A generic approach to the concept of water renewal timescales

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Timescales in oceanography – Motivations

How to :

- Make sense of the huge amounts of results produced by complex numerical models
- Not ignore 99 % of the information (space-time slices of the output)
- Drastically reduce the amount of data
- Produce simple answers / figures

One answer: Compute the timescales associated with the water renewal.

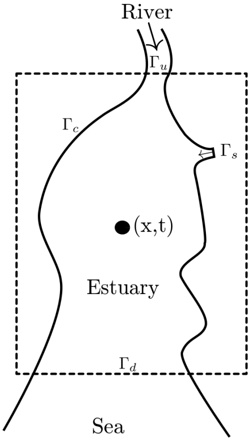
- Relevant diagnostics for the dynamics of water masses and for pollution issues
- Complete and mathematically-based formalism: Constituent-oriented Age and Residence time Theory,[1] (CART)

[1] www.climate.be/CART

Definitions of the timescales

Define a domain of interest (e.g. estuary, delta, bay) and consider a particle at time *t* and position **x**

- Age $= t(\rightsquigarrow)$
- Residence time $= t(\rightsquigarrow)$
- Exposure time $= t(\rightsquigarrow) + t(\rightsquigarrow)$
- Return coefficient $= t(\rightsquigarrow)/(t(\rightsquigarrow) + t(\rightsquigarrow))$



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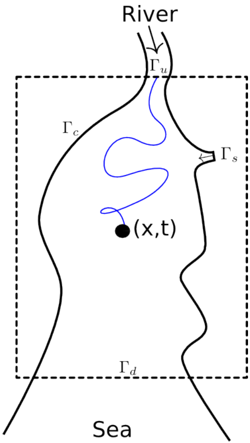

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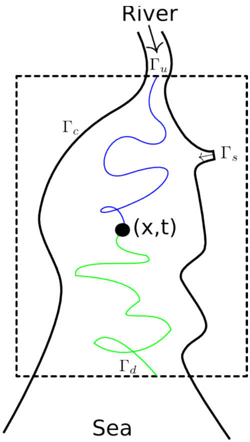

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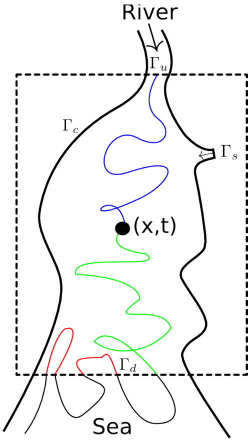

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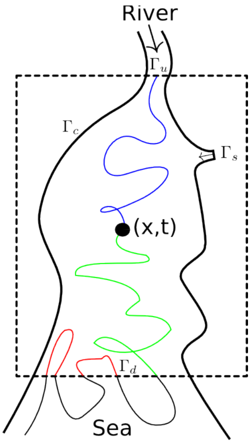
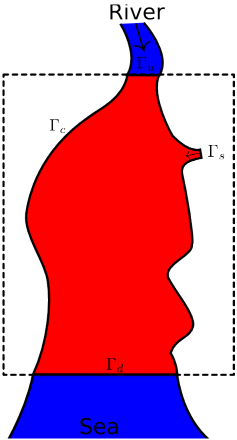
- Exposure time $= t(\rightsquigarrow) + t(\rightsquigarrow)$
  Total time spent inside the domain
- Return coefficient = $t(\rightsquigarrow)/(t(\rightsquigarrow) + t(\rightsquigarrow))$
  Measure of the propensity to return into the domain after leaving it for the first time



The water renewal

Processes by which water initially located in the domain of interest (the "original water") is progressively replaced by water originating from its environment (the "renewing water").

- Split the water into two passive tracer : $1 = C_o + C_r$
- The residence time is computed on base of the original water C_o: the time needed to leave the domain of interest
- The age is computed on base of the renewing water C_r: the time needed to fill the domain of interest



How to compute the timescales at each grid point and time-step

In details in de Brye et al. (Journal of Marine Systems, 2012) or `www.climate.be/CART`

Depth-integrated age (a_r) of the renewing water C_r

$$
\begin{aligned}
\frac{\partial}{\partial t}\Big(HC_r\Big) + \boldsymbol{\nabla}\cdot\Big(H\boldsymbol{u}C_r\Big) &= \boldsymbol{\nabla}\cdot\Big(H\kappa\boldsymbol{\nabla}C_r\Big)\ , \\
\frac{\partial}{\partial t}\Big(H\alpha_r\Big) + \boldsymbol{\nabla}\cdot\Big(H\boldsymbol{u}\alpha_r\Big) &= \boldsymbol{\nabla}\cdot\Big(H\kappa\boldsymbol{\nabla}\alpha_r\Big) + HC_r\ , \\
a_r &= \frac{\alpha_r}{C_r}\ ,
\end{aligned}
$$

with α_r an intermediate variable called the age concentration.

Depth-integrated residence time θ_R

$$
\frac{\partial}{\partial \tau}\Big(H\theta_R\Big) + \boldsymbol{\nabla}\cdot\Big(H(-\mathbf{u})\theta_R\Big) = \boldsymbol{\nabla}\cdot\Big(H\kappa\boldsymbol{\nabla}\theta_R\Big) + H\ .
$$

This equation must be resolved backward in time ($\tau = t_0 - t$)!

Applications

The **Scheldt Estuary** (Belgium / The Netherlands)

The **Mahakam Delta** (Indonesia – Borneo Island)

SLIM model
Overview

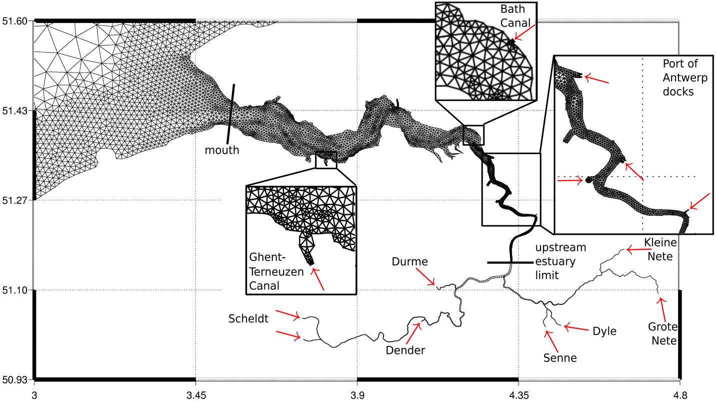
Second-generation Louvain-la-Neuve Ice-ocean Model (SLIM)

http://www.climate.be/SLIM

- Shallow water equations
- Discontinuous Galerkin Finite Element Method (DG-FEM)
- 1D, 2D and 3D models
- Fully implicit time integration
- Implicit wetting-drying
- Coupling 1D/2D

Application: the Scheldt Estuary

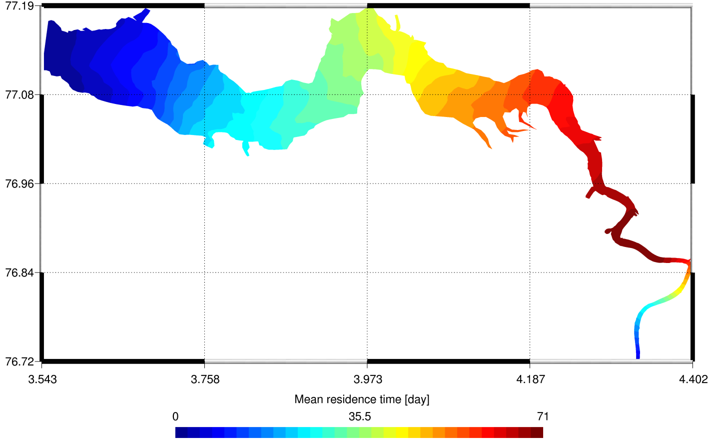
- Highly polluted
- Mean discharge of 150 m^3/s
- Tidal range $\approx$ 3.8 m
- 2D for shelf & estuary, 1D for river network



Described in de Brye et al. 2010, Coastal Engineering

Residence time

Tide averaged, Mean situation (Q)



Tide averaged residence time: small variabilities along the section of the river

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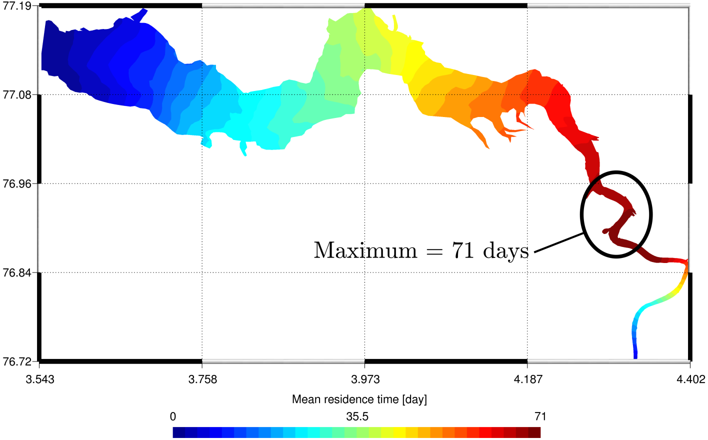

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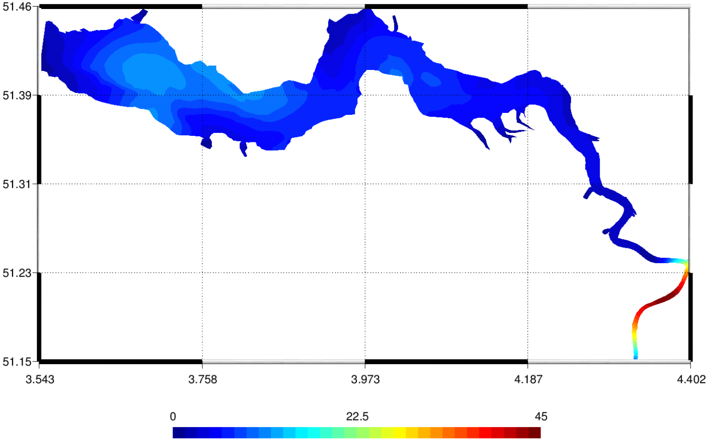

Tidal amplitude of residence time: high variability, timescales at high tide and low tide are really different!

Residence time

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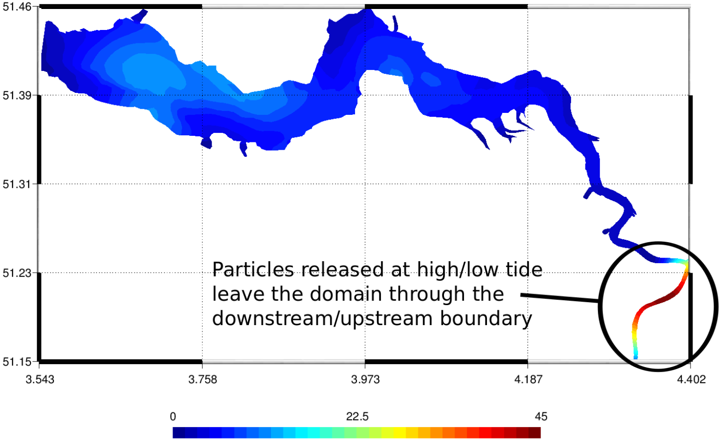

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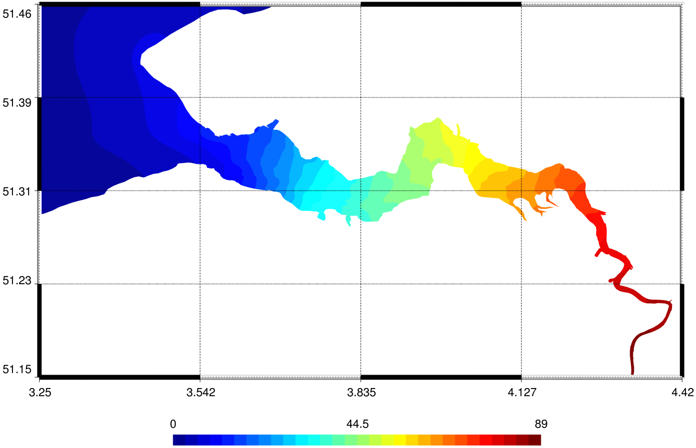
Exposure time



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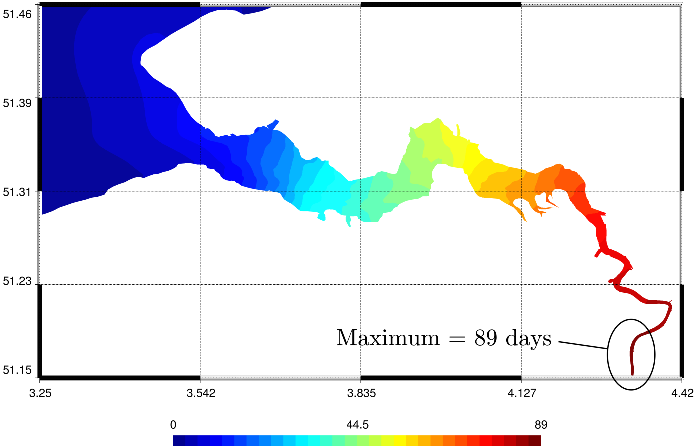

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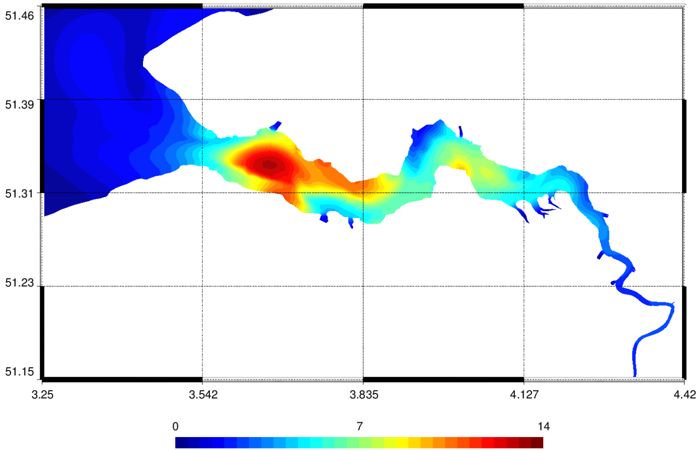

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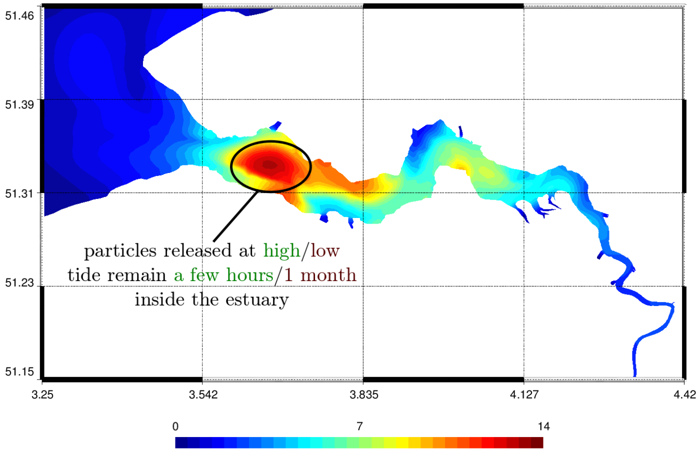

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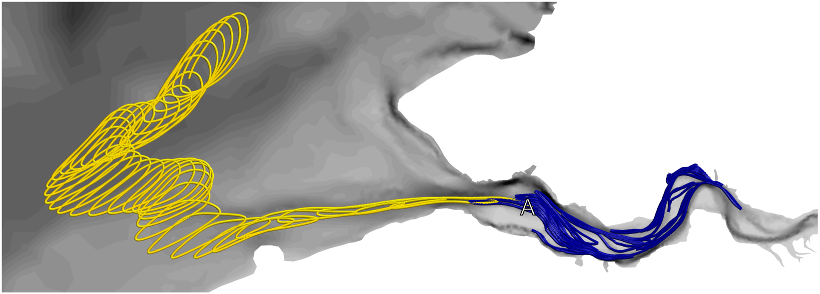
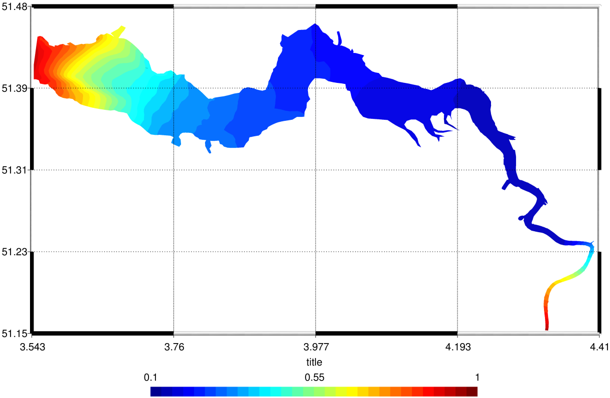


Release of lagrangian particles at high tide and low tide (diffusion is neglected). Kind of bottle-neck upstream of the mouth.

Return coefficient

Relative difference between exposure time and residence time



The return coefficient is a measure of the propensity to return into the domain of interest after leaving it for the first time.

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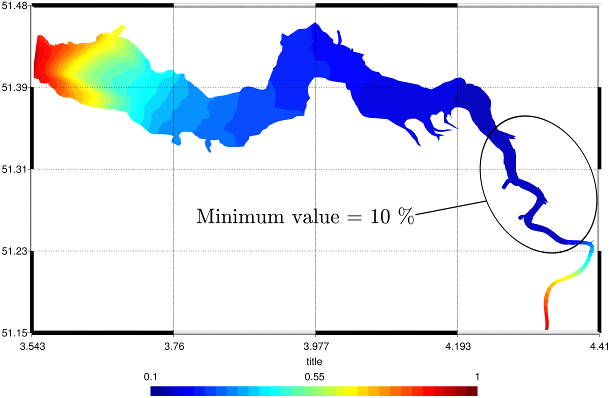

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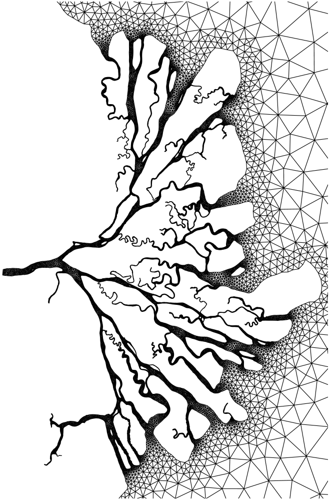
The Mahakam Delta

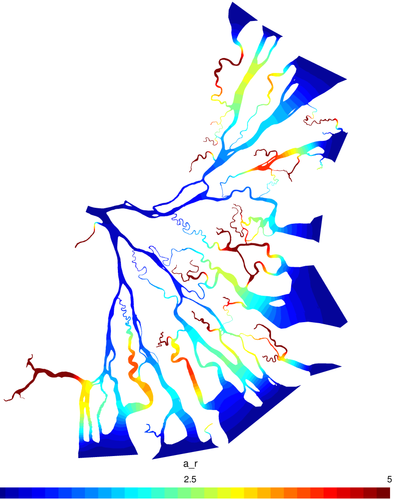


- Complicated geometry
- Mean discharge of 4000 m^3/s
- Tidal range $\approx$ 2 m
- 2D for Strait, Delta & Lakes
- 1D for river network

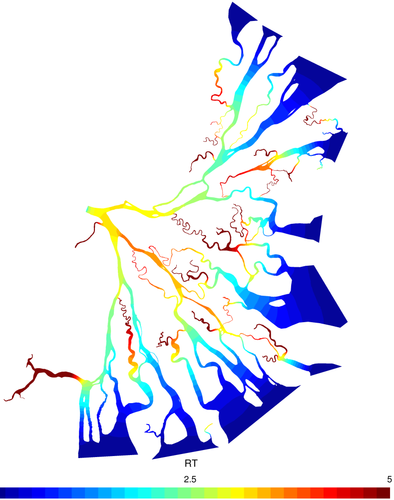
Described in de Brye et al. 2011, Ocean Modelling

Age and residence time

Timescales in the channels depict large differences



Age of renewing water (tide averaged)



Residence time (tide averaged)

Conclusion

- The study of timescales allows for a different and clear understanding of complex systems
- The age of a water mass is a usefull and easy implemented diagnostic
- The residence and exposure times are more difficult to compute (backward iterations) but are in direct link with many environmental issues
- In the Scheldt Estuary: the residence time/exposure time depends on when the particle is released (high tide/low tide)
- In the Mahakam Delta: the timescales allow for a clear notification of the important branches
- All the references in `www.climate.be/SLIM` and `www.climate.be/CART`