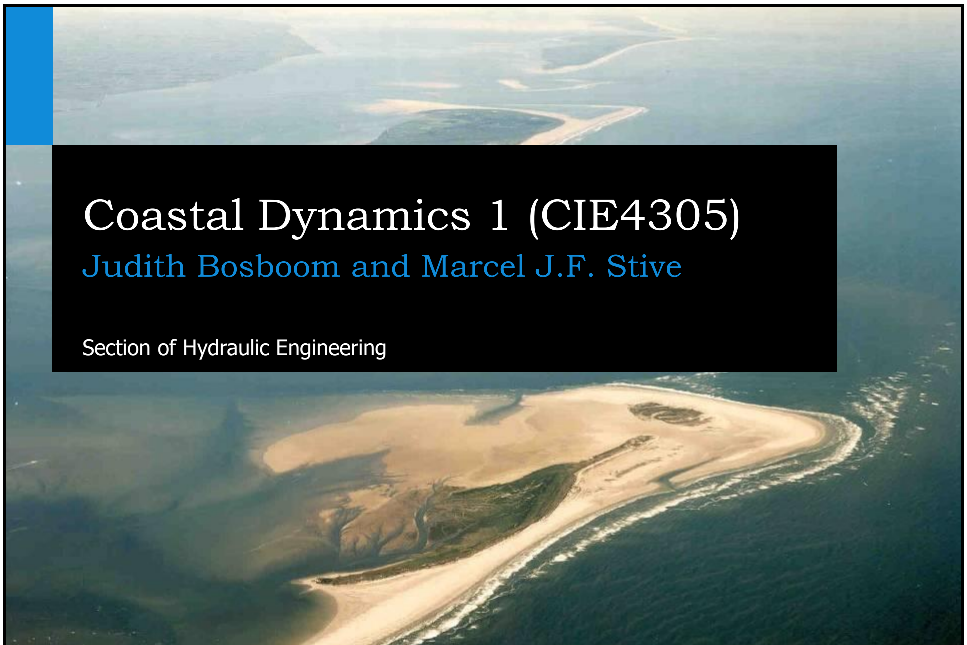


Coastal Dynamics 1 (CIE4305)

Judith Bosboom and Marcel J.F. Stive

Section of Hydraulic Engineering

9.

Coastal inlets and tidal basins

Coastal Dynamics 1

Contents

Coastal inlets and tidal basins

Chapter 9 of lecture notes

9-A Introduction

Wave versus tidal influence

Wave dominated features

- dynamic sandy coastal profile with bars and dunes
- beach slope dependent of wave characteristics

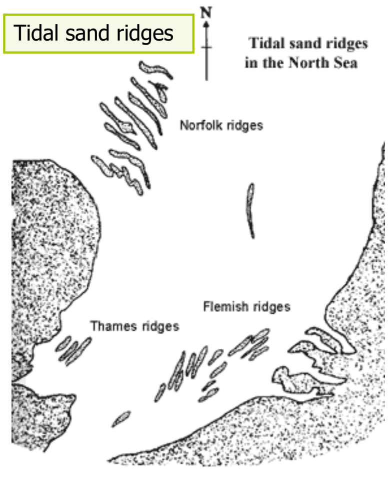
Tide dominated features

- tides smear beach morphology
- wide, low-gradient and muddy tidal flats
- salt marshes, mangroves
- tidal ridges

9-A Introduction

Wave and tidal influence

Tidal sand ridges

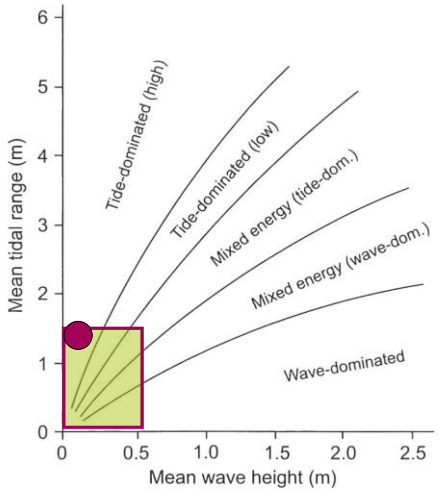


Dorset, UK

Wave formed spit and tidal deltas

9-A Introduction

Relative influence of waves and tide determines coastal features



- Tide-dominated coast can exist:
  - not only in macro-tidal areas
  - but also in a micro-tidal area where waves are low
- Convergence at low energy end of spectrum => small differences in tide or waves may result in different coastal character

From Hayes (1979) / Davis and Hayes (1984)

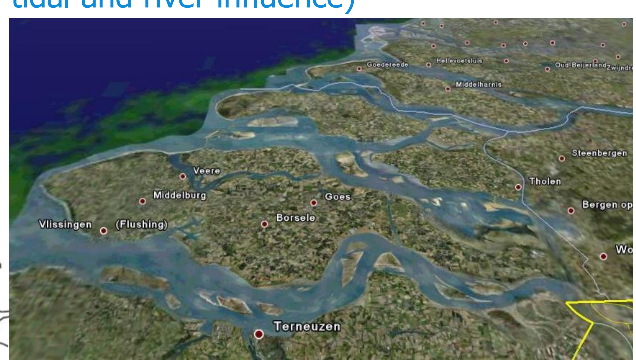
9-A Introduction

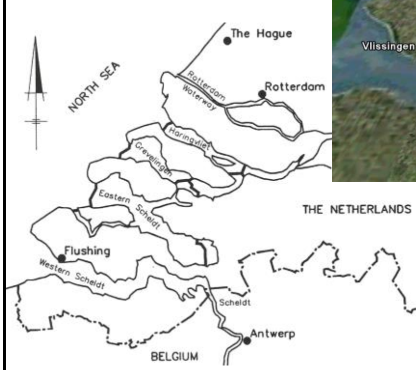
Physical systems considered

- Tidal basins and lagoons (tide dominant)
- Estuaries (mixed tidal and river dominance)
- Tidal rivers (tidal penetration but river dominates)

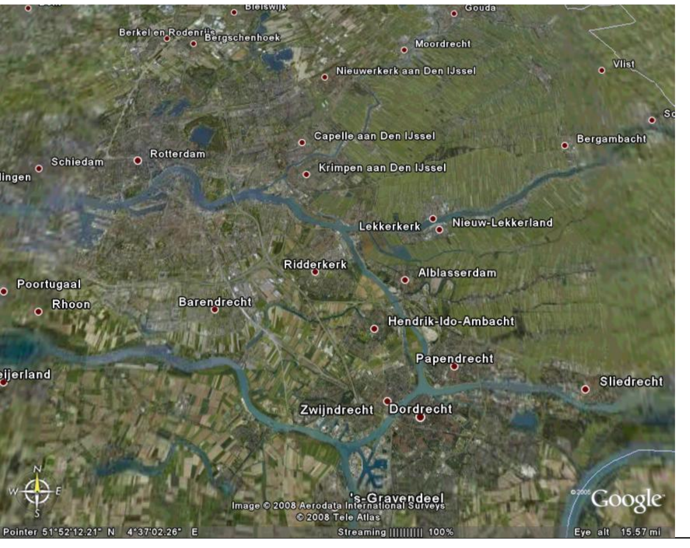
9-A Introduction
Tidal basins and lagoons (tide dominant)

9-A Introduction
Estuaries (mixed tidal and river influence)

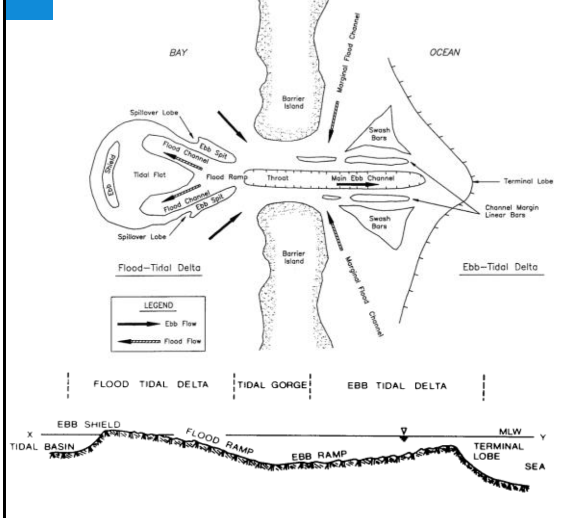




9-A Introduction
Tidal river (tidal penetration but river dominates)



9-A Introduction
Ebb-tidal delta, flood tidal delta, inlet and adjacent coast



Red Fish Pass, courtesy CERC

Note the distinct flood-tidal delta (e.g. US E-coast)

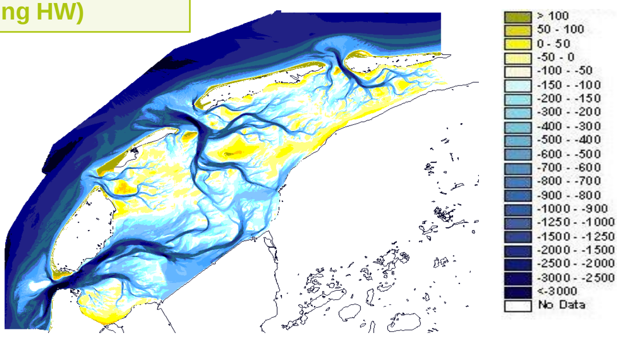
9-A Introduction

Or: flood delta covers entire basin (entire basin morphologically active)

e.g. Wadden Sea

Channels and flats (accomodating HW)

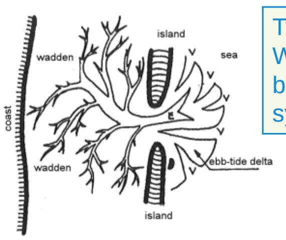
depth (cm)



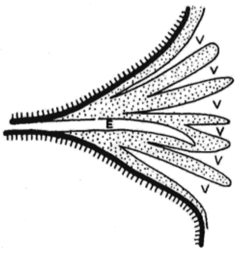
9-A Introduction

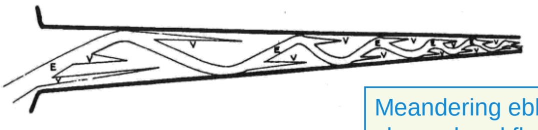
Van Veen's cartoons of different basin types

Typical Wadden Sea barrier inlet system



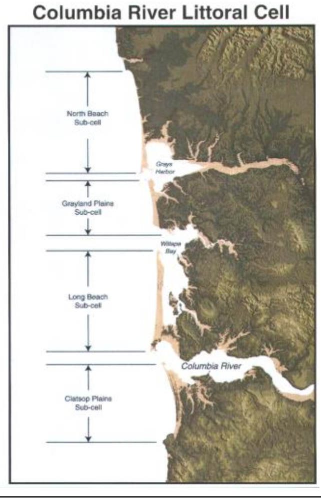
Wide estuary (e.g. Thames)

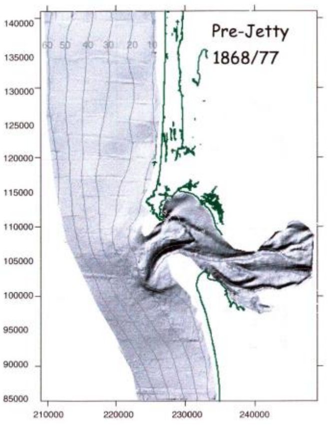




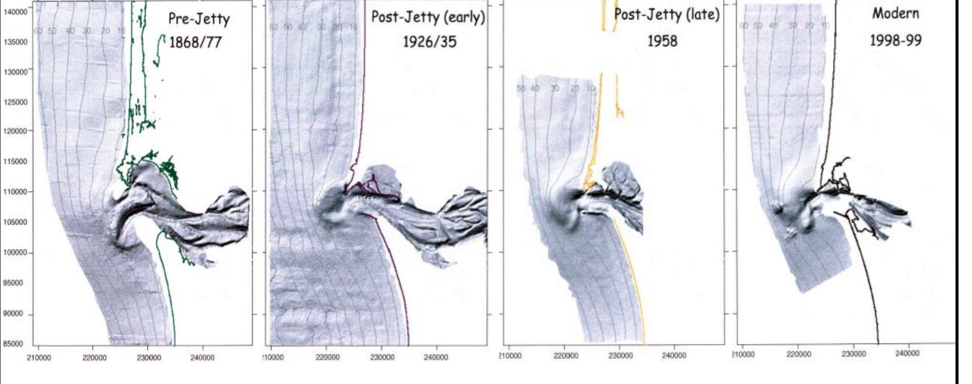
Meandering ebb (E) channel and flood chutes (V). E.g. Scheldt Estuary

9-A Introduction
Example of human influence (1)





9-A Introduction
Example human influence (2)



Coastal inlets and tidal basins

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A. Introduction
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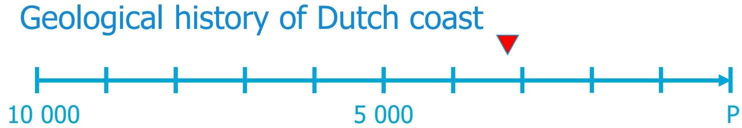
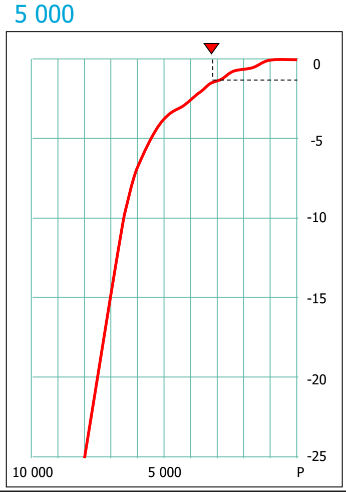
G. Case: Oosterschelde

9-B Adjacent (barrier) coast

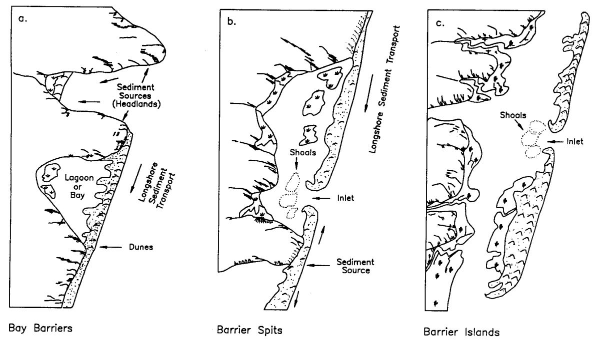
Geological history of Dutch coast





Year (BP)
3250
Sea-level (m)
- 2
Rate (m/100y)
+ 0.2

9-B Adjacent barrier coast



Cape Hatteras

Distinct flood delta

9-B Adjacent barrier coast

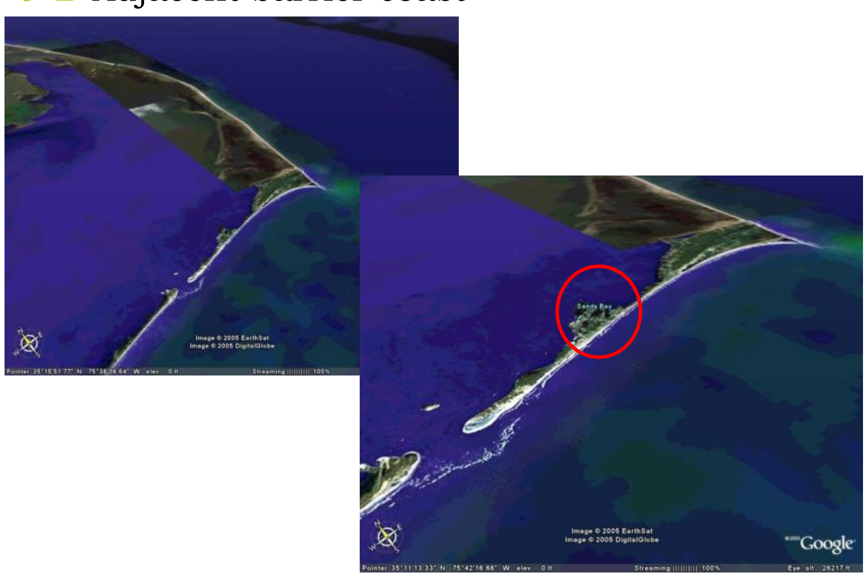
Pictures courtesy Brad Murray

9-B Adjacent barrier coast

Overwash

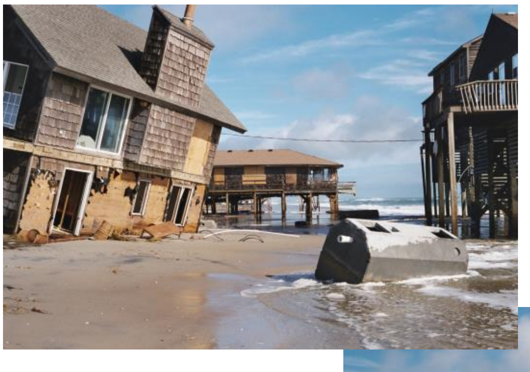
9-B Adjacent barrier coast

9-B Adjacent barrier coast



9-B Adjacent barrier coast

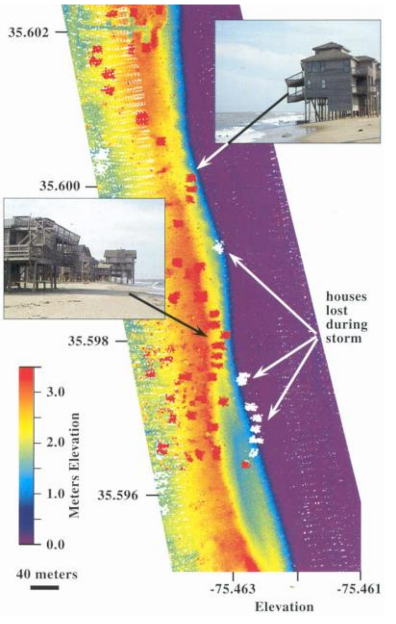
Breach due to Isabel, sept 18 2003 (picture sept 26)

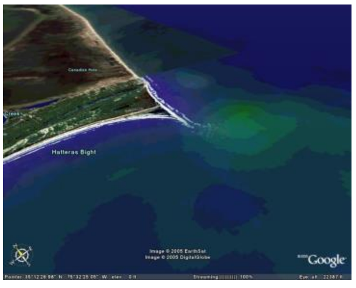


Rodanthe after Isabel

9-B Adjacent barrier coast

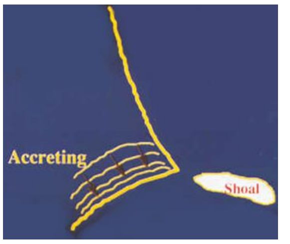
Lidar surveys of Rodanthe (NC) after hurricane Dennis



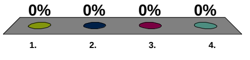


9-B Adjacent barrier coast

What is origin of the sediment contained in the shoal?



1. From southward longshore transport
2. From eastward longshore transport
3. ✓ From both directions
4. Abstain



Coastal inlets and tidal basins

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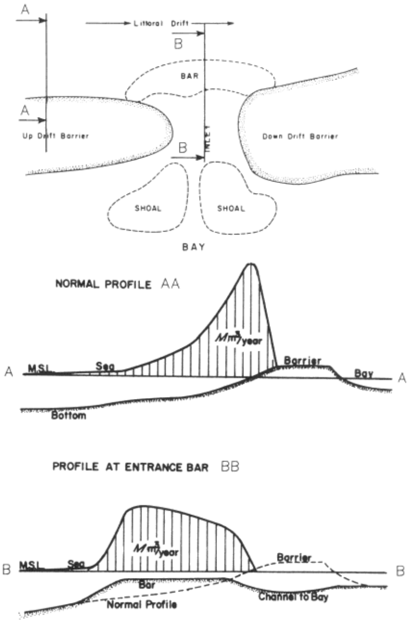
9-C Ebb-tidal delta
Littoral (longshore) drift

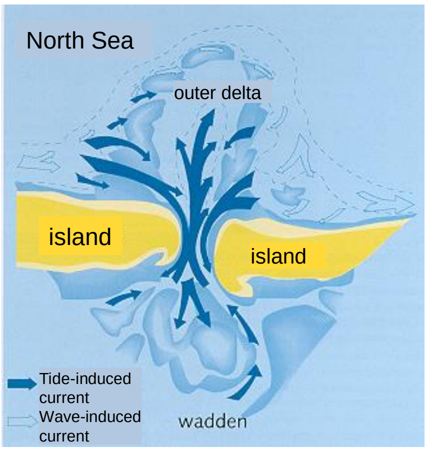
What is definition of volume of ebb-tidal delta?



9-C Ebb-tidal delta
Tide-induced and wave-induced currents

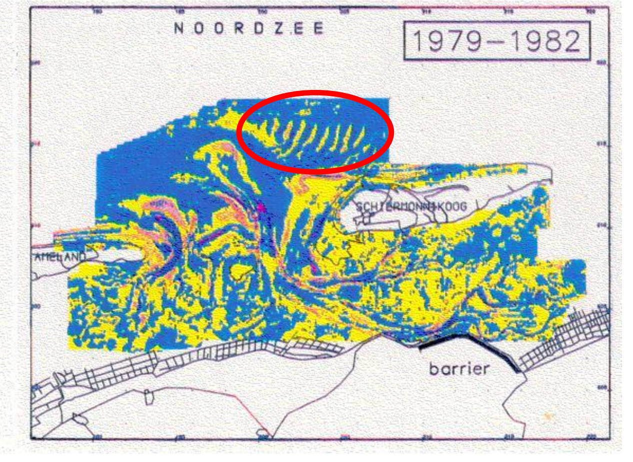
By-passing mechanisms:

1. Direct, wave-driven by-passing at ebb-tidal delta edge (under high waves): **"bar by-passing"**
2. Combination of tidal by-passing via the inlet and ebb-tidal delta and subsequent transport to downdrift side by high waves (as in 1.)



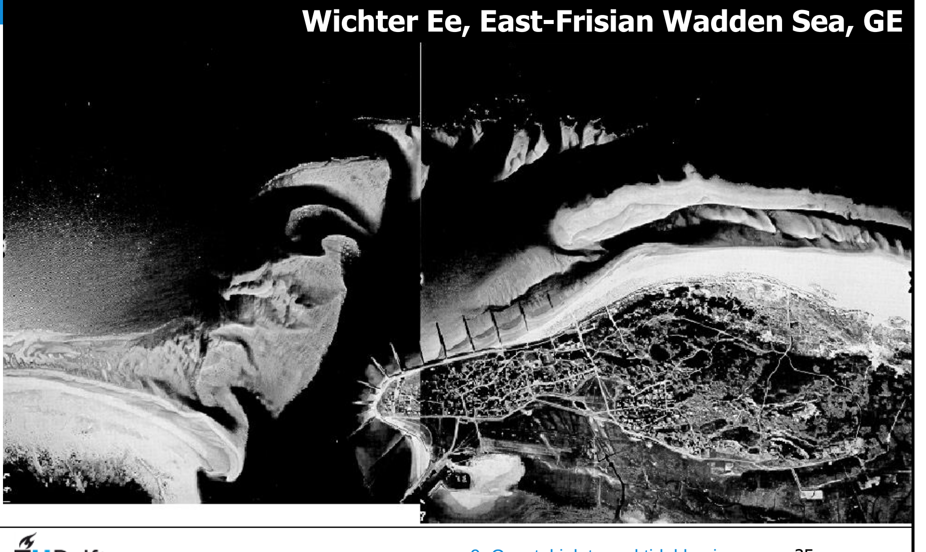
9-C Ebb-tidal delta

Bar by-passing (1)

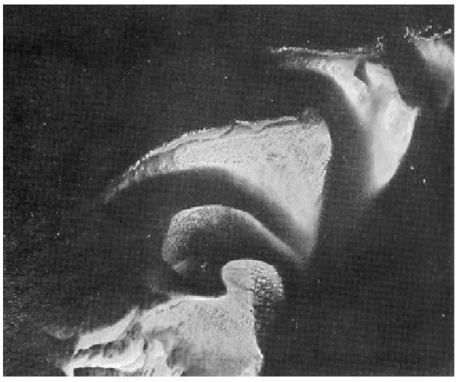


9-C Ebb-tidal delta

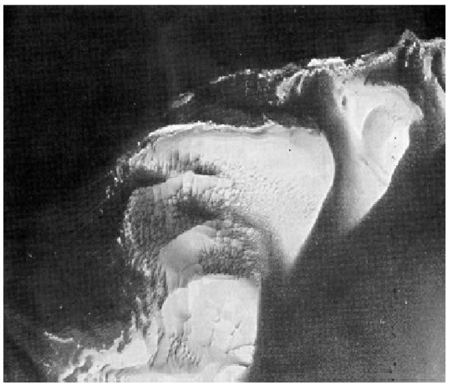
Bar by-passing (2)



9-C Ebb-tidal delta
Bar by-passing (3)

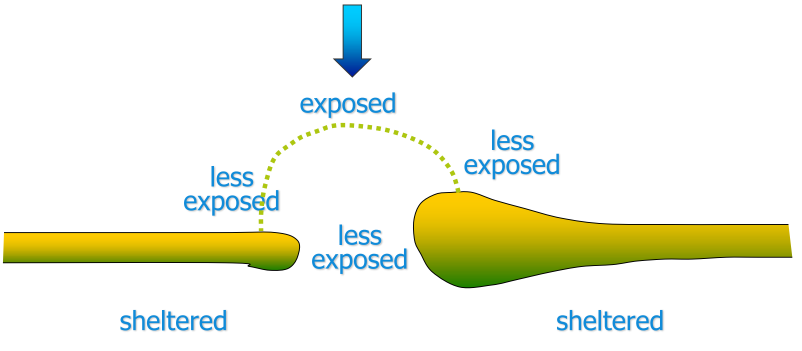


PRE-STORM

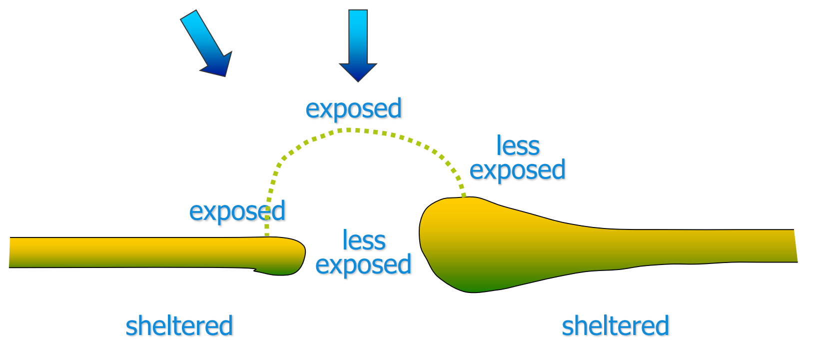


POST-STORM

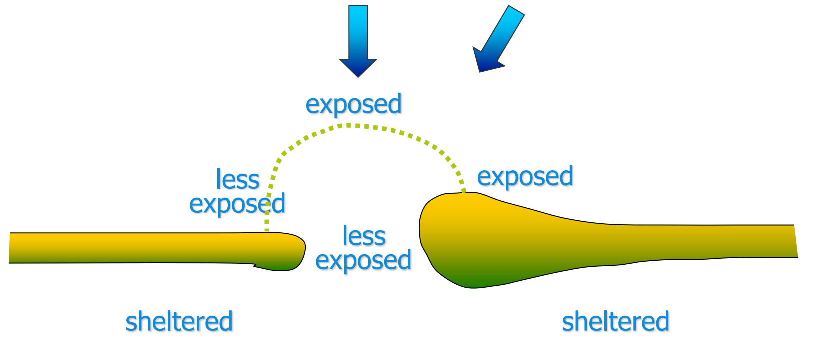
9-C Ebb-tidal delta
Wave exposure (normal incidence)



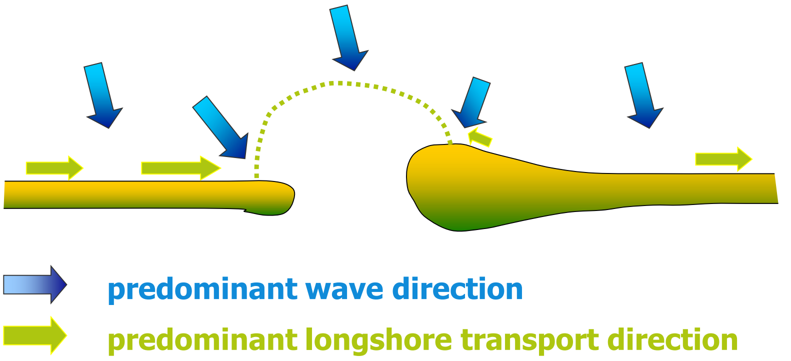
9-C Ebb-tidal delta
Wave exposure (oblique incidence)



9-C Ebb-tidal delta
Wave exposure (oblique incidence)

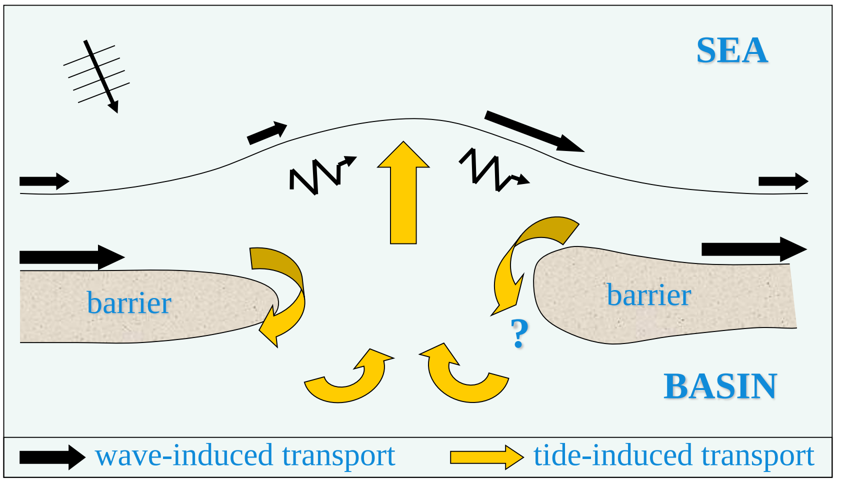


9-C Ebb-tidal delta
Drumstick shaped islands



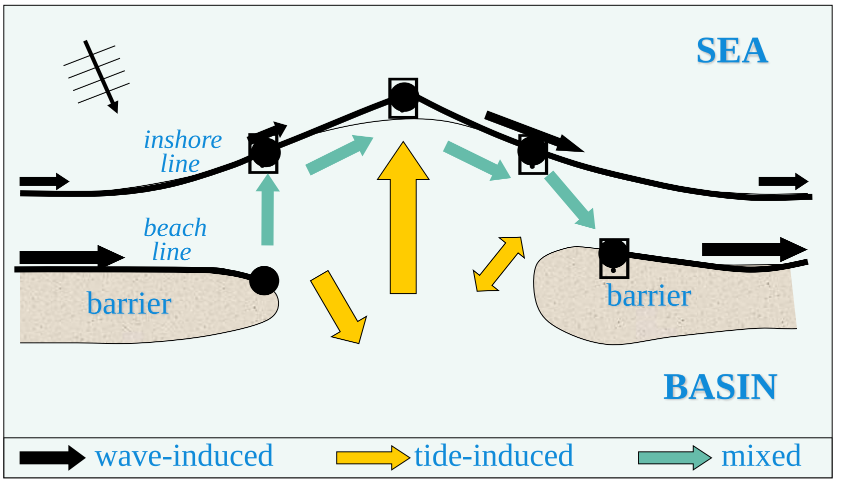
9-C Ebb-tidal delta

Conceptual model of sediment transport at inlet and ebb-tidal delta



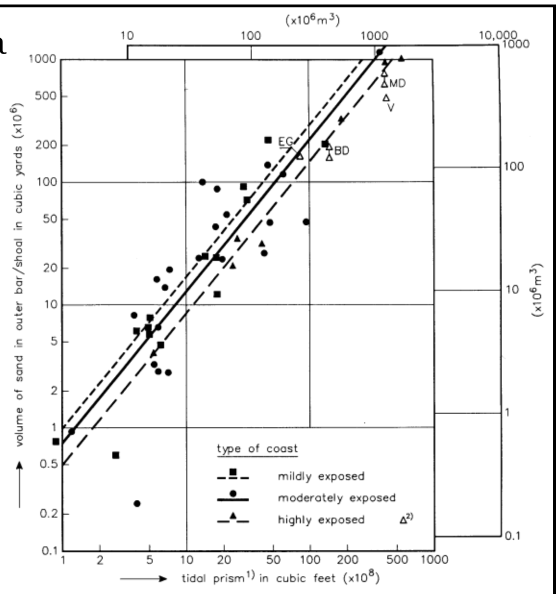
9-C Ebb-tidal delta

Schematized into a two-line approach



9-C Ebb-tidal delta

Empirical relationship for ebb-tidal delta volume



$V_{od} = c_{od} \; P^{1.23}$

1) springtide ior diurnal range
2) dutch Wadden Sea inlets

Coastal inlets and tidal basins

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G. Oosterschelde

9-D Inlet stability

Seasonal inlet: opens during typhoon season (through flash floods or breaching), closes during dry season

9-D Inlet stability

Topsail Island (NC) during Hurricane Fran (1996). A new inlet was cut across the barrier island

Before

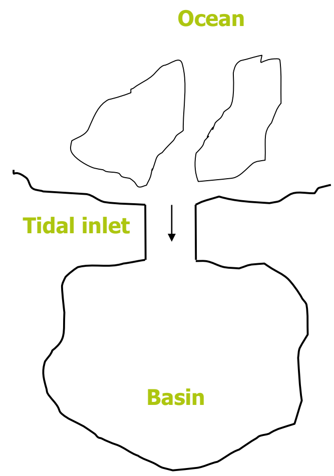
After

9-D Inlet stability

Empirical equilibrium cross-sectional area

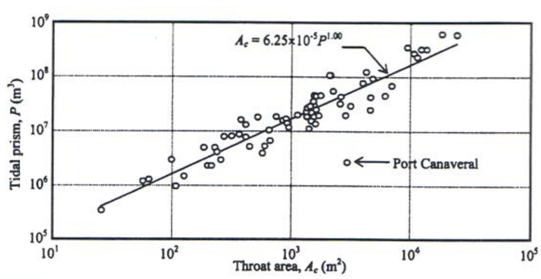
$$A_{eq} = CP^{q}$$

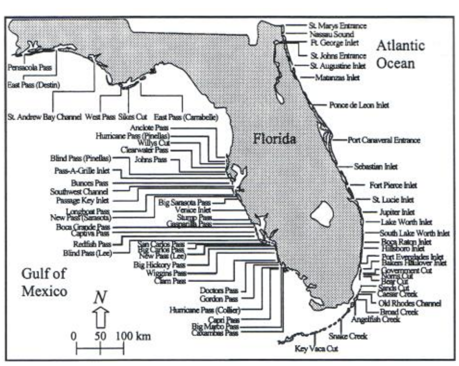
A = cross-sectional area (m^2)
P = generally spring tidal prism (m^3)
C = generally dimensional empirical parameter
q = dimensionless empirical parameter



9-D Inlet stability

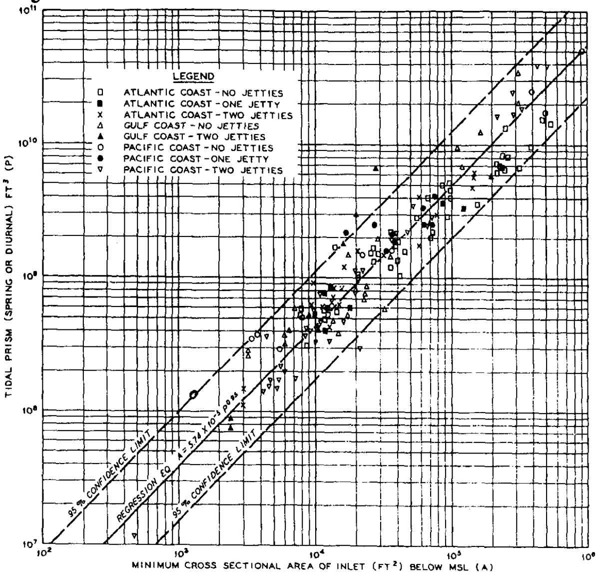
Powell et al. (2006)





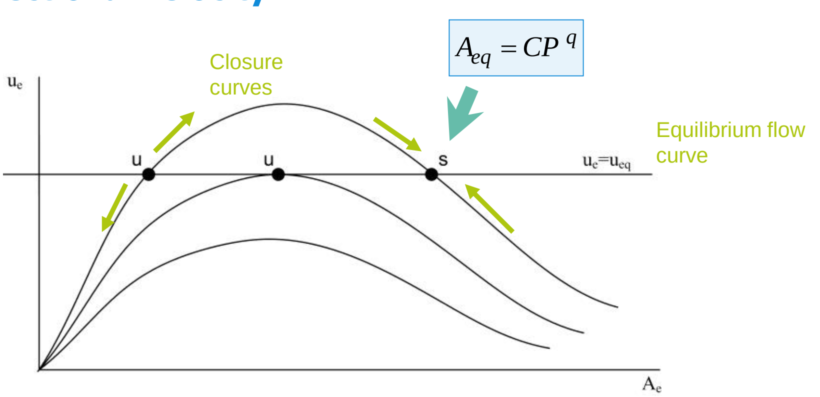
9-D Inlet stability

Jarrett (1976)



9-D Inlet stability

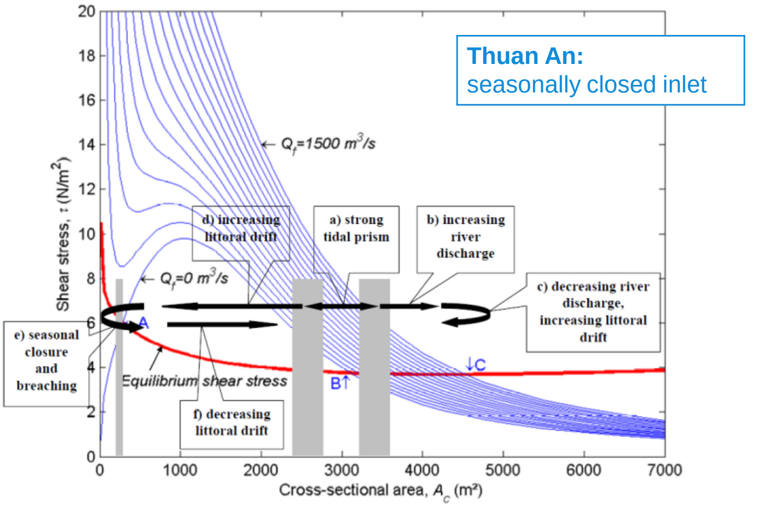
Escoffier's model for the equilibrium cross-sectional velocity



U => unstable equilibrium
S => stable equilibrium

9-D Inlet stability

The dependency of equilibrium on forcing processes



9-D Inlet stability

C and q according to Escoffier's model

$$P=\int_0^{\frac{1}{2}T} A_e u\,dt=\int_0^{\frac{1}{2}T} A_e\hat{u}\sin\left(\tfrac{2\pi}{T}t\right)dt=\frac{TA_e}{\pi}\hat{u} \;\Rightarrow\; \hat{u}_e=\frac{\pi P}{A_e T}$$

according to Escoffier: $\hat{u}_{eq}\approx 0.9\text{m/s}$ $\Rightarrow$

$$A_{eq}=\frac{\pi P}{\hat{u}_{eq}T}$$

$$A_{eq}=CP^q$$

with semi-diurnal tide (T = 44,700 s) and $\hat{u}_{eq}\approx 0.9$ m/s

C = 7.8 10^{-5} (m^{-1})
q = 1

Approach to inlet stability based on sediment transport considerations

Equilibrium condition **OUT = IN**:

- Ebb-tidal capacity of the entrance is large enough to flush out the imported sediment or:
- Annual mean ebb-tidal sediment flux (**OUT**) = the fraction of the littoral drift (alongshore transport) that is not bypassed and hence enters the inlet (**IN**).

OUT = IN

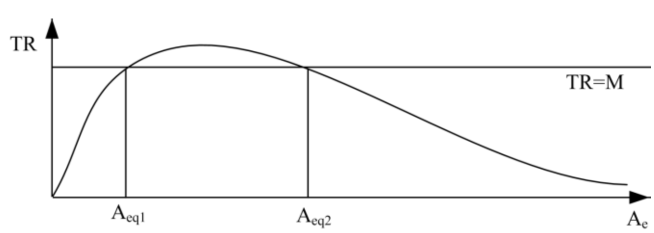
$$TR = k\hat{u}_e^n l^m$$

$$l = \alpha\sqrt{A_e}$$

$$\Rightarrow \underbrace{TR = k\alpha^m \hat{u}_e^n A_e^{m/2} \quad = \quad M}_{M = k\alpha^m \hat{u}_{eq}^n A_{eq}^{m/2}}$$

Relation to empirical stability criterion

$$M = k\alpha^m \hat{u}_{eq}^n A_{eq}^{m/2}$$



with:

$$\left.A_{eq} = \frac{\pi P}{\hat{u}_{eq} T}\right\} \quad C = \left(\frac{MT^n}{k\alpha^m \pi^n}\right)^{\left(\frac{2}{m-2n}\right)} \quad q = \frac{n}{n-m/2}$$

Clustering of data to obtain the constants C and q

Data sets must consist of inlets that show phenomenological similarity (i.e., have similar values for *k*, *n*, *m* and *α*) implying:

- **similar wave driven littoral drift;**
- **similar tide characteristics (form number, amplitude);**
- **similar grain size and grain density;**
- **similar shape of the cross-section.**

$$q = \frac{n}{n - m/2}$$

$$C = \left(\frac{MT^{n}}{k\alpha^{m}\pi^{n}} \right)^{\left(\frac{2}{m-2n}\right)}$$

Observations of the A-P relationship

Jarret's dataset (1976) with the shaded boxes not fulfilling our recommendations

Location	All inlets		No jetty or one jetty		Two jetties	
	C	*q*	*C*	*q*	*C*	*q*
All inlets	2.41 10-4	0.93	3.65 10-5	1.04	1.48 10-3	0.83
Atlantic coast	6.04 10-5	1.02	1.98 10-5	1.08	6.70 10-4	0.87
Gulf coast	9.03 10-4	0.84	6.94 10-4	0.86	1.43 10-3	0.81
Pacific coast	4.75 10-4	0.88	8.83 10-6	1.10	1.88 10-3	0.82

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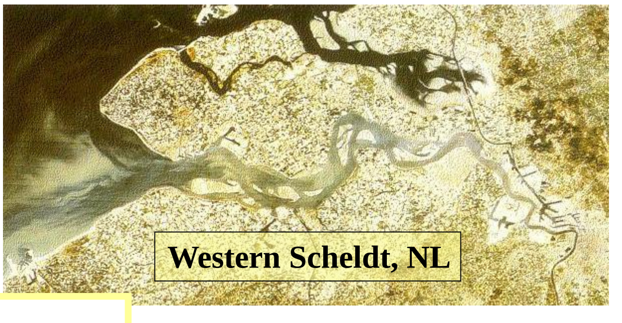
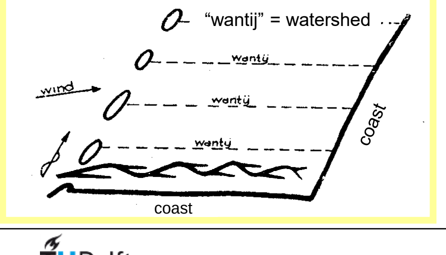
9-E Inner basin phenomena

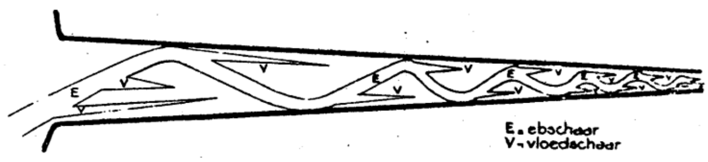
Funnel shaped basins of South Western delta

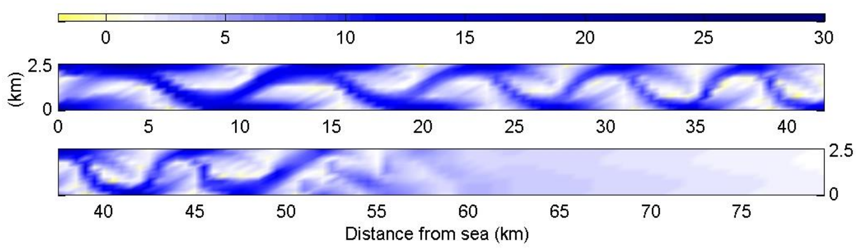




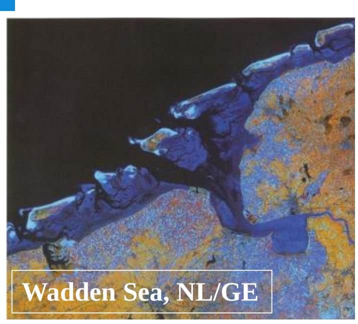
9-E Inner basin phenomena

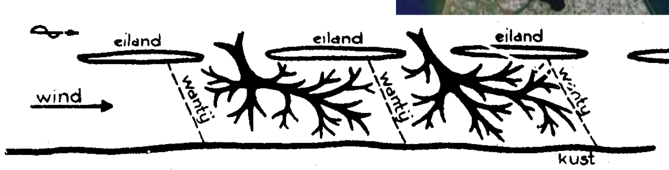
Numerical stability analysis (Hibma et al., 2000)





9-E Inner basin phenomena

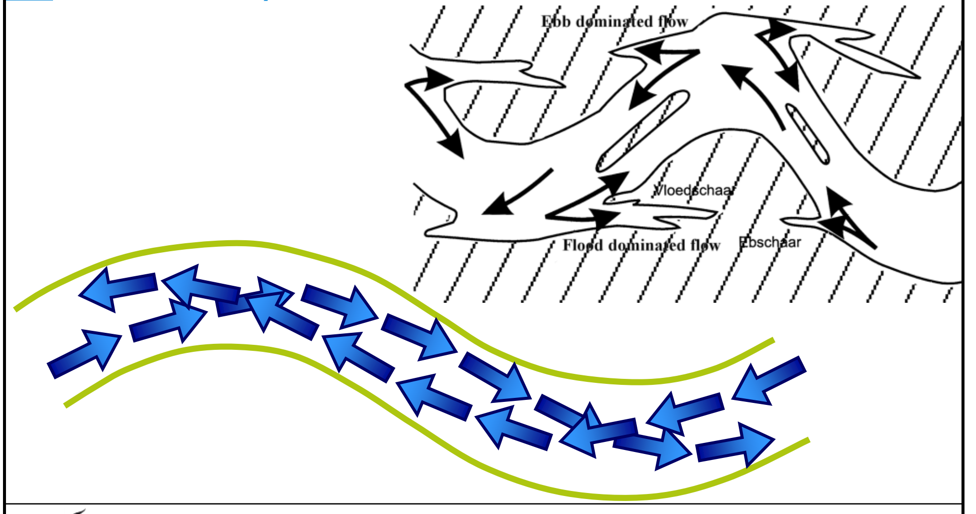




“wantij” = watershed
“eiland” = island
“kust” = coast

9-E Inner basin phenomena

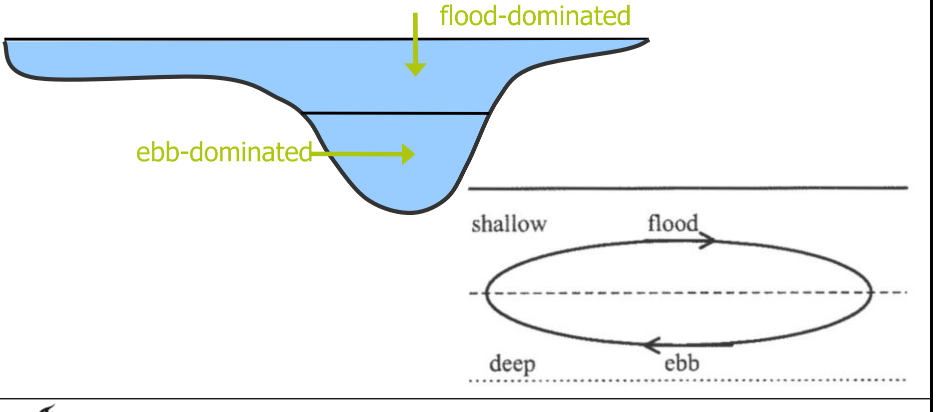
Inertia leads to overshoots (leading to ebb and especially flood chutes)



9-E Inner basin phenomena

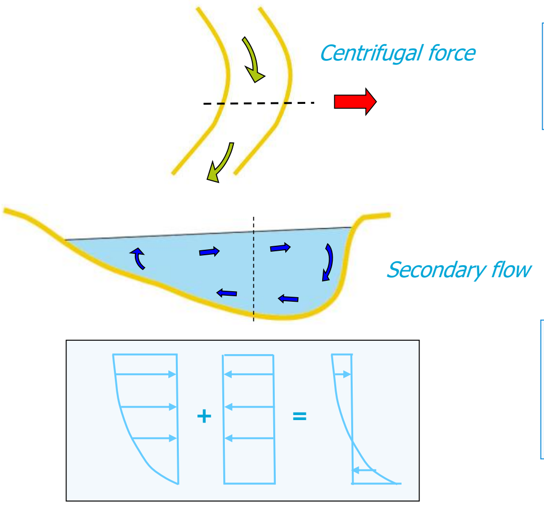
Bathymetry induced tide-averaged current

- Deep channels often ebb-dominated (tide-averaged flow in ebb-direction)
- Intertidal areas flood-dominated (tide-averaged flow in flood-direction)



9-E Inner basin phenomena

Secondary flow in a channel bend (see Chapter 5)

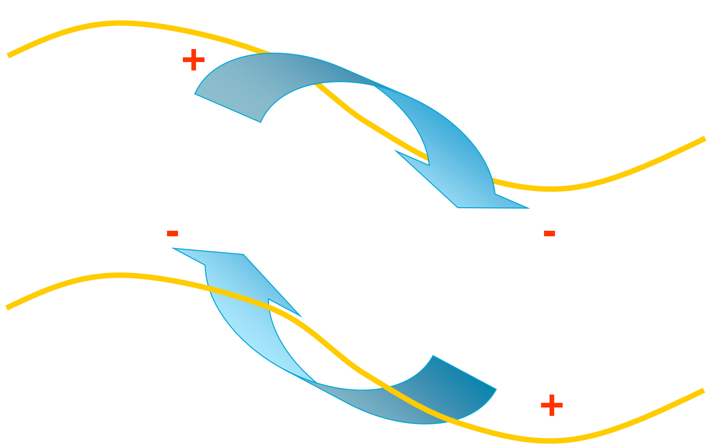


Effect Coriolis reverses sign from ebb to flood

Why is a river's outside bend deeper than the inside bend?

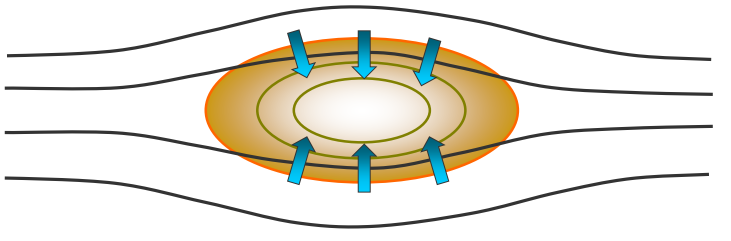
9-E Inner basin phenomena

Horizontal circulation in meandering flow channel due to water level differences in bends



9-E Inner basin phenomena

Curvature-induced secondary transport towards a shoal



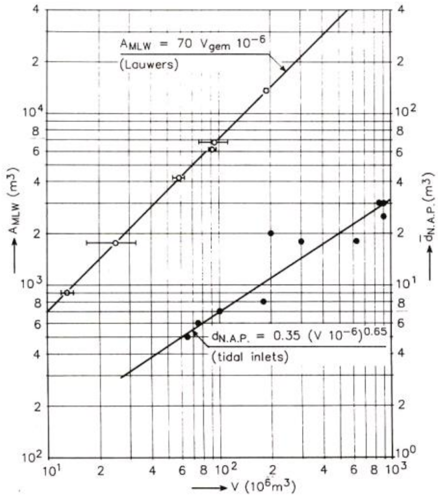
9-E Inner basin phenomena

Texel dam: 3D effects (curvature-induced) result in lee-side accretion, we thought! No, ebb currents feed sediment to this area, we found out later!

9-E Inner basin phenomena

Along channel cross-section also related to tidal prism in a fully developed inner basin

$$A_{MSL} = C_A P_{AB}$$

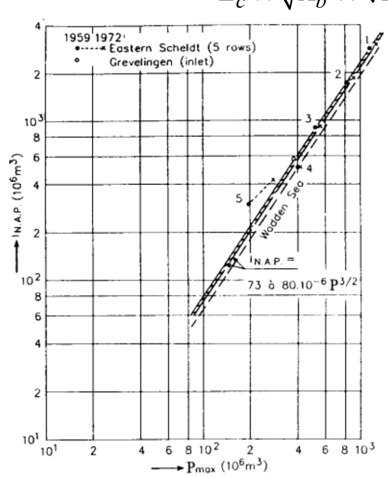


9-E Inner basin phenomena

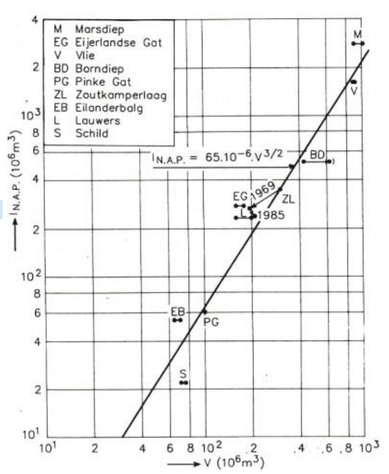
Total channel volume as a function of tidal prism

$$A_c \therefore P \qquad L_c \therefore \sqrt{A_b} \therefore \sqrt{P} \qquad \Rightarrow V_c = A_c L_c \propto P\sqrt{A_b} \propto P^{3/2}$$

Vc



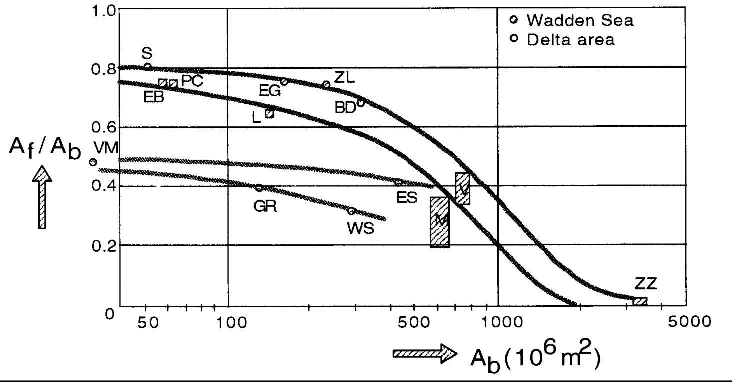
Vc



9-E Inner basin phenomena

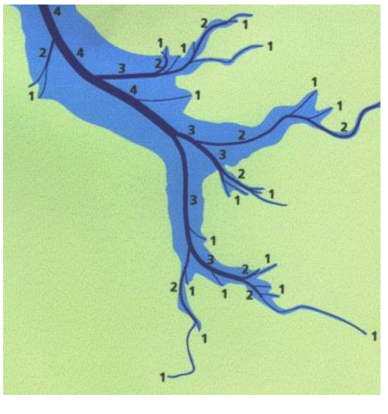
Relative flat area compared to basin area

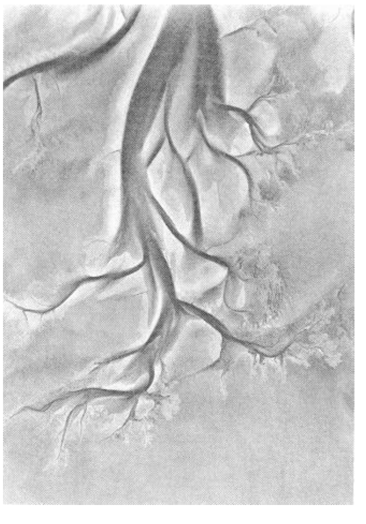
$$A_f = A_b - A_{ch} = A_b - \frac{V_c}{D_c} \approx A_b - \alpha \frac{P\sqrt{A_b}}{D_c} \approx A_b - \beta \frac{H_m}{D_c} A_b^{3/2}$$



9-E Inner basin phenomena

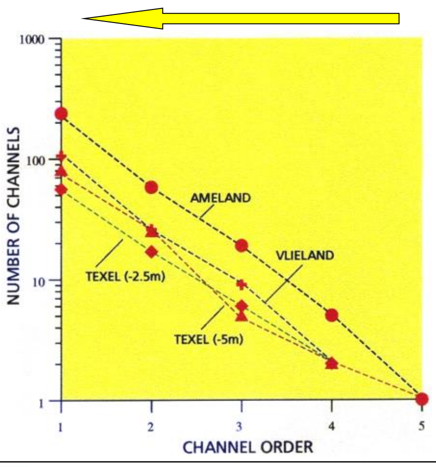
Channel hierarchy





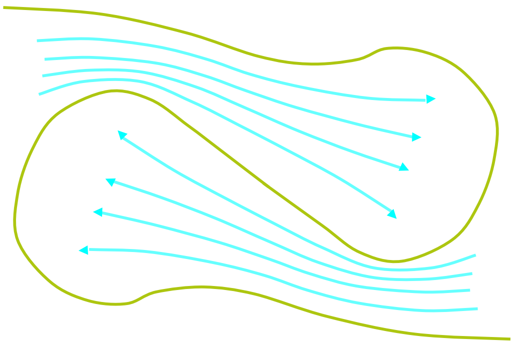
9-E Inner basin phenomena
Horton's hierarchical analysis

exponential increase indicates fractality

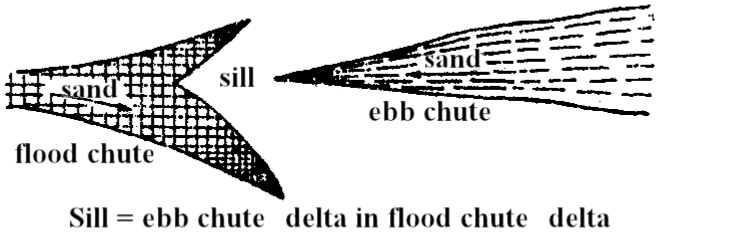


Cleveringa & Oost, 1999

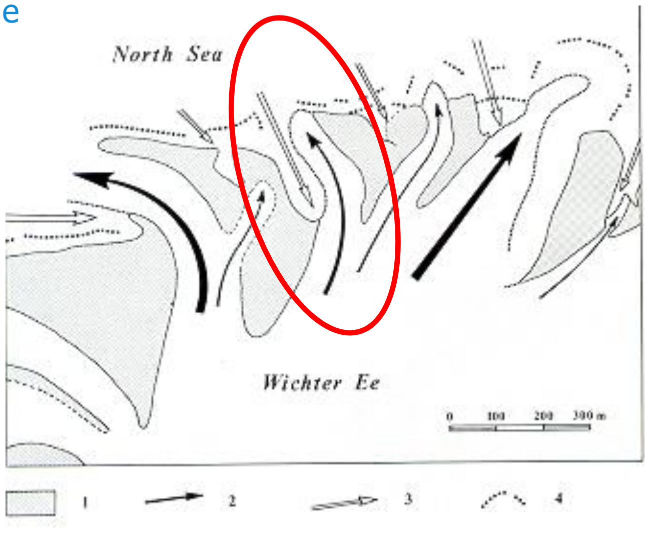
9-E Inner basin phenomena
Threshold formation



9-E Inner basin phenomena
Threshold formation



9-E Inner basin phenomena
Example



Coastal inlets and tidal basins

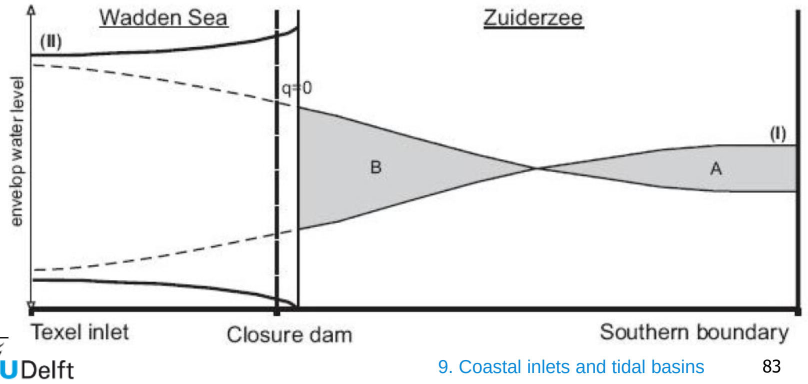
Chapter 9 of lecture notes

A. Introduction
B. Adjacent (barrier) coast
C. Ebb-tidal delta
D. Inlet stability
E. Inner basin phenomena
F. Net import or export
G. Case: Oosterschelde

9-Intermezzo Tidal prism

Only for a short basin (<<1/4L) with little intertidal storage: P = A x h [(mean) surface area x tidal range]

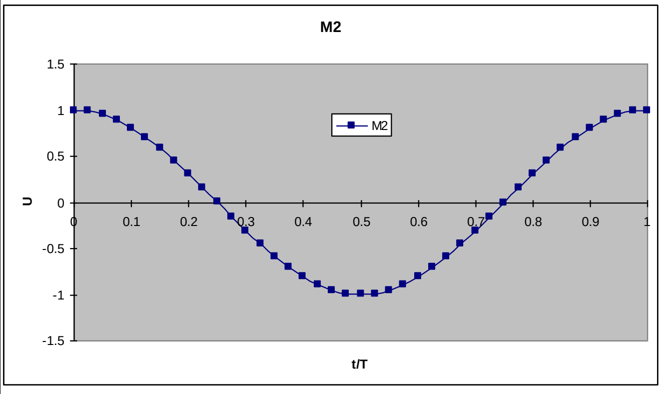
- The total amount of water that flows into a basin or out again with movement of the tide, excluding any fresh water flow
- The volume of water present between mean low and mean high tide



9-F Net import or export

Residual sediment transport M2

$s = cu^3$ $\quad u(t) = \hat{u}\cos(\omega t)$

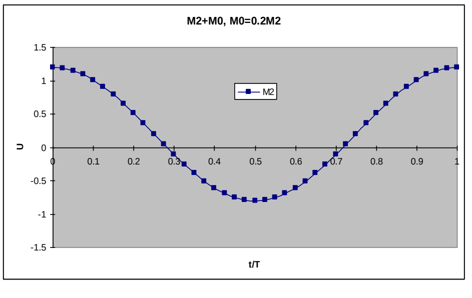


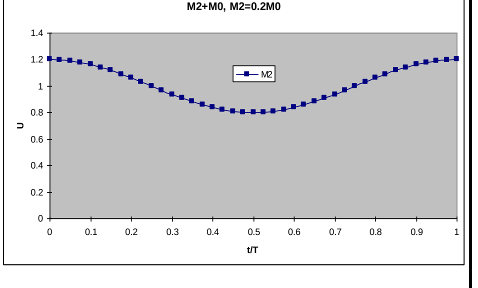
$$\overline{s} = \frac{1}{T}\int_0^T s(t)\,\mathrm{d}t = 0$$

9-F Net import or export

Residual sediment transport M0+M2

$s = cu^3$ $\quad u(t) = u_0 + \hat{u}_{M2}\cos(\omega_{M2} t)$

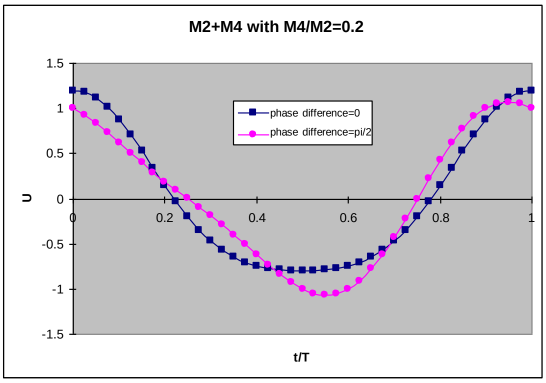




$$\overline{s} = cu_0^3 + \frac{3}{2}c\hat{u}_{M2}{}^2 u_0$$

9-F Net import or export
Residual sediment transport M2+M4

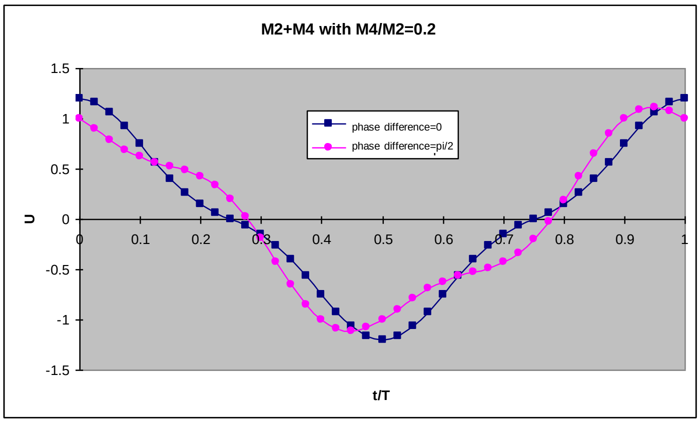
$s = cu^3 \qquad u(t) = \hat{u}_{M2}\cos(\omega t) + \hat{u}_{M4}\cos\left(2\omega t - \phi\right)$



$$\overline{s} = \frac{3}{4} c\hat{u}_{M2}{}^2\hat{u}_{M4}\cos\phi$$

9-F Net import or export
Residual sediment transport M2+M6

$s=cu^3 \qquad u(t) = \hat{u}_{M2}\cos(\omega t) + u_{M6}\cos\left(3\omega t - \phi\right)$



$$\overline{s} = 0$$

9-F Net import or export

Residual sediment transport

Van de Kreeke & Robaczewska (1993)

$$s = cu^3$$

$$u(t) = u_0 + \hat{u}_{M2}\cos(\omega_{M2}t) + \sum_i \hat{u}_i \cos(\omega_i t - \varphi_i)$$

$$\frac{\overline{s}}{c\hat{u}_{M2}^{\;3}} = \frac{3}{2}\frac{u_0}{\hat{u}_{M2}} + \frac{3}{4}\frac{u_{M4}}{\hat{u}_{M2}}\cos\varphi_{M4-2} + \frac{3}{2}\frac{\hat{u}_{M4}}{\hat{u}_{M2}}\frac{\hat{u}_{M6}}{\hat{u}_{M2}}\cos\left(\varphi_{M4-2} - \varphi_{M6-2}\right)$$

- In addition to the main component of tidal flow M2, the residual flow (M0) and the overtides M4 and M6 are important
- The phase lags between the overtides and M2 are important

What if residual flow is not small?

$\frac{<S>}{fu_{M2}^3} = \frac{3}{2}\varepsilon_{M0}$	M_0, M_2
$+\frac{3}{4}\varepsilon_{M4}\cos\beta$	M_4, M_2
$+\frac{3}{2}\varepsilon_{M4}\varepsilon_{M6}\cos(\beta-\gamma)$	M_4, M_6, M_2
$+\frac{3}{2}\varepsilon_{S2}\varepsilon_{MS4}\cos(\alpha_1-\alpha_3)$	S_2, MS_4, M_2
$+\frac{3}{2}\varepsilon_{N2}\varepsilon_{MN4}\cos(\alpha_2-\alpha_4)$	N_2, MN_4, M_2
$+\frac{3}{2}\varepsilon_{K1}\varepsilon_{O1}\cos(\alpha_5+\alpha_6)$	K_1, O_1, M_2
$+\varepsilon_{M0}^3$	M_0
$+\frac{3}{2}\varepsilon_{M0}\varepsilon_{S2}^2$	M_0, S_2
$+\frac{3}{2}\varepsilon_{M0}\varepsilon_{N2}^2$	M_0, N_2
$+\frac{3}{2}\varepsilon_{M0}\varepsilon_{M4}^2$	M_0, M_4
$+\frac{3}{2}\varepsilon_{M0}\varepsilon_{MS4}^2$	M_0, MS_4
$+\frac{3}{2}\varepsilon_{M0}\varepsilon_{MN4}^2$	M_0, MN_4
$+\frac{3}{2}\varepsilon_{M0}\varepsilon_{M6}^2$	M_0, M_6
$+\frac{3}{2}\varepsilon_{M0}\varepsilon_{K1}^2$	M_0, K_1
$+\frac{3}{2}\varepsilon_{M0}\varepsilon_{O1}^2$	M_0, O_1
$+\frac{3}{4}\varepsilon_{MS4}\cos(\Delta\sigma_1 t-\alpha_3)$	MS_4, M_2
$+\frac{3}{4}\varepsilon_{MN4}\cos(\Delta\sigma_2 t+\alpha_4)$	MN_4, M_2
$+3\varepsilon_{S2}\varepsilon_{M0}\cos(\Delta\sigma_1 t-\alpha_1)$	S_2, M_0, M_2
$+\frac{3}{2}\varepsilon_{S2}\varepsilon_{M4}\cos(\Delta\sigma_1 t-\alpha_1+\beta)$	S_2, M_4, M_2
$+\frac{3}{2}\varepsilon_{S2}\varepsilon_{MN4}\cos((\Delta\sigma_1+\Delta\sigma_2)t-\alpha_1+\alpha_4)$	S_2, MN_4, M_2
$+3\varepsilon_{N2}\varepsilon_{M0}\cos(\Delta\sigma_2 t+\alpha_2)$	N_2, M_0, M_2
$+\frac{3}{2}\varepsilon_{N2}\varepsilon_{M4}\cos(\Delta\sigma_2 t+\alpha_2-\beta)$	N_2, M_4, M_2
$+\frac{3}{2}\varepsilon_{N2}\varepsilon_{MS4}\cos[(\Delta\sigma_1+\Delta\sigma_2)t+\alpha_2-\alpha_3]$	N_2, MS_4, M_2
$+\frac{3}{2}\varepsilon_{M6}\varepsilon_{MS4}\cos(\Delta\sigma_1 t-\alpha_3+\gamma)$	M_6, MS_4, M_2
$+\frac{3}{2}\varepsilon_{M6}\varepsilon_{MN4}\cos(\Delta\sigma_2 t+\alpha_4-\gamma)$	M_6, MS_4, M_2
$+\frac{3}{4}\varepsilon_{K1}^2\cos(2\Delta\sigma_3 t-2\alpha_5)$	K_1, M_2
$+\frac{3}{4}\varepsilon_{O1}^2\cos(2\Delta\sigma_3 t+2\alpha_6)$	O_1, M_2
$+3\varepsilon_{M0}\varepsilon_{S2}\varepsilon_{N2}\cos((\Delta\sigma_1+\Delta\sigma_2)t-\alpha_1+\alpha_2)$	M_0, S_2, N_2
$+3\varepsilon_{M0}\varepsilon_{M4}\varepsilon_{MS4}\cos(\Delta\sigma_1 t-\alpha_3+\beta)$	M_0, M_4, MS_4
$+3\varepsilon_{M0}\varepsilon_{M4}\varepsilon_{MN4}\cos(\Delta\sigma_2 t+\alpha_4-\beta)$	M_0, M_4, MN_4
$+3\varepsilon_{M0}\varepsilon_{MS4}\varepsilon_{MN4}\cos((\Delta\sigma_1+\Delta\sigma_2)t-\alpha_3+\alpha_4)$	M_0, MS_4, MN_4
$+3\varepsilon_{M0}\varepsilon_{K1}\varepsilon_{O1}\cos(2\Delta\sigma_3 t-\alpha_5+\alpha_6)$	M_0, K_1, O_1
$+\frac{3}{2}\varepsilon_{S2}\varepsilon_{N2}\varepsilon_{M4}\cos[(\Delta\sigma_1-\Delta\sigma_2)t-\alpha_1-\alpha_2+\beta]$	S_2, N_2, M_4
$+\frac{3}{2}\varepsilon_{S2}\varepsilon_{N2}\varepsilon_{MS4}\cos(\Delta\sigma_2 t+\alpha_1+\alpha_2-\alpha_3)$	S_2, N_2, MS_4
$+\frac{3}{2}\varepsilon_{S2}\varepsilon_{N2}\varepsilon_{MN4}\cos(\Delta\sigma_1 t-\alpha_1-\alpha_2+\alpha_4)$	S_2, N_2, MN_4
$+\frac{3}{2}\varepsilon_{S2}\varepsilon_{M4}\varepsilon_{M6}\cos(\Delta\sigma_1 t-\alpha_1-\beta+\gamma)$	S_2, M_4, M_6
$+\frac{3}{2}\varepsilon_{S2}\varepsilon_{MS4}\varepsilon_{M6}\cos(2\Delta\sigma_1 t-\alpha_1-\alpha_3+\gamma)$	S_2, MS_4, M_6
$+\frac{3}{2}\varepsilon_{S2}\varepsilon_{MN4}\varepsilon_{M6}\cos[(\Delta\sigma_1-\Delta\sigma_2)t-\alpha_1-\alpha_4+\gamma]$	S_2, MN_4, M_6
$+\frac{3}{4}\varepsilon_{S2}\varepsilon_{K1}^2\cos[(\Delta\sigma_1-2\Delta\sigma_3)t-\alpha_1+2\alpha_5)$	S_2, K_1
$+\frac{3}{2}\varepsilon_{N2}\varepsilon_{M4}\varepsilon_{M6}\cos(\Delta\sigma_2 t+\alpha_2+\beta-\gamma)$	N_2, M_4, M_6
$+\frac{3}{2}\varepsilon_{N2}\varepsilon_{MS4}\varepsilon_{M6}\cos[(\Delta\sigma_1-\Delta\sigma_2)t-\alpha_2-\alpha_3+\gamma]$	N_2, MS_4, M_6
$+\frac{3}{2}\varepsilon_{N2}\varepsilon_{MN4}\varepsilon_{M6}\cos(2\Delta\sigma_2 t+\alpha_2+\alpha_4-\gamma)$	N_2, MN_4, M_6
$+\frac{3}{4}\varepsilon_{N2}\varepsilon_{K1}^2\cos[(\Delta\sigma_2+2\Delta\sigma_3)t+\alpha_2-2\alpha_5)$	N_2, K_1
$+\frac{3}{4}\varepsilon_{M4}\varepsilon_{S2}^2\cos(2\Delta\sigma_1 t-2\alpha_1+\beta)$	M_4, S_2
$+\frac{3}{4}\varepsilon_{M4}\varepsilon_{N2}^2\cos(2\Delta\sigma_2 t+2\alpha_2-\beta)$	M_4, N_2
$+\frac{3}{4}\varepsilon_{MS4}\varepsilon_{S2}^2\cos(\Delta\sigma_1 t-2\alpha_1+\alpha_3)$	MS_4, S_2
$+\frac{3}{4}\varepsilon_{MS4}\varepsilon_{N2}^2\cos[(2\Delta\sigma_2+\Delta\sigma_1)t-\alpha_3+2\alpha_2]$	MS_4, N_2
$+\frac{3}{4}\varepsilon_{MN4}\varepsilon_{S2}^2\cos[(2\Delta\sigma_1+\Delta\sigma_2)t-2\alpha_1+\alpha_4]$	MN_4, S_2
$+\frac{3}{4}\varepsilon_{MN4}\varepsilon_{N2}^2\cos(\Delta\sigma_2 t+2\alpha_2-\alpha_4)$	MN_4, N_2
$+\frac{3}{4}\varepsilon_{S2}\varepsilon_{O1}^2\cos[(\Delta\sigma_1+2\Delta\sigma_3)t-\alpha_1+2\alpha_6)$	S_2, O_1
$+\frac{3}{4}\varepsilon_{N2}\varepsilon_{O1}^2\cos[(\Delta\sigma_2-2\Delta\sigma_3)t+\alpha_2-2\alpha_6)$	N_2, O_1

Chu et al. (2015)

9-F Net import or export

Relative phase-lag

$$u(t) = \hat{u}_{M2}\cos(\omega t - \varphi_{M2}) + \hat{u}_{M4}\cos\left(2\omega t - \varphi_{M4}\right)$$

$$\omega = \omega_{M2} = \frac{1}{2}\omega_{M4}$$

This can be written as $u(t) = \hat{u}_{M2}\cos(\omega t') + \hat{u}_{M4}\cos\left(2\omega t' - \left(\varphi_{M4} - 2\varphi_{M2}\right)\right)$

with $\omega t' = \omega t - \varphi_{M2}$ or $t' = t - \dfrac{\varphi_{M2}}{\omega}$

Phase-lag between M2 and M4 is thus $\phi = \varphi_{M4} - 2\varphi_{M2}$

Phase-lag between M2 and M6 is $\phi = \varphi_{M6} - 3\varphi_{M2}$

5-M Tidal asymmetry

See also Chapter 6 and 9

Sediment transport $s = cu^3 \Rightarrow \langle s \rangle = c\langle u^3 \rangle$

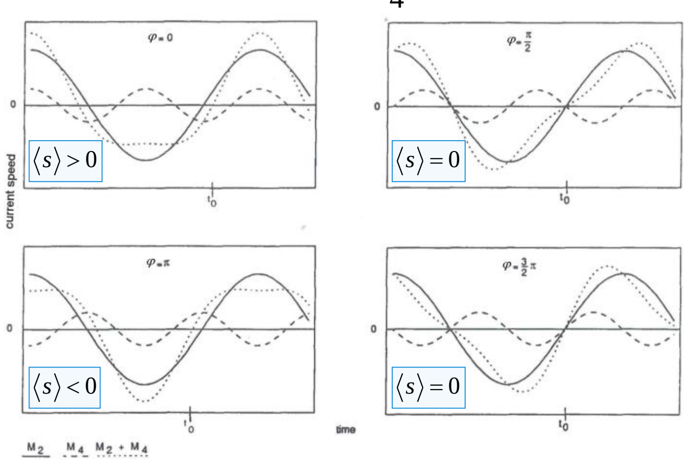
$$u(t) = \hat{u}_{M2}\cos(\omega t) + \hat{u}_{M4}\cos\left(2\omega t - \phi\right) \qquad \langle s \rangle = \frac{3}{4}c\hat{u}_{M2}^2\hat{u}_{M4}\cos\phi$$

Flood dominance (sediment import)

$h_{HW} > h_{LW}$

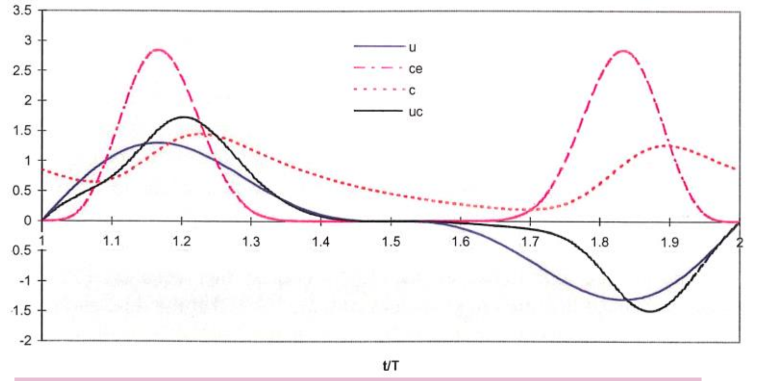
Ebb-dominance (sediment export)

$h_{LW} > h_{HW}$



9-F Net import or export

Residual transport suspended load (fine sediment)



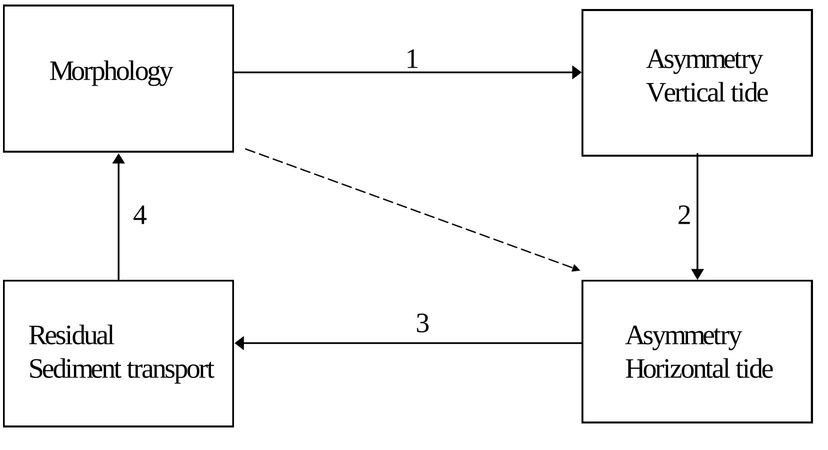
$$u = \sin(\omega t) + 0.5\sin(2\omega t) \qquad c_e \propto u^2$$

$$\frac{\partial c}{\partial t} = \frac{c_e - c}{T_a} \qquad s \propto uc$$

From Wang et al.

9-F Net import or export

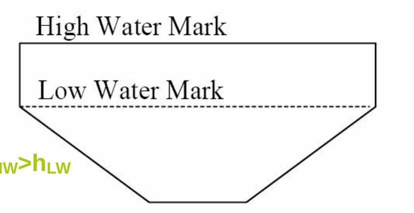
Morphology ⇔ tidal asymmetry



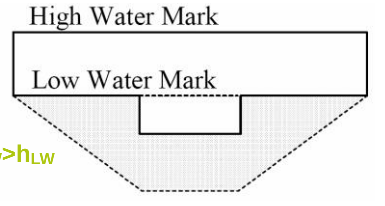
5-M Tidal asymmetry

Propagation of high tide and low tide at different average water **depths** depending on basin geometry

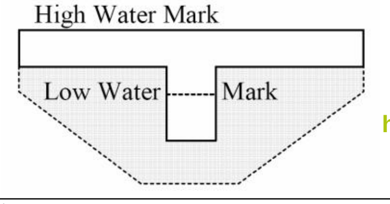
- for large enough tidal amplitude and not too deep channels



$h_{HW}>h_{LW}$



$h_{HW}>h_{LW}$



$h_{HW}<h_{LW}$

- for deep channels and extensive intertidal areas

9-F Net import or export

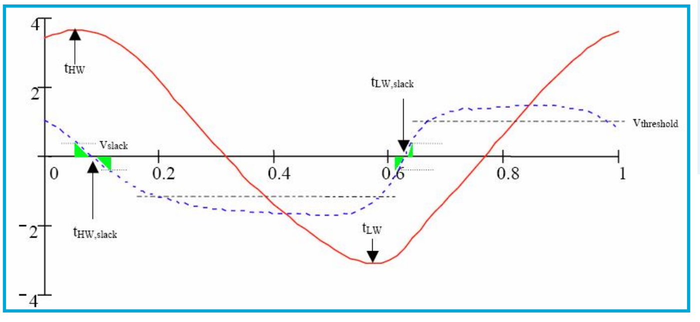
Conditions for net import or export

NET FLOOD-TRANSPORT	NET EBB TRANSPORT	TIDAL ASYMMETRY
Small storage flat area	Large storage flat area	u_{max} flood/ebb
Long shallow channels	Long deep channels	u_{max} flood/ebb
Fast tidal rise at sea	Fast tidal fall at sea	u_{max} flood/ebb

5-M Tidal asymmetry

Additional effect for suspended fine material => fines need time to settle

- Fines settle around flow reversal
- Controlled by durations of slack water
- If duration of slack around high water is longer => more fines settle at flow reversal from flood to ebb => import



HW slack
- From flood to ebb
- Often around HW

LW water slack
- From ebb to flood
- Often around LW

Now you may think that large intertidal storage gives export of fines, but ....

9-F Net import or export

Management and engineering problems

- Natural Causes

- Sea level rise
- Opening of a new inlet during a storm
- Lengthening of inlet

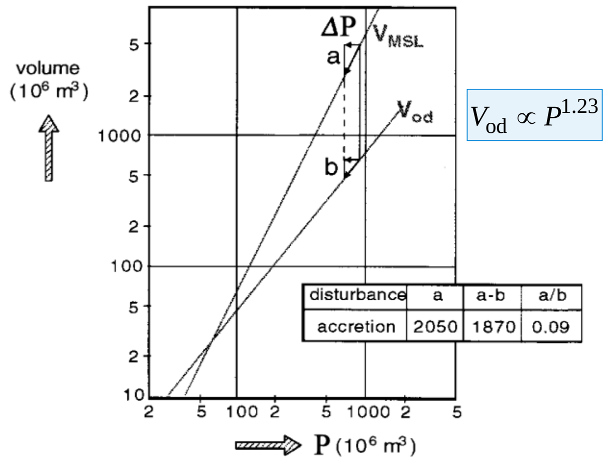
- Man-made Causes

- Reduction of lagoon surface area
- Opening of a ne w inlet by dredging
- Inlet improvements; navigation channels and breakwaters
- Bottom subsidence

9-F Net import or export

Accretion of new land

$V_c \propto P^{3/2}$

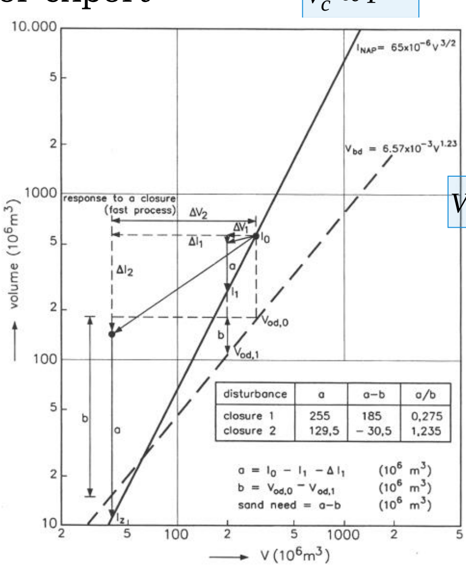


$V_{od} \propto P^{1.23}$

9-F Net import or export

Two closures

$V_c \propto P^{3/2}$

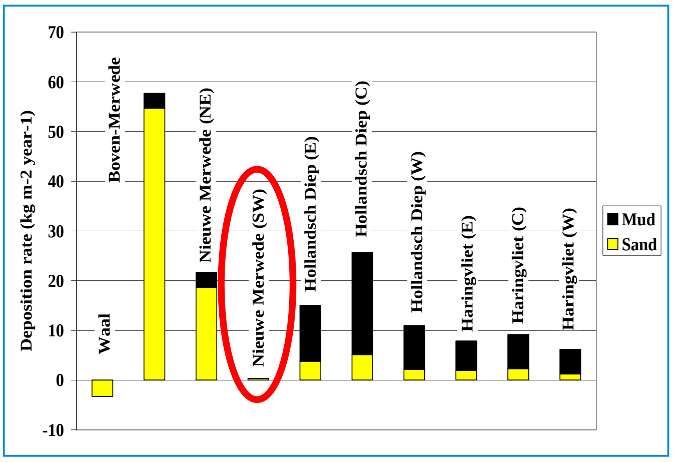


$V_{od} \propto P^{1.23}$

where
V: tidal prism P
I: channel volume V_c

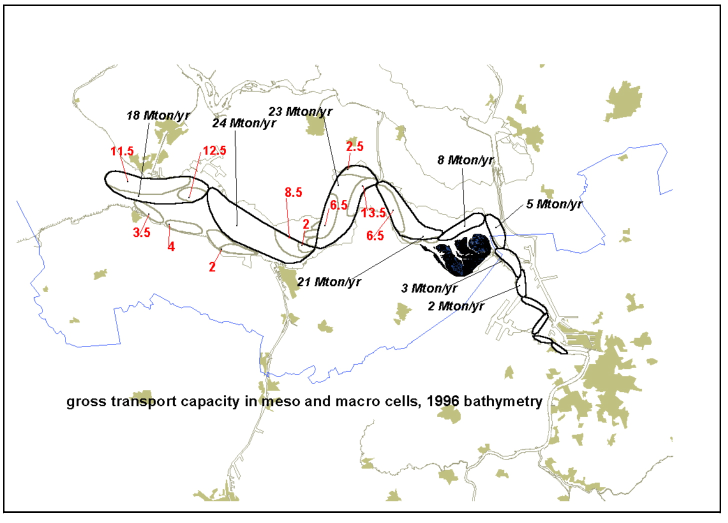
9-F Net import or export

Infilling of the Rhine-Meuse estuary after the Delta works



9-F Net import or export

Western Scheldt transport cells



Exam questions 2010

Inlet stability of short basin with no flats (april)

- Definition tidal prism
- Responsible agents for opening and closing
- Explanation Escoffier curve and (un)stable equilibrium
- Effect on the inlet gorge of reclamation (explained in terms of Escoffier's curve)

Dynamic basin equilibrium (june)

- Nature of horizontal tide in the inlet for basin in equilibrium
- Give a simple mathematical expression for a flood-dominant horizontal tide
- Why does the basin become more flood-dominant after reclamation (assume that flats are unaffected and flood-tidal delta spans entire basin)?
- Effect on outer delta

Coastal inlets and tidal basins

Chapter 9 of lecture notes

A. Introduction
B. Adjacent (barrier) coast
C. Ebb-tidal delta
D. Inlet stability
E. Inner basin phenomena
F. Net import or export
G. Case: Oosterschelde

9-G Case Oosterschelde From M. Eelkema

Introduction (1)

The Dutch Delta Coast:

- 1 estuary: the Western Scheldt (Westerschelde)
- 1 tidal basin: the Eastern Scheldt (Oosterschelde, E.S.)
- 2 closed tidal basins: Grevelingen & Haringvliet

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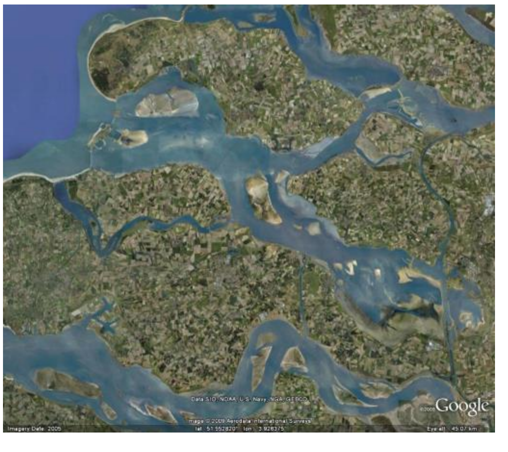
Introduction (2)

The Eastern Scheldt tidal basin:

- ±50 km long
- on average 6 km wide
- Basin area: 350 km^2
- Tide takes in roughly 900 million m^3 per tidal period
- no fresh water influence



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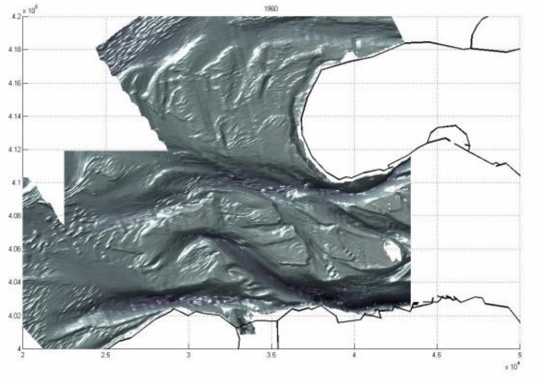
Bathymetry Oosterschelde 1960-2000 (flat)



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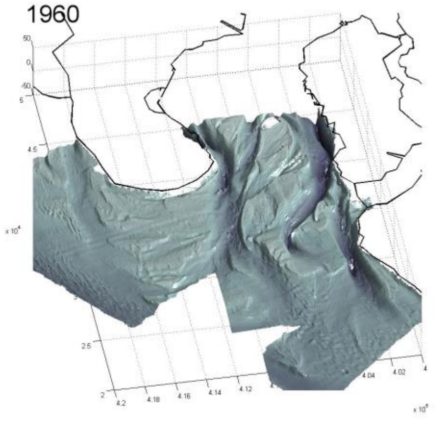
Bathymetry Oosterschelde 1960-2000



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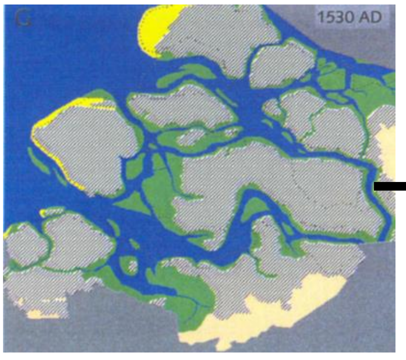
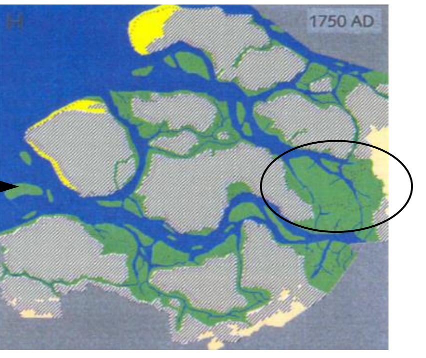
Evolution before 1800 (1)





Storm in 1530 A.D. floods 200 km^2 in the back end

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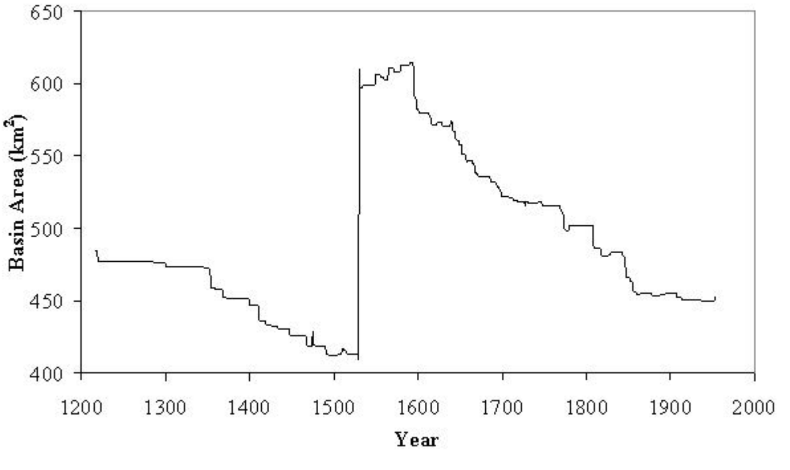
Evolution before 1800 (2)



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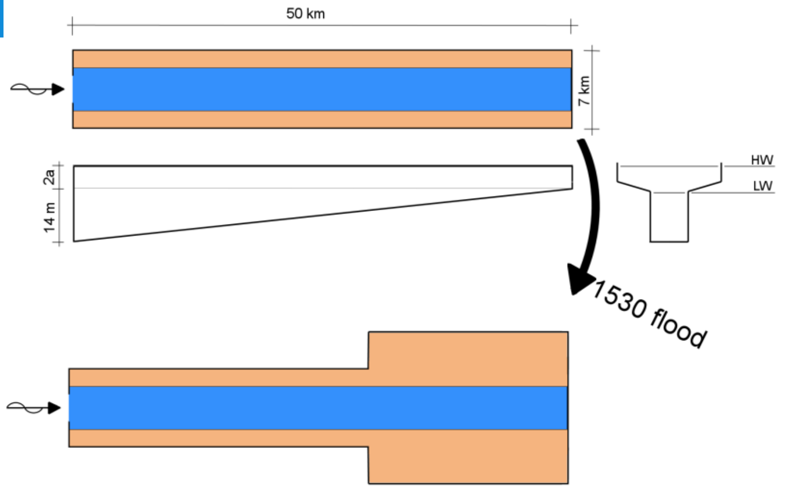
Modeling the evolution



Result of instantaneous inundation: Tidal volume at mouth decreases!

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Modeling the evolution

- Initial decrease seems counter-intuitive, but is the result of decrease in tidal range
- At the location of the inundation volumes will increase, and so will the depth
- Initial decrease at the mouth will turn into increase when rest of basin deepens
- Effect on time-scale of adaptation unknown (MSc-thesis!)

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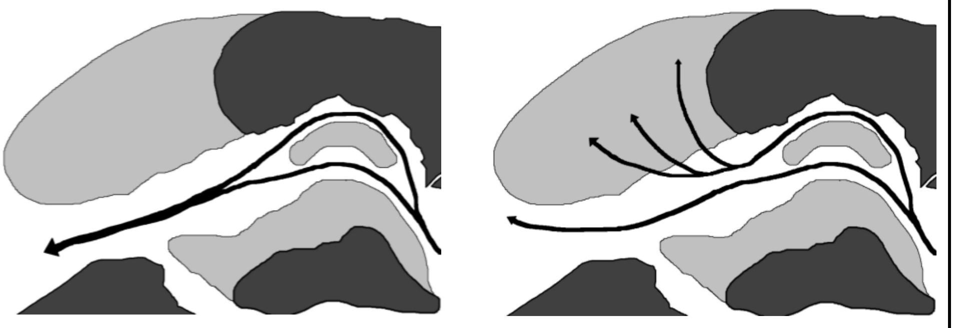
Evolution before 1800 (3)



Pre-1530 situation → Situation around 1700

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Evolution before 1800 (4)

Possible cause of shift on ebb-delta:

Sha & Van den Berg (1993):

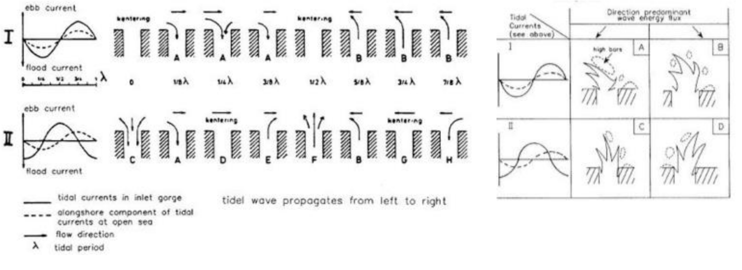

Table:

Inlet	Type: model	Type: reality 1850	Remarks
W.-Schelde	C-D	C	SW-coast
O.-Schelde	C-D	C	
Grevelingen	C-D	C	
Haringvliet	C-D	C-D	
Vlie	B	B	Wadden Sea
Amelander Gat	B	B	
Friesche Zeegat	B	B	
Marsdiep	A	A	

However; are the inundations large enough to cause this shift?

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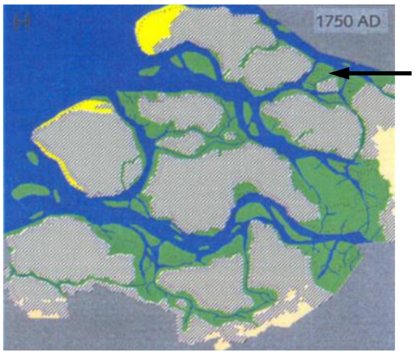
Evolution before 1800 (5)



New situation from 1600 to 1800:

- Tidal divide disappeared (starting from ±1700)
- Mouth has scoured from ±10 to 30 meters
- Channels inside basins also scoured
- Channels on ebb-delta have shifted

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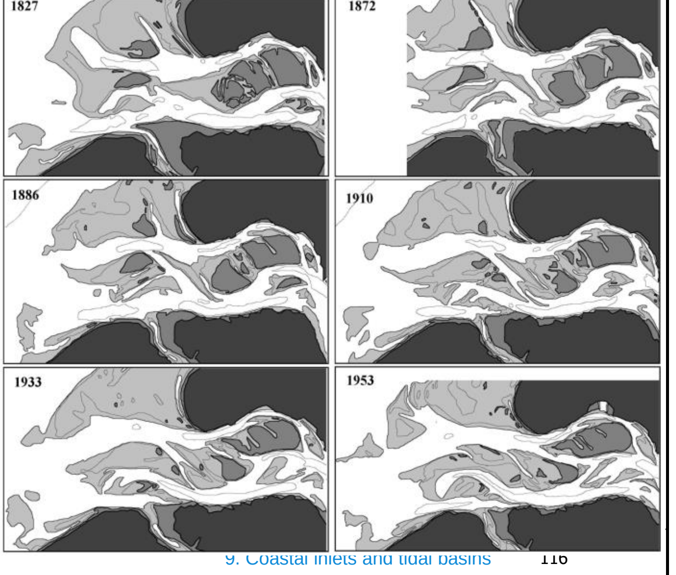
Evolution before 1950

Between 1800 - 1950:

- Prism grows ± 10%
- Mouth scoured from 30 to 50 meters
- basin exports 300 to 400 million m^3 of sand



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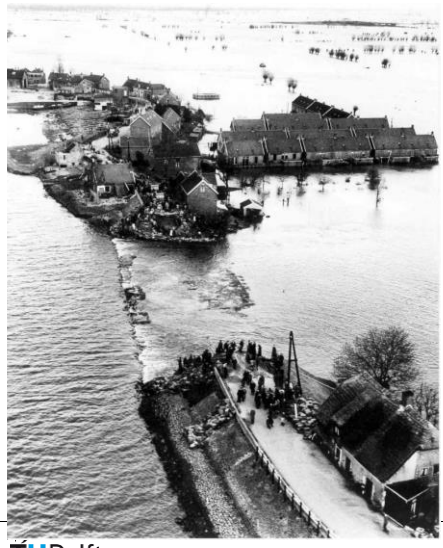
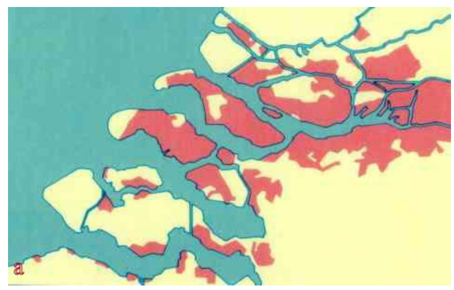
Flood of 1953



- 1835 people killed
- 1700 km^2 inundated



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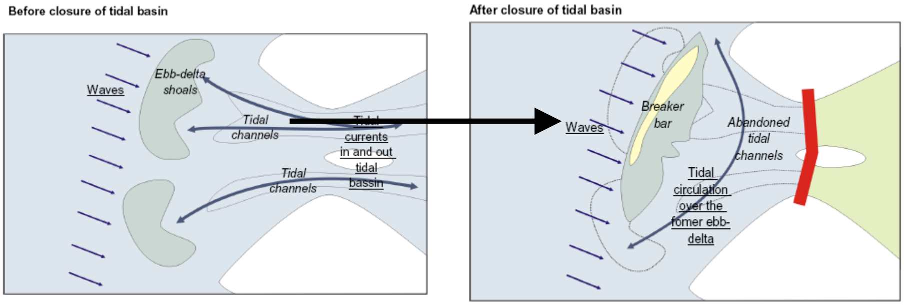
Effects of the Delta works on ebb-deltas

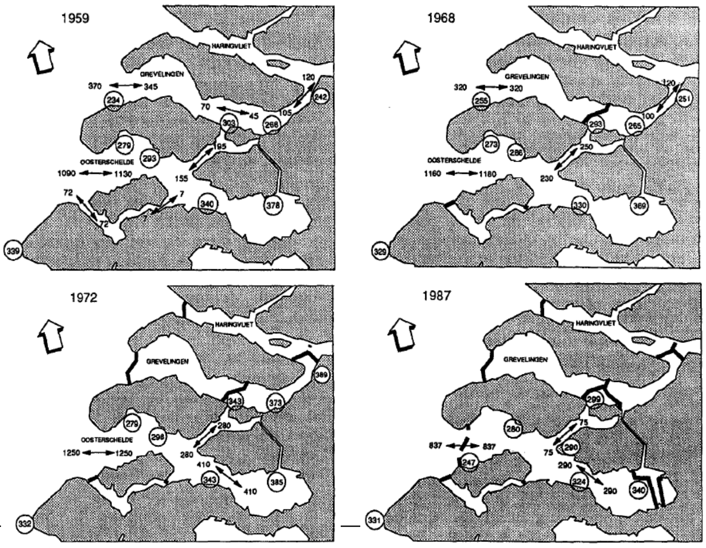
Grevelingen & Haringvliet



$$V_0 = C_V P^{1.23}$$

9-G Case Oosterschelde

Effects of the Delta works on E.S.



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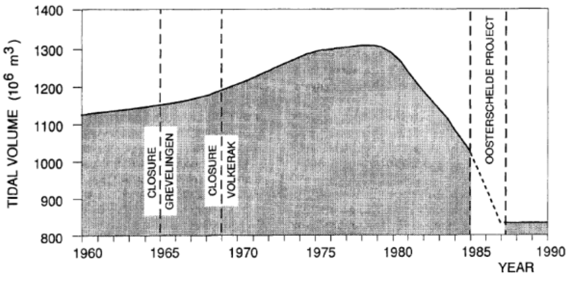
Effects of the Delta works on E.S.



Reduction of Tidal volumes

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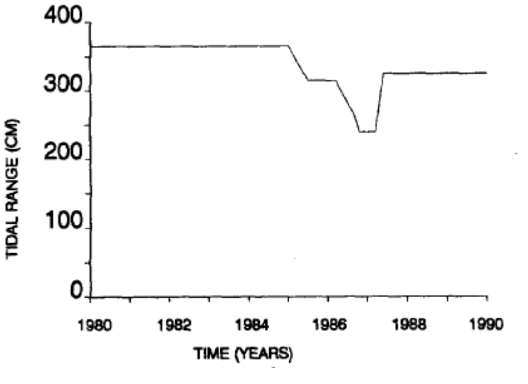
Effects of the Delta works on E.S.



Reduction of Tidal range

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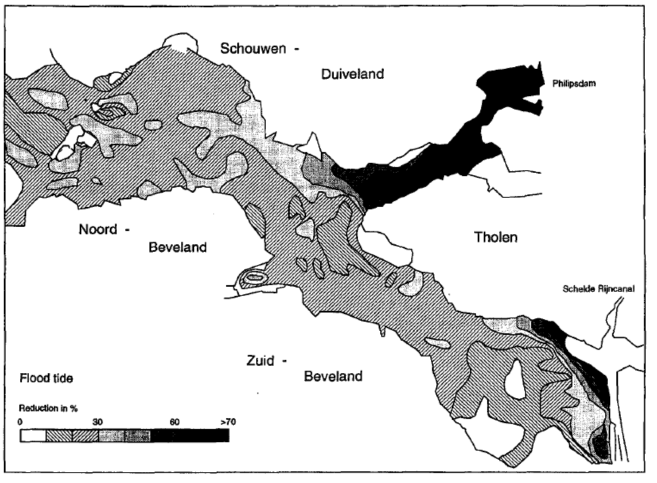
Effects of the Deltaworks on E.S.



Reduction of current velocities

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Morphological response

$$V_c = C_V P^{1.5}$$

$$\downarrow$$

$$P_{new} < P_{old}$$

$$\downarrow$$

$$V_{c,new} < V_{c,old}$$

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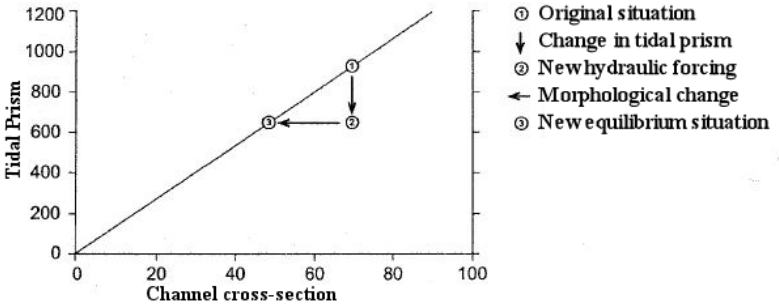
Morphological response



Basin changes from exporting to importing, and sedimentation in the channels

↓

Estimated sediment requirement: 400-600 million m^3

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Is that all there is to it?

No! Tidal flats are maintained by currents, and broken down by waves

Equilibrium in flat volume and height:
Maintaining forces (currents, range) ≈ Erosive forces (waves)

If: Maintaining forces (currents, range) < Erosive forces (waves)

↓

Decrease in flat area and flat height

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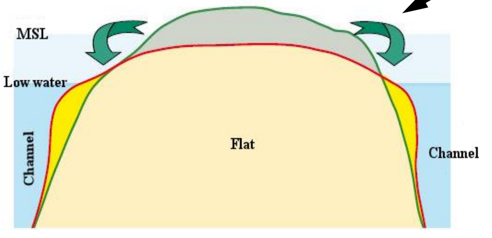
Morphological response: Sand Hunger

This is what happens in the Eastern Scheldt:

Decrease in flow velocities → Decrease in sediment transport capacity through channels

→ Decrease in sediment transport towards tidal flats



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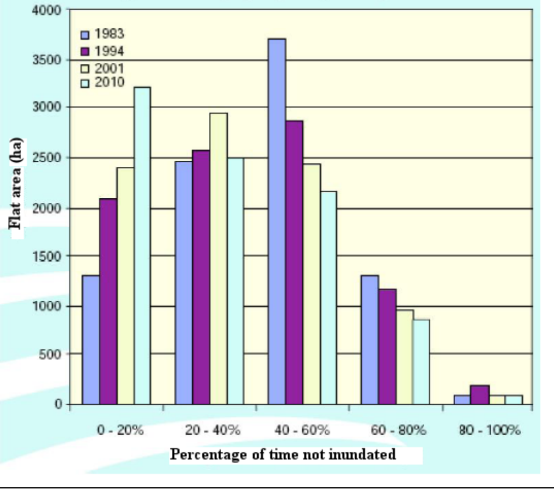
Morphological response: Sand Hunger



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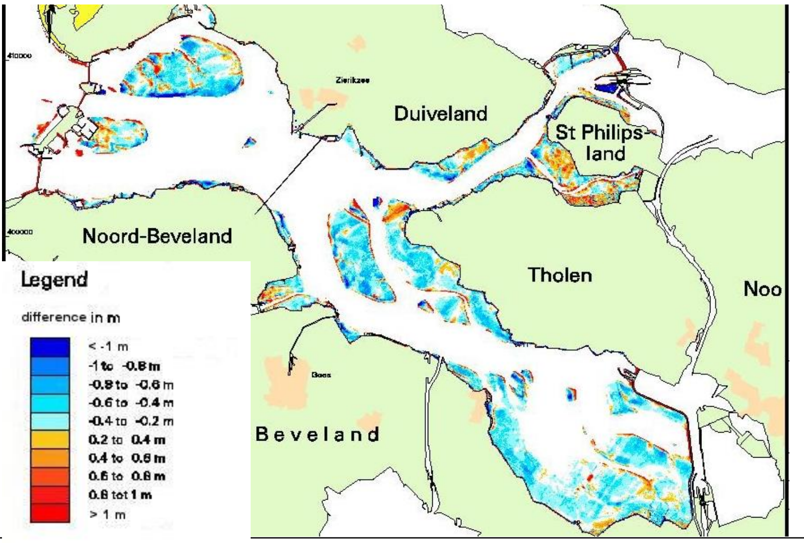
Morphological response: Sand Hunger



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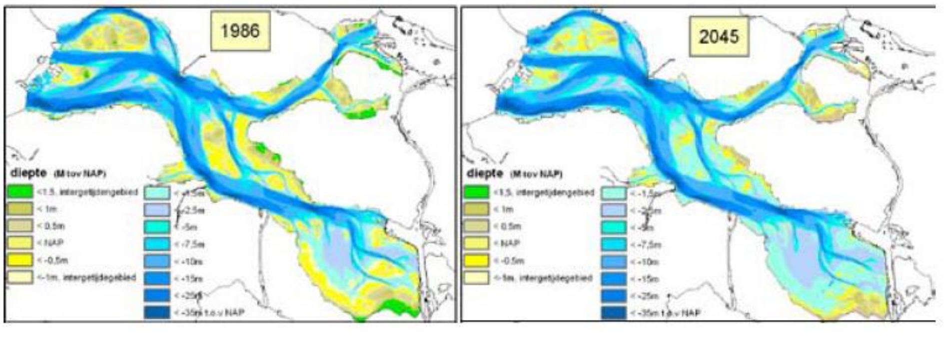
Prognosis

Sediment needed inside Eastern Scheldt: 400-600 million m^3

Sediment available on tidal flats: <150 million m^3



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Sand Hunger

So what? Why do we care?

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Sand Hunger

And? Why else do we care?

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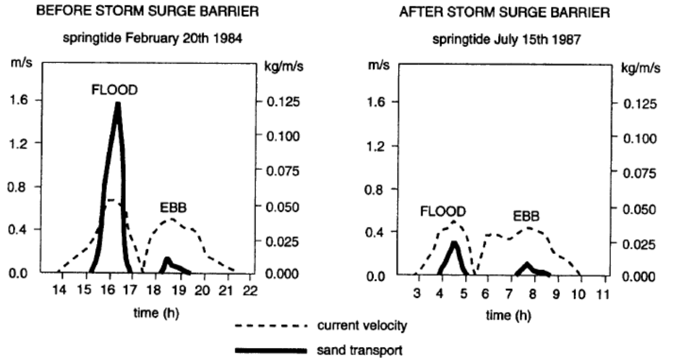
Sediment import

Import will fix the sand hunger, right?

Sadly, no:



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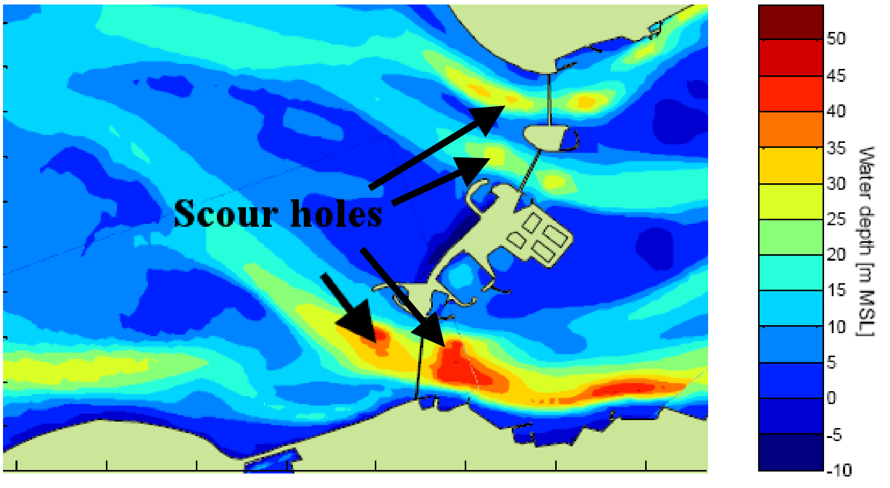
Probable cause for the sediment blockage



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Probable cause for the sediment blockage

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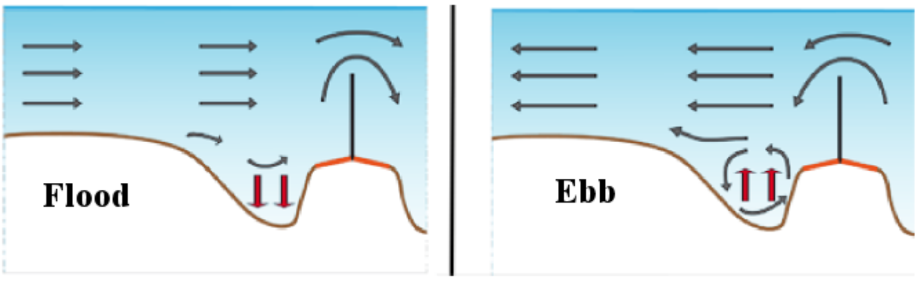
Probable cause for the sediment blockage



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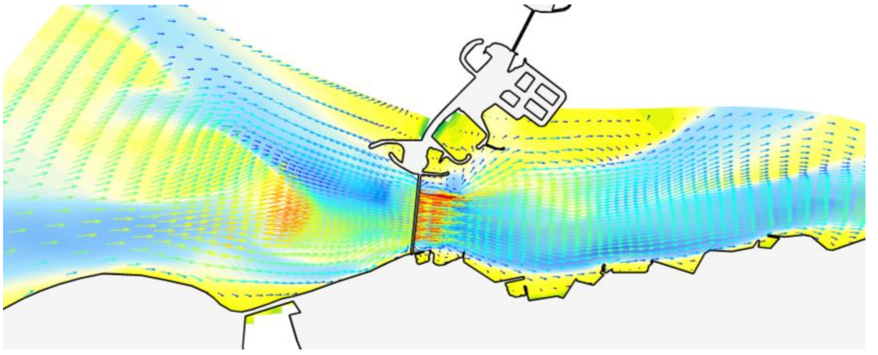
Complex area to model



Flood flow pattern

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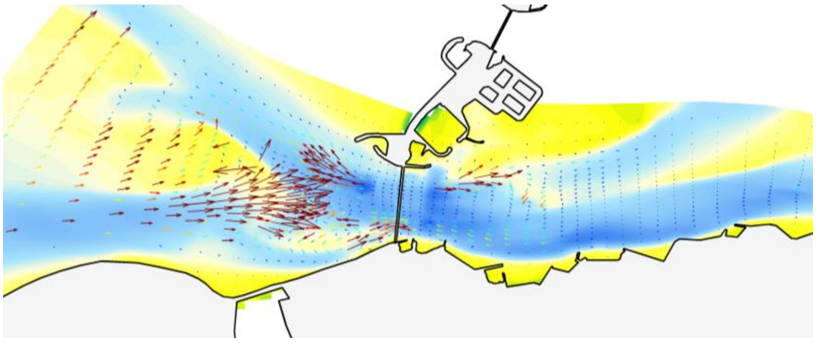
Complex area to model



Tide-average transport

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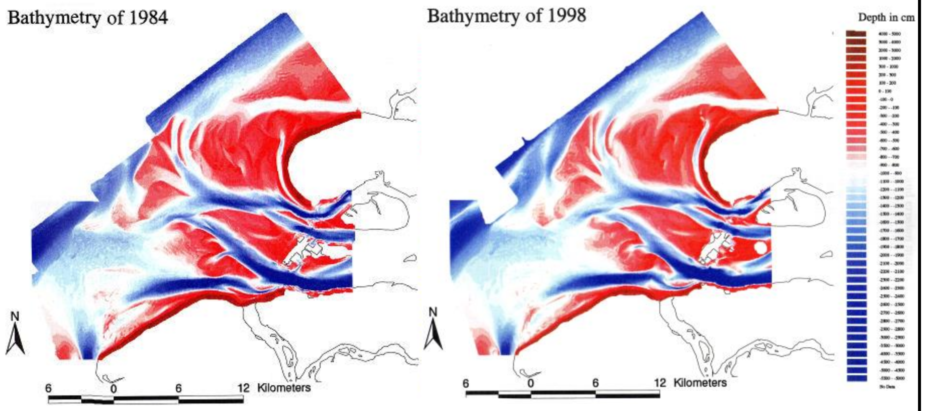
Effects on the Ebb-delta



$$V_0 = C_V P^{1.23}\,?$$

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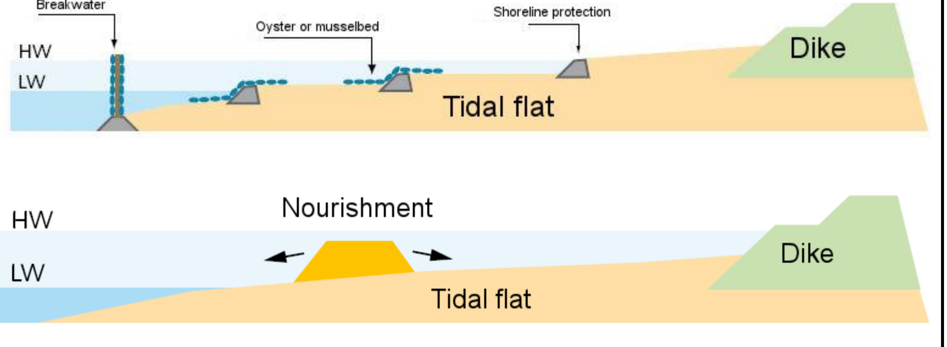
Possible methods to preserve tidal flats



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Possible methods to preserve tidal flats

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Possible methods to increase currents/transport