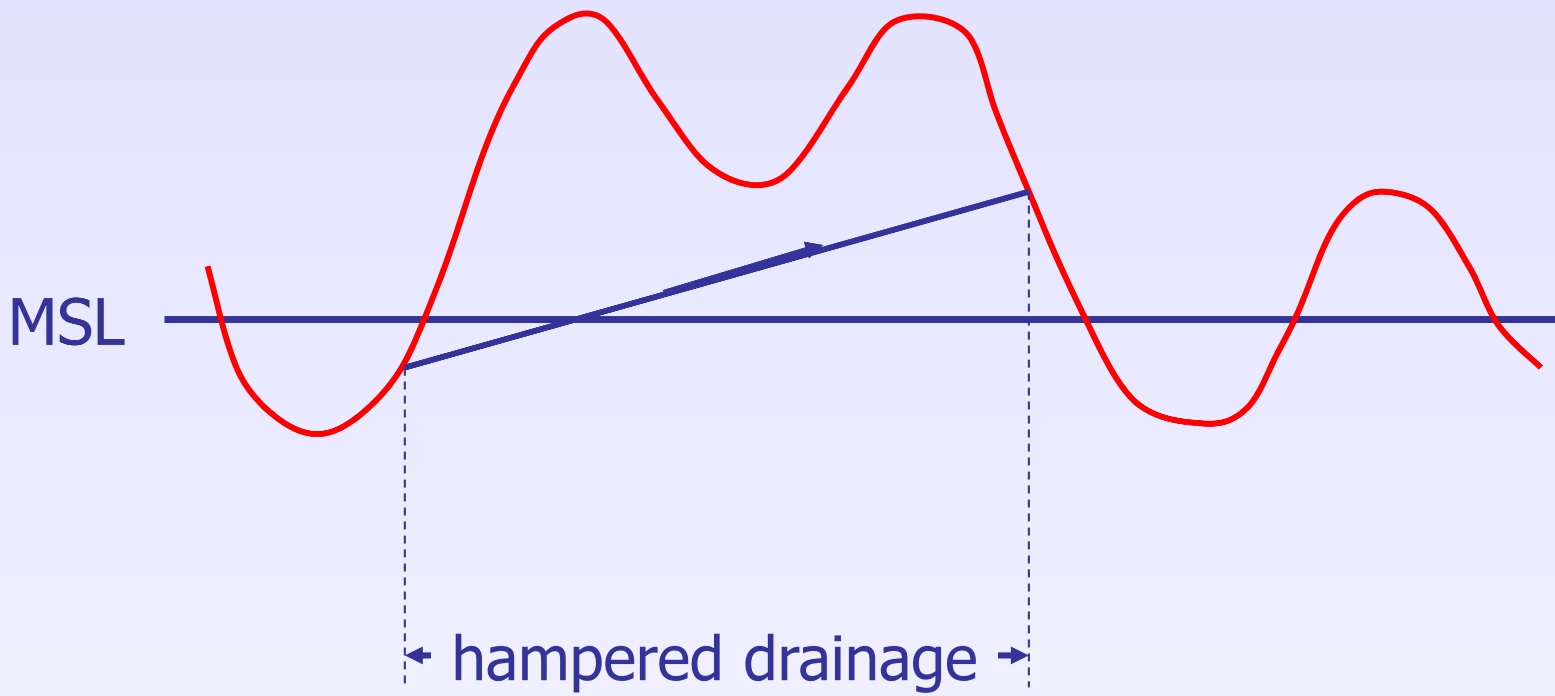
IN	OUT
River discharge	Abstraction of water
Drainage on the reservoir	Drainage to the sea
Rain on the reservoir	Evaporation from the reservoir
Decrease in storage	Increase in storage

$$\frac{\mathrm{d}S}{\mathrm{d}t} = I - O$$

Coastal reservoirs – water balance



Coastal reservoirs – water balance



Coastal reservoirs – salt balance

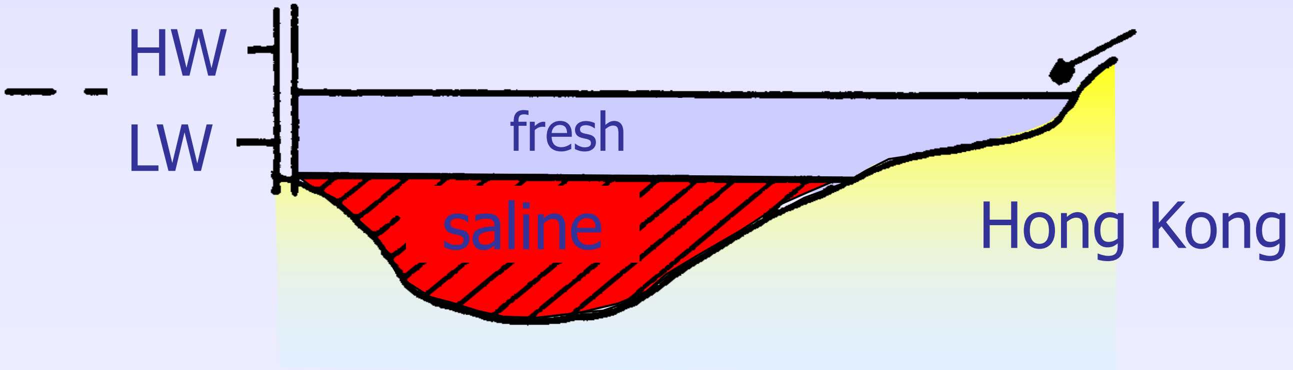
IN	OUT
Salt load or the river	Salt drained to the sea
Drainage of brackish water on the reservoir	Abstraction of water from the reservoir
Underground inflow of saline water	Increase in amount of salt stored
Diffusion of salt from the bottom	
Locking of ships	
Leakage of sluices gates	

$$\frac{\mathrm{d}\, cS}{\mathrm{d}\, t} = c_i I - c_o O$$

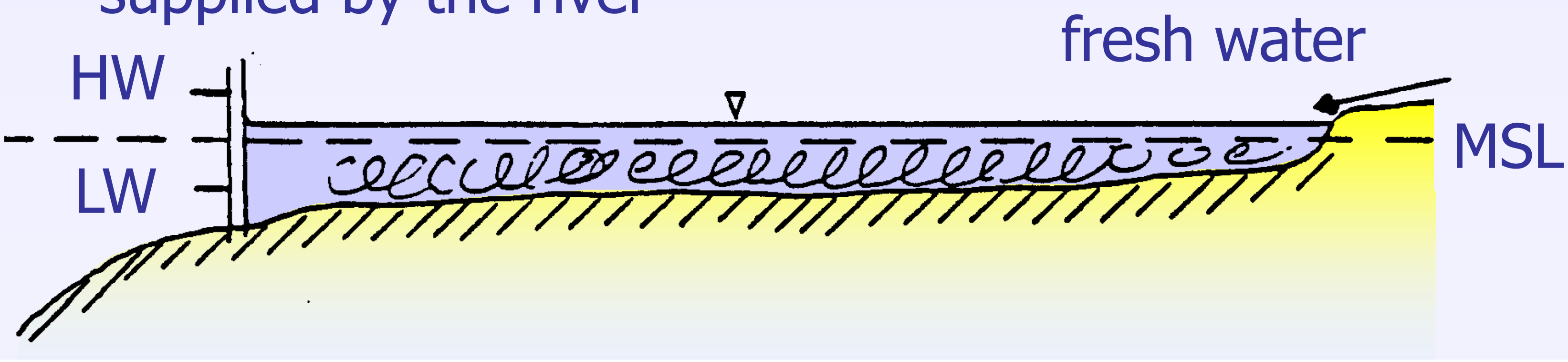
Coastal reservoirs – salt balance

The initial desalinization of the reservoir after the closing of the dam can be achieved in two ways:

1. Removal of the saline water by pumping to the sea



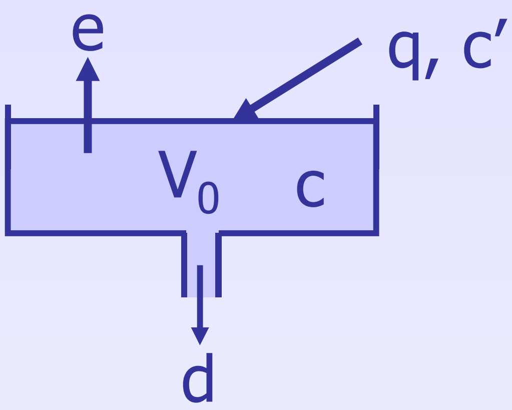
2. Gradual desalinization by draining off to the sea the mixture of the saline water with the fresh water supplied by the river



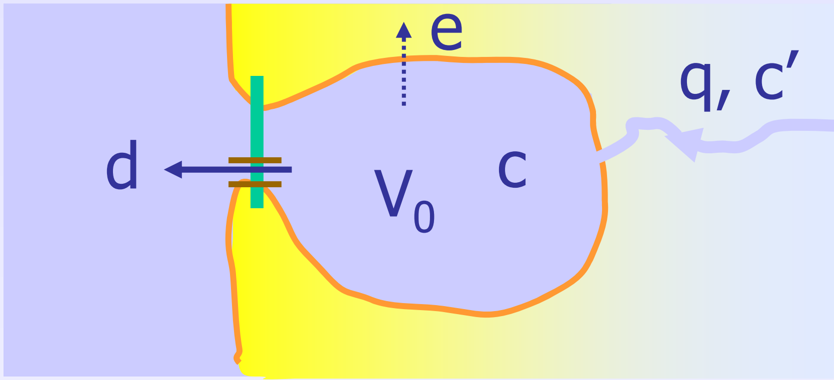
Coastal reservoirs – salinity with time

Mixing equation of theoretical physics:

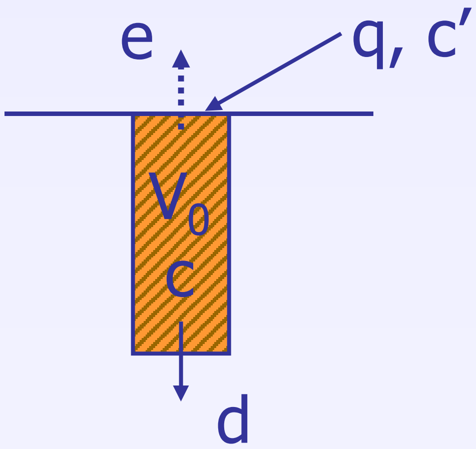
Container:



Coastal reservoir:



Column of soil:



Coastal reservoirs – salinity with time

- **Water balance:**

$$q = e + d$$

- **Salt balance:**

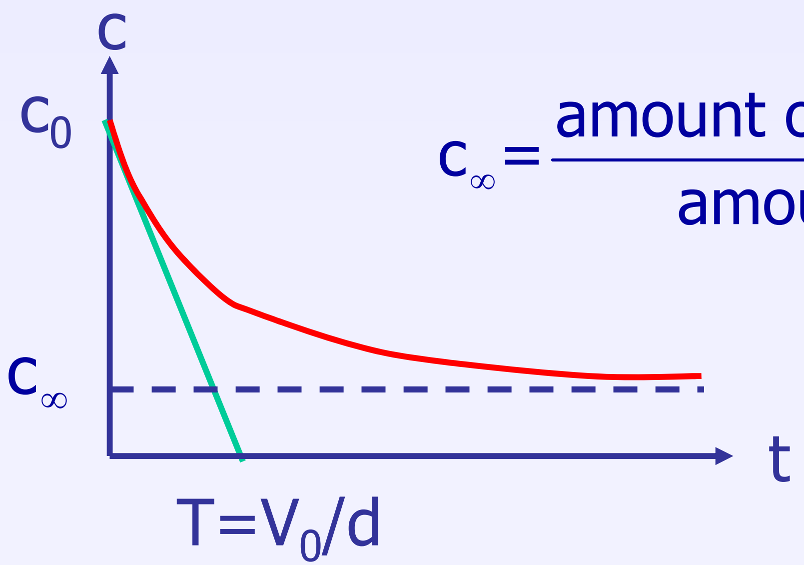
$$qc' \mathrm{d}t = dc\, \mathrm{d}t + V_0\, \mathrm{d}c \quad \rightarrow \quad \boxed{V_0 \frac{\mathrm{d}c}{\mathrm{d}t} = -dc + qc'}$$

$$\boxed{c = K \exp\left(-\frac{d}{V_0} t\right) + N}$$

with

$$K = c_0 - N$$

$$N = \frac{qc'}{d} = c_\infty$$



$$c_\infty = \frac{\text{amount of salt reaching the reservoir}}{\text{amount of water drained off}}$$

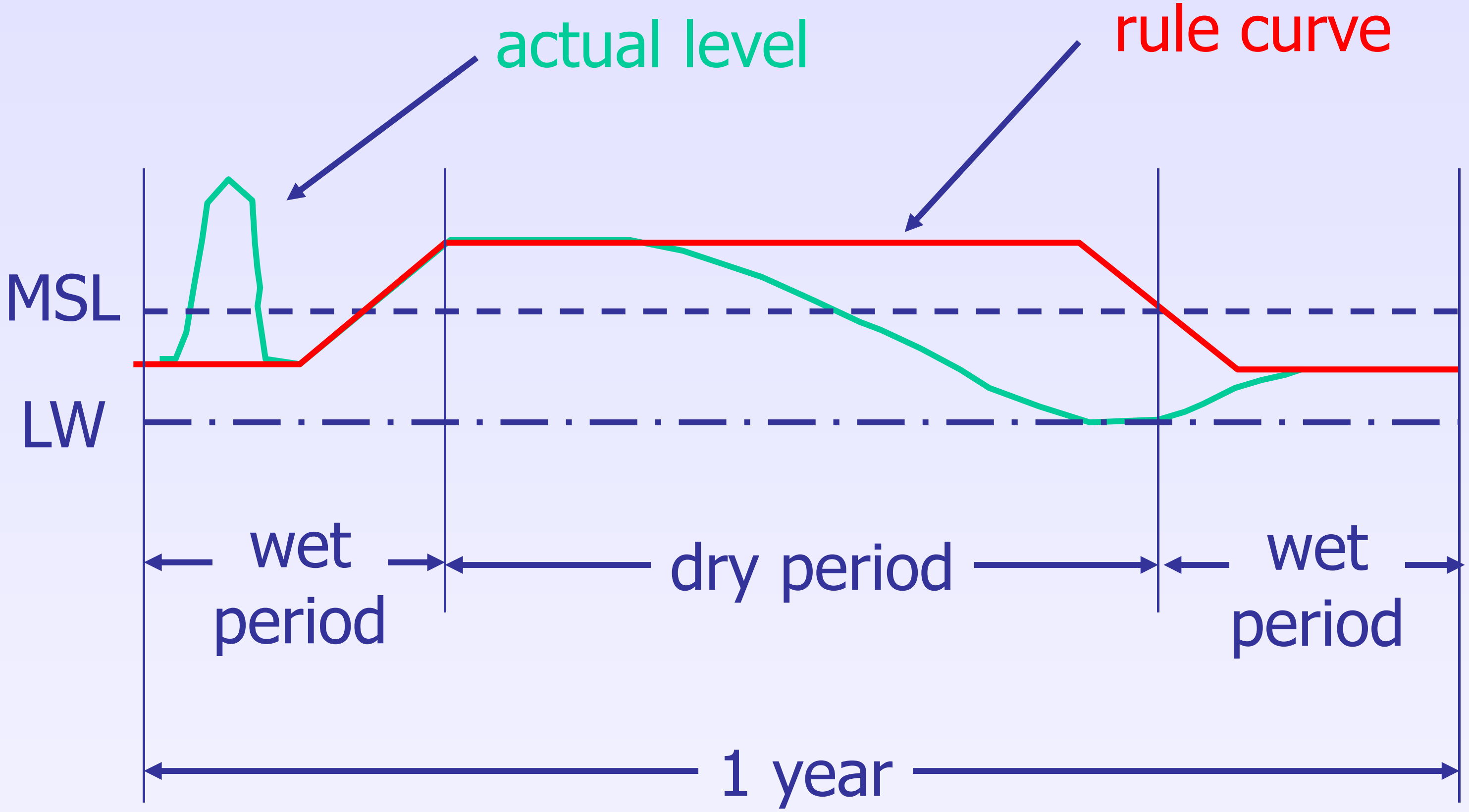
Hydrology of Catchments, Rivers and Delta's

Coastal reservoirs – salinity with time

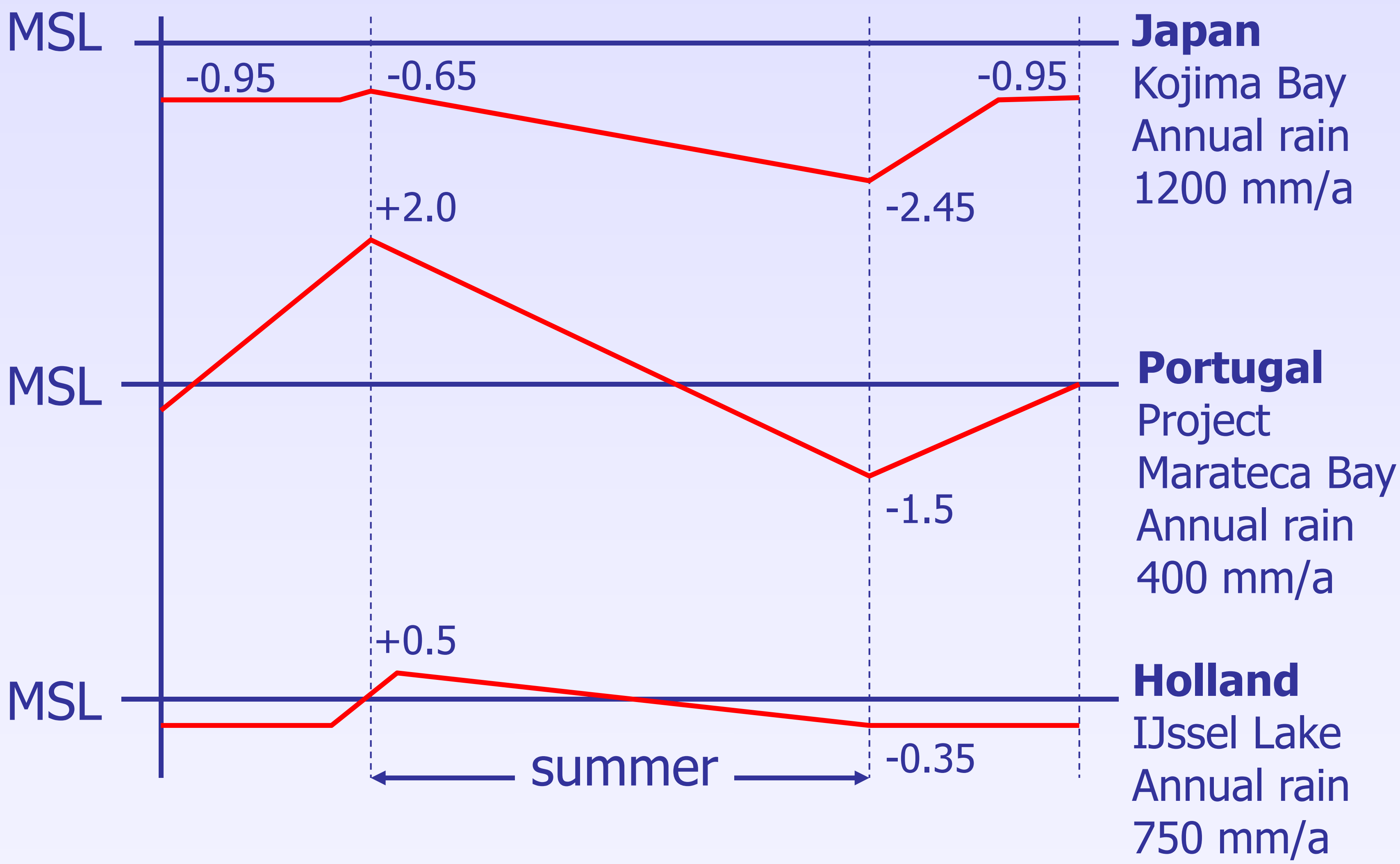
c/c_0

After:					
$T=V_0/d$	1 year	2 years	5 years	10 years	20 years
1	0.37	0.135	0.006	0.000	0.000
2	0.61	0.37	0.08	0.006	0.000
10	0.90	0.82	0.61	0.37	0.135

Coastal reservoirs – NOP



Coastal reservoirs – NOP



Case histories – IJssel lake

IN (in 10^9 m^3 per year)		**OUT** (in 10^9 m^3 per year)	
River discharge (IJssel)	10.14	Evaporation	0.80
Drainage high ground	3.30	Abstraction irrigation water	2.00
Drainage polder areas	2.60	Abstraction flushing water	2.00
Rainfall on the lake	0.90	Drainage to the sea	12.14
Locking, leakage	p.m.		
	16.94		16.94

IN (in 10^6 kg Cl^- per year)		**OUT** (in 10^6 kg Cl^- per year)	
Salt load river	1097	Total evacuation	2448
Drainage high grounds	130		
Drainage polder areas	900		
Rainfall on the lake	9		
Locking, leakage	212		
Diffusion	100		
	2448		2448

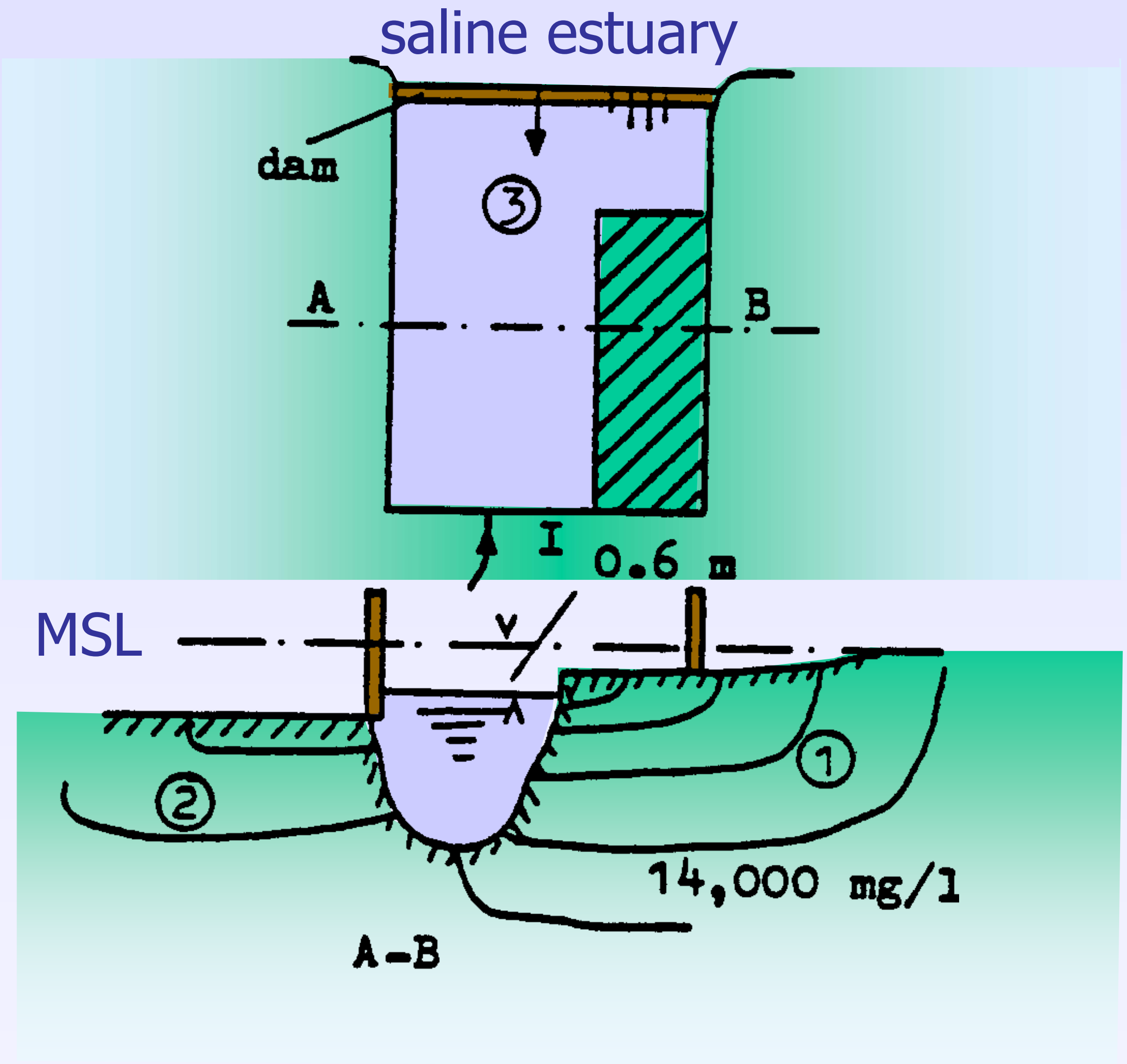
Case histories – IJssel lake

$$c_{\infty} = \frac{2448 \times 10^{6} \text{ kg } Cl^{-}}{(12.14 + 2.00 + 2.00) \times 10^{9} m^{3}}$$

$$= 152 \text{ mg } Cl^{-}/l$$

T= V/d=13E9/11.4E9=1.1 year

Case histories – Braakman



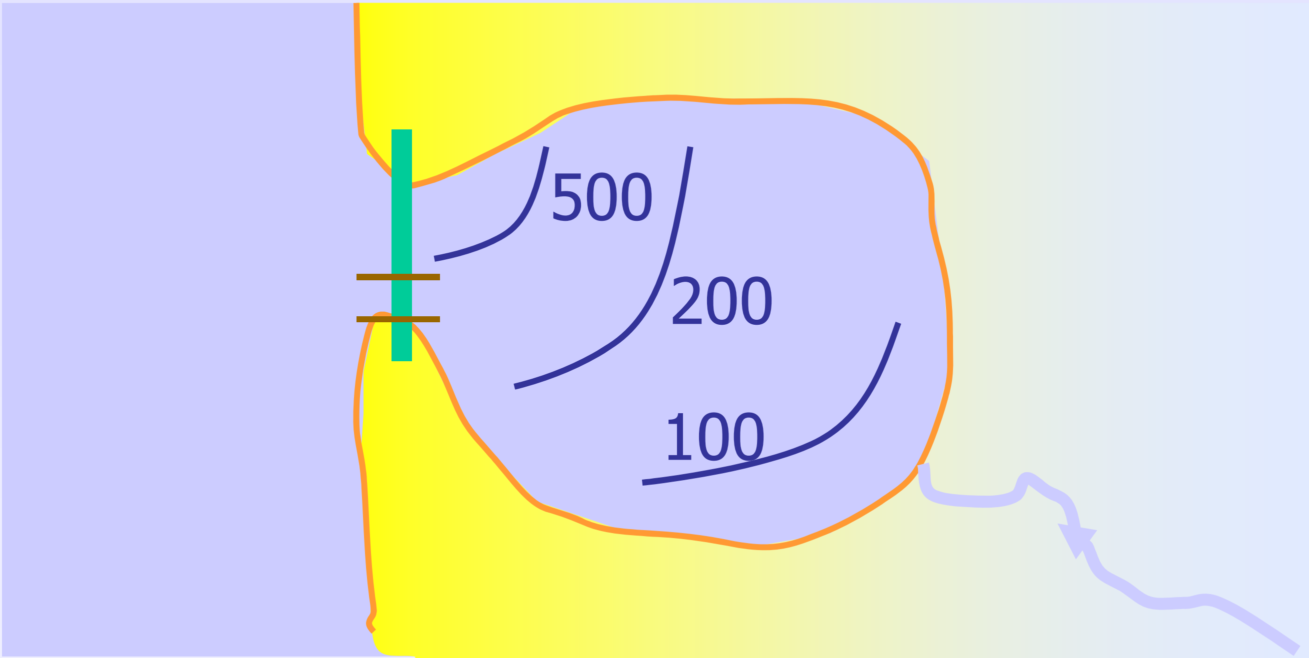
Case histories – Braakman

IN (in 10^6 m^3 per year)		**OUT** (in 10^6 m^3 per year)	
Inflow I from the south	3.00	Loss by seepage (2)	1.64
Rain on reservoir	1.05	Drainage to the sea	2.77
Ground water inflow (1)	1.09	Evaporation	0.90
Seepage under dam (3)	0.18		
	5.32		5.32

IN (in 10^6 kg Cl^- per year)		**OUT** (in 10^6 kg Cl^- per year)	
Inflow I from the south	0.3	Loss by seepage (2)	6.68
Rain on reservoir	0.02	Drainage to the sea	11.54
Ground water inflow (1)	15.34		
Seepage under dam (3)	2.56		
	18.22		18.22

$$c_\infty = \frac{18.22 \times 10^6 \text{ kg } Cl^-}{(1.64 + 2.77) \times 10^6 m^3} = 4100 \text{ mg } Cl^-/l$$

Case histories



Effect of embanking on the hydrological conditions

Embanking has repercussions in:

A. Hydrological effects

1. The longitudinal overland flow
2. The over-bank storage
3. The flooding of the strip between the channel and the dike

B. Morphologic effects

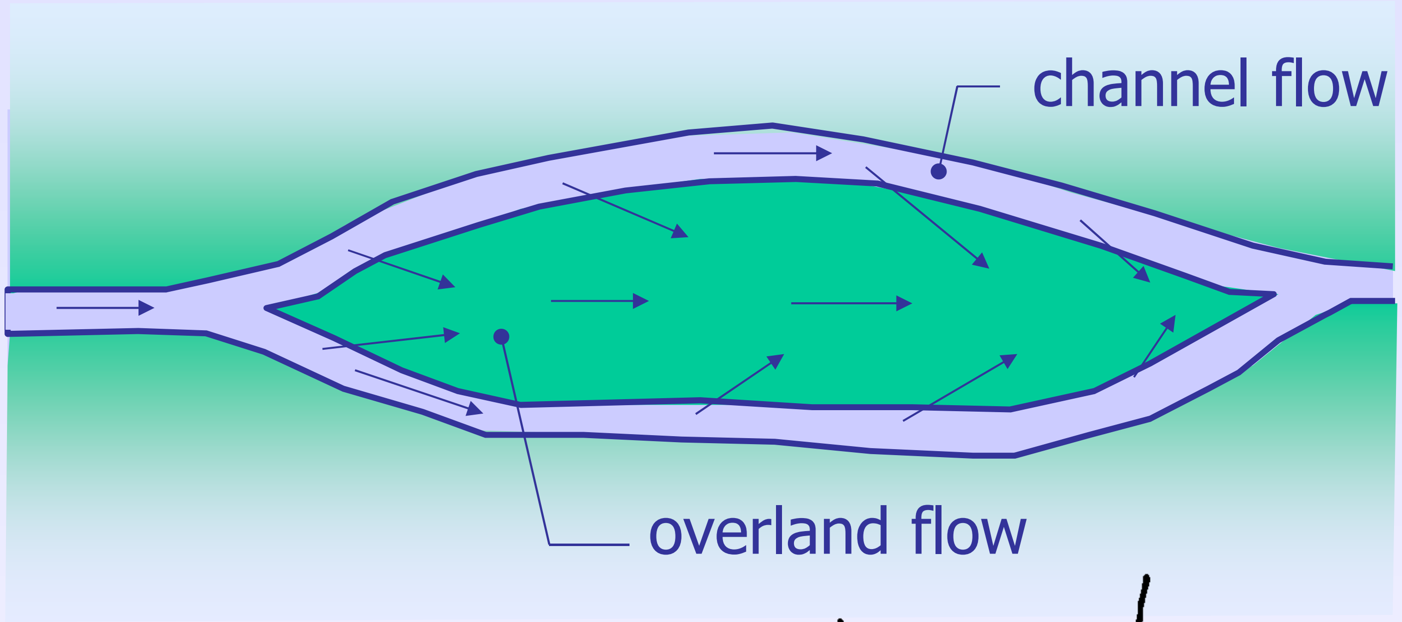
4. The necessity of river training
5. The natural process of delta building up
6. The position of the river bed

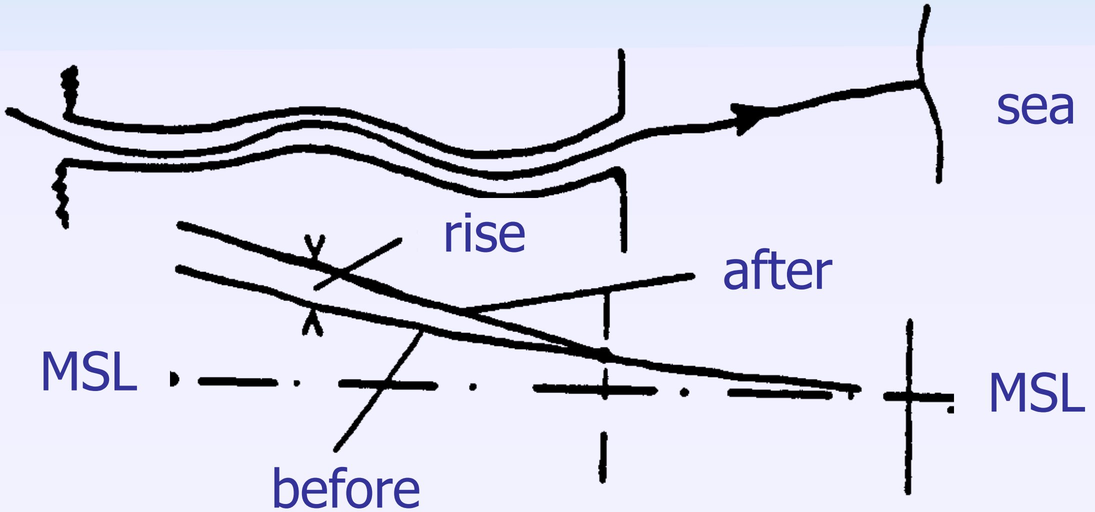
C. Environmental effects

7. The hygienic conditions of the land areas
8. The water management in the land areas
9. The cropping pattern and farm management

Hydrological effects

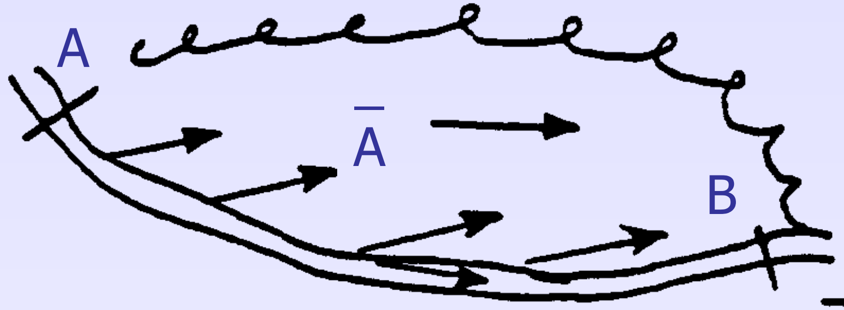
1. Longitudinal overland flow





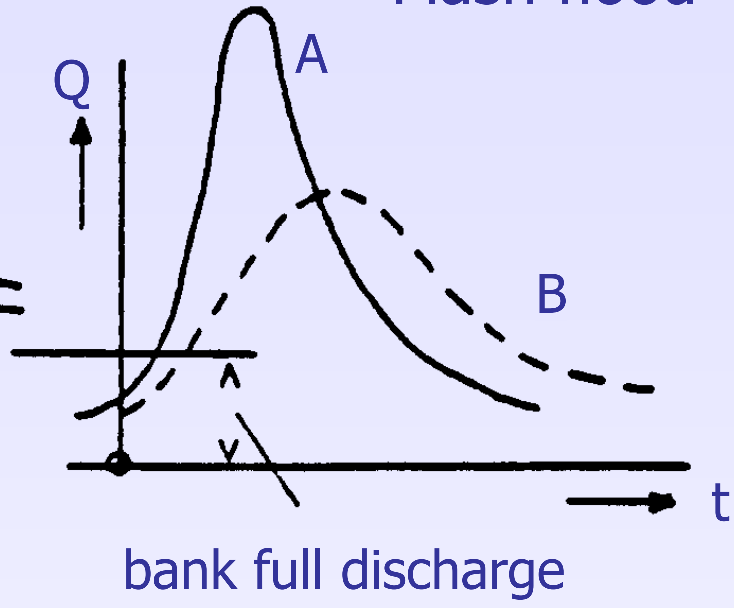
Hydrological effects

2. Overbank storage

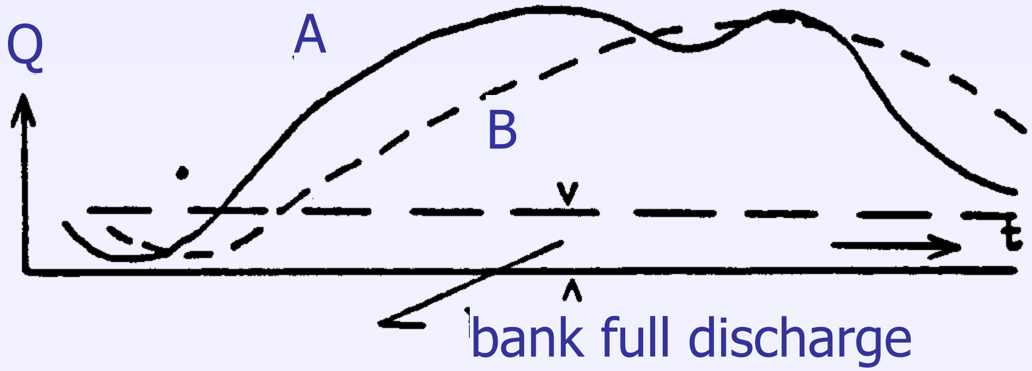


$$Q_{lat} = A\frac{dh}{dt}$$

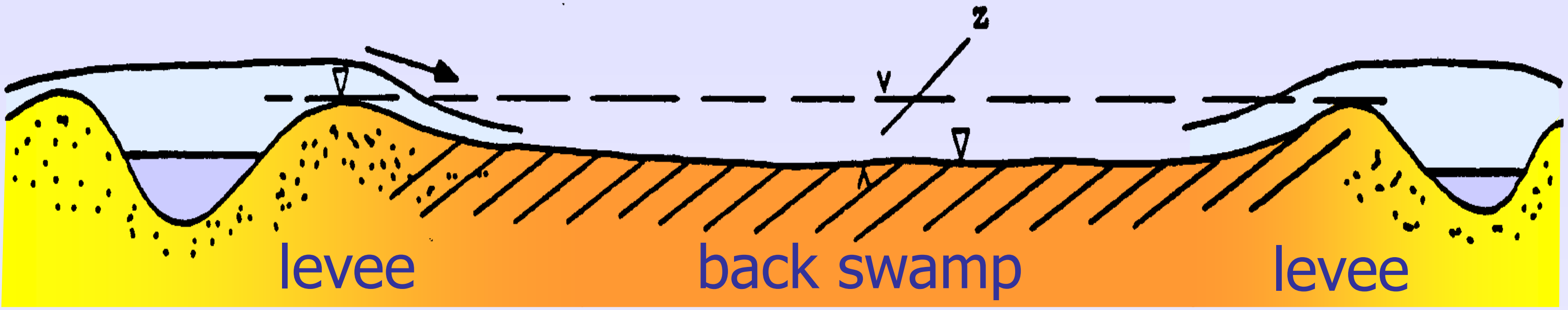
Flash flood

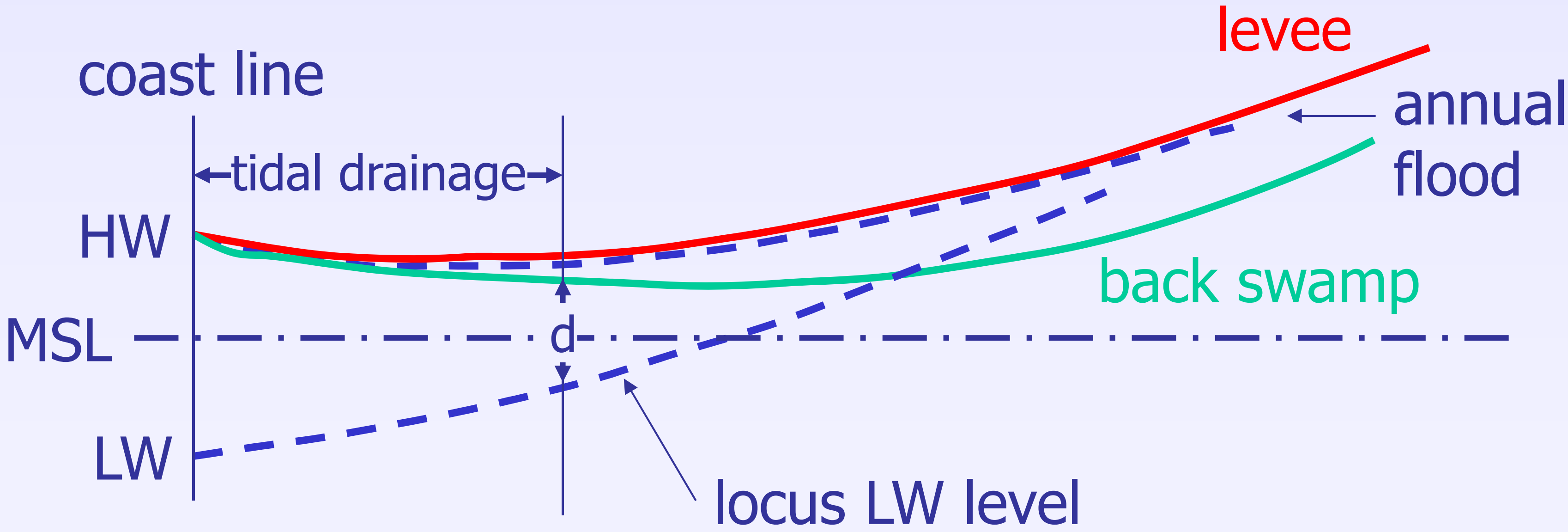


Gentle flood

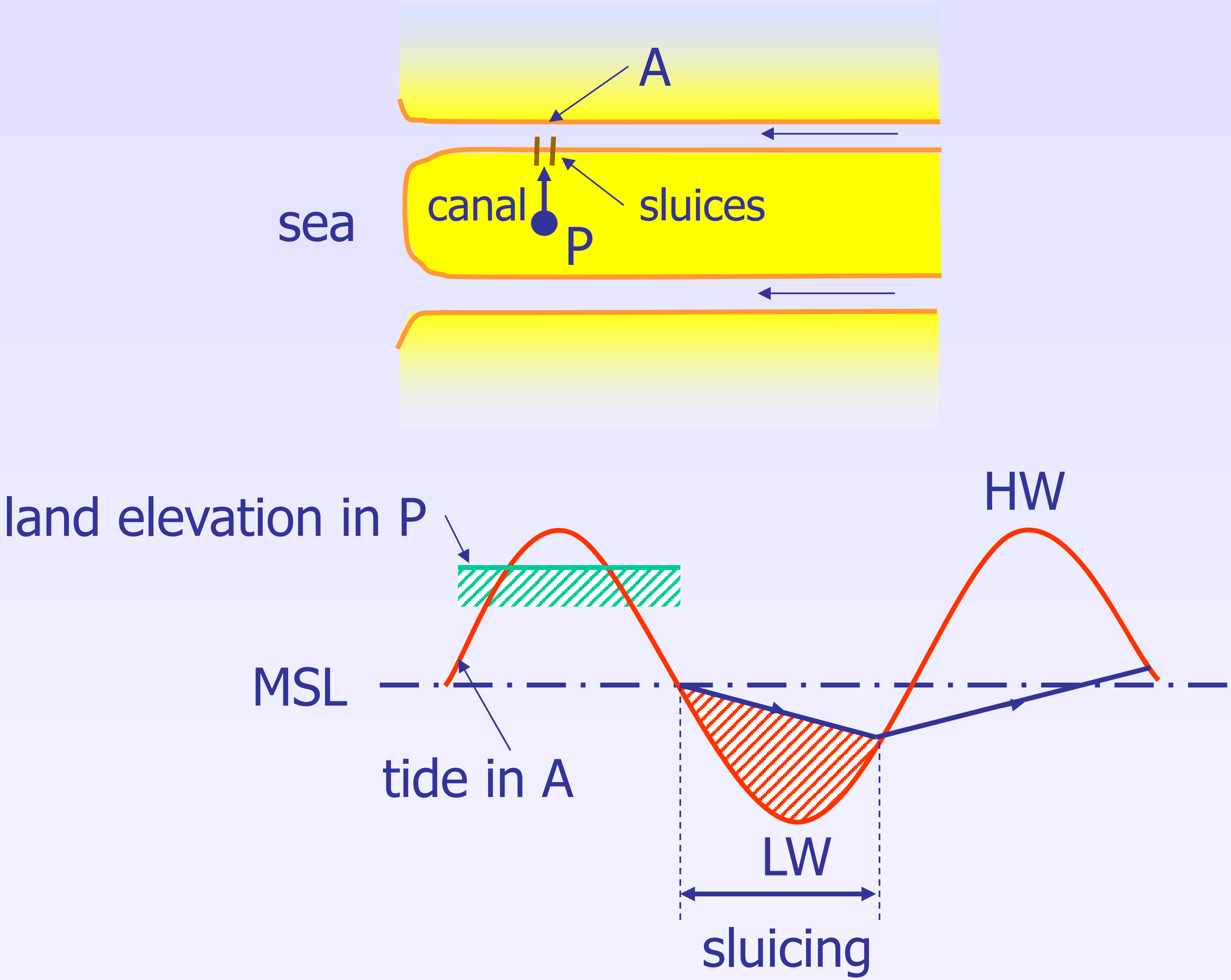


Drainage of level areas





Drainage of level areas



Hydrology of Catchments, Rivers and Delta's