A gentle introduction to numerical modeling

Georg Umgiesser
Coastal Oceanography
ISMAR-CNR, Venezia, Italy
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
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 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

Adjacent marine system

Atmosphere

Water in motion + Sediments;
Dissolved matter;
Suspended matter;
Fauna et flora.

Bottom sediments

Land system
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 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

\[
\frac{\partial \rho}{\partial t} = \nabla \cdot \rho \mathbf{v} \quad \nabla \cdot \mathbf{v} = 0
\]

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

\[
\frac{\partial \rho_\alpha}{\partial t} + \nabla \cdot \rho_\alpha \mathbf{v}_\alpha = X_\alpha + I_\alpha
\]

Where:

\(X_\alpha\) is the production (or destruction) rate for variable \(\alpha\) by external agents;

\(I_\alpha\), is the production (or destruction) rate for variable \(\alpha\) by internal agents, i.e., other system variables.
Conceptual ecosystem modeling

Hydrodynamic engine $\Rightarrow$ (currents, sea levels, density) + waves

Exchanges
- Water
- Pollutants
- Sediments
- Organic matter
- Nutrients
- Phytoplankton
- Zooplankton
- Other?
Fate of a contaminant in the coastal ocean

Coastal Modelling.
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
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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:
\[ \frac{1}{r} \frac{\partial (u r)}{\partial r} + \frac{1}{r} \frac{\partial (u_r)}{\partial \theta} + \frac{\partial w}{\partial z} = 0 \]

(c) Spherical:
\[ \frac{1}{(R+z)\cos \theta} \frac{\partial u_\theta}{\partial \theta} + \frac{1}{(R+z)\cos \phi} \frac{\partial (u_\phi \cos \theta)}{\partial \phi} + \frac{\partial [(R+z)^2 u_r]}{\partial z} = 0 \]

(d) Orthogonal:
\[ \frac{1}{h_1 h_2 h_3} \left\{ \frac{\partial (h_2 h_3 u_1)}{\partial \xi_1} + \frac{\partial (h_3 h_1 u_2)}{\partial \xi_2} + \frac{\partial (h_1 h_2 u_3)}{\partial \xi_3} \right\} = 0 \]
Grids: 1D “branched” grid

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

Dr. Ali Harzallah (INSTM)
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

Georg Umgieesser
Coastal Oceanography
ISMAR-CNR, Venezia, Italy
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 km² 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
Sediment Transport Modeling

**FEM**
Hydrodynamic Model

**SWAN**
Wave Model

Current variables and others
- current speed
- current direction
- water depth
- suspended sediment concentration

**INTEGRATED MODEL**

**SEDTRANS96**
Sediment Transport Model

Wave variables
- significant wave height
- wave period
- wave direction

Bed and sediment variables
- bed structure
- sediment transport rates

Sediment characteristics
- grain size
- critical shear stress
- density
- settling velocity
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

Bottom shear stress (N/m$^2$) during a Sirocco event.
Maximum stress $\tau_{\text{max}}$ (N/m$^2$) due to wave and currents, during a Sirocco event.

$$\tau_{\text{max}} = [(\tau_m + \tau_w \cos \phi)^2 + (\tau_w \sin \phi)^2]^{0.5}$$
Ecological Model: State variables and fluxes
Phytoplankton concentration in the lagoon of Venice

Day 130

Day 140
Managing fresh water in lagoons

- the Cabras lagoon in Sardinia: salinity trend
Dealing with residence times

Residence time is an indicator for the renewal capability of a basin. Residence time is controlled through fresh water fluxes and exchange with the open sea.
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
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 km²
- Shallow water (max depth 8m)
- Single passage with the open sea
- Aquaculture activity
- Wastewater and sewage discharge
Wind driven circulation

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

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

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

POM shelf model

SHYFEM shelf model

SHYFEM lagoon model
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 pollution risk and the unfavorable situations for water quality, depending on the meteo-marine regimes (wind and tide).
Map of the Venice Province

- **Red circles** = 9 treatment plants
- **Pink circles** = 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).