A gentle introduction to numerical modeling

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Coastal Oceanography

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Overview

- Models as complement to observations
- Typical applications of models
- Different types of models
- Features of models
  - Dimensionality
  - Numerical grids

Part of the material presented here is with courtesy of
Vladimir G. Koutitonsky, Rimouski, Québec, Canada

What is a Model?

A Model is a partial, simplified and mostly inadequate representation of the real world

A Model can never describe the whole complexity of the system modeled

A Model has to make basic, very often unjustified assumptions of the system it wants to describe

A Model has to neglect most of the complicated, little understood relationships of the system

So why do we use models?

Models : a complement to observations

Measurements are the primary source of information on the coastal ocean, its ecosystem and its variability. There is no point of attempting to model a coastal zone without having data !

However, data are difficult to obtain because of

- The technology of sensing instruments and platforms;
- The costs of observations over long durations and large domains.

In this context, models become important as a complement to observations.

Models : a complement to observations

Models complement observations in coastal management by:

1. Interpolating in 4 dimensions (space-time) the observations;
2. Predicting the future evolution of the system;
3. Simulating the impacts of non-observed forcing scenarios.

Modeling applications

1. Coastal management:

   Coastal erosion;

   Harbour construction.

2. Operational management:

   Prediction (waves, tides, storm surges);

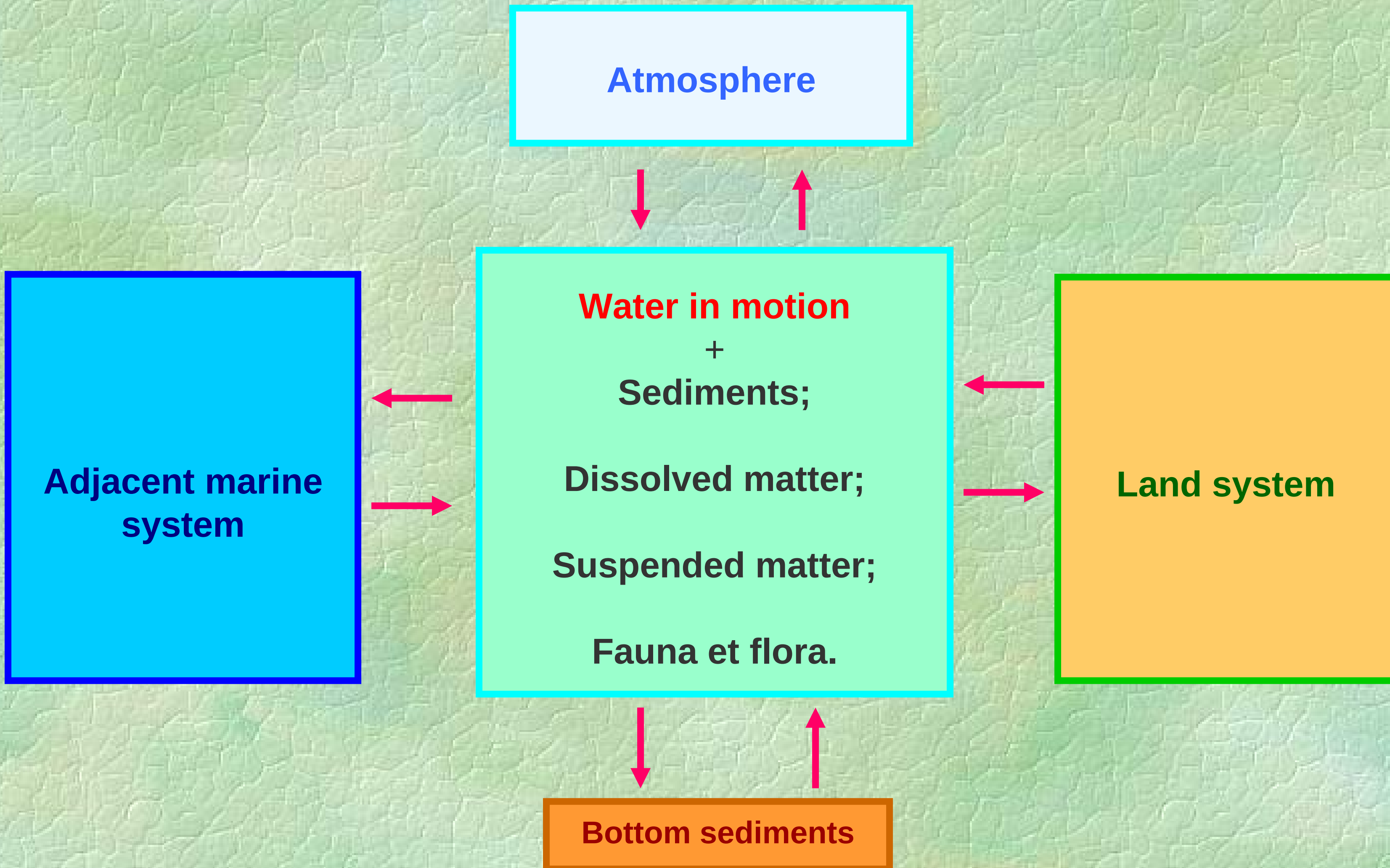
   Hazardous navigation;

   Impact studies;

   Ecosystem protection.

3. Scientific research.

Conceptual modeling approach



The coastal ocean: a dynamic system

Dynamics : **System + Forces = Response**

Dynamics : Abiotic compartment (hydrodynamics)

Conservation of mass

Conservation of momentum

Dynamics : Biotic compartment (ecodynamics)

Energy – matter transformations

The coastal ocean: the equations

Hydrodynamics :

Conservation of mass, momentum, energy, salt

Equation of state

Dispersion :

Conservation of tracer or pollutant

Sediments :

Semi-empirical equations of material movement

Ecosystem :

Highly simplified equations of energy – matter transformations

The hydrodynamic engine (HD)

The hydrodynamic model is the « engine » that transports and mixes all ecosystem constituents, including the water itself.

The hydrodynamic equations of conservation of mass and momentum are solved numerically, in every cell of a computational grid, taking into account the information present in adjacent cells.

Coastal ocean dynamics

$$\frac{\partial \rho}{\partial t} = \nabla \bullet \rho \, \mathbf{v}$$

$$\nabla \cdot \mathbf{v} = 0$$

$$\frac{\partial (\rho \, \mathbf{v})}{\partial t} + \nabla \cdot \rho \, \mathbf{v} \, \mathbf{v} + 2\rho\Omega \wedge \mathbf{v} = -\nabla P - \rho \, \mathbf{g} + \rho \, \mathbf{F}$$

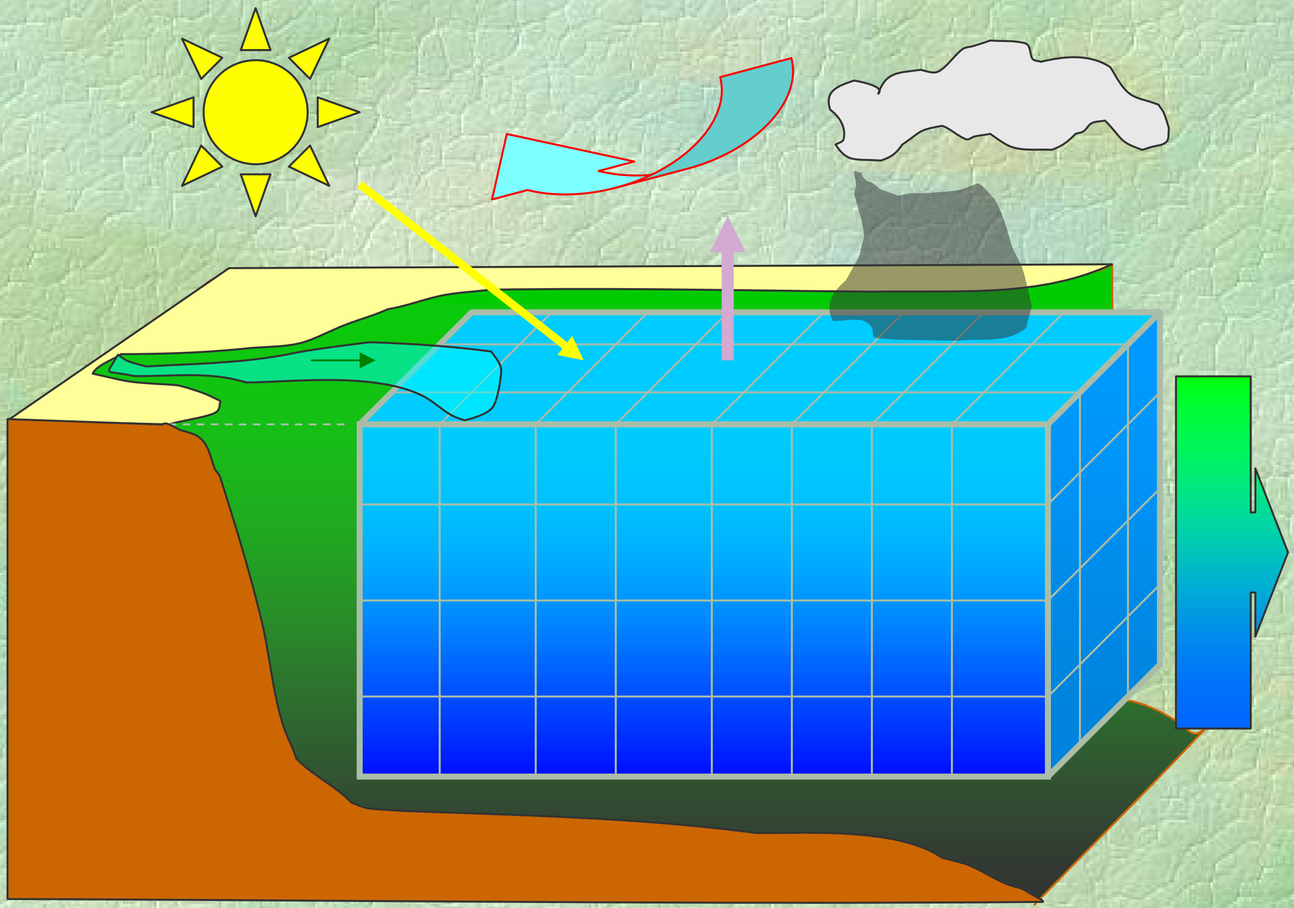
$$\frac{\partial \rho_\alpha}{\partial t} + \nabla \bullet \rho_\alpha \, \mathbf{v}_\alpha = X_\alpha + I_\alpha$$

Where:

X_α is the production (or destruction) rate for variable α by <u>external agents</u>;

I_α, is the production (or destruction) rate for variable α by <u>internal agents,</u> i.e. other system variables.

Conceptual ecosystem modeling

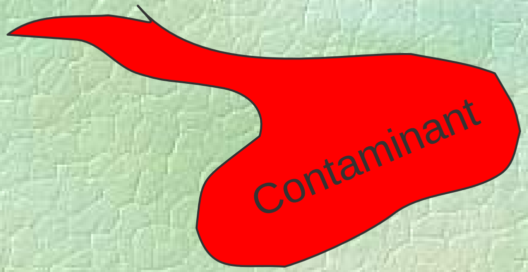


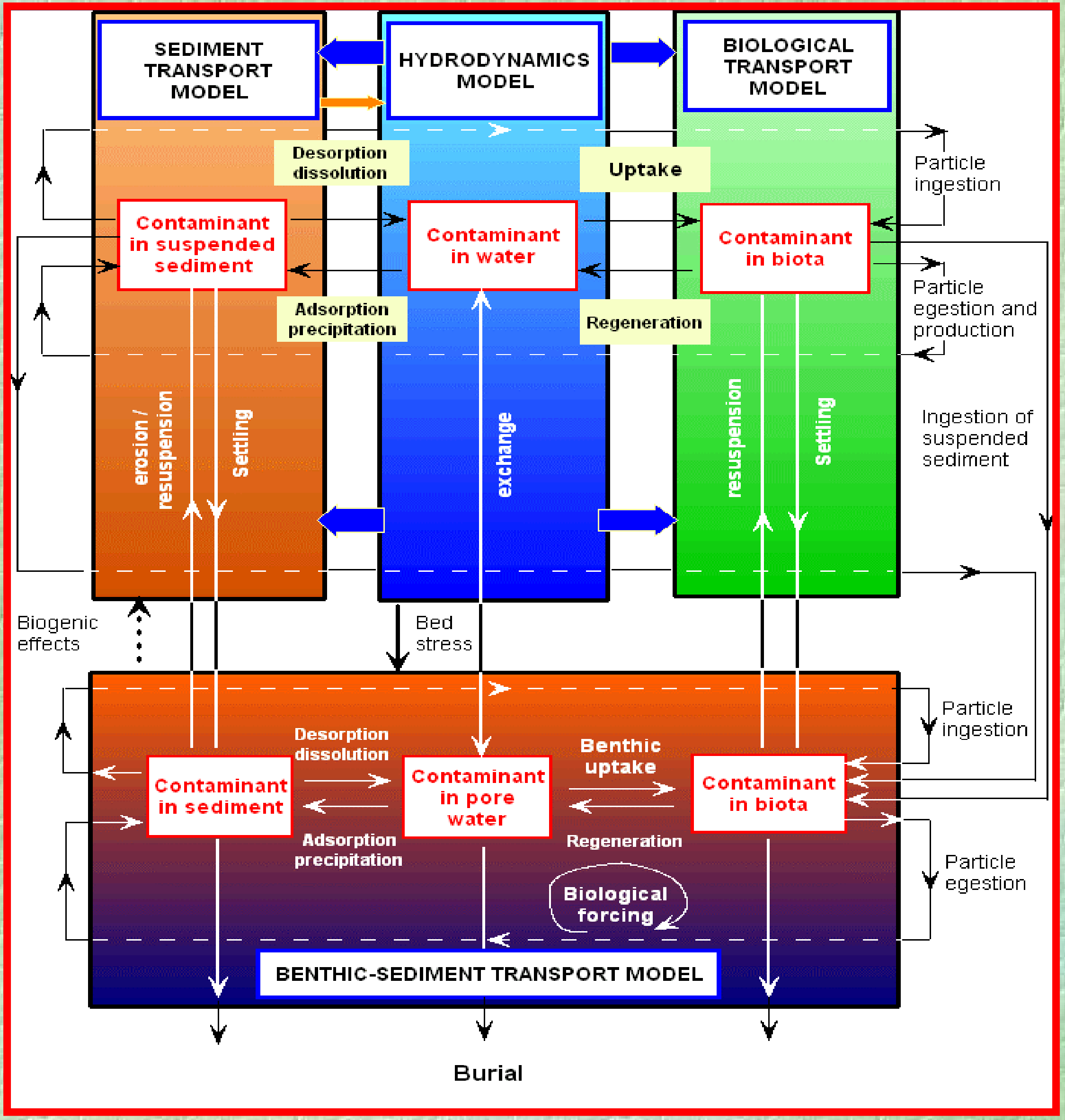
Exchanges

- Water
- Pollutants
- Sediments
- Organic matter
- Nutrients
- Phytoplankton
- Zooplankton
- Other ?

Hydrodynamic engine ⇒ (currents, sea levels, density) + waves

Fate of a contaminant in the coastal ocean





GESAMP - IAEA (1991).

Coastal Modelling.

Transport models

The hydrodynamic engine is then coupled to appropriate numerical models that transport some ecosystem constituents.

There are three major classes of transport models:

- Dispersion models
- Sediment transport models
- Ecosystem models or Water quality models

Transport models

Dispersion models deal with :

Transport and diffusion of tracers

Dispersion of pollutants

Sediment transport models deal with :

Cohesive (e.g. mud) sediment transport

Non-cohesive (e.g. sand) sediments transport

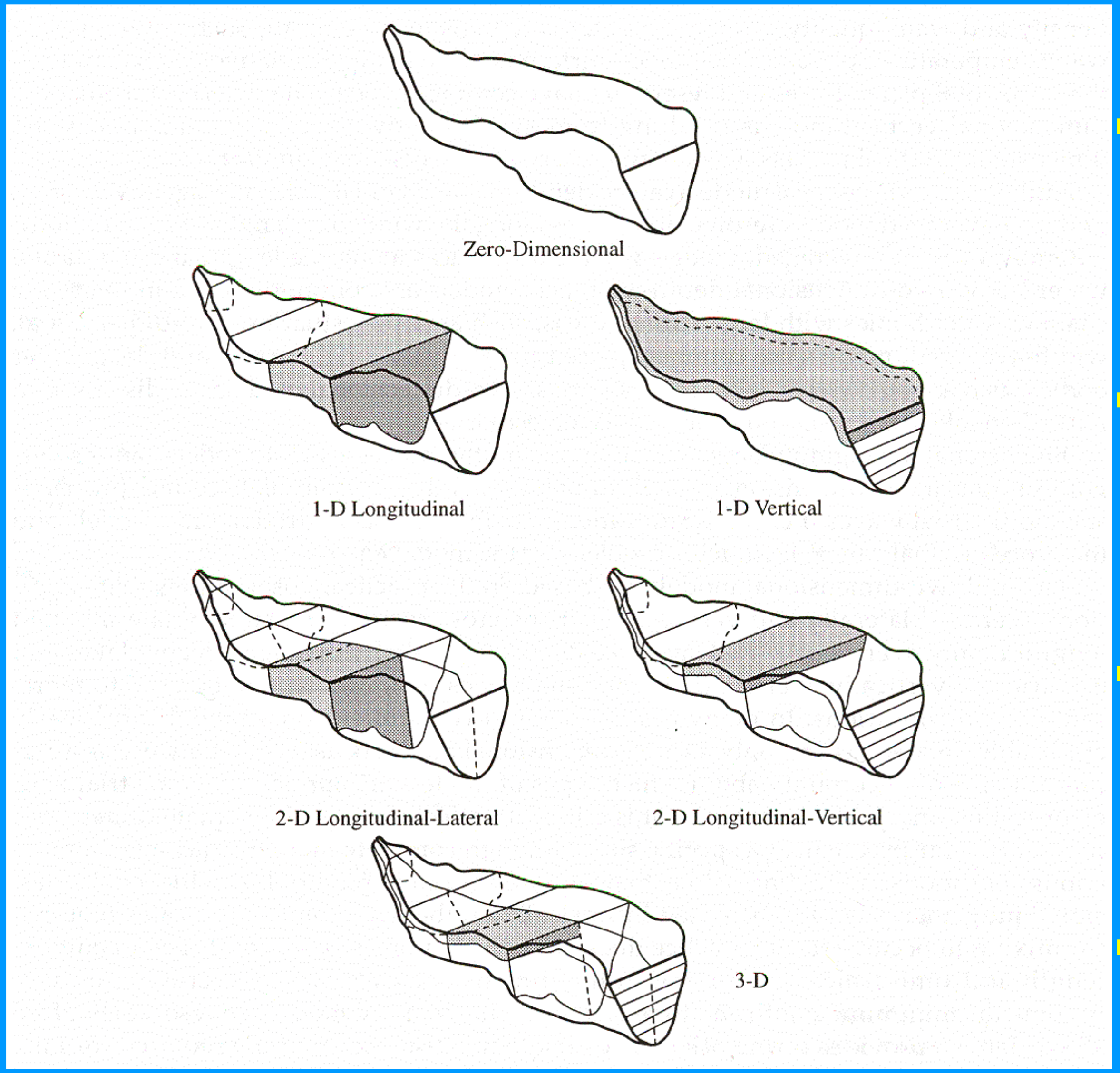
Transport models

Ecosystem or *Water quality* models deal with interactions between some or all of the following:

- Nutrients
- Bacteria
- Phytoplankton and Chlorophyll-a
- Zooplankton
- Organic matter and Detritus
- Dissolved Oxygen

as a function of hydrodynamics and light.

Model dimensions



0 D

1 D

2 D

3 D

Choice

1D,

2D,

or 3D ?

Model	1D	2DH	2DV	3D
Boundary forcing				
River flow	√	√	√	√
Tides	√	√	√	√
Wind stress	√	√	√	√
Bottom stress	√	√	√	√
Currents	√	√	√	√
Upwelling	-	-	-	√
Internal Response				
Tidal circulation	√	√	√	√
Residual circulation	√	√	√	√
Barotropic circulation	√	√	√	√
Inertial motion	√	√	√	√
Buoyancy intrusion	√	√	√	√
Baroclinic circulation	-	-	-	√
Vertical shear	-	-	√	√
Coriolis effect	-	√	-	√
Topographic waves	-	√	-	√
Internal waves	-	-	√	√
Thermal stratification	-	-	√	√
Local turbulence	-	-	√	√

Model classification

Model classification	Class type
Geographical	Ocean (e.g., Atlantic)
	Regional (e.g., Red Sea)
	Coastal (e.g., bays, lagoons)
Physical	Thermodynamic
	Hydrodynamic
Surface approximation	Free surface
	Rigid lid
Density stratification	Baroclinic
	Barotropic
Vertical structure	Z-level
	Sigma-level
	Isopycnal
	Semi-spectral

Coordinate systems

Cartesian

or

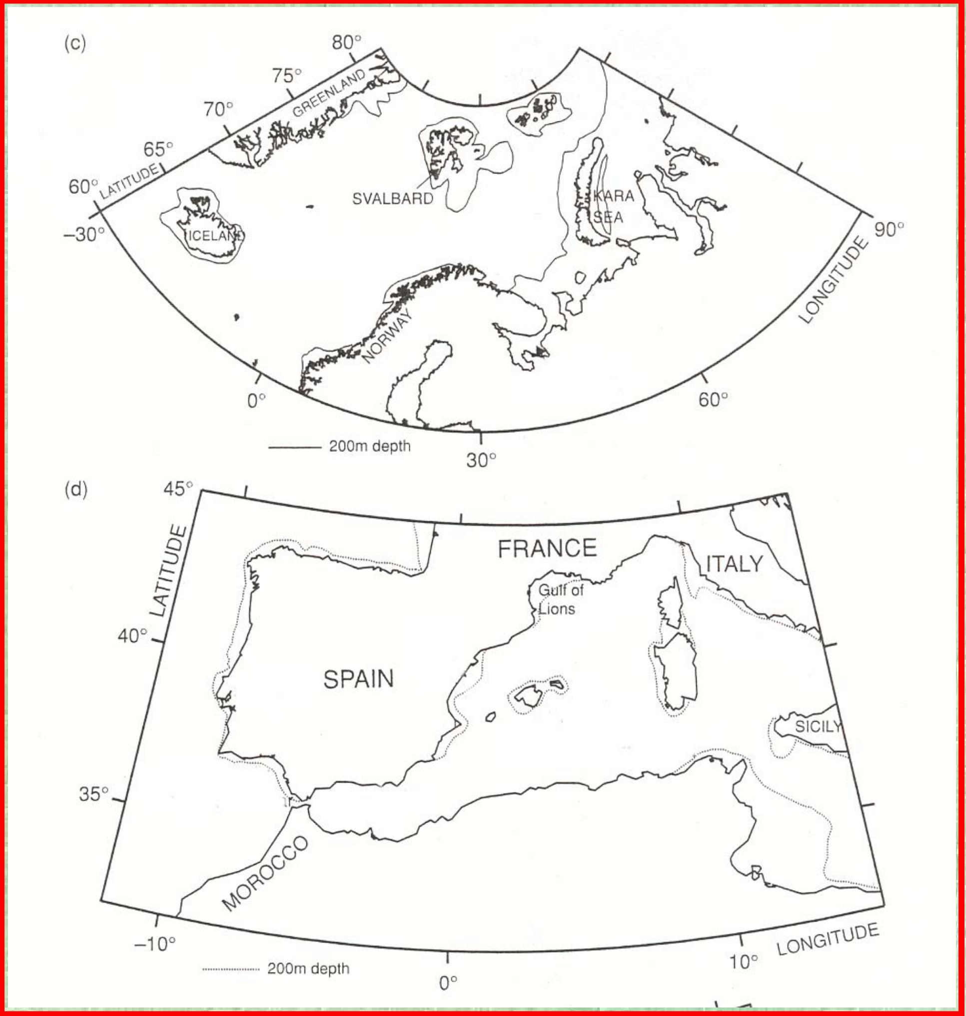
Spherical

or

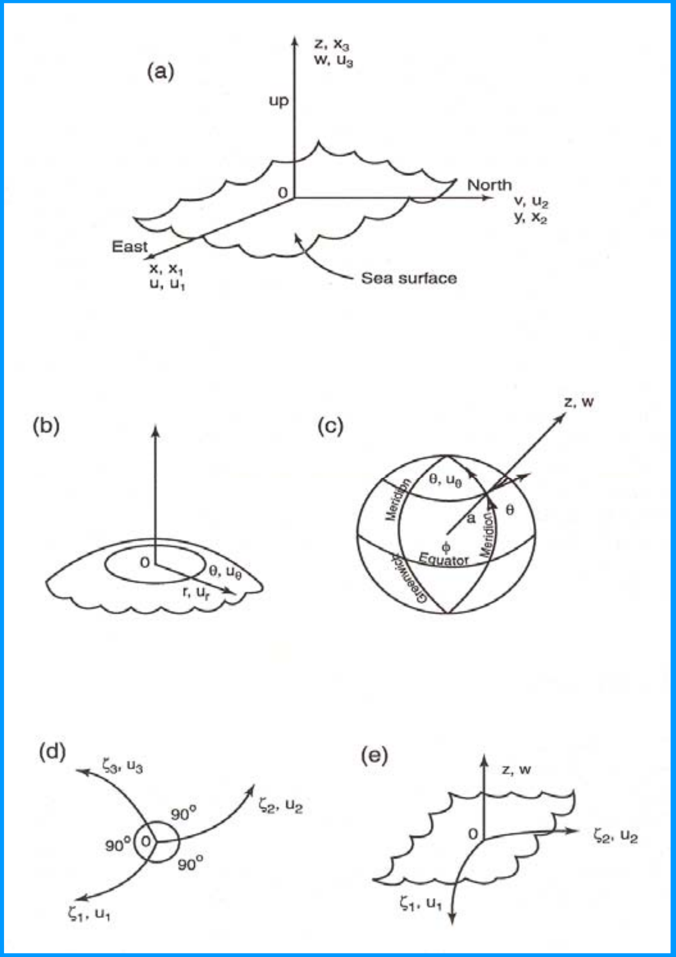
Cylindrical

or

Curvilinear ?



Coordinate systems



(a) Cartesian:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0$$

(b) Cylindrical:

$$\frac{1}{r}\frac{\partial (u_r r)}{\partial r}+\frac{1}{r}\frac{\partial (u_\theta r)}{\partial \theta}+\frac{\partial w}{\partial z}=0$$

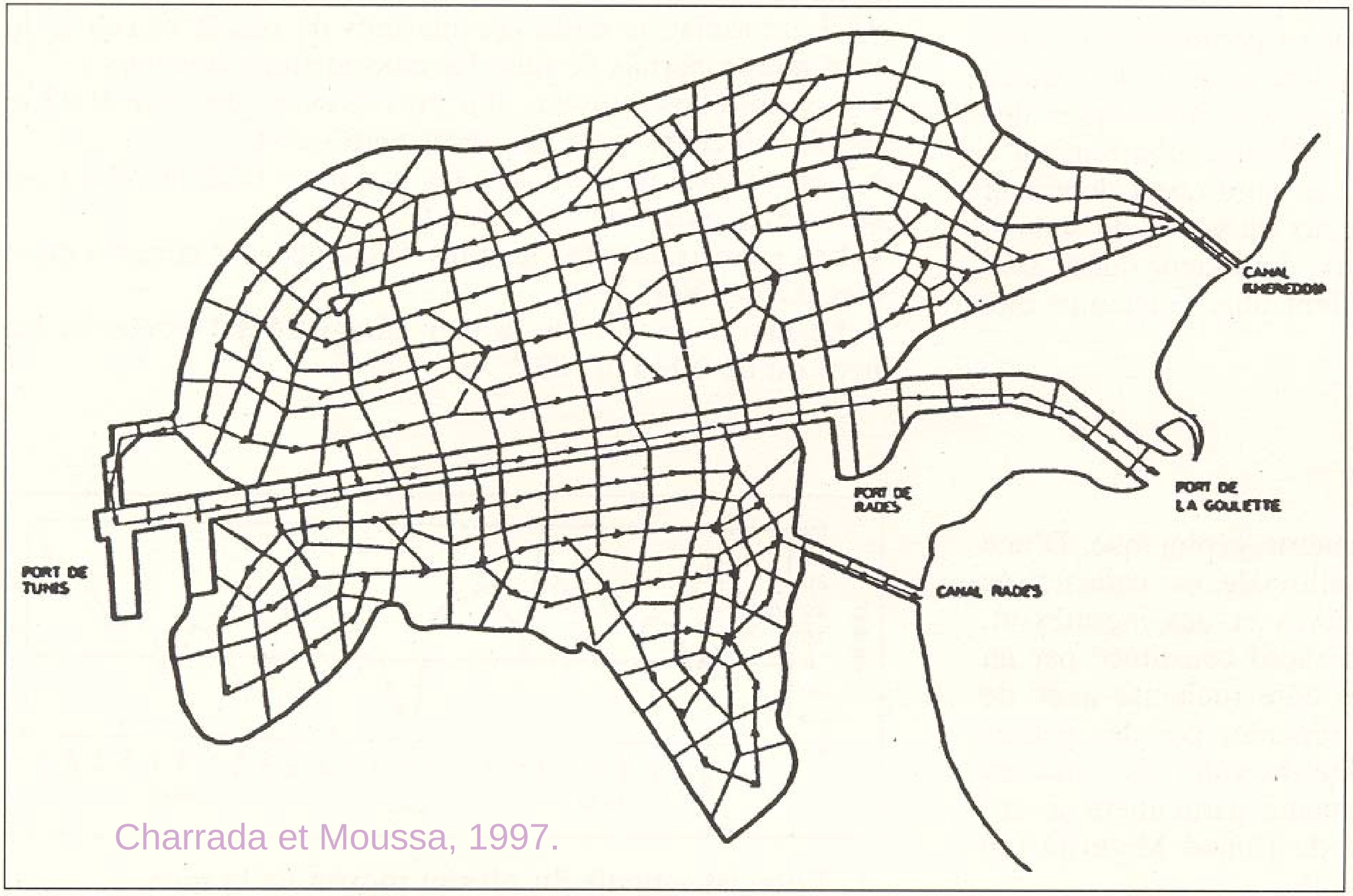
(c) Spherical:

$$\frac{1}{(R+z)\cos\theta}\frac{\partial u_\theta}{\partial \theta}+\frac{1}{(R+z)\cos\phi}\frac{\partial (u_\phi \cos\theta)}{\partial \theta}+\frac{\partial \left[(R+z)^2 u_r\right]}{\partial z}=0$$

(d) Orthogonal:

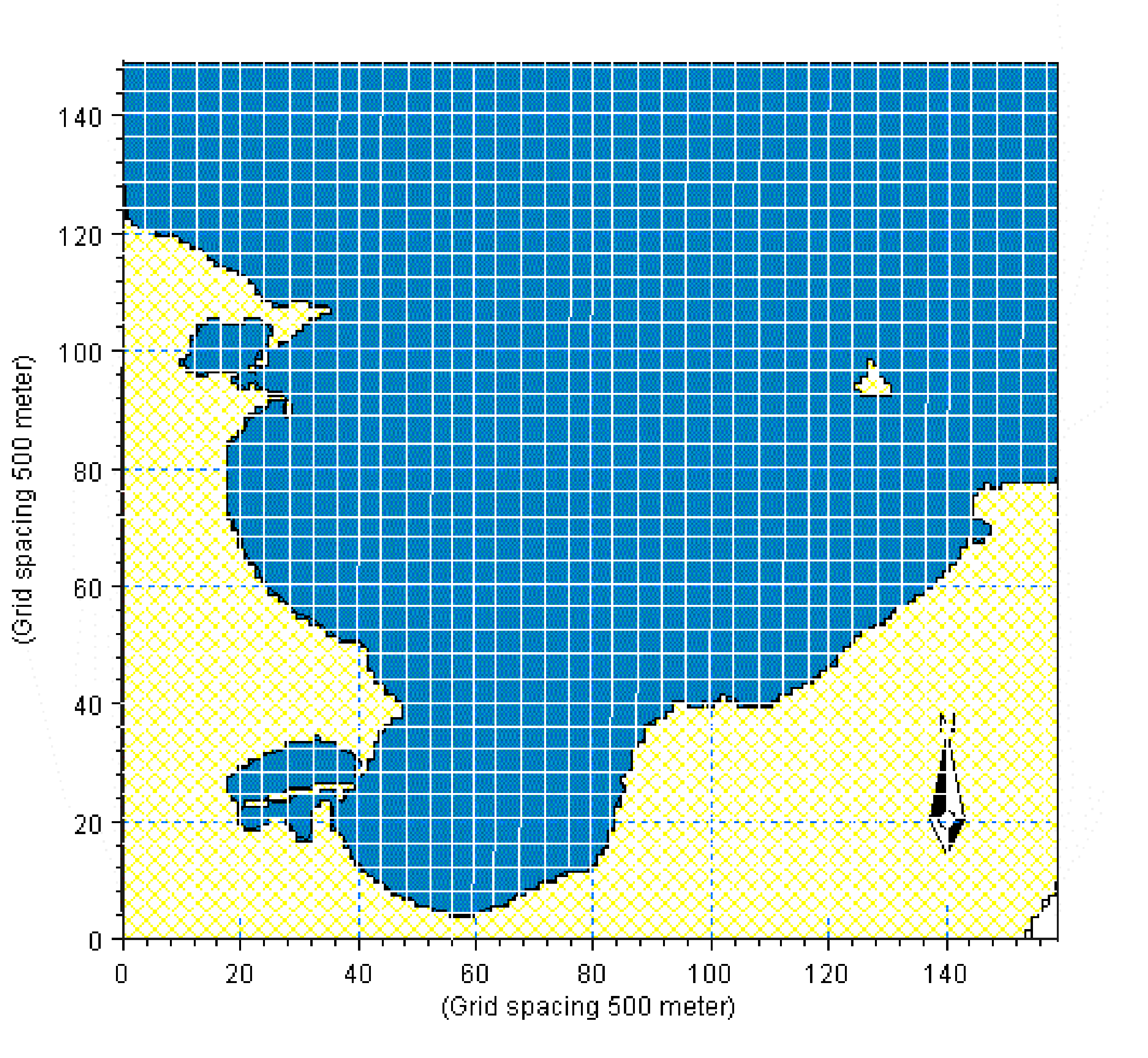
$$\frac{1}{h_1h_2h_3}\left\{\frac{\partial(h_2h_3u_1)}{\partial\xi_1}+\frac{\partial(h_3h_1u_2)}{\partial\xi_2}+\frac{\partial(h_1h_2u_3)}{\partial\xi_3}\right\}=0$$

Grids: 1D “ branched ” grid



Charrada et Moussa, 1997.

Grids: Rectangular Cartesian grid



Grids: Rectangular variable Cartesian grid

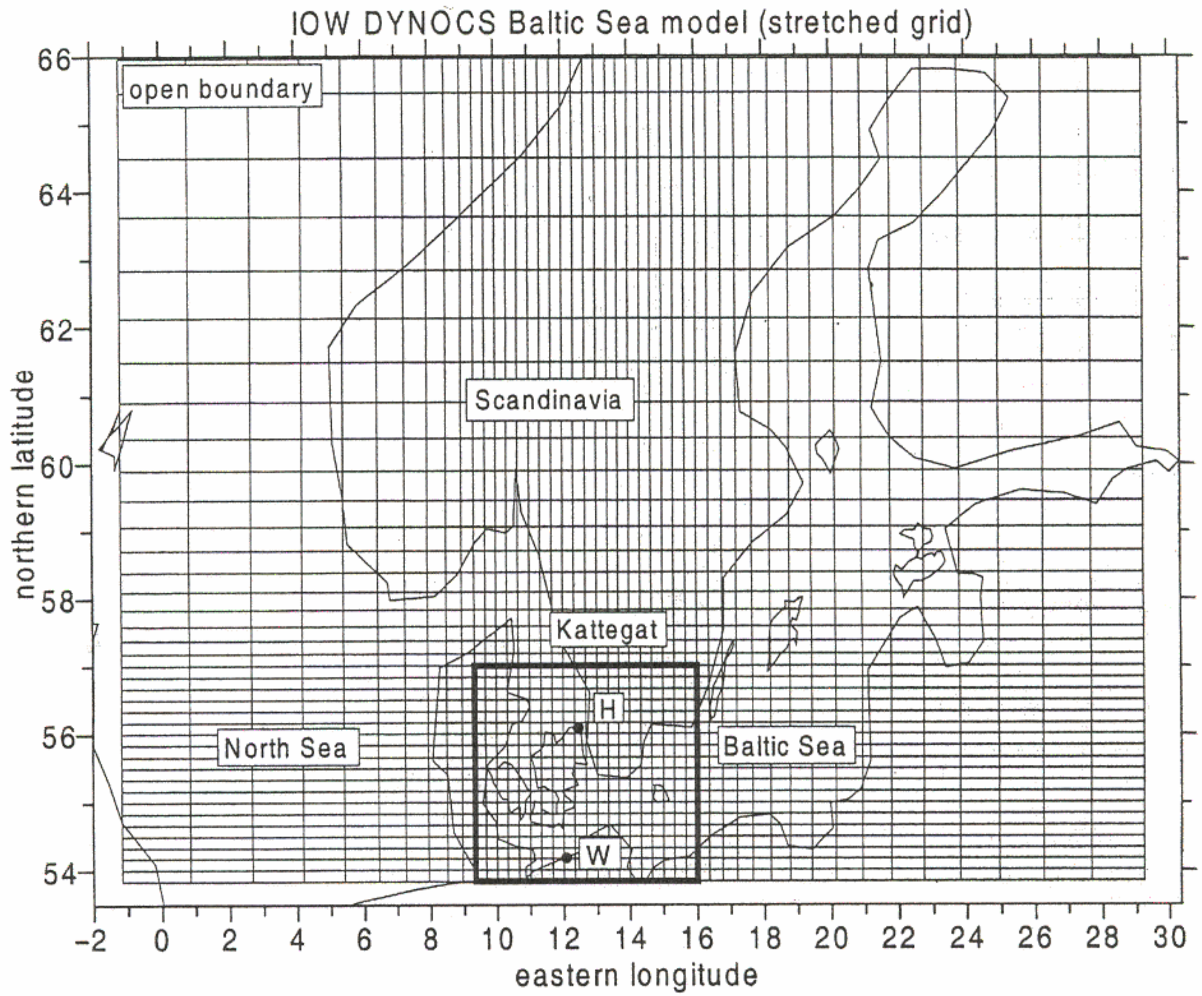
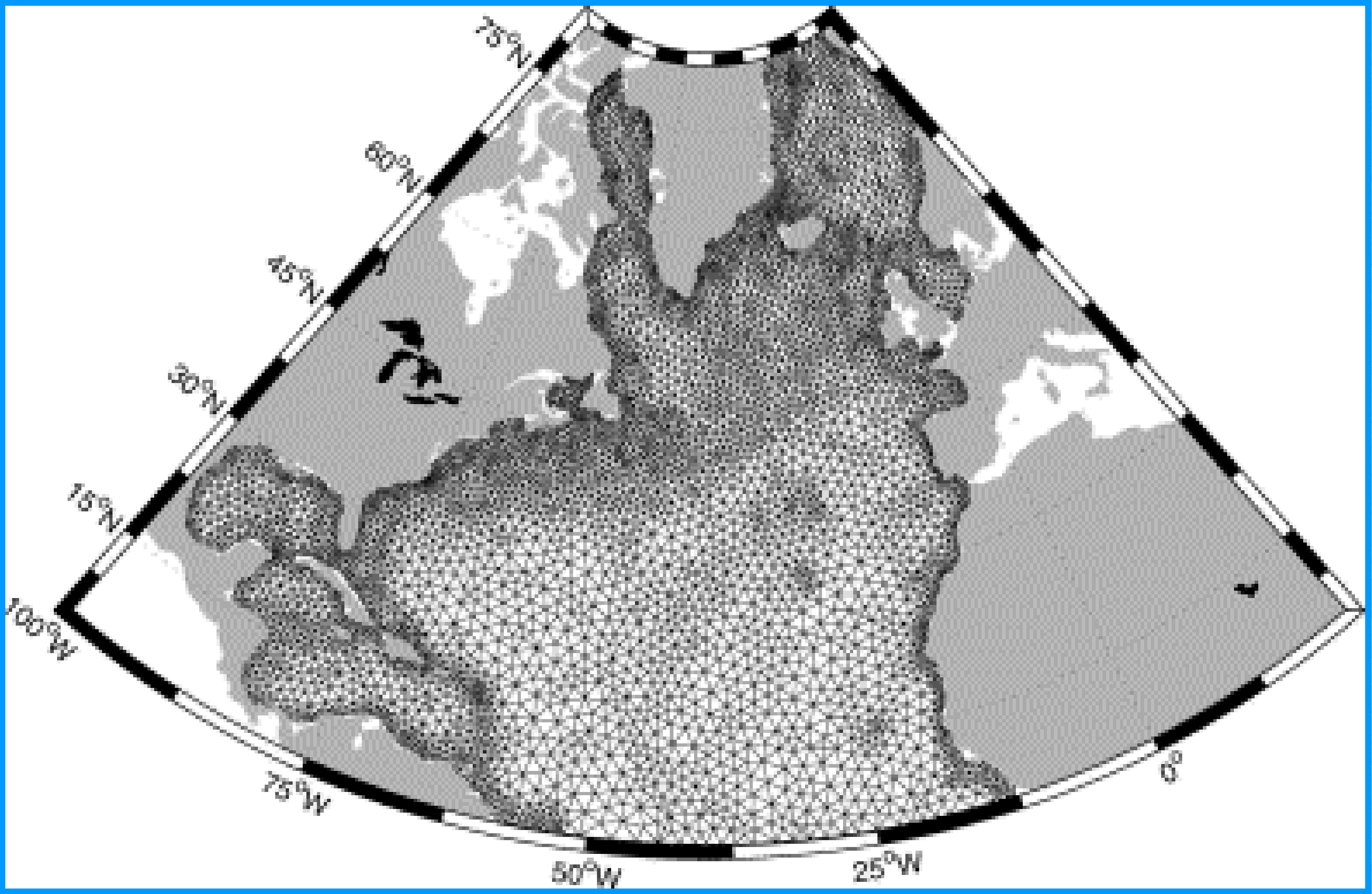
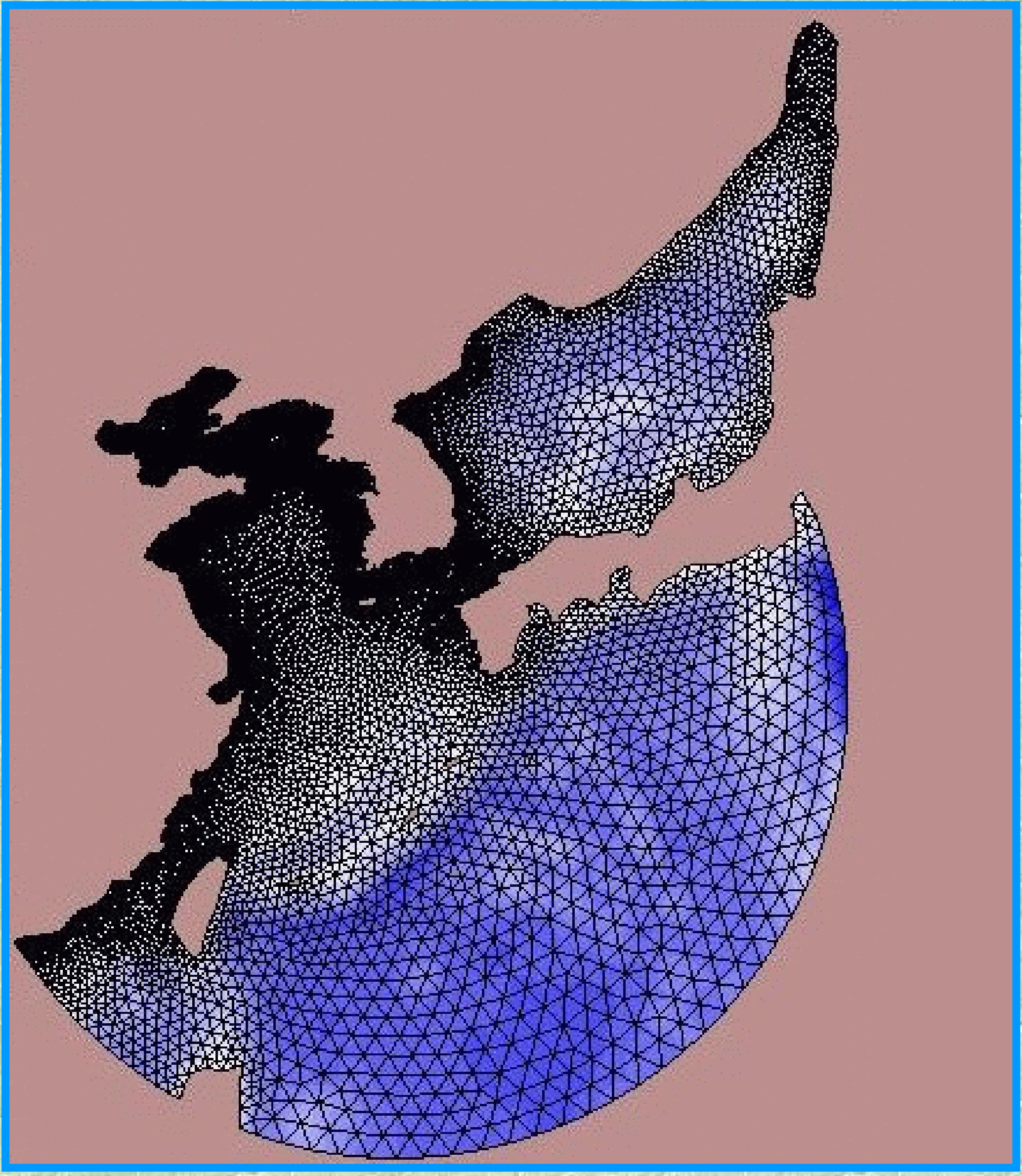


Figure 3 Telescoping grid of the entrances to the Baltic. Adapted from Schmidt et al. (1998: 354). By permission of *Deutsche Hydrographische Zeitschrift*.

Grids: Finite element (FE) triangular grid



Grids: Finite element grid



Grids: Finite element (FE) quadrilateral grid.

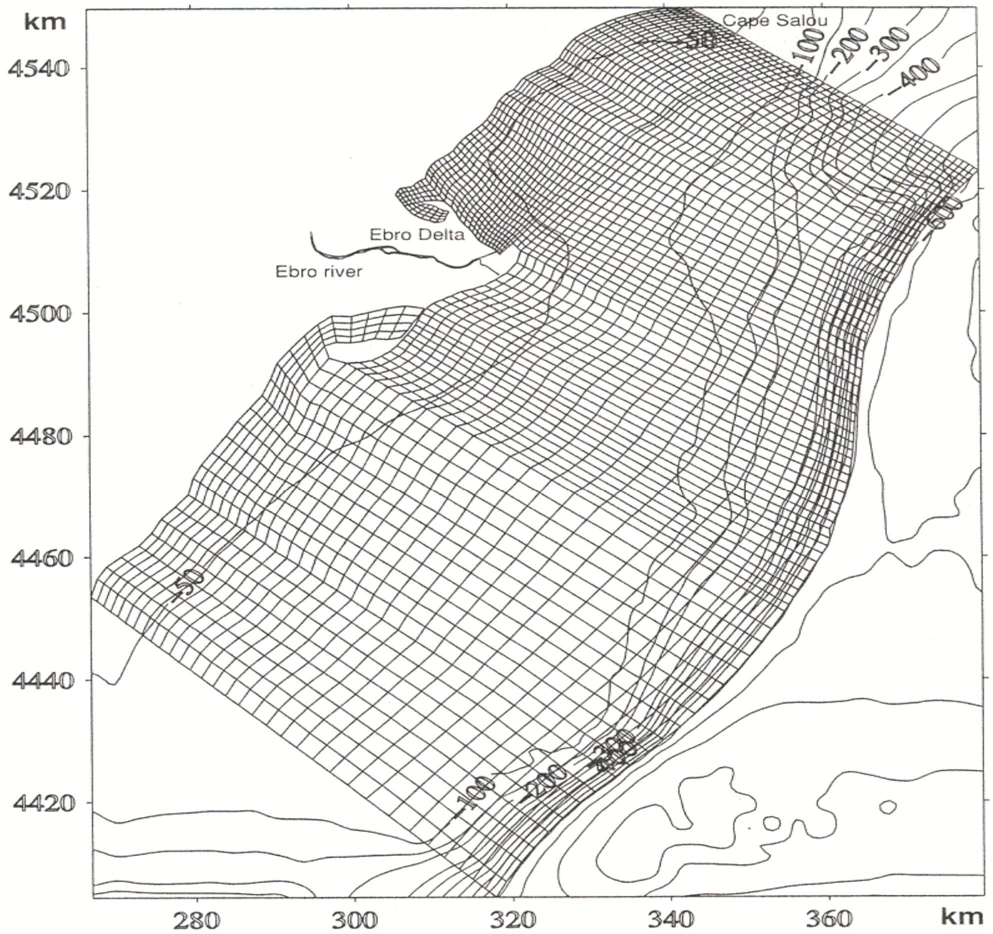
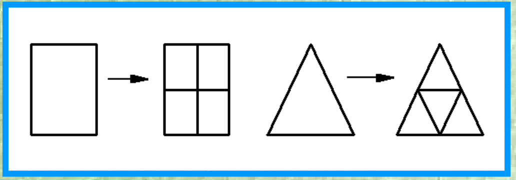
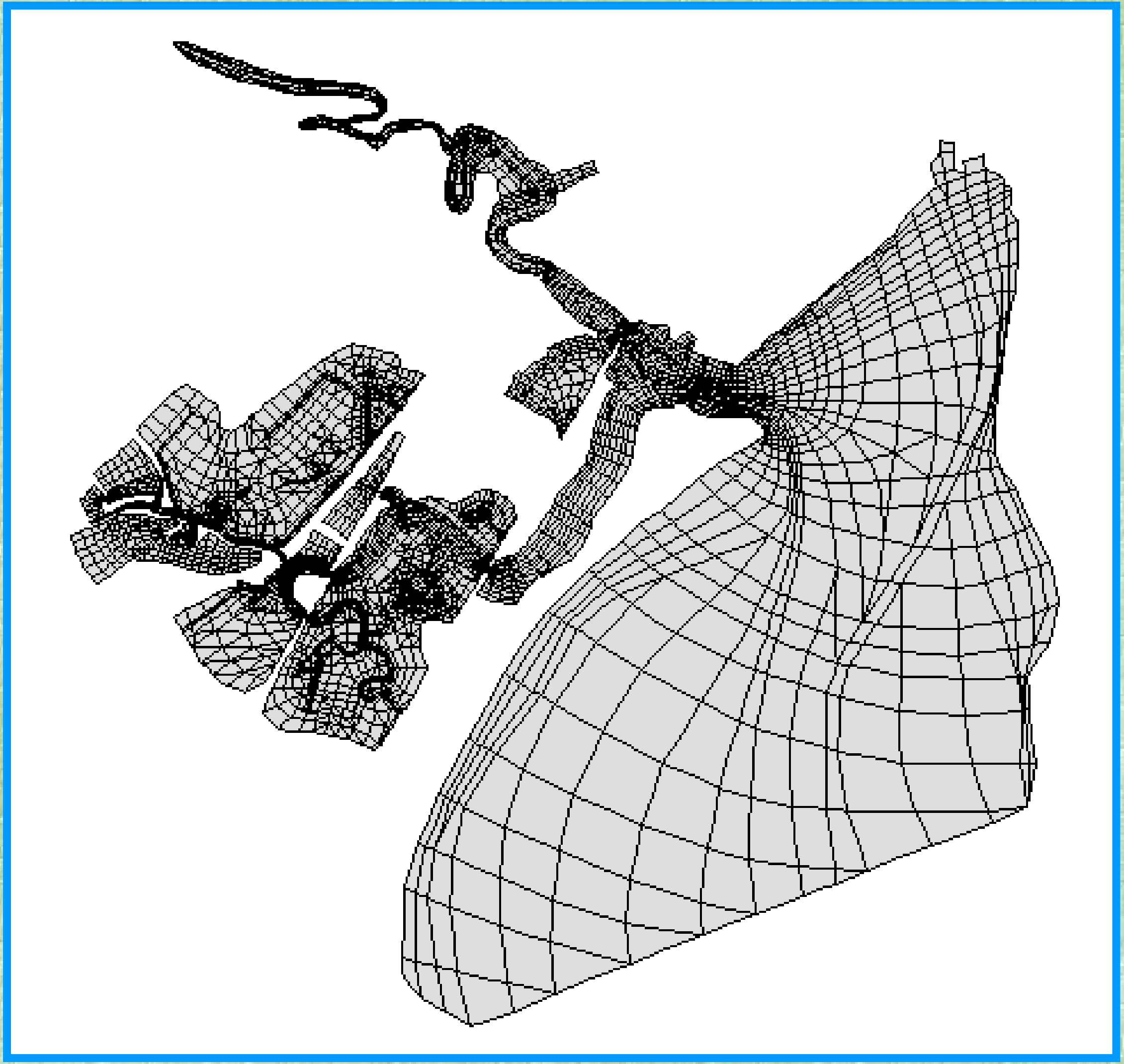


Figure 2 Quadrilateral finite element grid of the Catalan Shelf, northeast Spain. By courtesy of M. A. Maidana & M. Espino.

Finite element (FE) mixed grid





Curvilinear orthogonal grid

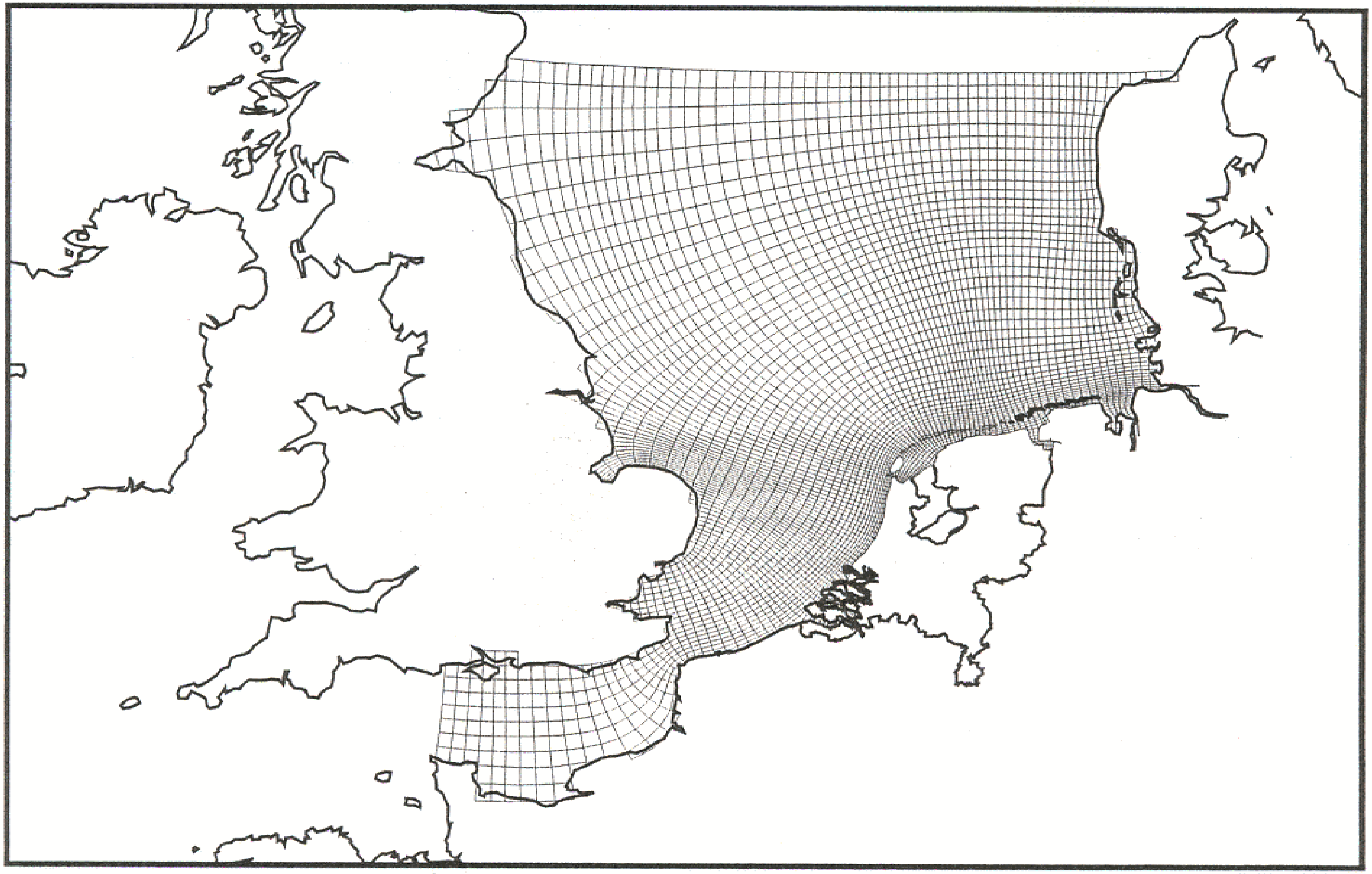
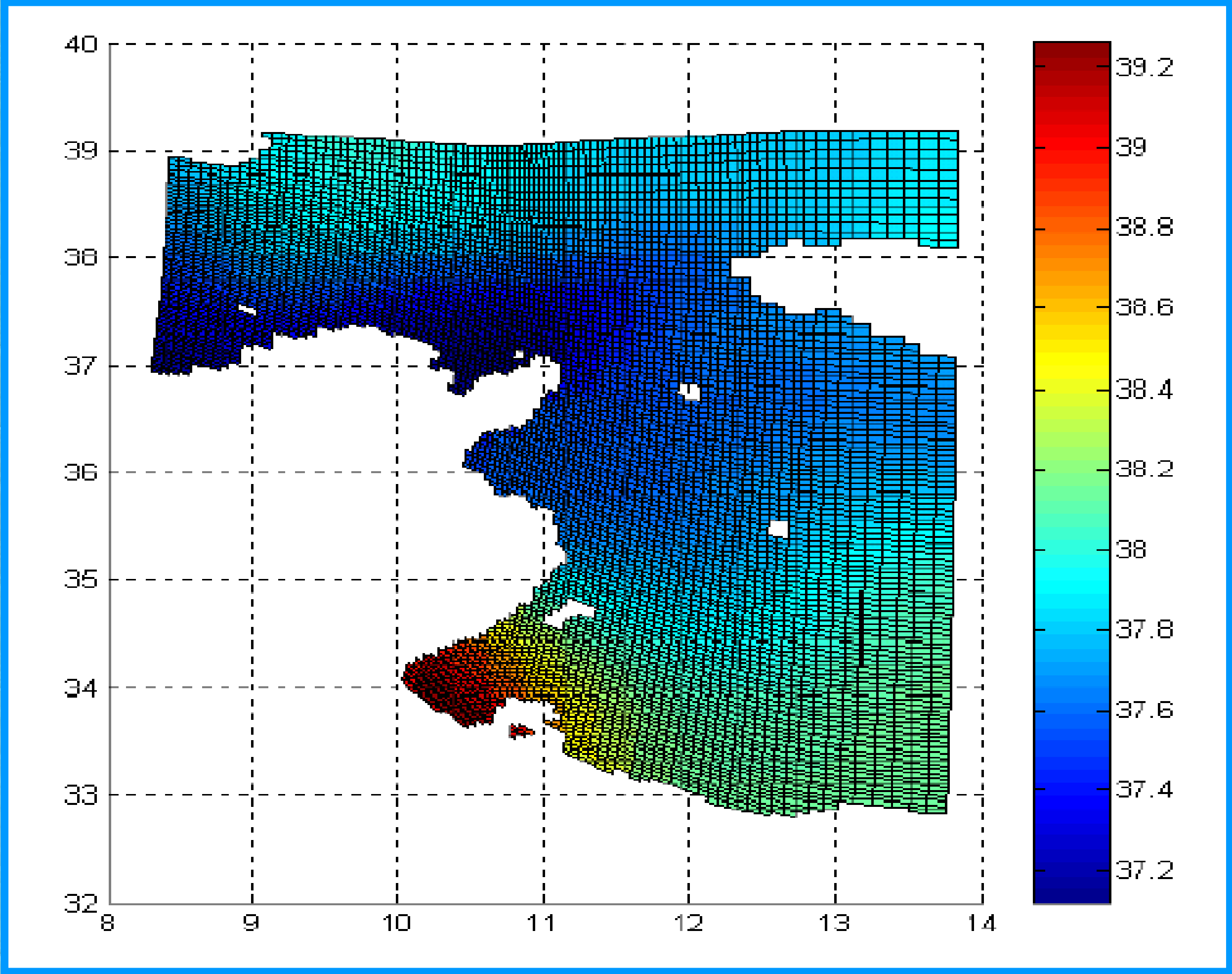


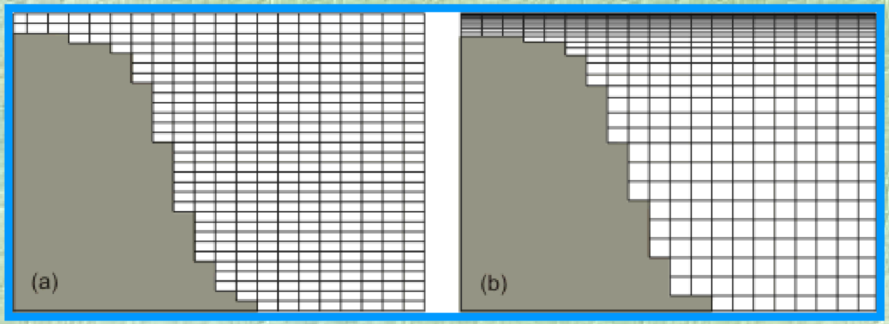
Figure 4 Curvilinear grid of the NZB (North Sea Basis) model. By courtesy of E. de Goede, WL-Delft Hydraulics.

Curvilinear grid

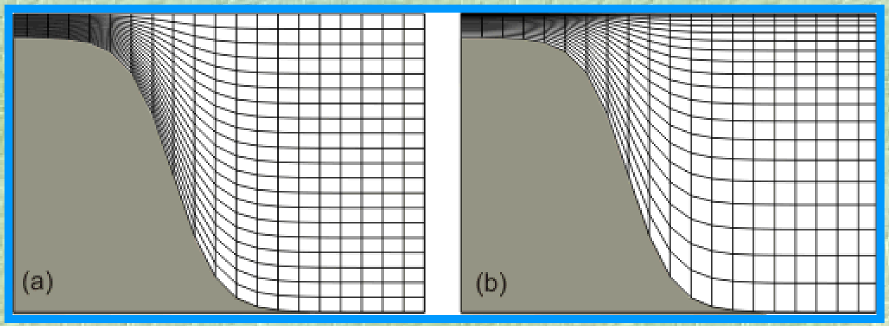


Vertical discretization

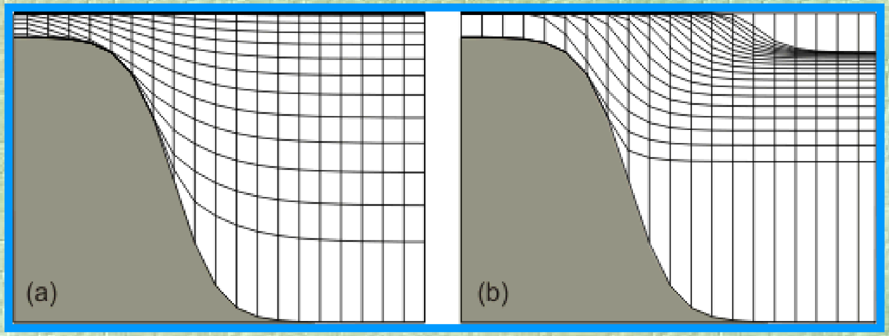
Z - levels



Sigma - levels



Isopycnal - levels



Numerical modeling as a tool for the impact assessment and management of coastal lagoons: The Venice Lagoon as an example

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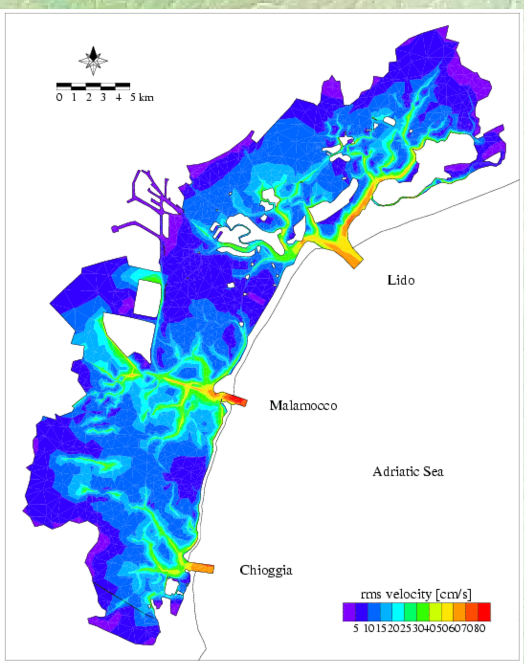
The Venice lagoon: a prototype of a coastal environment

- Overview
- Hydrodynamic modeling
- Exchanges between the lagoon and the Adriatic Sea
- Sediment transport and ecological modeling
- Other applications

The Venice Lagoon

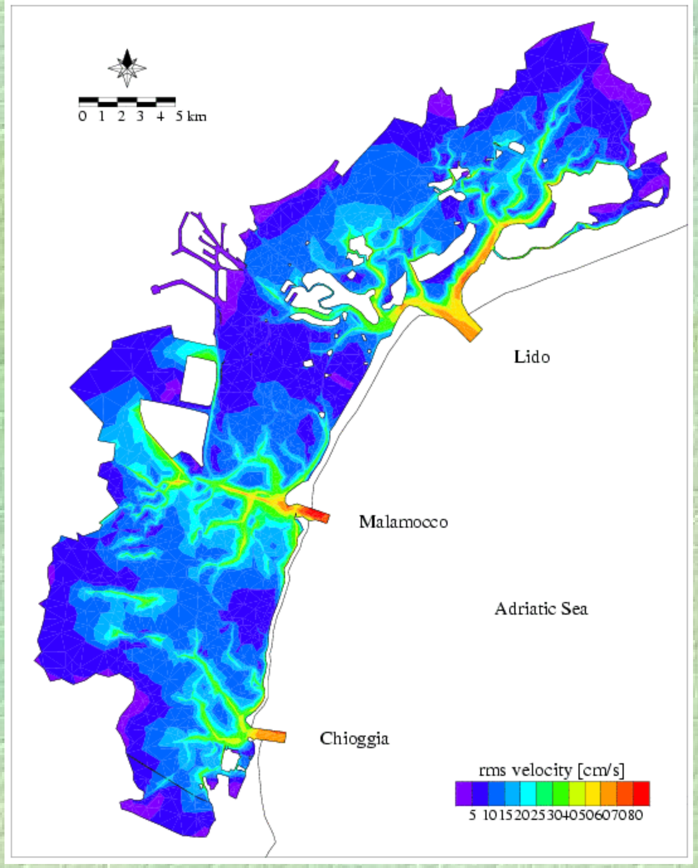
- 50 km long
- 10 km wide
- 300,000 inhabitants
- 3,000,000 tourists annually
- 1.5 m average depth
- tidal range 1.0 m
- 50 km^2 salt marshes

Modeling Research Fields of ISMAR-CNR



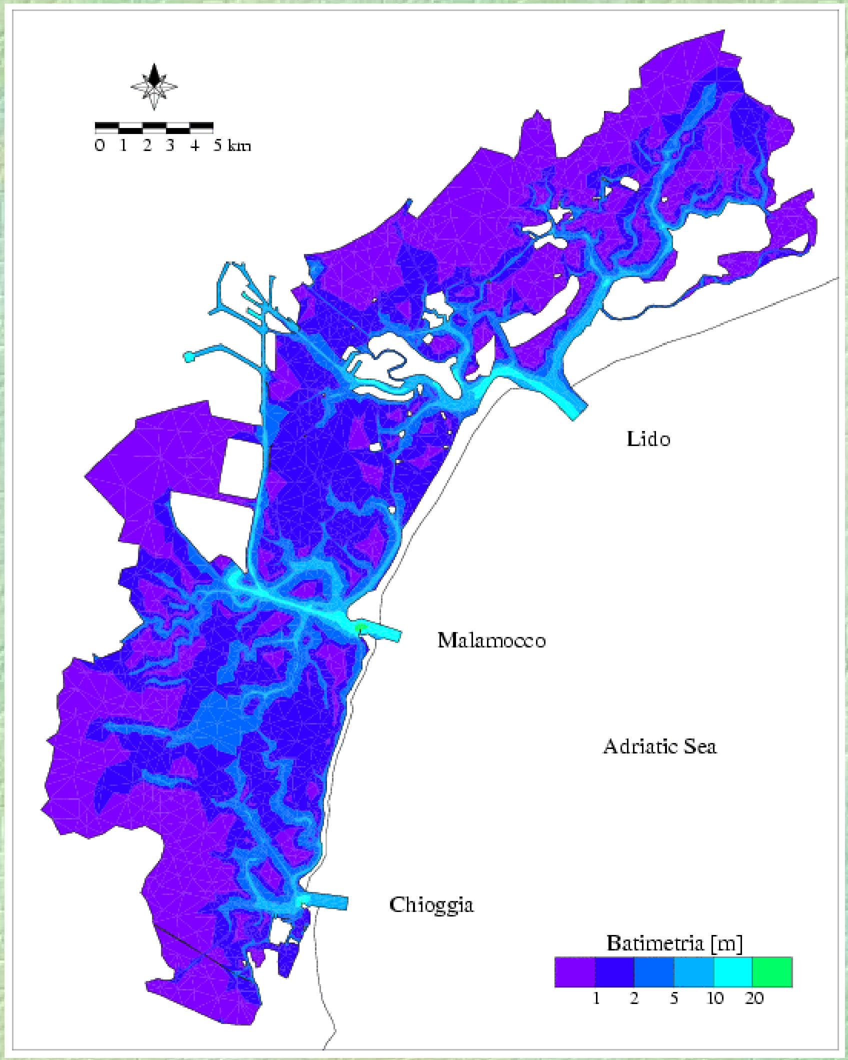
- Hydrodynamic circulation and water levels
- Salinity/Temperature modeling
- Wave modeling
- Sediment transport
- Ecological processes and water quality
- Exchanges through the inlets
- Integrated modeling (coastal zone management)

Hydrodynamic model



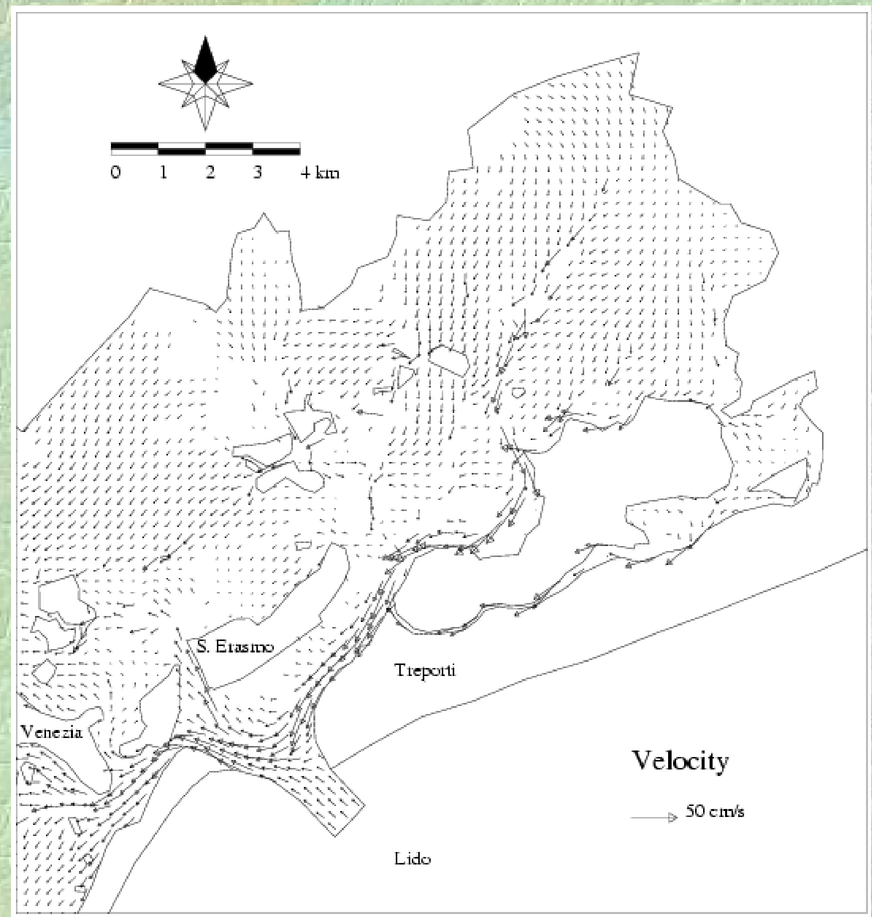
- finite elements
- primitive equations
- semi-implicit time stepping scheme
- z or sigma coordinates in the vertical
- description of tidal marshes

Hydrodynamic model: grid and bathymetry

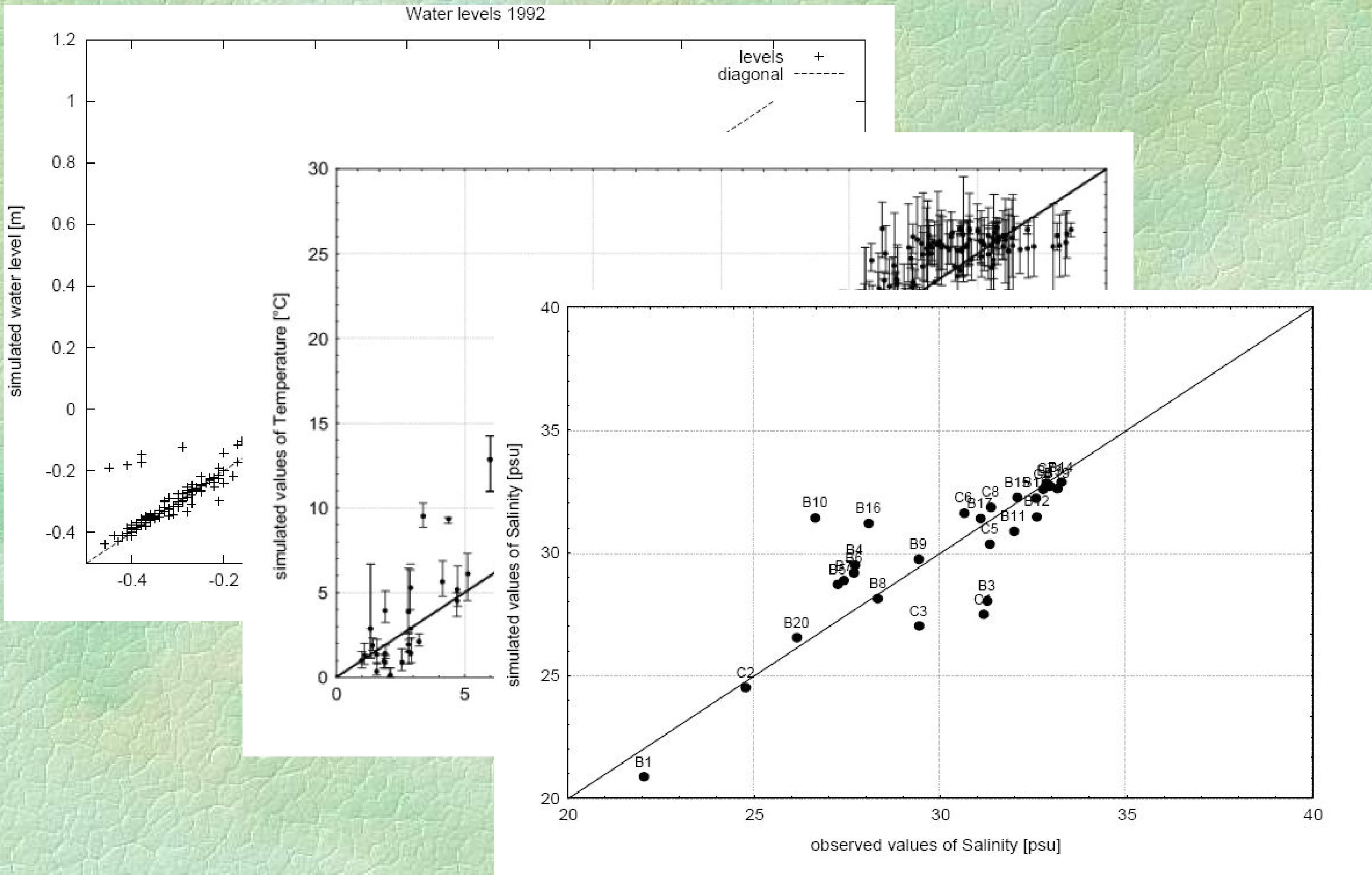


Tidal flats in the northern lagoon

Treatment of tidal flats



Validation of SHYFEM



Hydrodynamic Studies

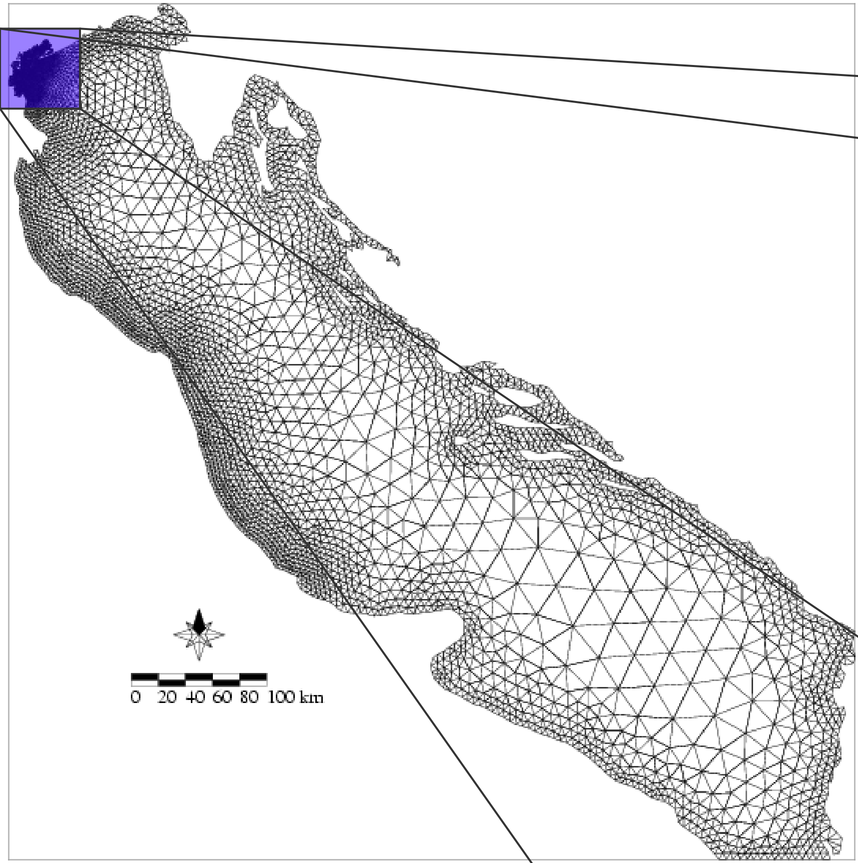
Circulation with only tides

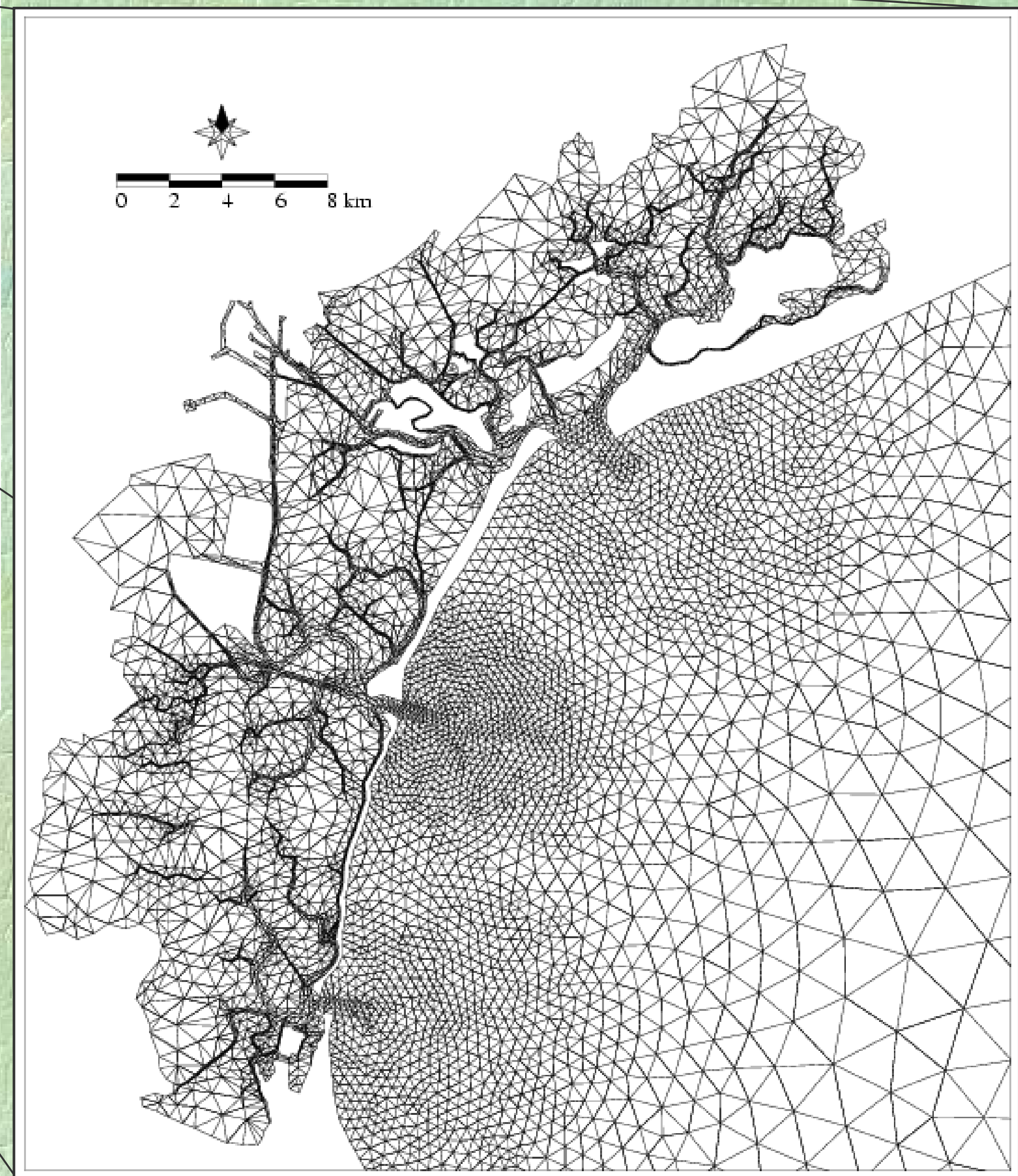
Circulation with Scirocco winds

Circulation with Bora winds

Exchanges with the Adriatic Sea

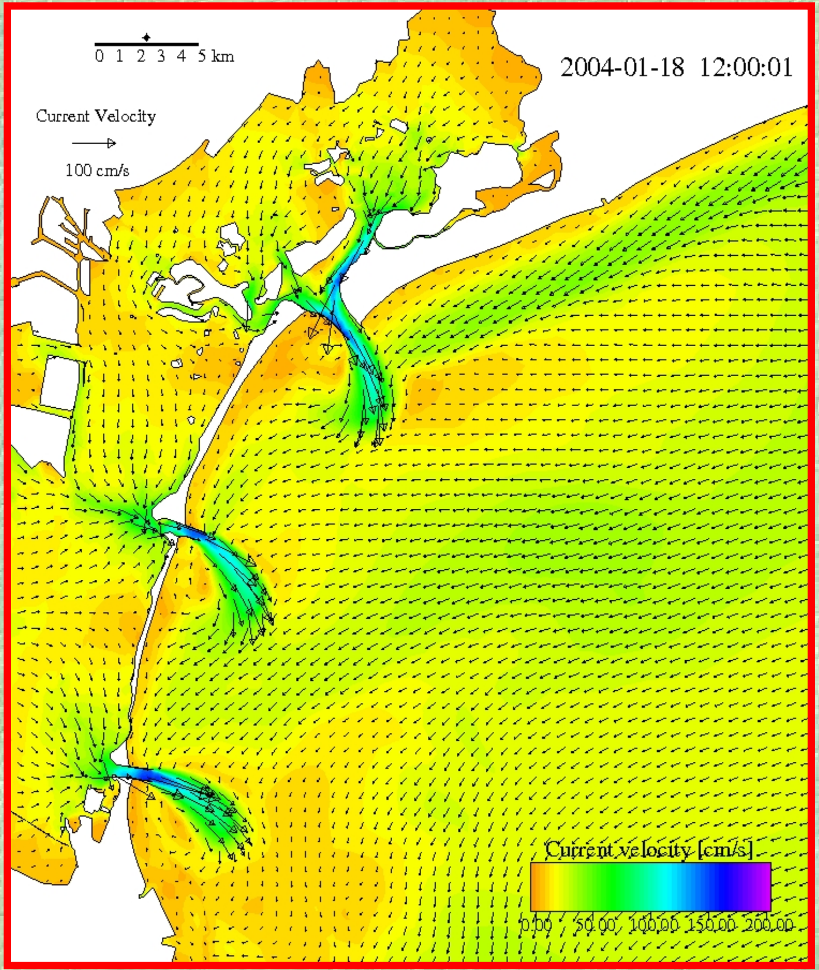
- Modeling at interfaces is complicated
- Boundaries must be moved far from the investigated area
- Two areas must be modeled to describe the inlets



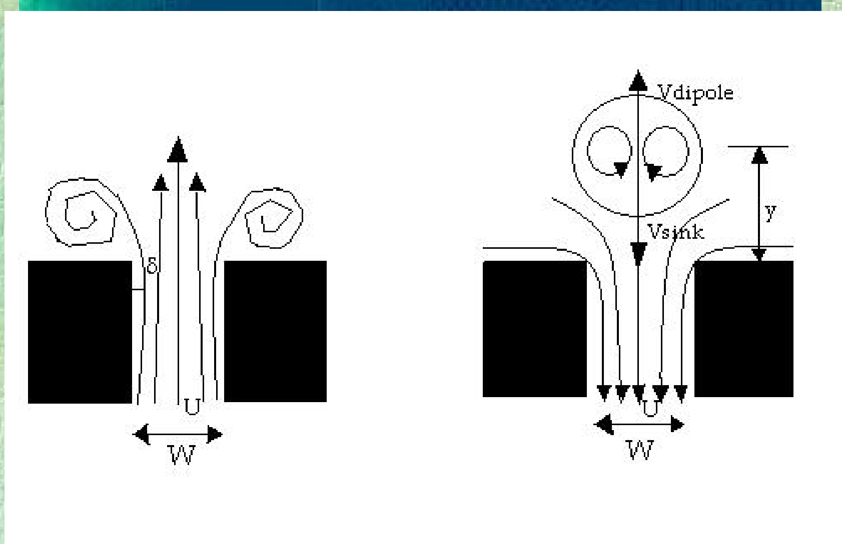


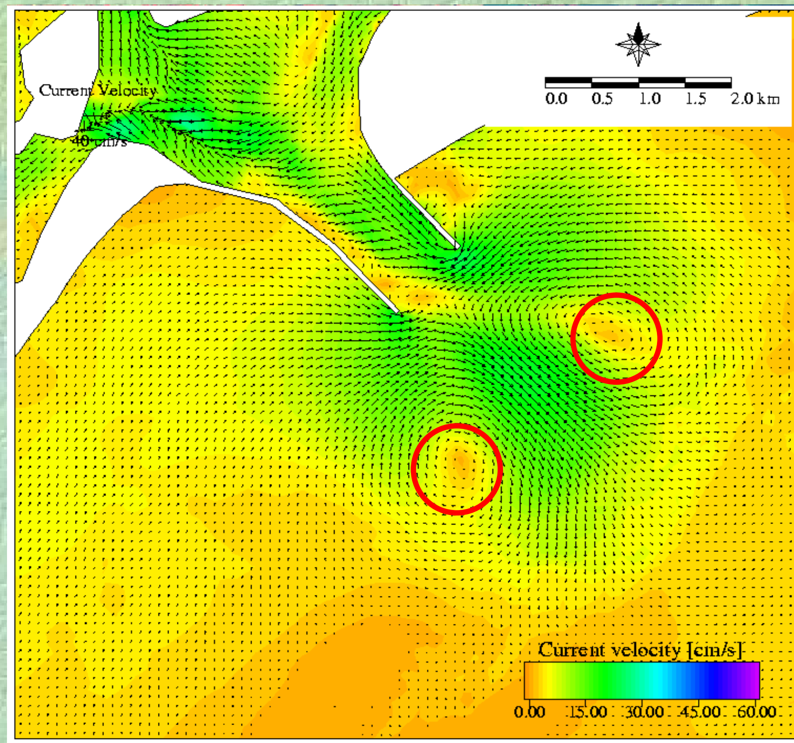
Finite element grid of the Adriatic Sea - Venice Lagoon

Interaction with longshore current



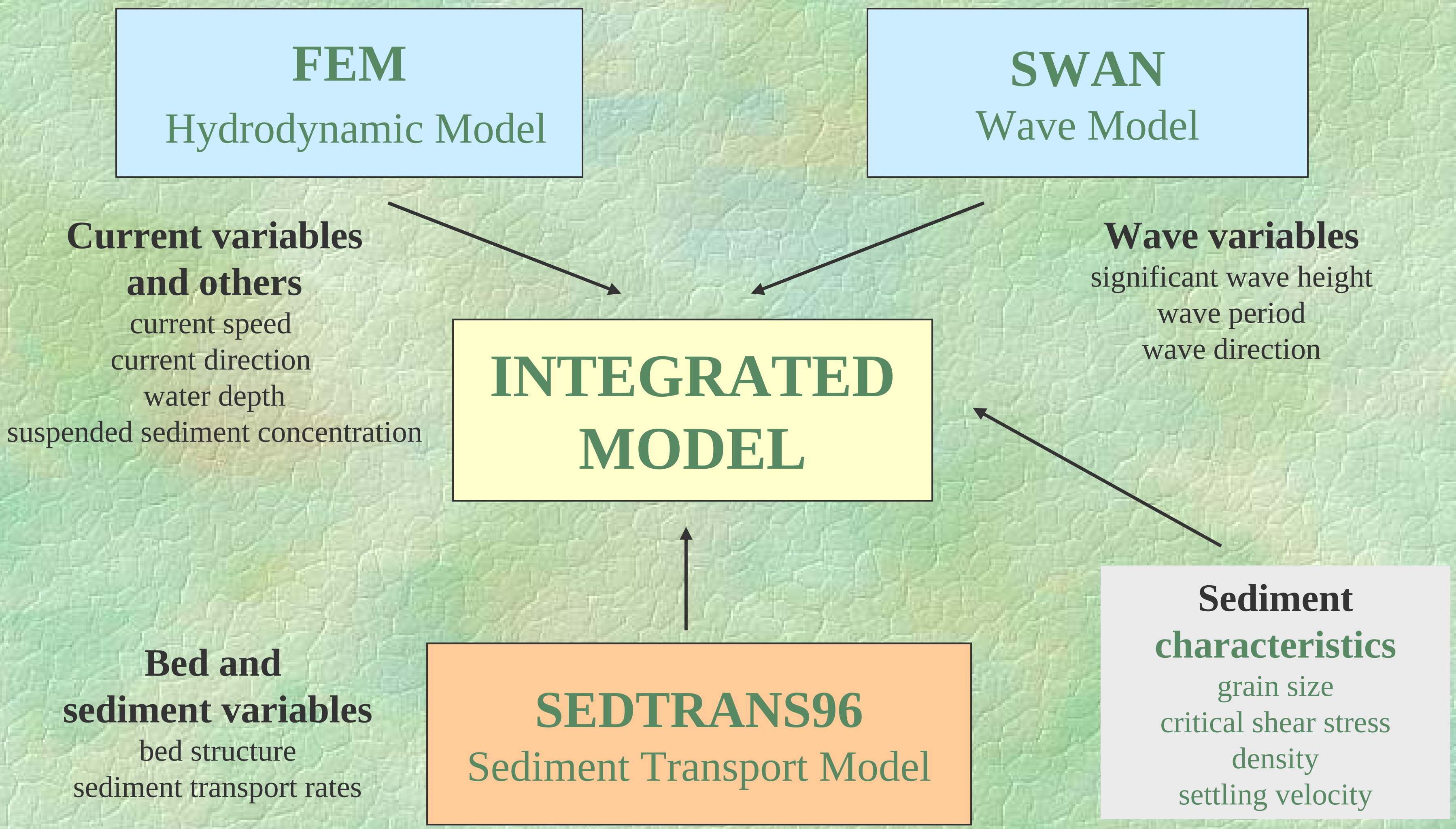
Comparison between the Theoretical Model and the SHYFEM Model



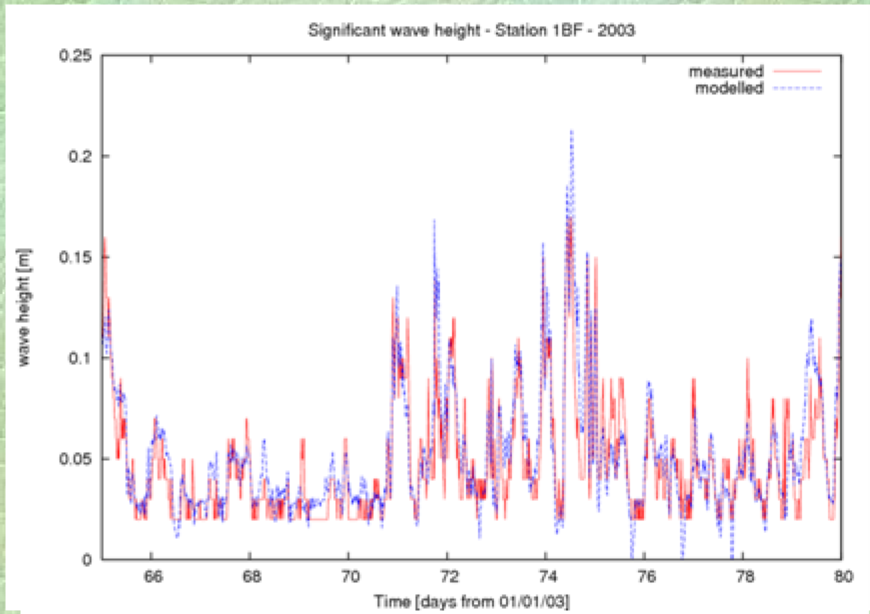


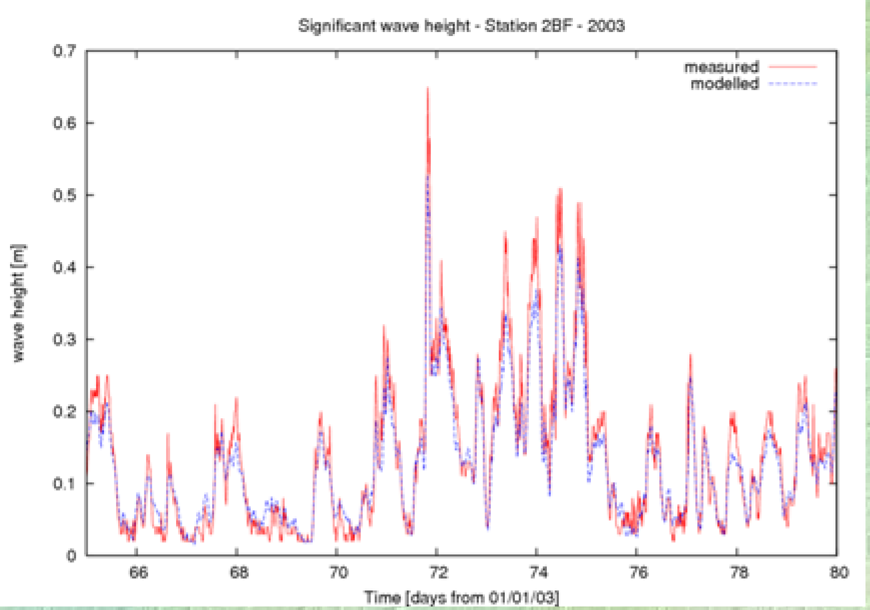
Lido Inlet

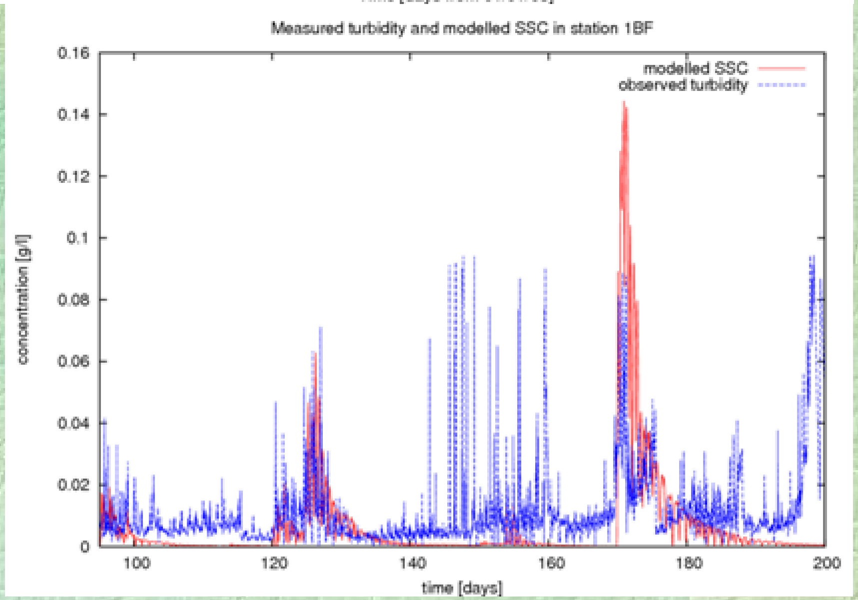
Sediment Transport Modeling

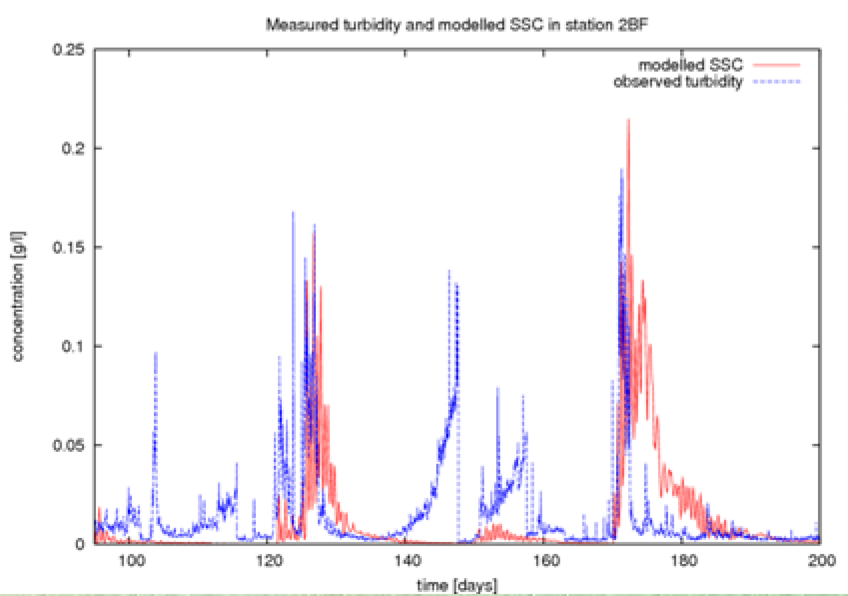


Validation – Wave - SSC





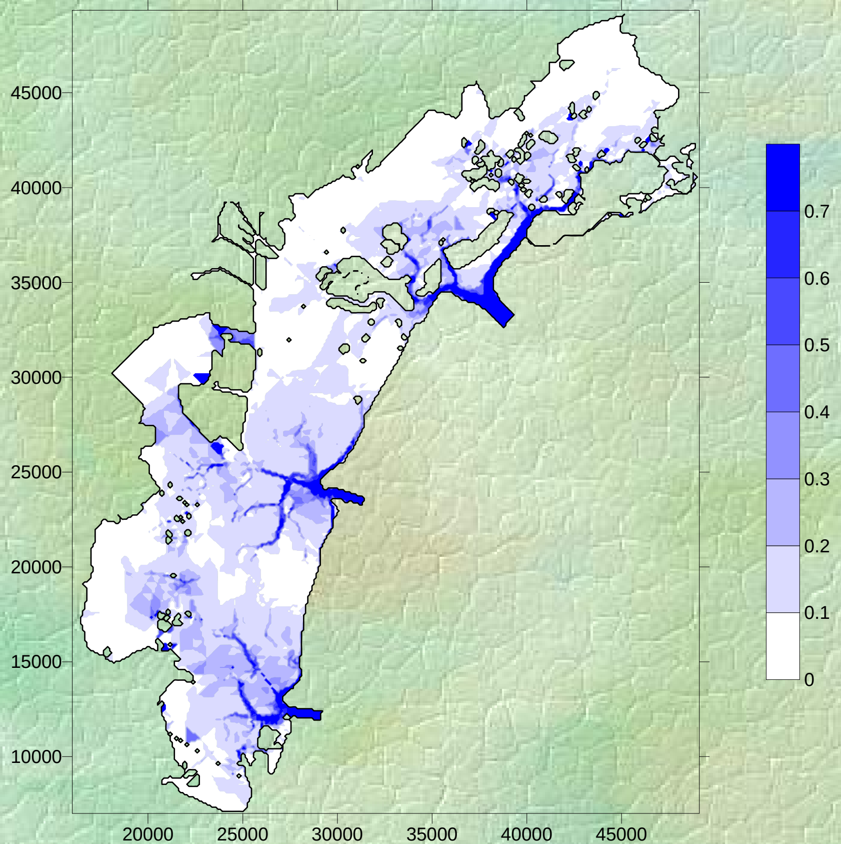


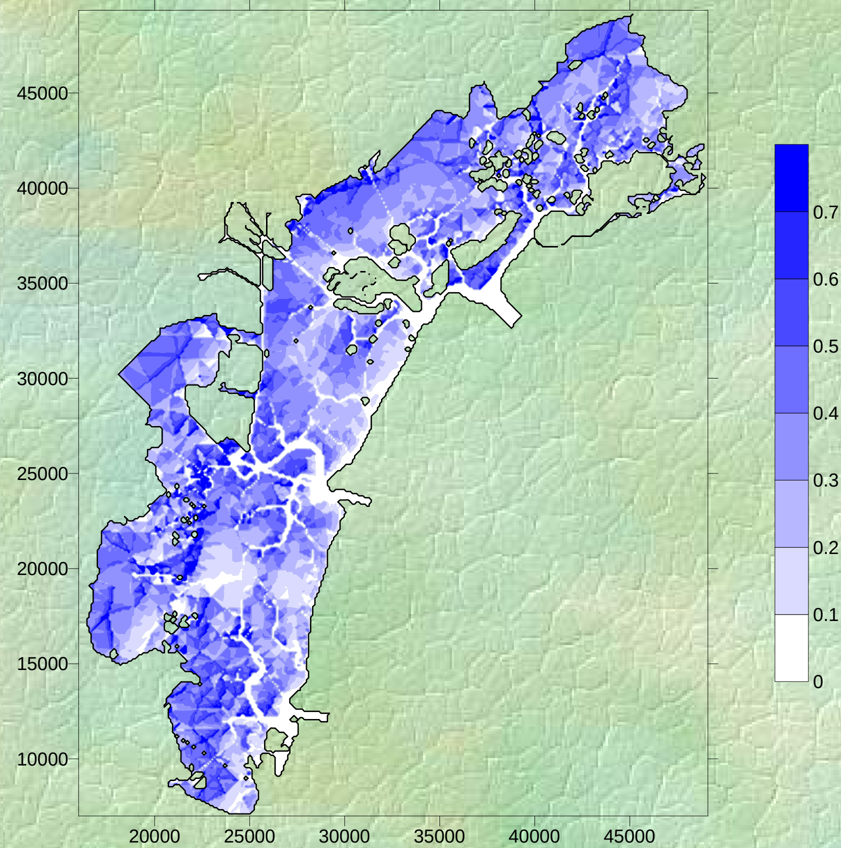


Bottom stress modeling

- Bottom stress is important for the erosion and deposition of sediments
- Bottom stress depends on current speed and wind waves
- Strong differences between channels and shallow areas

Shear stress: a specular view





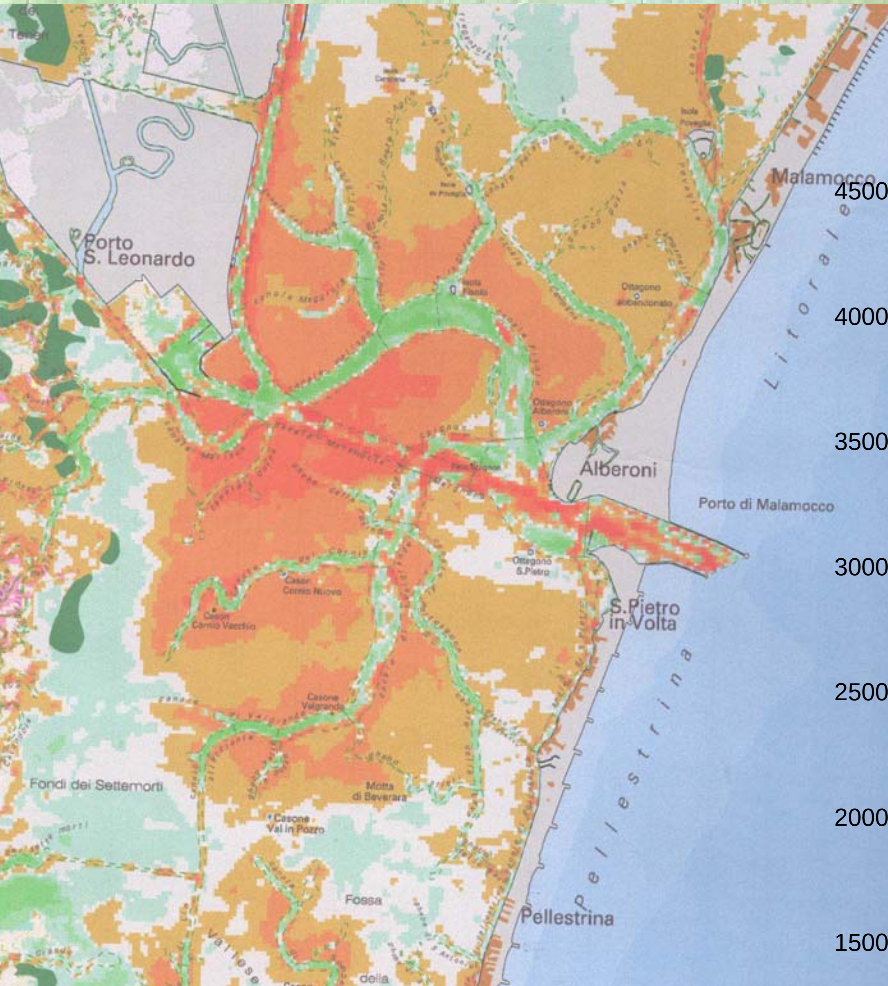
CURRENTS ONLY

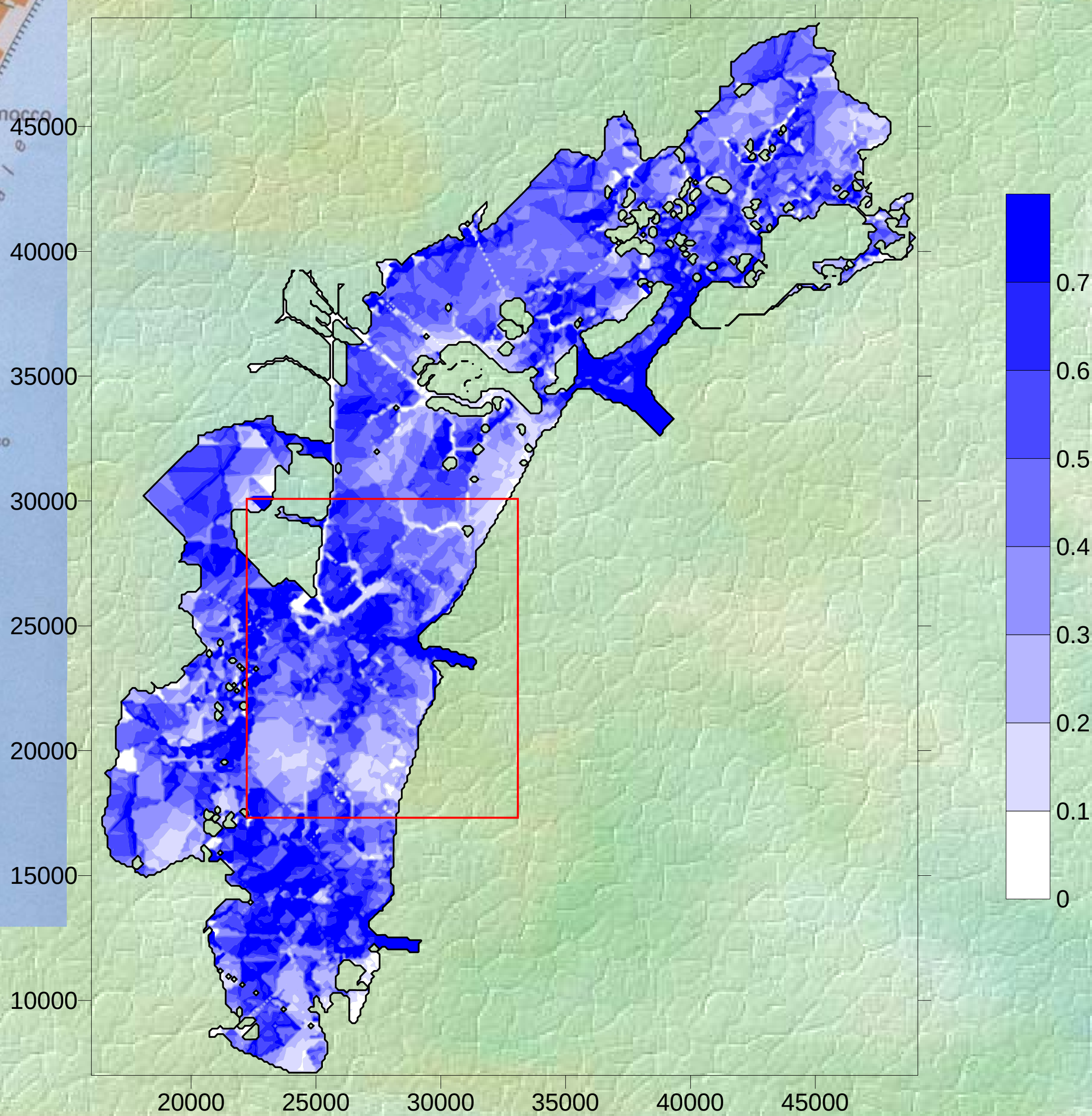
WAVES ONLY

Bottom shear stress (N/m^2) during a Sirocco event.

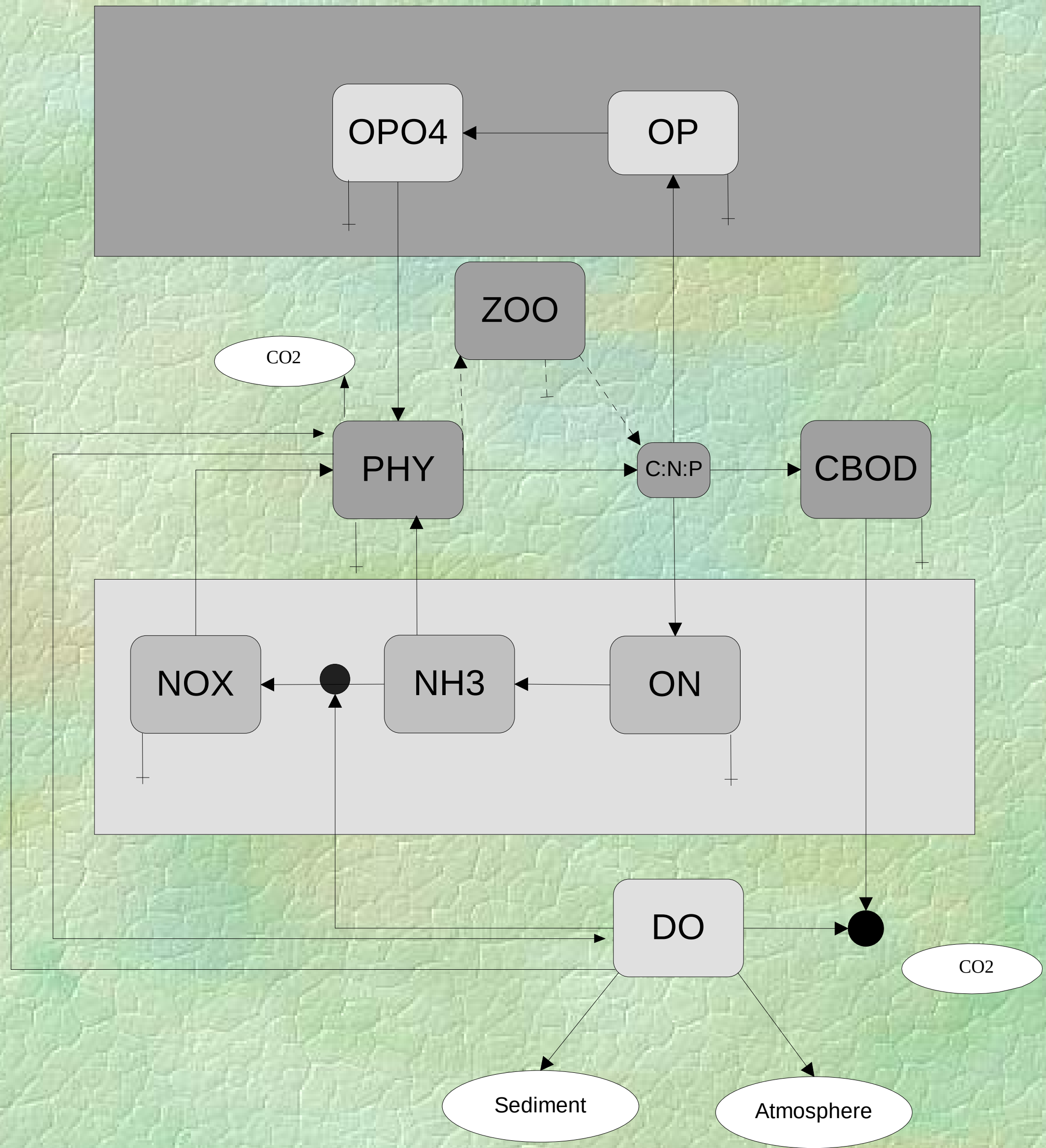
Maximum stress τ_{max} (N/m^2) due to wave and currents, during a Sirocco event.

$$\tau_{max} = [(\tau_m + \tau_w \cos\phi)^2 + (\tau_w \sin\phi)^2]^{0.5}$$

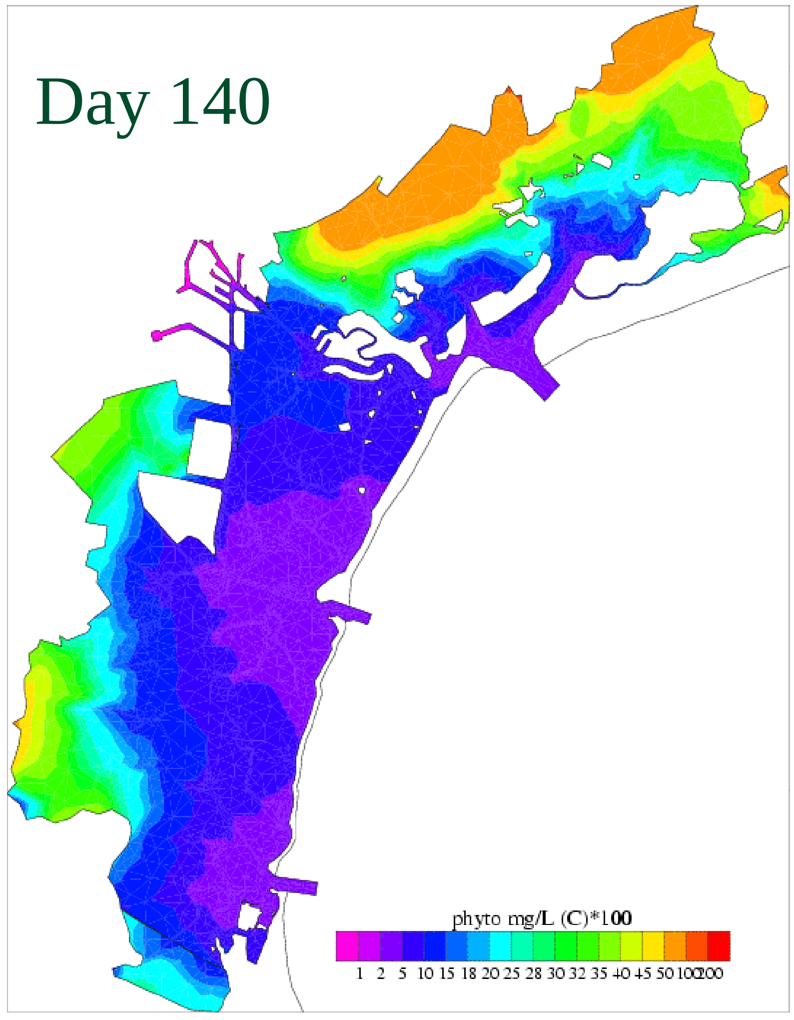




Ecological Model: State variables and fluxes

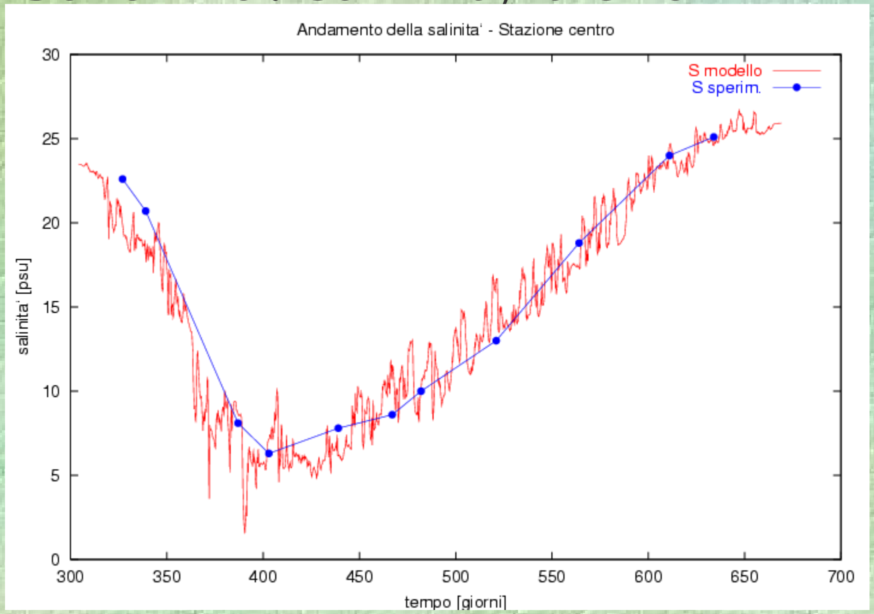


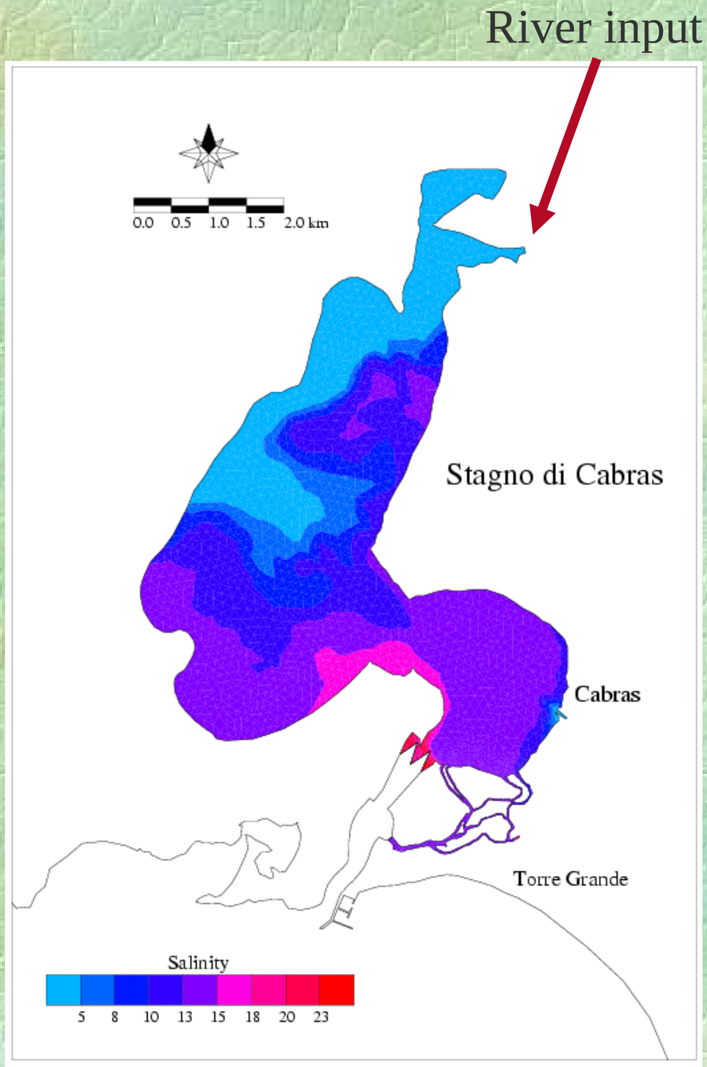
Phytoplankton concentration in the lagoon of Venice

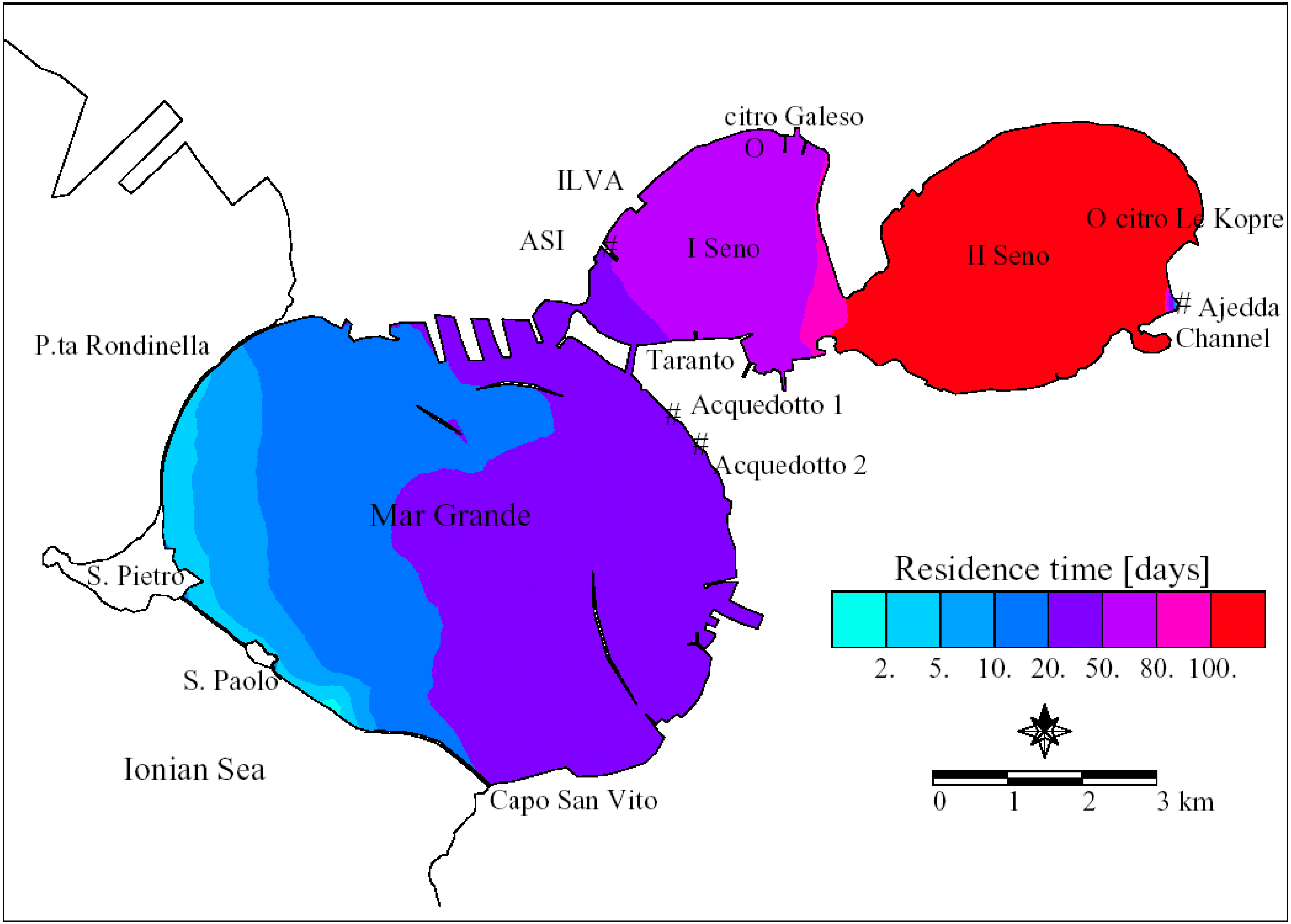


Managing fresh water in lagoons

- the Cabras lagoon in Sardinia: salinity trend

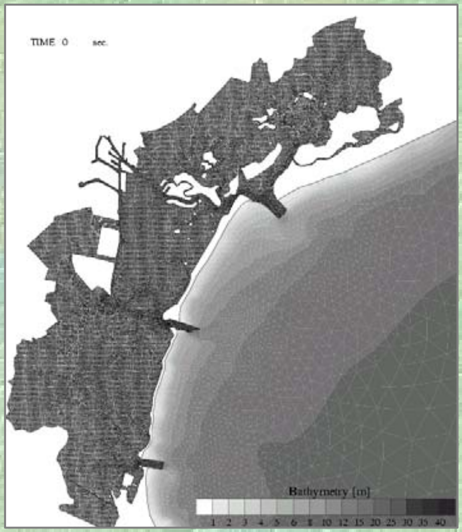


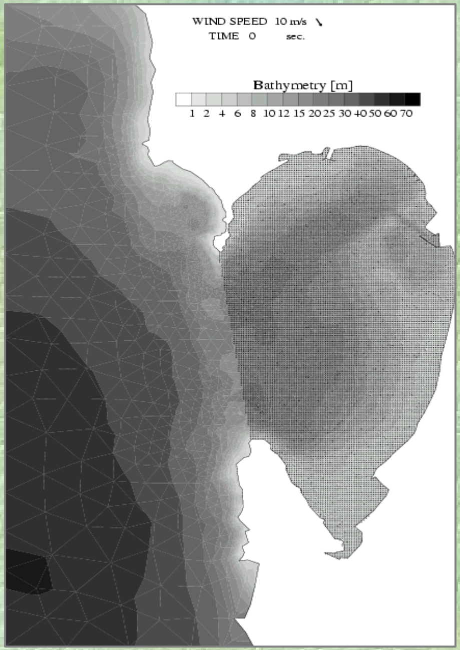




citro Galeso
ILVA
ASI
I Seno
O citro Le Kopre
II Seno
Ajedda
Channel
P.ta Rondinella
Taranto
Acquedotto 1
Acquedotto 2
Mar Grande
Residence time [days]
2.
5.
10.
20.
50.
80.
100.
S. Pietro
S. Paolo
Ionian Sea
Capo San Vito
0
1
2
3 km

Residence times and turn over time

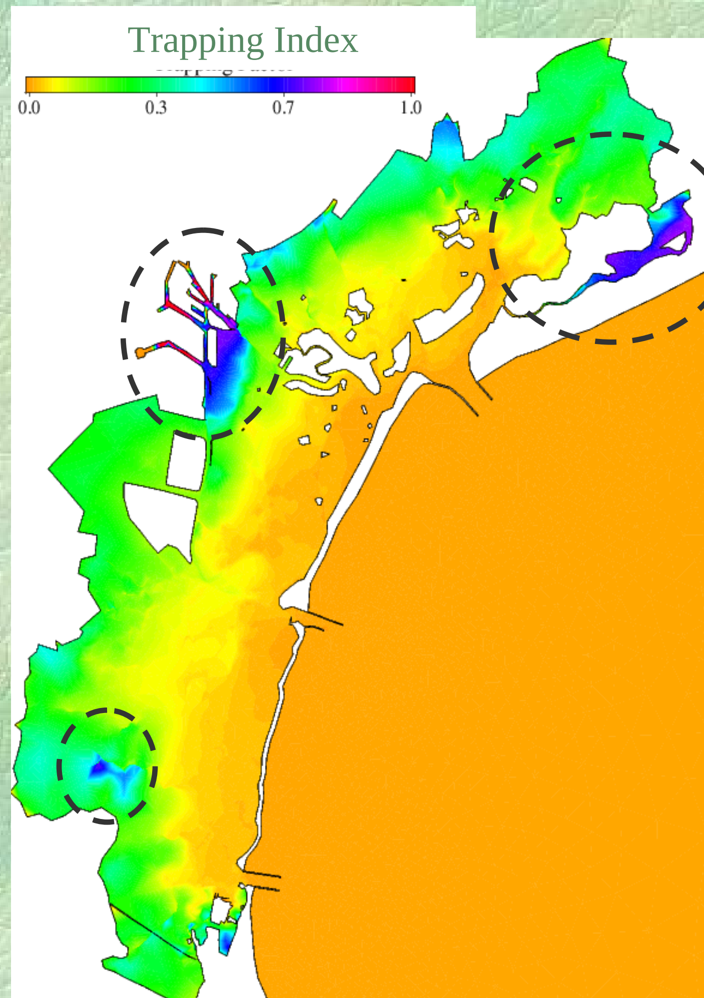


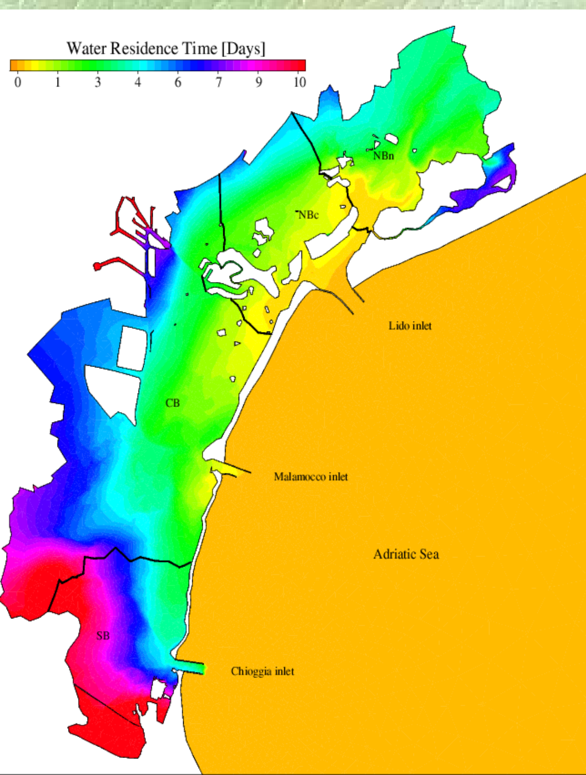


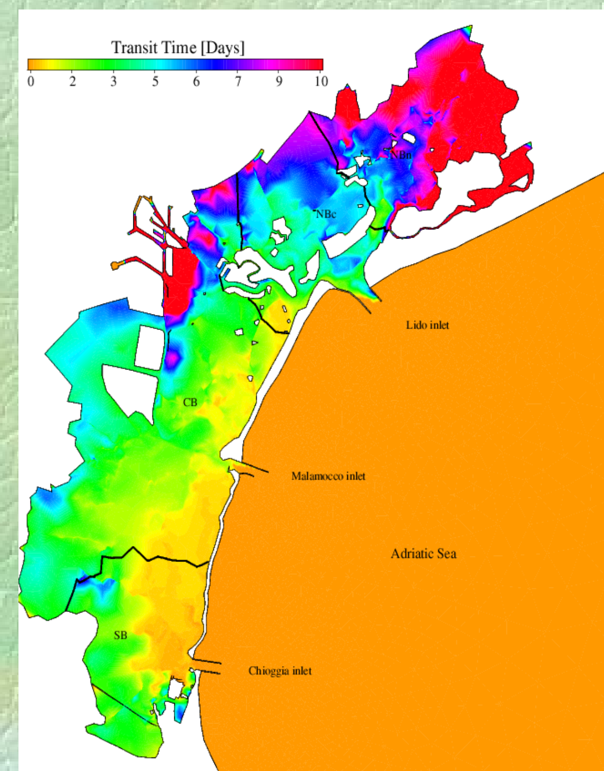
- Simulate transport processes and dispersion of tracers and pollutants
- Estimate the renewal time of the basin
- Characterize water masses with the help of time dependent parameters
- Correlate physical, biological and chemical characteristics between each other

The Trapping Index

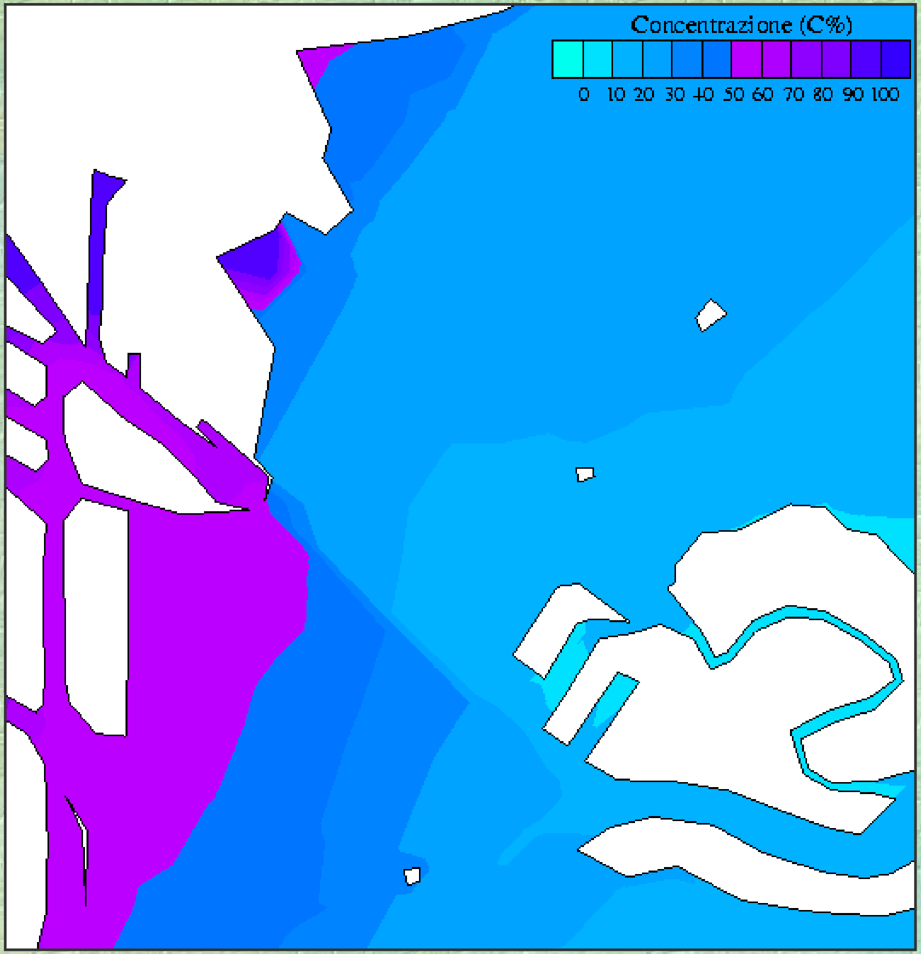
- Bora Simulation





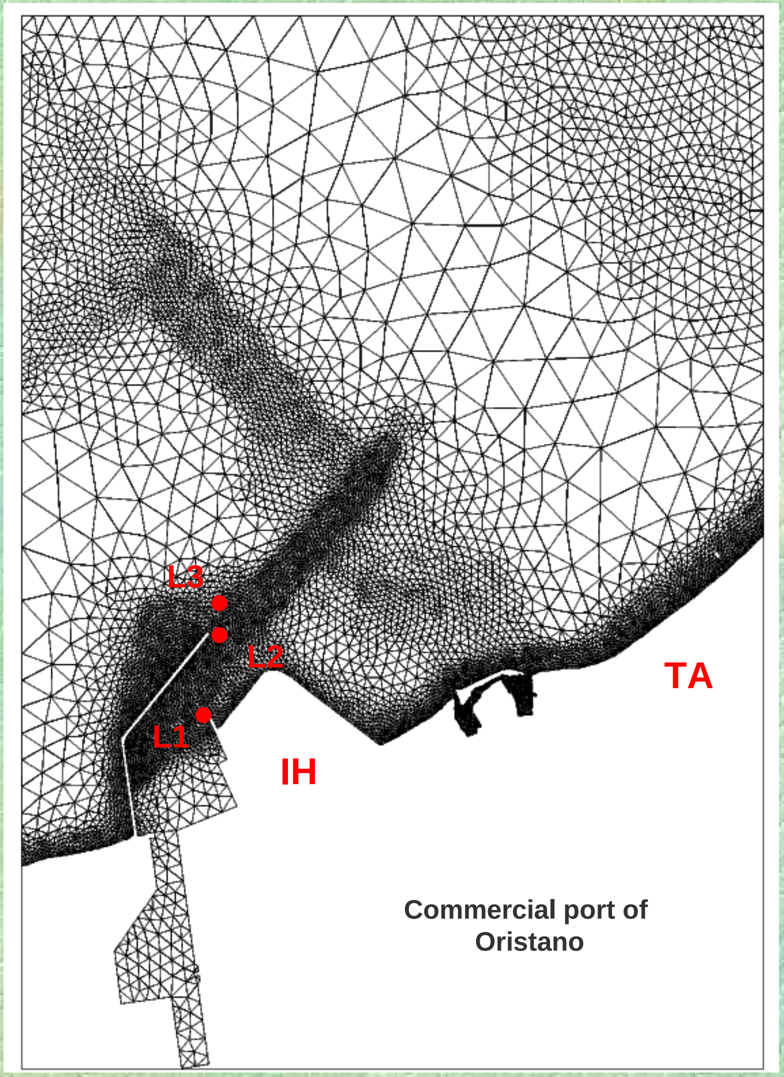


Identifying water masses



Impact of waste water discharge

- Plan sewage outfall in the sea
- Assess impact of the sewage outfall to the surrounding areas



Test area:

- Industrial port [IH]
- Possible sewage outlet position [L1, L2, L3]
- Touristic area [TA]

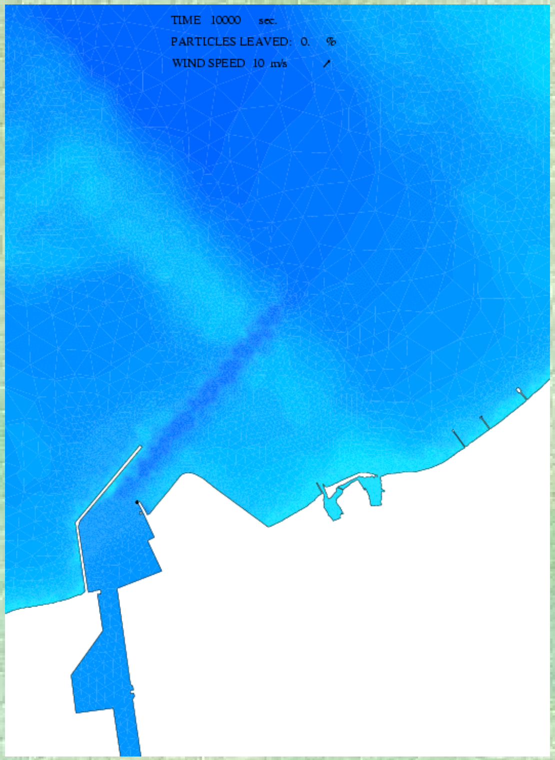
Test case:

- Different scenarios (tide, wind,…)
- Different sewage outlet positions [L1 L2 L3]
- Evaluation of the impact

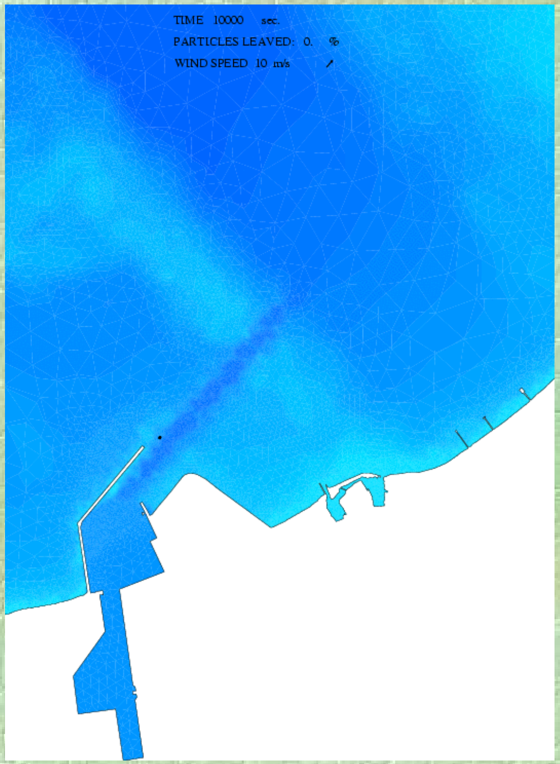
Evaluate impact of pollutants

- SW wind with speed of 8 m/s

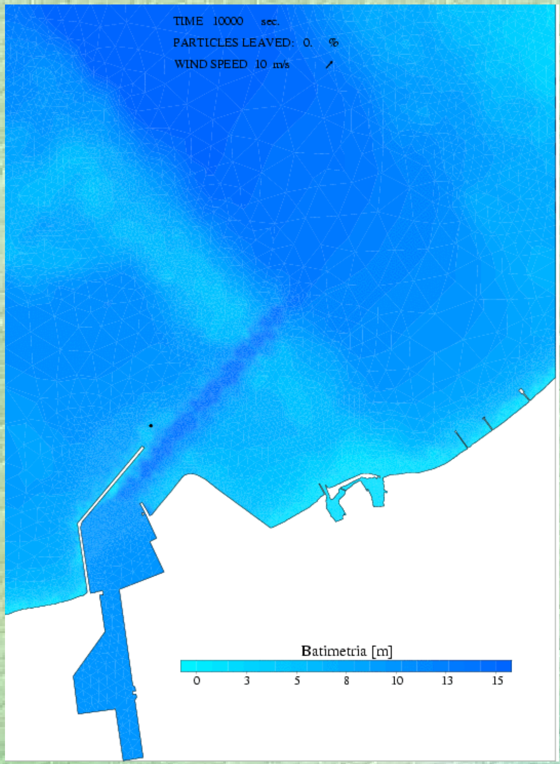
L1



L2

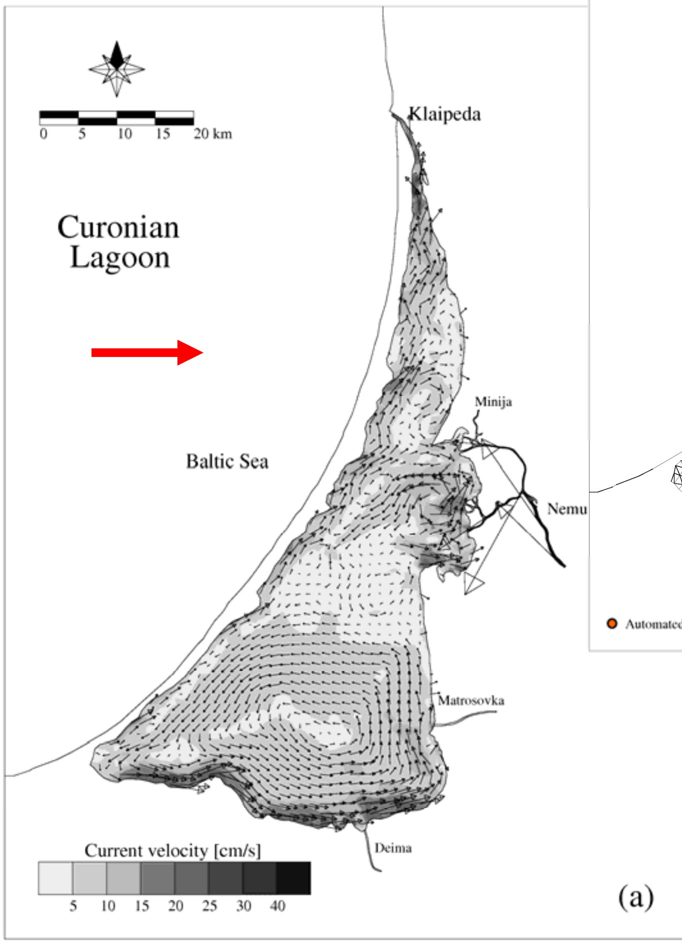


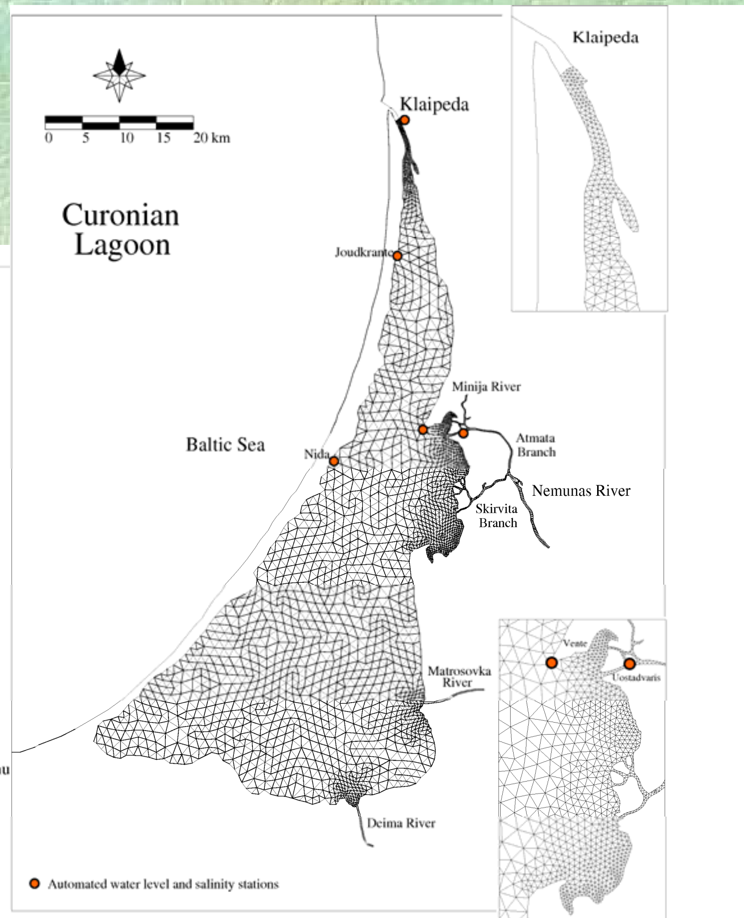
L3

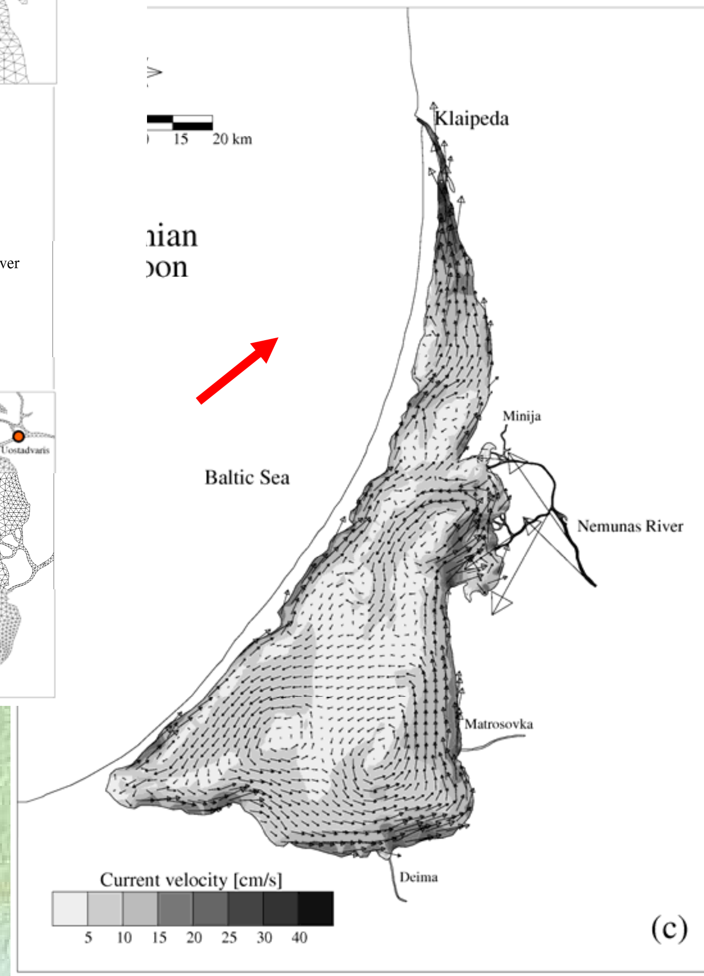


ISMAR-CNR Venezia
Applications in lagoons and the coastal zone

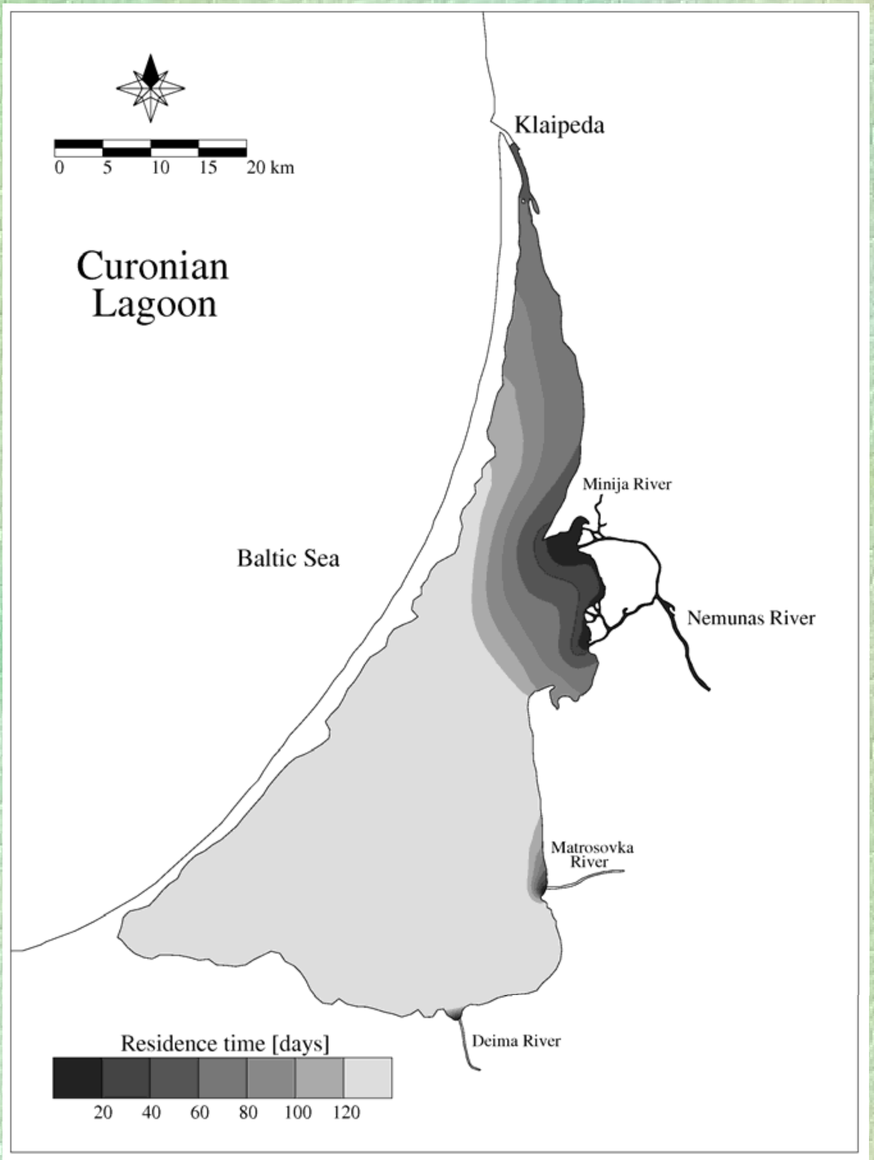
The Curonian Lagoon

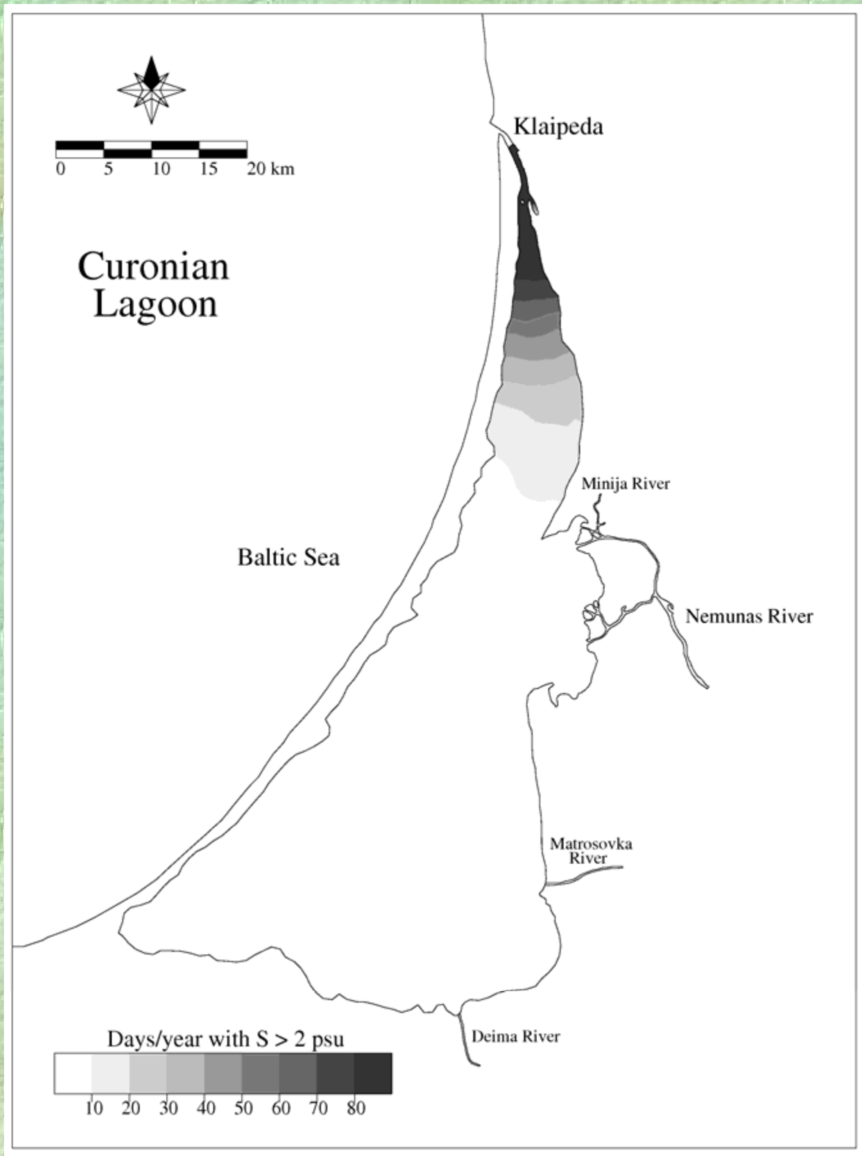




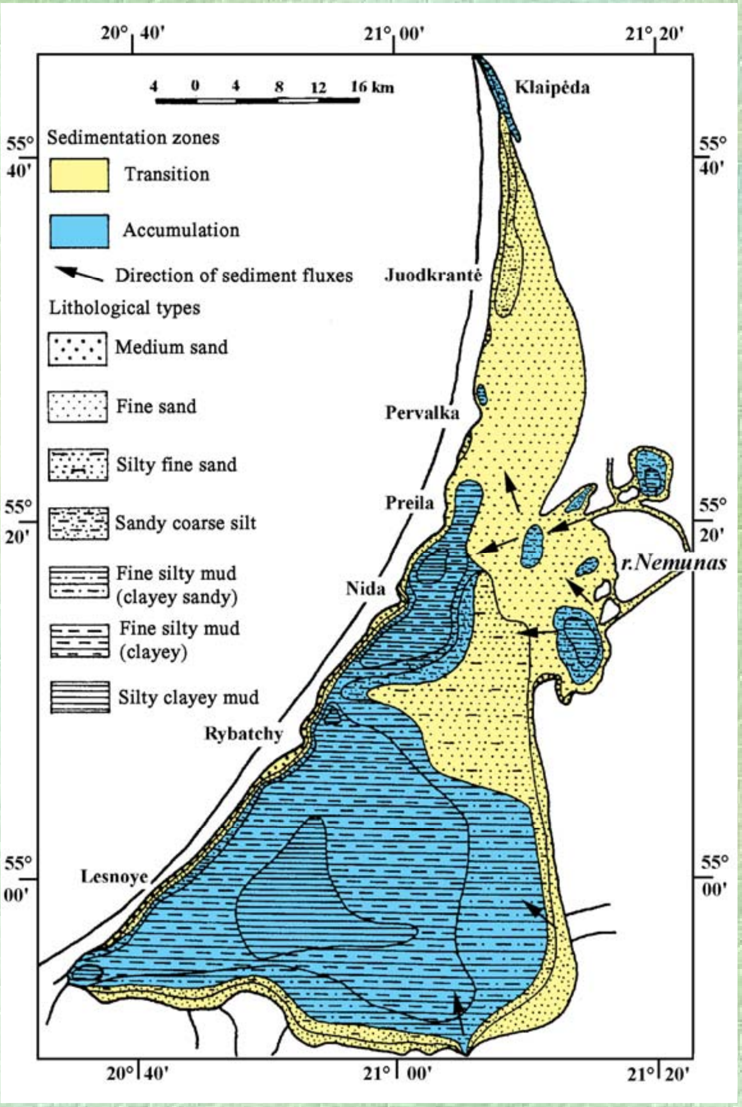


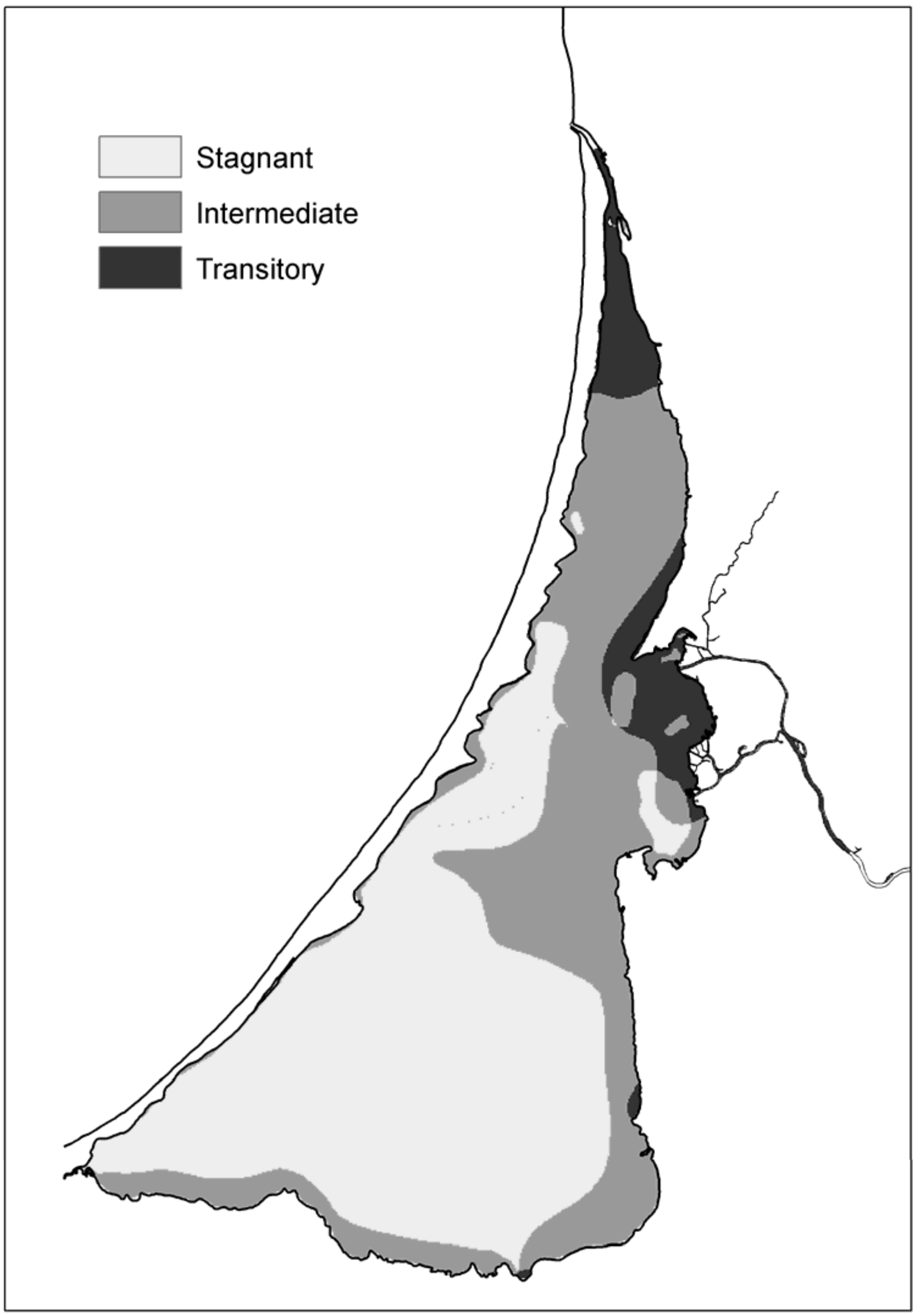
Residence time and salinity





Zonation



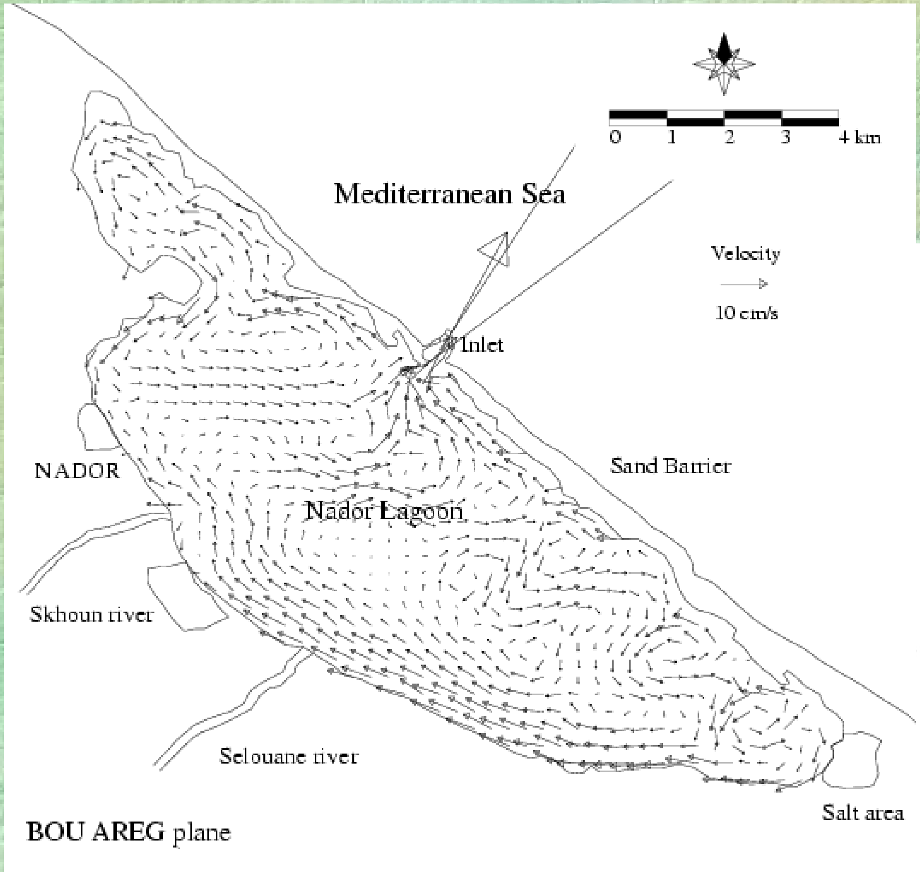


From Gulbinskas, 1995

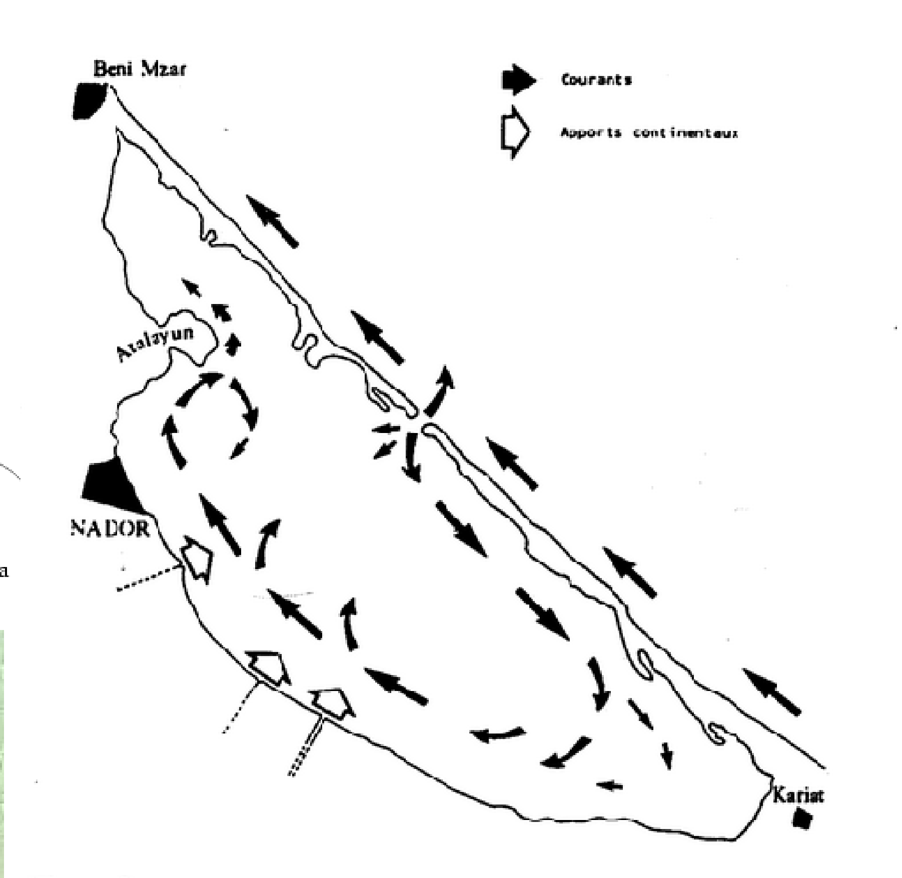
The Nador lagoon, Morocco

- Surface 115 km^2
- Shallow water (max depth 8m)
- Single passage with the open sea
- Aquaculture activity
- Wastewater and sewage discharge

Wind driven circulation



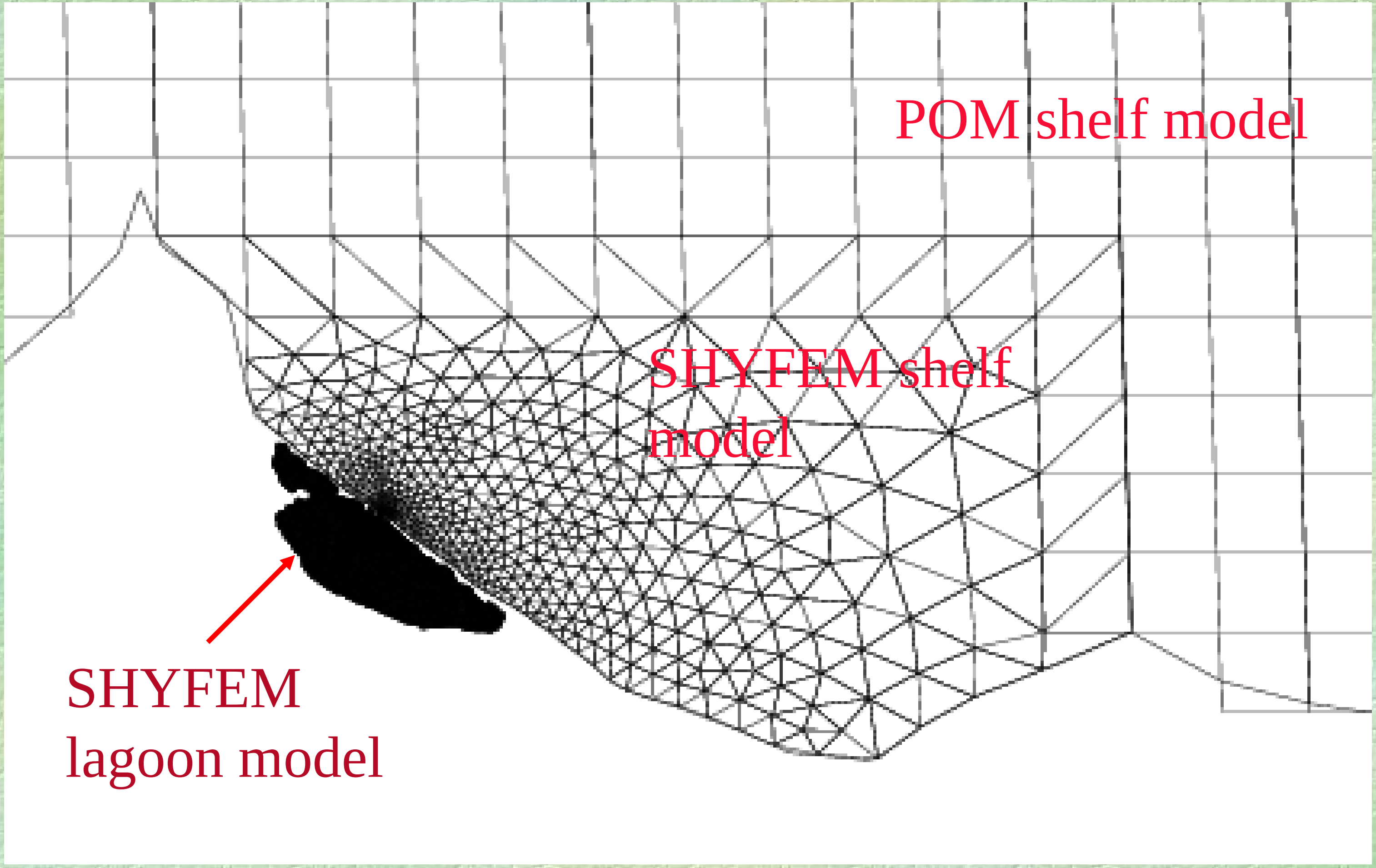
First results of the FEM model with prevailing ENE wind of 5 m/s



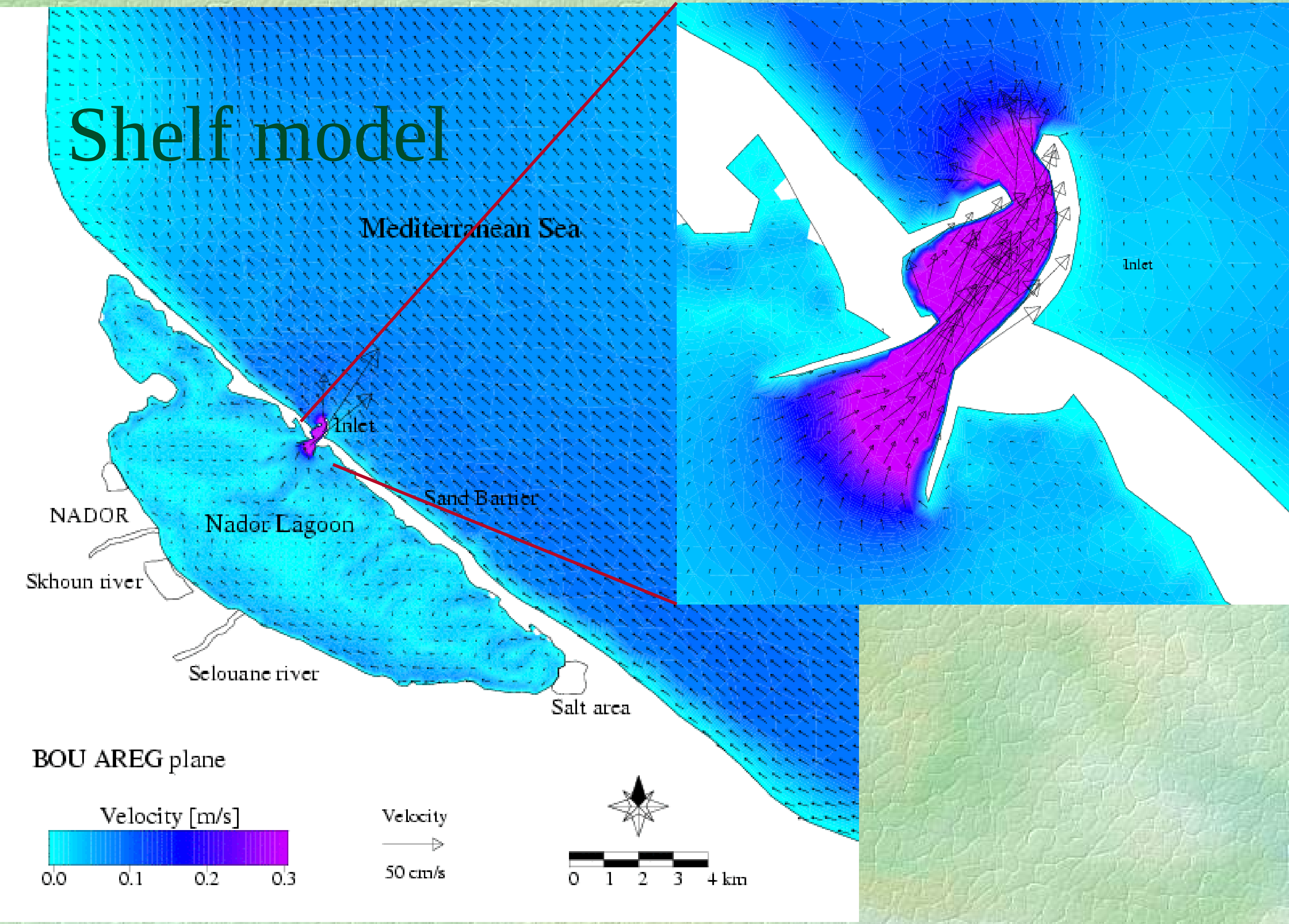
Circulation pattern proposed by O. Guelorget et al., 1987

The coupling with the shelf model

The finite difference grid of the shelf model and the finite element grid of the Nador lagoon



Shelf model



Mediterranean Sea
Inlet
Sand Barrier
NADOR
Nador Lagoon
Skhoun river
Selouane river
Salt area
BOU AREG plane
Velocity [m/s]
0.0
0.1
0.2
0.3
Velocity
50 cm/s
0
1
2
3
4 km
Inlet

Sea water intrusion

- The model can be used to simulate various scenarios of how the sea water mixes with the lagoon waters
  - under WSW winds
  - under ENE winds

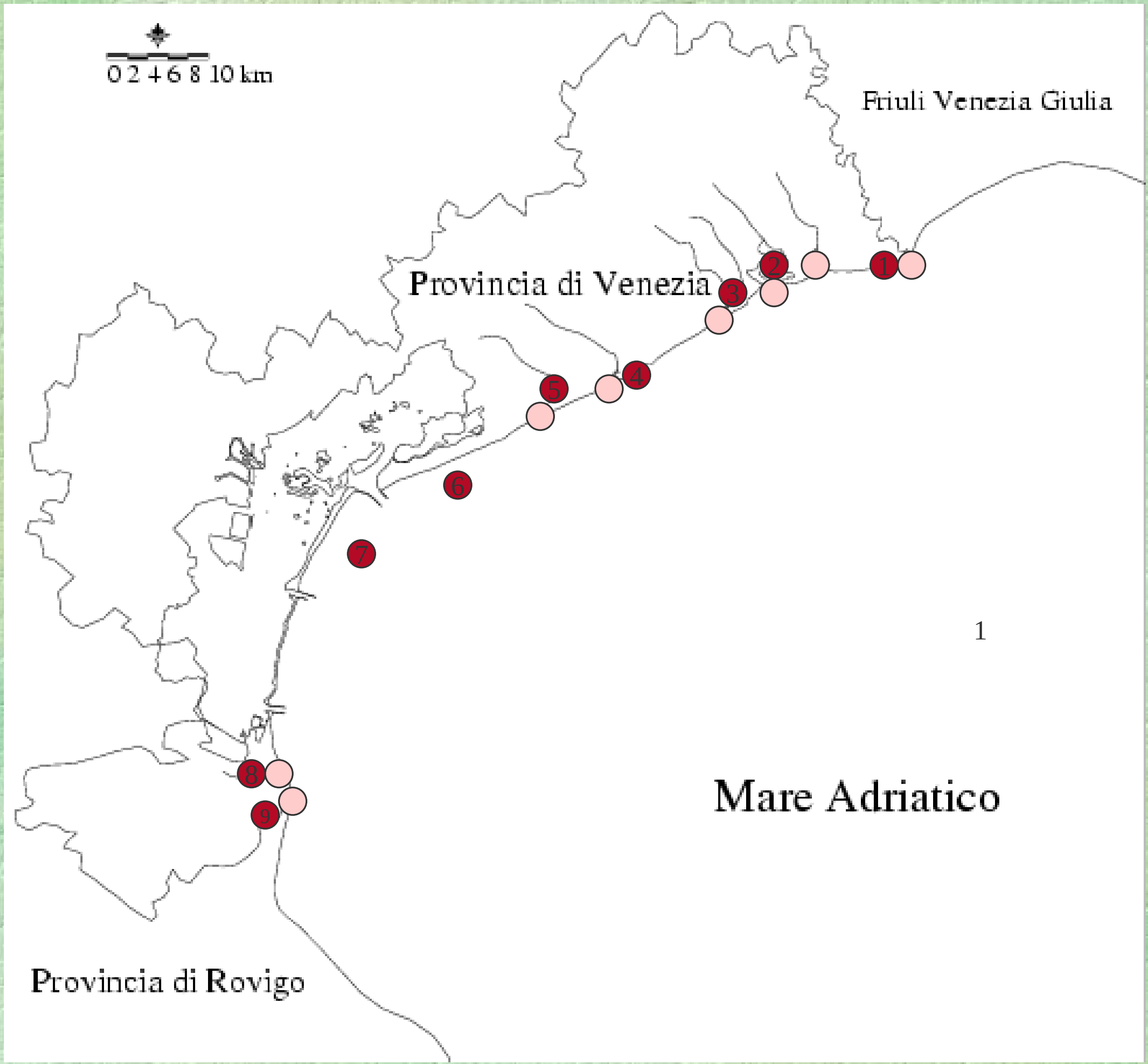
BIOPRO

The study has been carried out in the framework of the BIOPRO project, promoted and funded by the Environmental Policies Office of the Venice Province, in collaboration with ARPAV, the environmental protection agency of the Veneto region, and ISMAR- CNR of Venice.

The purpose of the study is the description of dispersion of the bacterial pollution, coming from some treatment plants and the rivers located along the coast of the Venice Province .

The study may provide useful information to identify the zones with higher bacterial polution risk and the unfavorable situations for water quality, depending on the meteo-marine regimes (wind and tide).

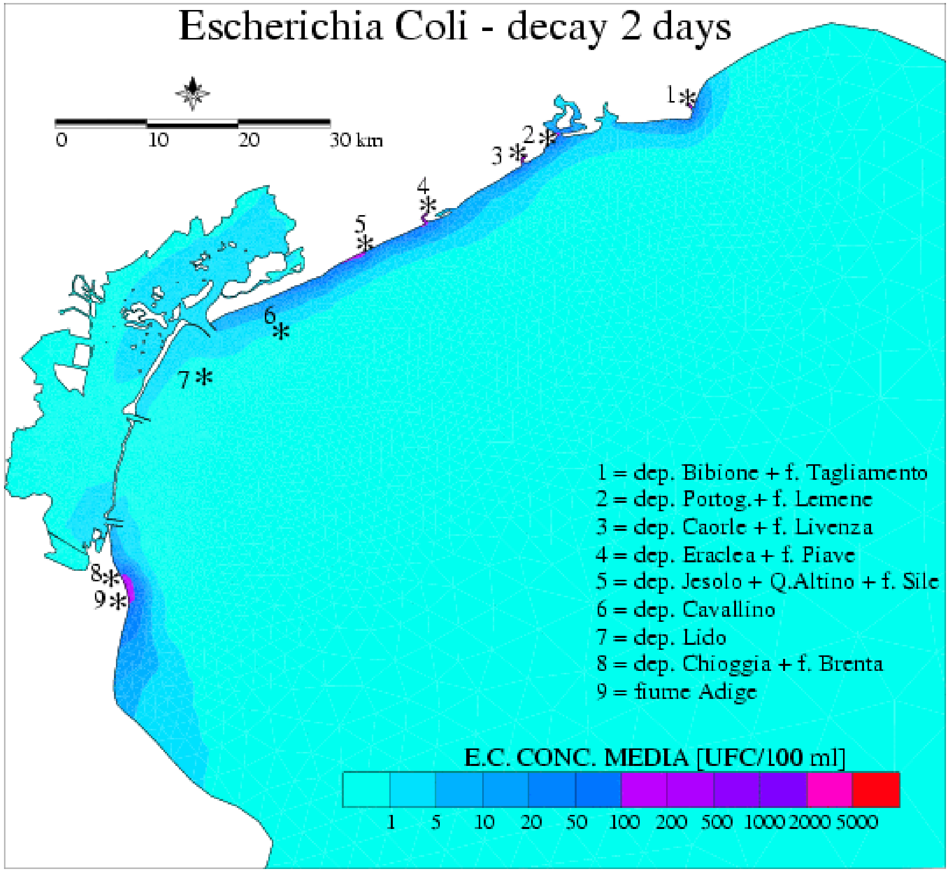
Map of the Venice Province

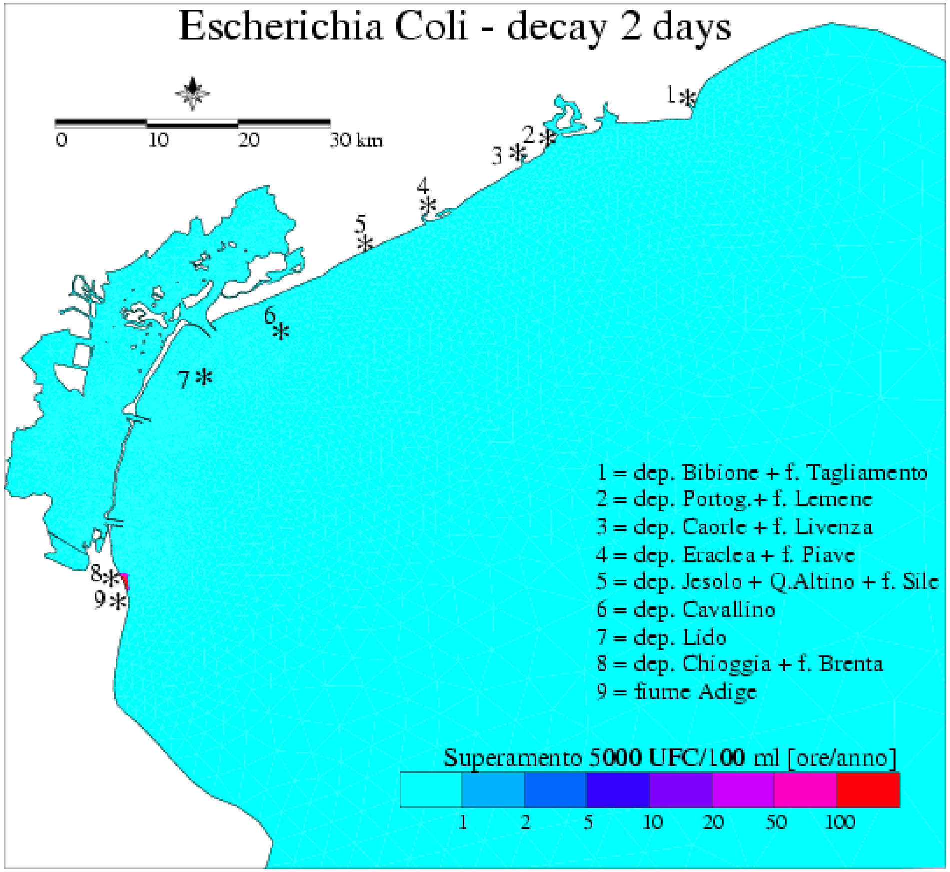


= 9 treatment plants

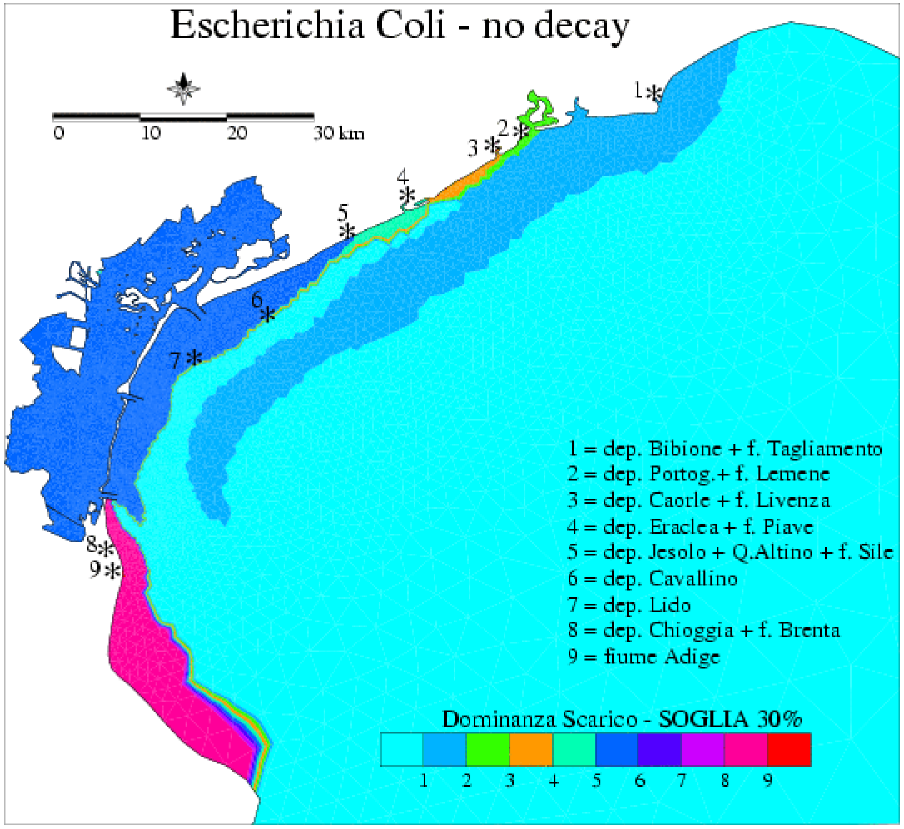
= 8 rivers

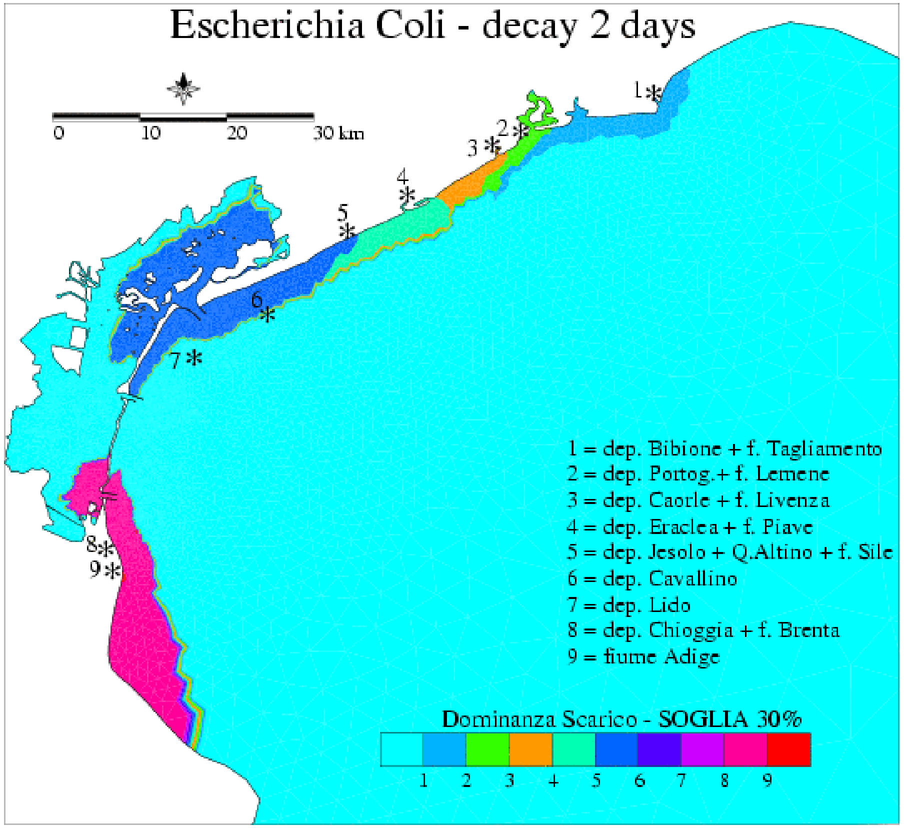
Escherichia Coli (aver and max) L=5000 UFC/100 ml (D.L. 152/99)





Area of influence of the sewage treatment plants (Escherichia Coli)





Animated simulations for EC

- Case without decay:
  - simulation for EC
- Case with decay (2 days):
  - simulation for EC

Conclusions

- Modeling tools are a valuable tools for assessing environmental problems in the coastal zone
- The Venice Lagoon is a prototype of lagoon where all possible processes can be studied ranging from hydrodynamic to ecological applications
- Modeling approach is needed for coastal zone management and sustainable development
- The models are available in the public domain for the application to other areas (see `http:/www.ve.ismar.cnr.it/shyfem`)