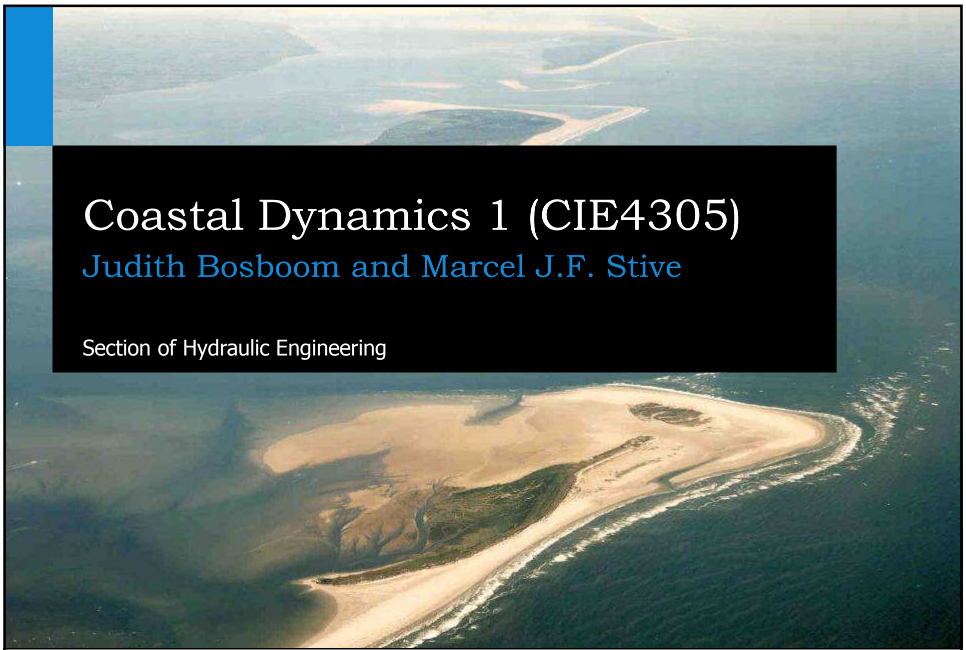

Coastal Dynamics 1 (CIE4305)

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Section of Hydraulic Engineering

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Challenge the future

5.

Coastal hydrodynamics – part II

Coastal Dynamics 1

Contents

1. Introduction
2. Large-scale coastal variation
3. Oceanic wind waves and tide
4. Global wave and tidal environments
5. **Coastal hydrodynamics (Chapter 5)**
6. Sediment transport
7. Cross-shore transport and profile development
8. Longshore transport and coastline changes
9. Coastal inlets and tidal basins
10. Coastal protection

Coastal Dynamics 1

Maple TA up to Chapter 5 – part I

Summary Data	Chapter 1+2 - Stage A	Chapter 1+2 - Stage B	Chapter 3 - Stage A	Chapter 3 - Stage B
# Attempts	200	188	193	190
Mean	92%	82%	93%	80%
Median	94%	86%	94%	83%

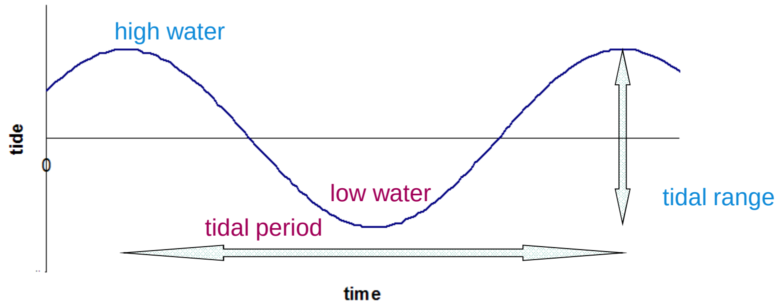
Summary Data	Chapter 4 - Stage A	Chapter 4 - Stage B	Chapter 5 - Part I - Stage A	Chapter 5 - Part I - Stage B
# Attempts	184	181	192	189
Mean	97%	90%	90%	69%
Median	100%	100%	88%	75%

Coastal hydrodynamics – part II

Chapter 5 of lecture notes (paragraph 5.7)

J. **What was the tide again?**
K. Along the shoreline
L. Entering tidal basins
M. Tidal asymmetry
N. Residual currents

5-J What was the tide again?

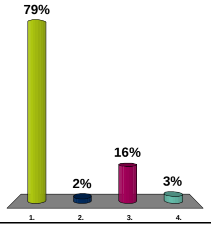


$$\eta = a\cos(\overbrace{\omega}^{\frac{2\pi}{T}} t - \beta)$$

tidal amplitude frequency phase

The period of the M2 tide is:

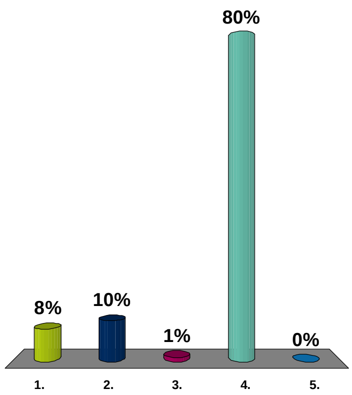
1. 12.25 hrs
2. 12 hrs
3. ✓ 12.42 hrs
4. 24 hrs 50 min



5-J What was the tide again?

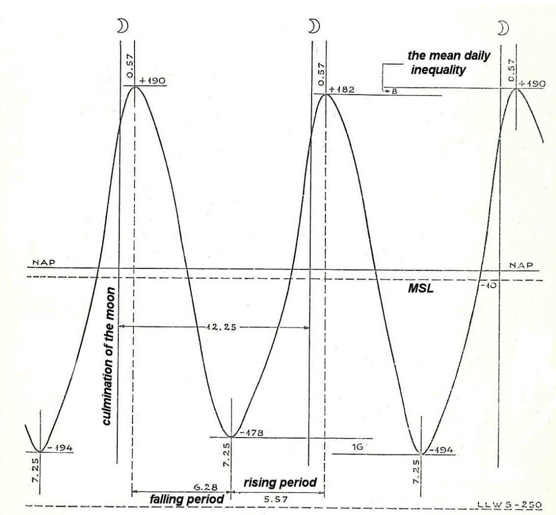
Which of the following statements is **wrong?**

1. The time between spring tide and neap tide is around 7 days
2. Asymmetry about the vertical axis refers to a forward or backward tilting signal
3. The flood direction along the Dutch coast is approximately northwards
4. The lowest tidal levels are generally found during neap tide
5. Daily inequality implies that the two high waters a day are not of equal magnitude



5-J What was the tide again?

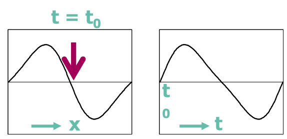
Average tidal curve Vlissingen



- Mean sea level
- LLWS = LAT
- Daily inequality
- Asymmetry
- Rising period
- Falling period

How can larger falling period be explained?

$C_{crest} > C_{trough}$

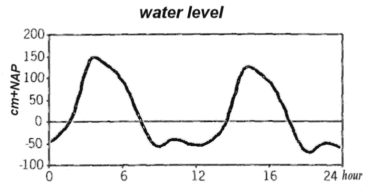


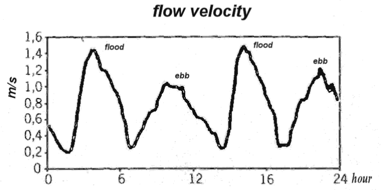
5-J What was the tide again?

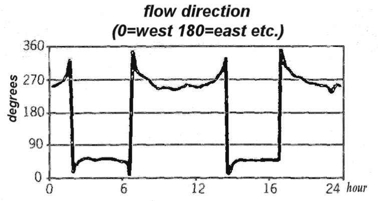
- Vertical tide
  - High water – low water
  - Falling period – rising period
- Horizontal tide
  - Ebb – flood
  - Ebb period – Flood period
  - Slack water (flow reversal from flood to ebb and v.v.)

Stroommeetpaal Maasmond, 5th of june 2004

A few km off the coast of the "Maasvlakte"



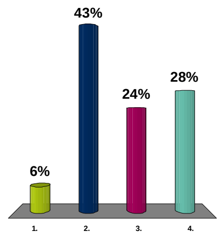




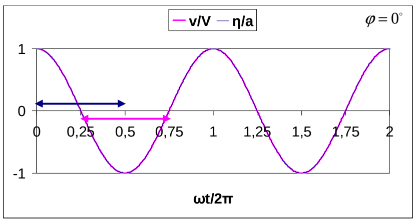
5-J What was the tide again?

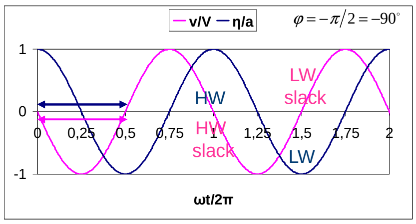
The falling period coincides with the ebb period, if…:

1. … the tidal propagation has a progressive character
2. ✔ … the velocity leads the surface elevation with a quarter period
3. … the velocity leads the surface elevation with a half period
4. … the velocity and the surface elevation are in phase

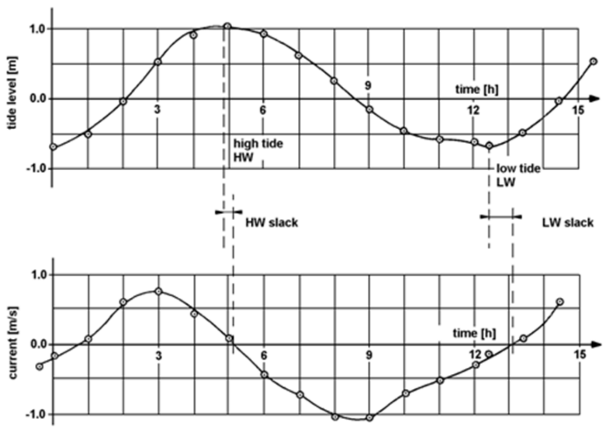


$$\eta = a\cos(\omega t - ky) \qquad v = V\cos(\omega t - ky - \phi)$$





5-J What was the tide again?



"HW" slack
- From flood to ebb
- Often just after HW

"LW" water slack
- From ebb to flood
- Often just after LW

Flood velocities positive

Coastal hydrodynamics – part II

Chapter 5 of lecture notes

J. What was the tide again?
K. Tidal propagation along the shore
L. Tidal propagation into basins
M. Tidal asymmetry
N. Residual currents

5-K Tidal propagation along the shore

Propagation of Kelvin wave alongshore

Acceleration (inertia) balances pressure gradient $\frac{\partial v}{\partial t} = -g\frac{\partial \eta}{\partial y}$

For a cosine wave:

$$\boxed{\begin{aligned} &\eta = a\cos(\omega t - ky) \\ &v = \frac{gak}{\omega}\cos(\omega t - ky) \\ &c = \frac{\omega}{k} = \sqrt{gh} \end{aligned}}$$

Velocity in phase with surface elevation: progressive wave

> Friction was neglected compared to inertia!

5-K Tidal propagation along the shore

The effect of bottom friction in the nearshore

$$\underbrace{\cancel{\frac{\partial v}{\partial t}}}_{\text{inertia (local acceleration)}} = \underbrace{-g\frac{\partial \eta}{\partial y}}_{\text{alongshore water level gradient}} \underbrace{-\frac{\tau_{by}}{\rho h}}_{\text{friction}}$$

> Assume linear friction:

$$\tau_{by} = \rho C_f v|v| \approx \rho r v$$

$$\Downarrow$$

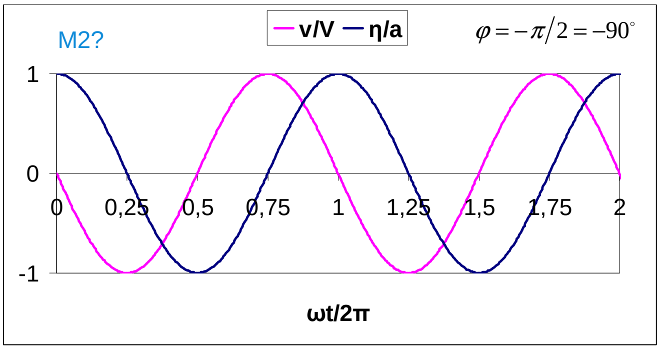
$$\boxed{g\frac{\partial \eta}{\partial y} = -\frac{r}{h}v}$$

$\rightarrow$

> Tidal velocity in phase with the negative alongshore water level gradient:
> $\varphi = -\pi/2 = -90^\circ$

5-K Tidal propagation along the shore

Velocity leads surface elevation due to bottom friction



$$v = -\frac{gh}{r}\frac{\partial \eta}{\partial y}$$

If amplitude does not vary along the coast:

$$\varphi = -\pi/2 = -90^\circ$$

$$\eta = a\cos(\omega t - ky) \qquad v = V\cos(\omega t - ky - \phi)$$

$$v = -\frac{gh}{r}\frac{\partial \eta}{\partial y} = -\frac{gh}{r}ak\sin(\omega t - ky) = \frac{gh}{r}ak\cos(\omega t - ky + \pi/2)$$

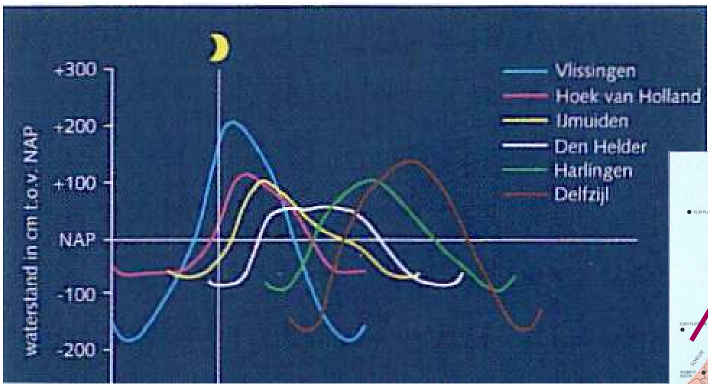
Generally:

$$-\pi/2 < \varphi < 0$$

5-K Tidal propagation along the shore

Average tide at stations along Dutch coast: phase ky, amplitudes and shapes vary

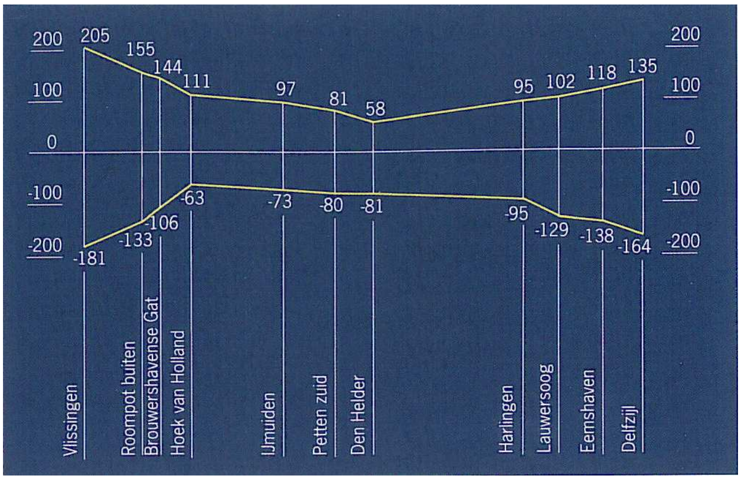
Skewness and asymmetry



$$\eta = a\cos(\omega t - ky)$$

5-K Tidal propagation along the shore

Average high and low water at stations along Dutch coast (in cm)



5-K Tidal propagation along the shore

Tidal currents along the shore: cross-shore distribution of the longshore tidal velocity

Linear friction: $v \propto h \dfrac{\partial \eta}{\partial y}$

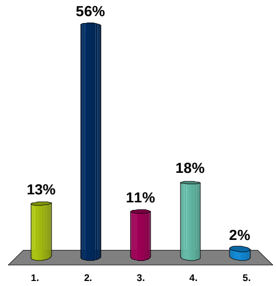
Quadratic friction: $v \propto \sqrt{h \dfrac{\partial \eta}{\partial y}}$

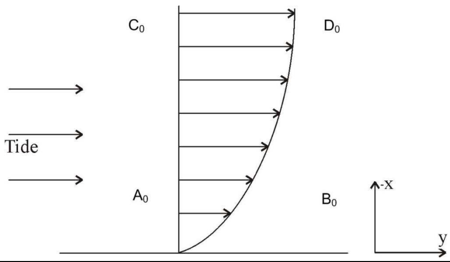
5-K Tidal propagation along the shore

At 12 m water depth, the tidal current velocity is 1 m/s. What is the velocity at 3 m?

1. 0.25 m/s
2. ✓ 0.5 m/s
3. 1.0 m/s
4. 2.0 m/s
5. Something else

Cross-shore grain-size distribution in tide- and wave-dominated environments?



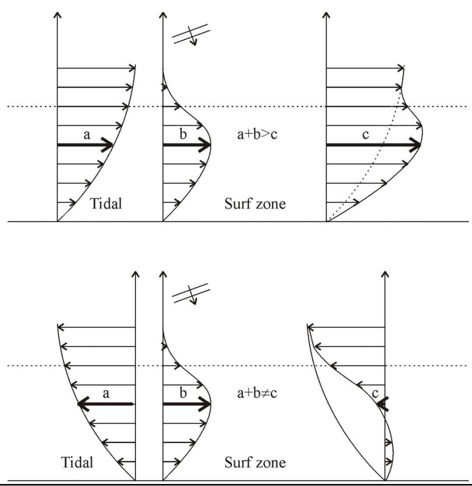


$$v \propto \sqrt{h} \Leftrightarrow v_2 = v_1 \sqrt{\frac{h_2}{h_1}}$$

5-K Tidal propagation along the shore

What is the effect of reversing tidal current on longshore sediment transport?

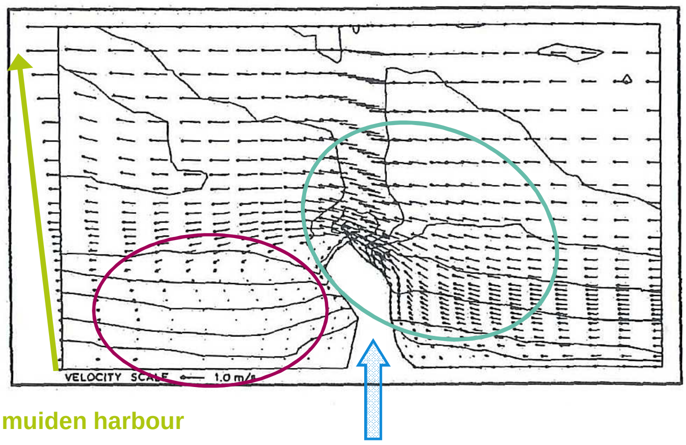
Wave- plus tide-induced longshore current



5-K Tidal propagation along the shore

Tidal currents around structures

See also 3D effects Texel dam page 398



IJmuiden harbour

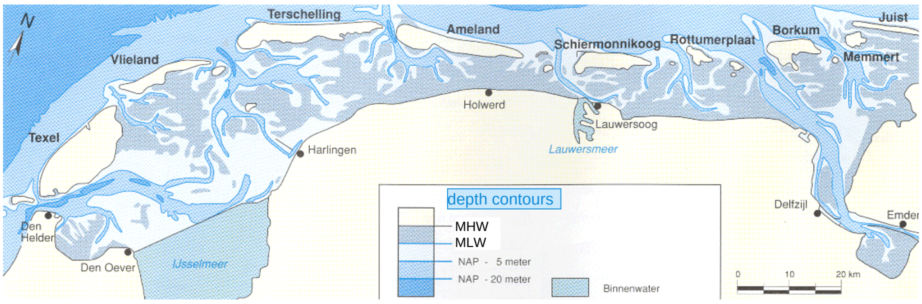
Coastal hydrodynamics – part II

Chapter 5 of lecture notes

J. What was the tide again?
K. Tidal propagation along the shore
L. Tidal propagation into basins
M. Tidal asymmetry
N. Residual currents

5-L Tidal propagation into basins

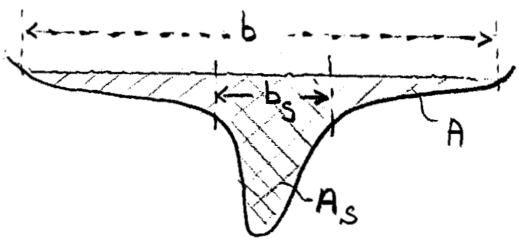
Channels and storage areas



5-L Tidal propagation into basins

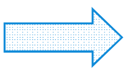
Schematization into main channel and storage areas

Cross-section



Further simplifications:

- No intertidal areas $b = b_s$
- Prismatic channel



1D long wave equation

5-L Tidal propagation into basins

1D long wave equation for small tide (a/h small)

Continuity equation

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

Momentum equation

$$\frac{\partial u}{\partial t} + \cancel{u\frac{\partial u}{\partial x}} + g\frac{\partial \eta}{\partial x} + \frac{\tau_b}{\rho h} = 0$$

Linear friction: $\tau_b = \rho C_f |u| u \approx \rho r u$

$$\Downarrow$$

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

Combine these two equations into one equation in terms of the surface elevation!

5-L Tidal propagation into basins

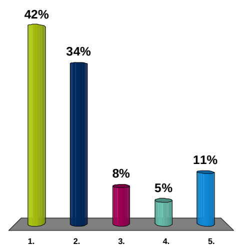
$$\underbrace{\overbrace{\frac{\partial^2 \eta}{\partial t^2} - gh\frac{\partial^2 \eta}{\partial x^2} + \frac{r}{h}\frac{\partial \eta}{\partial t}}^{\text{Eq. 2 => LHS without 1st term}}}_{\text{Eq. 1 => LHS without 3rd term}} = 0$$

Eq. 2 => LHS without 1st term

Eq. 1 => LHS without 3rd term

Do you recognize Eqs. 1 and/or 2?

1. ✓ Eq. 1 describes small amplitude wave propagation in shallow water.
2. Eq. 1 is a diffusion or heat equation.
3. Eq. 2 is the classical wave equation.
4. Eq. 2 describes tidal propagation in the oceans.
5. Abstain



5-L Tidal propagation into basins

1D long wave equation for small tide (a/h small)

- Now propagation in two directions!
- No damping
- Reflection at landward end of basin
- Standing wave pattern:
  - Water level and velocity 90° out of phase
  - Nodes and anti-nodes
- Phase velocity:

$$c = \sqrt{gh}$$

Diffusion equation: friction dominated flow

$$\frac{\partial^2 \eta}{\partial t^2} - gh\frac{\partial^2 \eta}{\partial x^2} + \frac{r}{h}\frac{\partial \eta}{\partial t} = 0$$

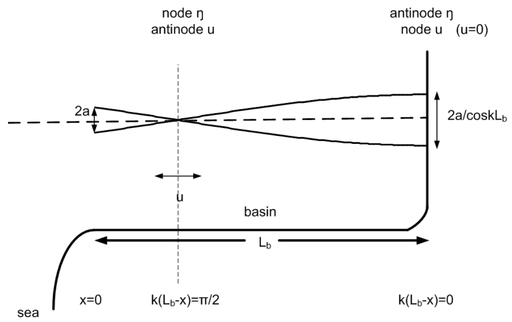
Classical wave equation: inertia dominated flow

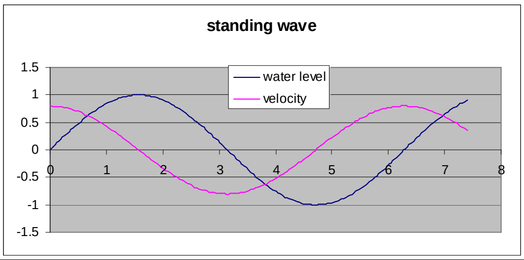
- Amplitudes are progressively damped with distance from the inlet
- No reflection at end of basin
- The velocity leads the surface elevation with 45°
- Phase speed is influenced by friction:

$$c = \sqrt{2\omega g h^2 r^{-1}}$$

5-L Tidal propagation into basins

Standing wave pattern

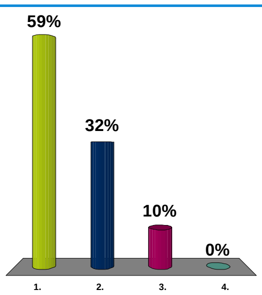




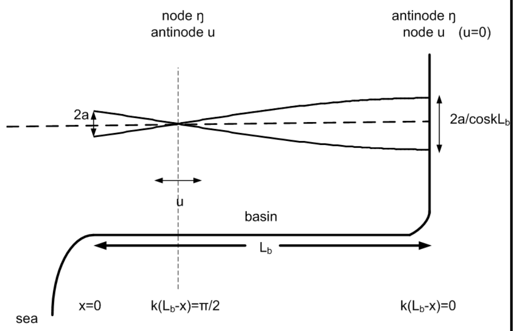
5-L Tidal propagation into basins

What is the resonance criterion (L_b vs. tidal wave length L)?

1. ✓ $L_b = 1/4\,L,\ 3/4\,L,\ 5/4\,L$ etc.
2. $L_b = 1/2\,L,\ 3/2\,L,\ 5/2\,L$ etc.
3. $L_b = L,\ 2L,\ 3L$ etc.
4. Something else



standing wave pattern



Resonance:

$$kL_b = \pi/2 \Rightarrow L_b = 1/4\,L$$

5-L Tidal propagation into basins

Most tidal basins: friction PLUS inertia

- Tidal wave is sum of incoming and reflected damped wave
- Partly propagating and partly standing character
- s_1 large => damping of the tide due to friction
- s_1 = 0 => no friction => resonance for $L_b = \frac{1}{4}L$ and $\frac{3}{4}L$

y-axis:

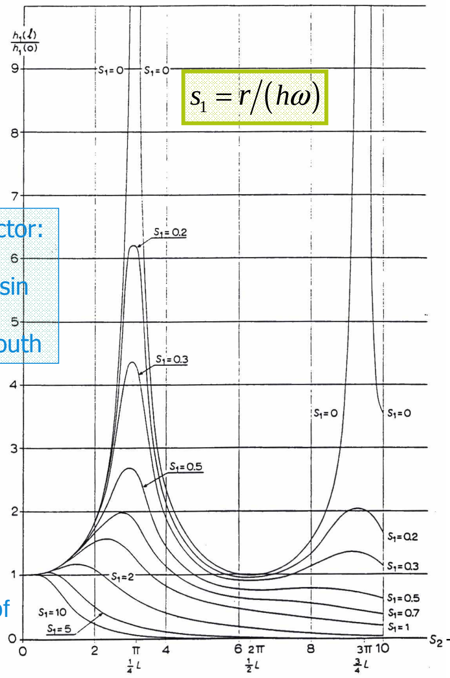
amplification factor: ratio of tidal amplitude at basin end over tidal amplitude at mouth

x-axis:

basin length in terms of

$$s_2 = 2\omega L_b \big/ \sqrt{gh}$$

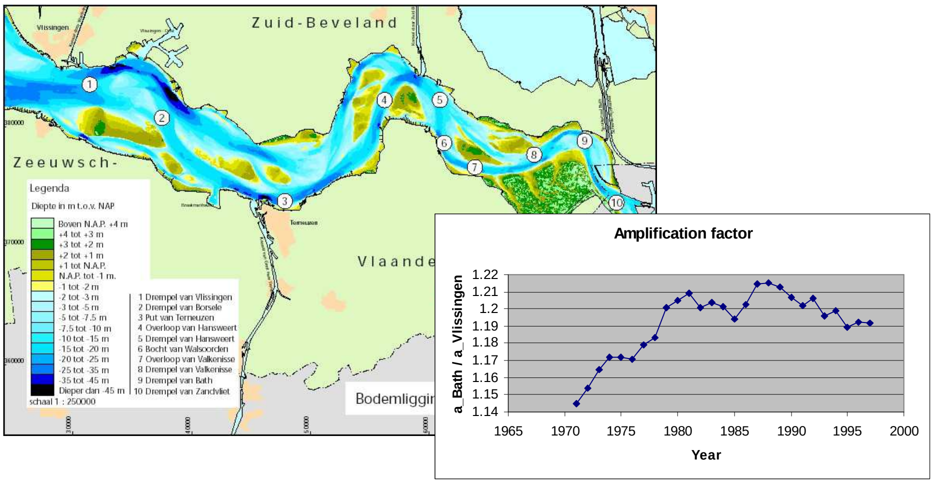
$$s_1 = r/(h\omega)$$



5-L Tidal propagation into basins

Example: Western Scheldt

dredging and sand mining has caused changes in c and L and hence in L/L_b



5-L Tidal propagation into basins

More factors that influence the amplitudes?

- Energy loss due to friction
- Energy convergence as a result of:
  - Width constriction (for instance funnel-shaped) estuary
  - Shoaling of the basin

Balance between energy loss due to friction and energy convergence due to width restriction, determines whether the tidal amplitudes increase or decrease along the channel axis

In absence of friction:

$$Encb_s = \text{const} \longrightarrow \hat{\eta}^2 \sqrt{ghb_s} = \text{const}$$

5-L Tidal propagation into basins

Short basin: pumping mode

$$\eta(t,x) = \eta(t,0) = \eta_0$$

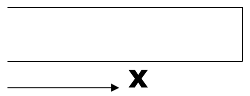
Water level and velocity 90° out of phase

$$Q(t,x) = A_s u_s = \frac{\partial \eta_0}{\partial t} \int_x^{L_b} b dx = \frac{\partial \eta_0}{\partial t} A_b \Leftrightarrow$$

$$\boxed{u_s(x,t) = \frac{\partial \eta_0}{\partial t} \frac{A_b}{A_s}}$$

basin area upstream of *x*

& introduction of saw-tooth asymmetry of velocity depending on depth channels and area of intertidal flats



Coastal hydrodynamics – part II

Chapter 5 of lecture notes

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N. Residual currents

5-M Tidal asymmetry

Shoaling process for wind waves was characterized by:

- increase in amplitudes
- peaking of the wave crest and a flattening of the trough
- relative steepening of the face and a pitched-forward wave shape

- Comparable effects for tidal propagation
- Easiest explained from combined effect of friction and continuity

5-M Tidal asymmetry

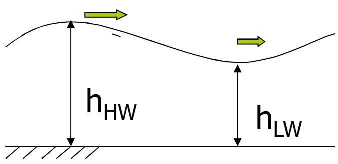
Pitched forward wave shape

In absence of friction:

$$c=\sqrt{gh}=\sqrt{g\left(h_0+\eta\right)} \text{ or } c=\sqrt{g\frac{A_s}{b}}$$

⇩

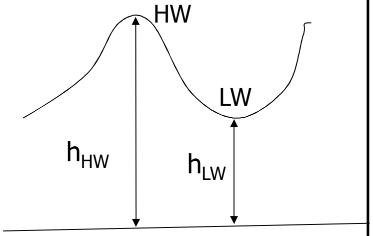
No intertidal areas:
High tide propagates faster than the low tide

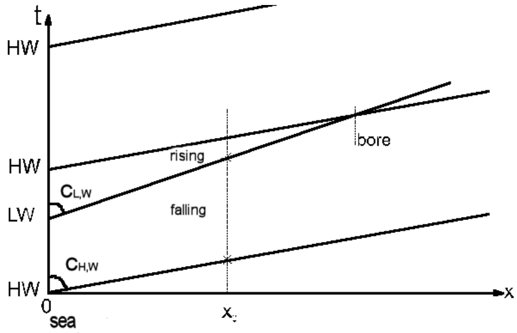


Friction gives an additional slowing down of the low tide
(since low tide “feels” the bottom more)

5-M Tidal asymmetry

If high water (HW) propagates faster than low water (LW):
rising period < falling period





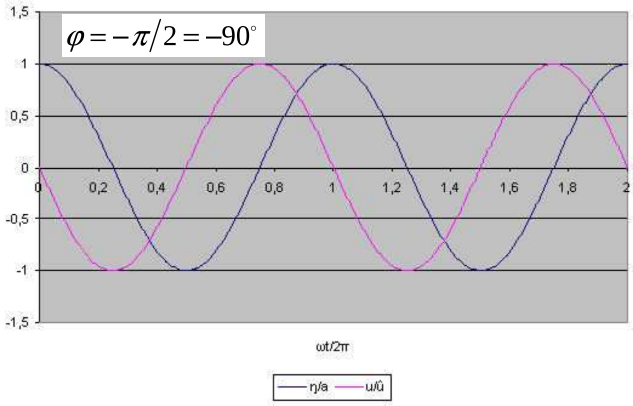
Extreme situation: tidal bore

Petitcodiac River, New Brunswick

Or: Araguari River in the Amazon system

5-K Tidal asymmetry

Shorter rising period means shorter flood duration (velocity leads surface elevation)



We found that in the absence of intertidal storage areas the high tide propagates faster than the low tide. But what does that mean for sediment transport?

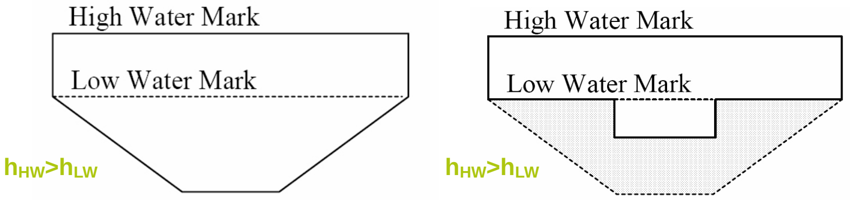
1. $h_{HW} > h_{LW} \Rightarrow c_{HW} > c_{LW}$
2. $c_{HW} > c_{LW} \Rightarrow$ smaller rising period than falling period
3. shorter rising period => shorter flood duration than ebb duration
4. shorter flood duration means larger maximum flood velocity than maximum ebb velocity
5. larger maximum flood velocity means net landward transport of sand

5-M Tidal asymmetry

Flood-dominance: **shorter flood-duration** than ebb-duration and **highest currents during flood**

- Larger water depths at high tide: high tide propagates faster
- Flood velocities larger than ebb velocities
- Controlled by a/h: ratio of tidal amplitude over channel depth

Large enough a/h => flood-dominance

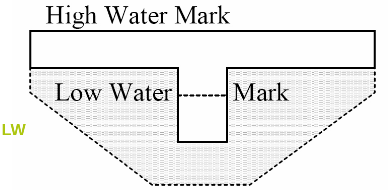


5-M Tidal asymmetry

Ebb-dominance: **shorter ebb-duration** and **highest currents during ebb**

- Flood dominance can be counteracted by larger intertidal storage
- Low water depth in intertidal marshes and flats => propagation of the high tide is slowed down more!!
- For deep channels and extensive intertidal areas
- Controlled by Vs/Vc: ratio of intertidal storage volume areas over channel volume
- For small ratio of tidal amplitude a to channel depth h most estuaries are ebb-dominant

$h_{HW} < h_{LW}$



5-M Tidal asymmetry

Tidal asymmetry controls sediment transport patterns

- Flood-dominant systems:
  - Shallow channels, little intertidal storage
  - Shorter flood duration, higher velocity floods
  - Sediment import to channels
- Ebb-dominant systems:
  - Deep channels, extensive intertidal storage areas
  - Shorter, higher velocity ebbs
  - Channels get flushed

feedback mechanism

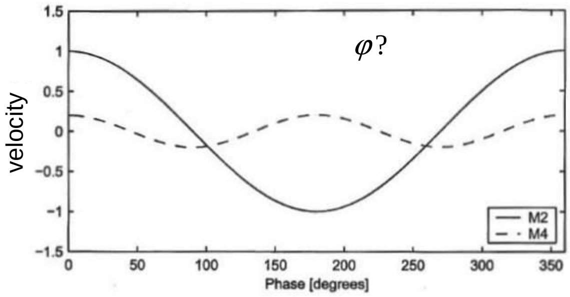
Basin geometry determines import or export

5-M Tidal asymmetry

Non-linear effects in shallow water generate so-called shallow water tides (with periods ≠ tidal forcing periods!)

A velocity signal with M2 + M4 reads:

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



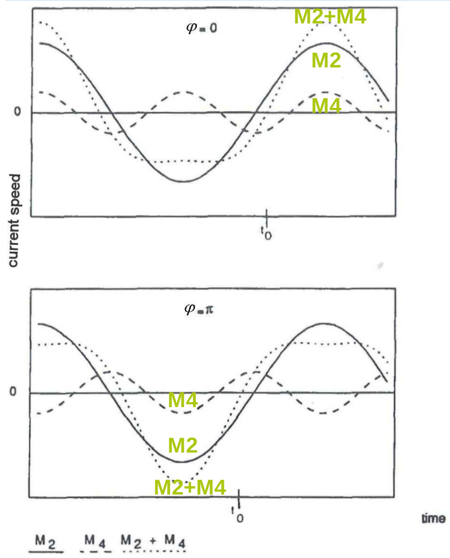
Overtides: higher harmonics of the basic tidal constituents (e.g. M4, M6 are overtides of M2)

5-M Tidal asymmetry

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

Flood dominance (positive skewness)

Ebb-dominance (negative skewness)



5-M Tidal asymmetry

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

Large flats, deep channels

Saw-tooth asymmetry

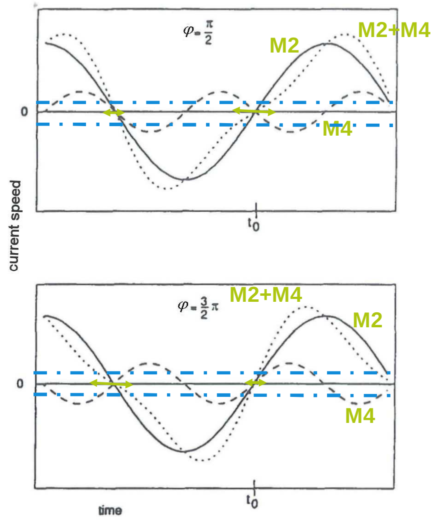
- flow reversal from flood to ebb is of shorter duration than flow reversal from ebb to flood (duration HW slack < LW slack)

Saw-tooth asymmetry dominant asymmetry in short basins

Saw-tooth asymmetry

- flow reversal from ebb to flood is of shorter duration than flow reversal from flood to ebb (duration LW slack < HW slack)

Little flats, shallow channels



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)

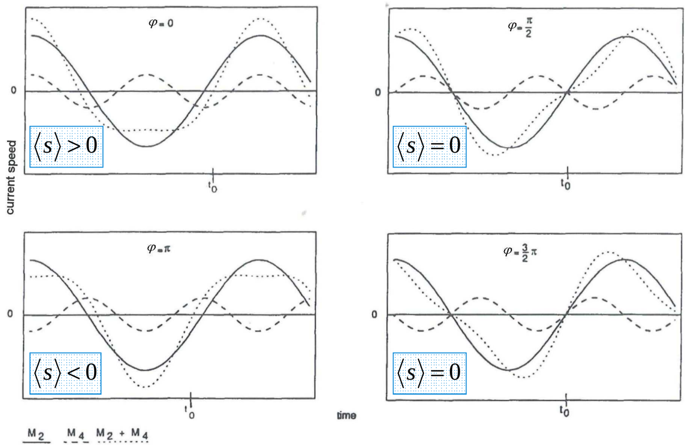
⇧ ?

$h_{HW} > h_{LW}$

Ebb-dominance (sediment export)

⇧ ?

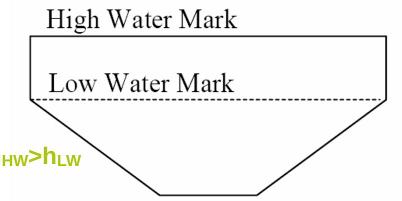
$h_{LW} > h_{HW}$



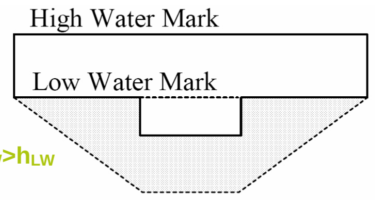
5-M Tidal asymmetry

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

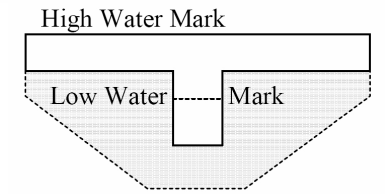
- for large enough tidal amplitude and not too deep channels



$h_{HW} > h_{LW}$



$h_{HW} > h_{LW}$



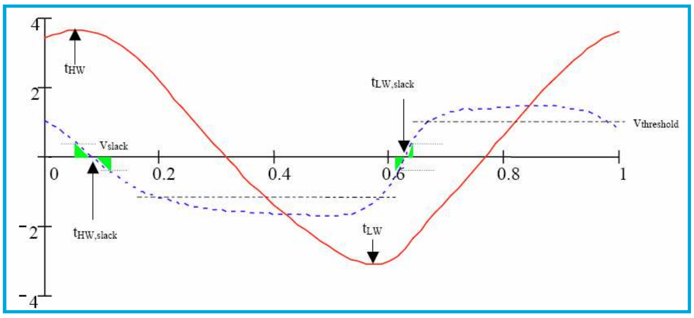
$h_{HW} < h_{LW}$

- for deep channels and extensive intertidal areas

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
- The longer the slack duration, the more fines can settle

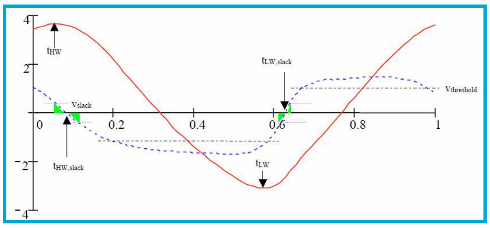


HW slack
- From flood to ebb
- Often around HW

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

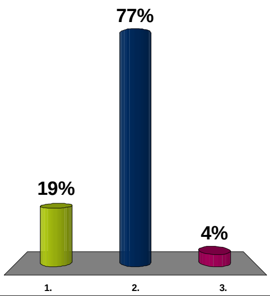
5-M Tidal asymmetry

Extra effect for finer sediment: the longer the slack duration the more fines can settle



What is the correct conclusion?

1. The longer HW slack (reversal from flood to ebb) enhances a net export of fine sediment
2. The longer HW slack (reversal from flood to ebb) enhances a net import of fine sediment
3. I do not know

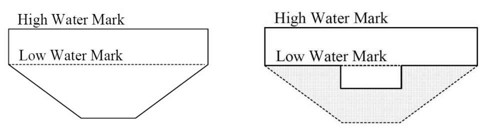


5-M Tidal asymmetry

But when do we get a longer HW slack than LW slack (and hence import of fines)?

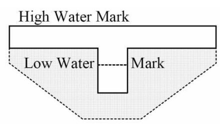
See Chapter 9!

- Such velocity saw-tooth asymmetry easily develops in short basins
- **(HW slack at high water + rate of velocity change smaller for larger water depths)**
- If $h_{H,W} > h_{L,W}$ (shallow channels or little intertidal storage) HW slack is longer than LW slack:



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

more sedimentation at HW due to smaller water depths



5-M Tidal asymmetry
Other reasons for tidal asymmetry

Besides:

- Tidal distortion in estuary due to geometry: friction and intertidal storage

We also have:

- Asymmetry of the tide at sea boundary
- Fresh-water run-off
- Residual currents (e.g. Stokes drift)

Coastal hydrodynamics – part II
Chapter 5 of lecture notes

J. What was the tide again?
K. Tidal propagation along the shore
L. Tidal propagation into basins
M. Tidal asymmetry
N. Residual currents (see in Chapter 9)