CURRENT CIRCULATION AND SEDIMENT TRANSPORT IN THE COASTAL ZONE IN FRONT OF THE DANUBE DELTA

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Abstract. The objective of this study is to simulate, through an interaction of two mathematical models, the current circulation and sediment transport in the Northern part of the Romanian coastal area. The area of study has a length of about 34 km, North – South oriented, between the Sulina and Sf. Gheorghe branches of the Danube River, extending for about 30 km offshore. First a 3-dimensional hydrodynamic model of 5500 triangular elements is used to simulate the current circulation pattern at different depths in the proximity of the coastal area. Closer to the coast, the resolution of the element is about 200 m. Parameters used as data input were the bathymetry map of the studied zone interpolated with the grid, the wind stress calculated from real values using the formula of Smith and Banke and the liquid discharge of the Danube River. The sediment transport model, that aims to simulate the sediment dynamics, is coupled with the hydrodynamic one and forced by solid discharge and sea bed sediment characteristics. Three ideal situations considering the most frequent wind regimes have been carried out to better understand the general pattern of the circulation. The anti-cyclonal current described in literature could be simulated and analysed with particular meteorological conditions. Subsequently, real data measured in 2002 have been used to force a one year simulation. The results show the presence of seasonal differences in the erosion and deposition dynamics mainly due to different wind regimes.

Key words: Danube Delta coast, modelling, sediment transport, coastal dynamics

INTRODUCTION

The Danube is the second longest river in Europe, with a length of 2857 km. Its source is in the mountains of the Black Forest in Germany. Its drainage basin covers an area of 817000 km^2 (Panin and Jipa, 2002).

It finally flows into the North-Western area of the Black Sea through three principal mouths: Chilia, Sulina and Sf. Gheorghe (Fig. 1).

Chilia is the Northern branch of the Danube. It has a length of 117 km mapping out the border between Romania and Ukraine. It carries half of the total Danube discharge in the Black Sea through 45 smaller branches, from which the biggest arms are Oceacov and Stambulu Vechi.

Sulina is the central branch and it accounts for 22% of the total discharge (Panin, non published data). It has a linear shape mainly due to the cut-off of many of its meanders made during the last century, that shortened it by 15% .

The Southern branch is Sf. Gheorghe, with the 28% of the total discharge. 5 km before the mouth of the river it splits into two smaller branches that make up the Sf. Gheorghe Delta.

The Danube Delta covers an area of 5800 km^2 (90% in Romania, and 10% in Ukraine) with a coastal length of 240 km, from which 165 km are Romanian territory.

The attention is focused on the coastal area between the two Southern branches: Sulina and Sf. Gheorghe. It is 34 km long and mainly North-South oriented.

It is probably the most important natural reservoir in South Eastern Europe.

The interest in this area is related to the coastal dynamics. During the last century the human influence modified it relevantly, causing a strong erosional rate.

For example the construction of the two Iron Gates dams along the river, in 1970 and 1985, caused a sharp decrease in the sediment load carried by the Danube, that is, 35 to 50% of its previous discharge (Panin, 1997). Another important effect was caused by the construction of the Sulina jetties, which began in the second half of the XIXth Century to reach now a length of 8 km (Stanica, 2004). This work caused a strong impact in the current circulation and therefore in the sediment dynamics, accounting for the increase of the erosional phenomenon in the Danube Delta coastal zone.

The objective of this study is to simulate, through two coupled mathematical models, the current circulation and the sediment transport in the coastal zone between the branches of Sulina and Sf. Gheorghe. The study is divided into two parts: one of ideal simulations with constant wind and discharge in order to better understand the effect of different wind directions and meteorological conditions on erosion or deposition; the second one simulates the annual water and sediment dynamics, through four simulations in order to investigate the seasonal differences, related to the seasonal meteorological conditions.

This work should be considered as the beginning of a collaborative project between Romania and Italy, aiming to implement and better calibrate the model, and to increase the quantity of the measured data used both as input and as comparison with the simulated results.

MODELS

A 3-dimensional hydrodynamic model (SHYFEM) together with a sediment transport model (SEDTRANS05) were used in this study. SHYFEM uses the hydrodynamic equations to simulate the values of the barotropic transport and of the water level at each point of the grid. The sediment transport module gives the erosional or depositional rate in each element of the grid and the sediment concentration flowing in and out from the water column.

Shyfem

SHYFEM (Shallow Water Hydrodynamic Finite Element Model) is a 3-dimensional hydrodynamic model developed at CNR-ISMAR of Venice (Umgiesser *et al*., 2004a,b; Umgiesser 2004; Ferrarin and Umgiesser, 2005; Scroccaro *et al.*, 2003, 2004) which solves the hydrodynamic Shallow Water equations.

For the spatial discretization, it uses the finite element method for the horizontal plane, and for the vertical one, a

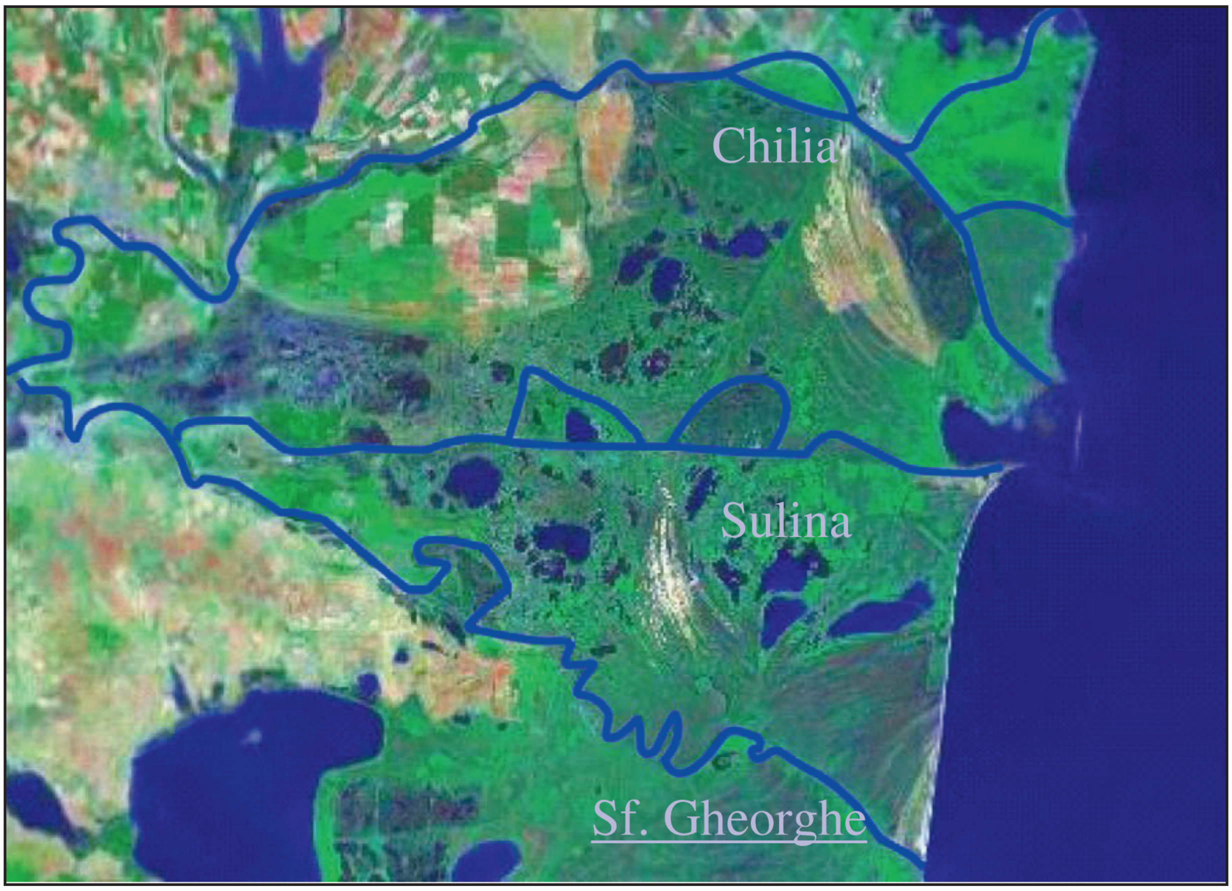

Fig. 1 Danube Delta map, division into the three main branches (figure from Google Earth modified by Elias Tahchi)

system of layers that divide the water column. The finite element method offers the advantage of a bigger flexibility allowing for change in the shape and the size of the elements in different places of the grid. This advantage makes the model very suitable for areas with a complex geometry and bathymetry.

For the temporal discretization it uses an algorithm with a semi-implicit time resolution, which has the advantage of both explicit and implicit methods.

The equations used by the model are the hydrodynamic equations in the Shallow Water approximation, derived from the momentum and mass conservation equations, simplified with the incompressibility condition and the hydrostatic approximation.

Relations between water level ζ, and velocity u and v (in the x and y directions, respectively) are presented as:

$$\frac{du}{dt} - fv = -\frac{1}{\rho_0}\frac{\partial p}{\partial x} + \frac{1}{\rho_0}\frac{\partial \tau_x}{\partial z} + A_H\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)$$

$$\frac{dv}{dt} + fu = -\frac{1}{\rho_0}\frac{\partial p}{\partial y} + \frac{1}{\rho_0}\frac{\partial \tau_y}{\partial z} + A_H\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right)$$

$$\frac{\partial \varsigma}{\partial t} + \frac{\partial Hu}{\partial x} + \frac{\partial Hv}{\partial y} = 0$$

where τ is the *stress*, g the gravity acceleration, $H=h+\zeta$ the water column total depth, h the undisturbed depth and ζ the water level, t the time, f the Coriolis parameter, ρ_0 the reference water density, p the pressure and A_H horizontal eddy viscosity.

Dividing the water column into L layers i (with $i=1,...,L$), where *1* is the superficial layer and L the bottom one, which have constant thickness except for the superficial one (with a variation due to the water level ζ), the transport U and V are defined as:

$$U_i = \int_{h_i} u dz \qquad V_i = \int_{h_i} v dz$$

where the integrals are calculated for each layer, between the lower and upper interface, and h_i is the thickness of the layer i.

Integrating vertically, the first equations become:

$$\frac{\partial U_i}{\partial t} - fV_i = Adv_i^x - h_i\frac{1}{\rho_0}\frac{\partial p_i}{\partial x} + \frac{1}{\rho_0}\left(\tau_x^{i-1} - \tau_x^i\right) + A_H\left(\frac{\partial^2 U_i}{\partial x^2} + \frac{\partial^2 U_i}{\partial y^2}\right)$$

$$\frac{\partial V_i}{\partial t} - fU_i = Adv_i^y - h_i\frac{1}{\rho_0}\frac{\partial p_i}{\partial y} + \frac{1}{\rho_0}\left(\tau_y^{i-1} - \tau_y^i\right) + A_H\left(\frac{\partial^2 V_i}{\partial x^2} + \frac{\partial^2 V_i}{\partial y^2}\right)$$

where the advective terms are:

$$Adv_i^x = \left(-U_i\frac{\partial U_i}{\partial x} - V_i\frac{\partial U_i}{\partial y}\right)/\,h_i$$

$$Adv_i^y = \left(-U_i\frac{\partial V_i}{\partial x} - V_i\frac{\partial V_i}{\partial y}\right)/\,h_i$$

The stress terms in every layer are described as:

$$\tau_x^i = \nu\rho_0\left(\frac{\partial u}{\partial z}\right)_i$$

$$\tau_y^i = \nu\rho_0\left(\frac{\partial v}{\partial z}\right)_i$$

where ν is the kinematic viscosity.

The bottom stress terms are calculated as:

$$\tau_x^{bottom} = c_B\rho_0 U_L\sqrt{U_L^2 + V_L^2}\,/\,h_L^2$$

$$\tau_y^{bottom} = c_B\rho_0 V_L\sqrt{U_L^2 + V_L^2}\,/\,h_L^2$$

where c_B is the bottom drag coefficient, U_L and V_L the two components of the bottom velocity.

The drag coefficient of the water is calculated with the *Chezy* equation:

$$c_B = g\,/\,C^2$$

where C is the Chezy coefficient which varies with the depth as:

$$C = k_s H^{1/6}$$

where k_s is the Strickler coefficient.

The drag coefficients relative to the water surface are calculated with the following formula:

$$\tau_x^{surf} = \rho_a C_D u_w\sqrt{(u_w^2 + v_w^2)}$$

$$\tau_y^{surf} = \rho_a C_D v_w\sqrt{(u_w^2 + v_w^2)}$$

where ρ_a is the air density, C_D the drag coefficient, u_w and v_w the wind velocity in the x and y directions, respectively.

The drag coefficients for the shear stress induced by the wind are parameterized by Smith and Banke (1975) as:

$$C_D^x = \left(0.066\left|u_w\right| + 0.63\right)\cdot 10^{-3}$$

$$C_D^y = \left(0.066\left|v_w\right| + 0.63\right)\cdot 10^{-3}$$

Sedtrans05

SEDTRANS05 is a numeric zero-dimensional model for the study of the bottom boundary layer dynamics and the sediment transport in continental shelf and in coastal environments.

This is the last version of the Sedtrans model, originally developed at the logical Survey of Canada-Atlantic (GSCA) in the '1980s. It is used to simulate the transport rate of sediments under the effect of current or combined current and waves.

The sediment dynamics is studied with a transport and diffusive module. The bottom sediments are studied with a direct advective scheme.

The sediment is composed of different grain size classes considered independently. Erosion and deposition processes mainly occur in the bottom boundary layer, which is formed between the water column and the sea bed. To calculate the bottom shear stress and the velocity profile, the program uses the bottom boundary layer theory (Grant and Madsen, 1986).

In order to calculate the bedload transport of non-cohesive sediments, it applies the algorithms of Yalin (1963) and Van Rijn (1993), whereas for the total transport (bedload+suspended) it uses the methods of Engelund and Hansen (1967) and Bagnold (1963).

The bottom level and sediment distribution due to erosion and deposition are updated at each time step.

The bottom is schematized through different layers, out of which only the superficial one is active.

Friction factor and bed shear stress

In order to predict the bottom shear stress and the velocity profile in the bottom boundary layer, the continental shelf bottom boundary layer theory formulated by Grant and Madsen (1986) is used.

To calculate the total bed roughness z_0, both grain roughness, bed form (ripple) and bedload roughness due to the sediment transport are considered.

Bedload transport

To predict the bedload transport of non-cohesive sediments there are five algorithms which can be used. The Van Rijn (1993) formula is applied in this study.

If the bottom stress is not high enough, the sediments stay in their inertial position.

The critical shear stress for motion initiation is:

$$\tau_{cr} = \theta_{cr}(\rho_s - \rho) g D$$

where ρ_s is the sediment density, D the average sieve diameter and θ_{cr} the dimensionless critical Shields parameter calculated with the Yalin method (Li *et al.,* 2001).

In the Van Rijn (1993) method, as in the previous Bagnold approach, the bedload transport consists of jumps of the particles under the effect of hydrodynamic and gravity force.

The instantaneous bedload is defined as the product between the saltation height and the bed concentration, and is calculated as:

$$q = \eta_i \alpha (s-1)^{0.5} g^{0.5} D^{1.5} D_*^{-0.3} \tau_m^{2.1}$$

where s is the ratio between the sediment and water density, η_i is the availability relative to the fraction i of bottom sediment, α is a constant equal to 0.053, and τ_m the shear stress parameter calculated as:

$$\tau_m = \frac{\tau_{cs} - \tau_{cr}}{\tau_{cr}}$$

with τ_{cs} the instantaneous skin friction current shear stress, and τ_{cr} the critical shear stress for the sediment motion initiation.

D_* is the dimensionless grain size calculated as:

$$D_* = \left[\frac{g(s-1)}{\nu^2}\right]^{1/3} D$$

SUSPENDED SEDIMENT TRANSPORT

When the sediment velocity in the bottom layer is comparable with the settling velocity a part of the sediments can be resuspended.

Once the sediments are in the water column, these can be transported and diffused by the current, as long as the force upwards is higher than the gravity force.

The critical shear stress for initiation of the suspended transport is calculated with the Van Rijn (1993) method:

$$1 < D_* < 10 \rightarrow \frac{u^*_{crs}}{w_s} = \frac{4}{D_*}$$

$$D_* > 10 \rightarrow \frac{u^*_{crs}}{w_s} = 0.4$$

where u^*_{crs} is the shear velocity, w_s the settling velocity calculated with the Soulsby's formula (1997):

$$w_s = \frac{\nu}{D}\left[\left(10.36^2 + 1.049 D_*^3\right)^{0.5} - 10.36\right]$$

The critical shear stress is calculated using the following formula:

$$\tau_{crs} = \rho (u^*_{crs})^2$$

Advection and diffusion equations

When the bottom shear stress is higher than the suspended critical shear stress, the particles enter in the water column and move under the current effect.

The concentration C of the suspended sediment is described by the 3-dimensional equation of advection and diffusion:

$$\frac{\partial C}{\partial t} + \frac{\partial uC}{\partial x} + \frac{\partial vC}{\partial y} + \frac{\partial wC}{\partial z} - w_s \frac{\partial C}{\partial z} = \nu_H \left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2}\right) + \nu_V \frac{\partial^2 C}{\partial z^2} + E$$

where ν_H and ν_V are the horizontal and vertical turbulent diffusion coefficient, respectively, while w_s is the settling velocity and E is the external source term.

Using this equation, the mass of sediment which can be advected with the current, settled due to gravity and diffused by turbulence, is conserved.

Its vertical boundary conditions are:

$$\left(-\nu_V \frac{\partial C}{\partial z}\right)_{z=0} + w_s C_{top} = 0$$

$$\left(+\nu_V \frac{\partial C}{\partial z}\right)_{z=bottom} + w_s C_{bot} = ED$$

where the first equation refers to the top of the surface layer, and the second to the bottom layer. *ED* is the net sediment flux between the bottom and the water column, thus equal to the difference between resuspension and deposition of each grain size material.

The term *ED* (*>0* if there is erosion) is calculated explicitly in case of erosion, implicitly in case of deposition, thus avoiding the possibility to obtain a negative concentration if the deposition rate is bigger than the quantity of sediments existing in the water column.

Sediment exchange with the bed

The net flux between the accumulated and resuspended sediments (*ED*) is calculated as the difference between the equilibrium concentration and the concentration present in the lower layer of the water column:

$$ED = w_s(\bar{C}_{eq} - C)$$

where $\bar{C}_{eq}$ is the average sediment concentration of equilibrium in the lower layer, calculated from the equilibrium concentration C_{eq} close to the bed and assuming a logarithmic velocity and concentration profile of the suspended sediment. *C* is the suspended sediment concentration present in the lower level for the considered sediment class.

This equation shows that when the sediment concentration close to the bed is smaller than the equilibrium value, the net flux of particles is from the bed to the water column (*ED>0*, erosion). On the contrary, if the concentration exceeds the equilibrium value the flux is in the opposite direction (*ED<0*, deposition).

The sediment concentration at the reference height (bed roughness z_0) is calculated following the Smith and McLean (1977) formula adapted for a different material.

$$C_{eq} = \frac{\eta_i \gamma_0 C_b \tau_*}{(1+\tau_*)}$$

with C_b the volume concentration of the sediment bed and

$$\tau_* = \frac{(\tau_{cws} + \tau_{cr})}{\tau_{cr}}$$

is the normalized excess of shear stress, τ_{cws} the skin-friction combined with the shear stress, τ_{cr} is the critical shear stress for the initiation of the motion and γ_0 the empirical sediment resuspension coefficient (Li and Amos, 2001).

Morphodynamics

Modifications in the bed elevation are obtained as the sum over the different sediment fraction of the net exchange due to suspended and bedload transport.

The net sediment exchange due to bedload is calculated using the sediment continuity equation:

$$\frac{\partial h}{\partial t} = \frac{1}{1+\varepsilon}\left(\frac{\partial q_x^b}{\partial x} + \frac{\partial q_y^b}{\partial y}\right)$$

where *h* is the variation of the bed elevation, ε the sediment porosity and q_x^b and q_y^b are the volumetric transport rate in the *x* and *y* directions.

The change in the bed elevation due to resuspension and redistribution of the suspended sediment is calculated as:

$$\rho_s(1-\varepsilon)\frac{\partial h}{\partial t} = -ED$$

with ρ_s the sediment density.

INPUT DATA

Grid

To apply the mathematical model it is necessary to create a numerical grid first.

The first step is the digitalization of a map; in this study the bathymetric map from 2002 is used.

The basin extends about 34 km to the North-South direction between Sulina and Sf. Gheorghe arms of the Danube. In the East-West direction, it covers an area between the shoreline and an offshore distance of approximately 30 km, reaching a depth of 40 m in the Southern zone.

The basin is then divided into 5493 triangular elements that vary in shape and dimension in order to have different resolutions in different zones. In this case, for example, in the area near the shoreline, the resolution is of about 200 m, while at the other basin border, in deep water, it is of about 2 km. There are 3022 vortexes of elements (nodes).

Once the grid is regular enough, the bathymetry is inserted.

Elements on the final grid are differentiated by the grain size of the bottom sediment. That is made by dividing the basin into three different zones: one constituted only of fine sand (200 μm), one made of 65% silt (20 μm) and of 35% clay (4μm), and the last one constituted of these three grain size classes in equal proportions.

The water column is divided into 15 layers. In the first 10 m, each layer is 1 m thick. At higher depths the thickness increases, reaching 13 m in the deepest layer.

Discharge

The discharge data used in this study are measured by the National Institute of Hydrology and Meteorology of Bucharest and have monthly frequency (one data each month).

The average liquid discharge from the Sulina mouth (22% of the total water mass carried by the Danube) has a value of 1390 m^3/s, which corresponds to 6318 m^3/s by the whole river (199 $km^3/year$). The only branch of the Chilia Distributary considered in this study is the Southern one called Stambulu Vechi, accounting for 60% of Chilia`s discharge (30% of the entire river discharge). This is the only one able to influence the studied zone, since the Sulina jetties stop all the sediments transported from the North close to the shoreline.

Solid discharge

The quantity of sediments that flow into the Black Sea carried by the Danube during 2002 had an average value of 1689 kg/s, which corresponds to an annual total of about 63 million tons. Out of these, 340 kg/s were carried by the Sulina branch.

As input into the model, the solid discharge is expressed as average concentration. The average concentration in 2002 was about 331 g/m^3.

The solid discharge distribution for the three branches is similar to the liquid one (22% through Sulina, 28% through Sf. Gheorghe and 50% through Chilia).

The solid discharge is divided into three grain size classes: fine sand (200 μm), silt (20 μm) and clay (4 μm).

Most of the sediments transported by the Danube are silty. Sand and clay have more or less the same percentage (6%-8%). The data are shown in Table 1.

Table 1 Percent composition of the sediments discharged by the three Danube branches divided by the grain size (Ungureanu *et al*., 2005; Olariu *et al.*, 2005), and total average solid discharge (kg/s) from the values measured in 2002

Branch	Fine sand	Silt	Clay	Discharge
Sulina	8%	86%	6%	340 (kg/s)
Sf. Gheorghe	8%	86%	6%	433 (kg/s)
Stambulu Vechi	6%	86%	8%	464 (kg/s)

Wind

The wind data used in this study are measured in the meteorological station at Sulina by the Regional Meteorological Centre of Drobogea (Ministerul Mediului si Gospodaririi Apelor, Administratia Nationala de Meteorologie), and has a frequency of four values per day (one every 6 hours).

The wind data are inserted into the model as stress values, calculated using the Smith and Banke formula.

Analyzing the wind data measured in 2002, the three predominant wind directions of wind are North, South and North-East (percentages are shown in Table 2).

Table 2 Average frequency values of the wind in 2002 in the main directions (%)

N	NE	E	SE	S	SW	W	NW	Still
19.0	15.7	10.3	7.1	14.4	12.9	7.4	12.3	0.9

A different analysis is made on the wind velocity. For 0.9% of the year 2002, the wind was considered still. The highest percentage (49.7%) was measured for wind velocities between 1 and 5 m/s, the second most frequent wind velocities (33.9%) are between 5 and 10 m/s; velocities between 10 and 15 m/s were present 9.3% of the year, and higher than 15 m/s in 6.2% of the time. The wind velocities are strongly related to the wind directions. The average velocities in the different directions are shown in Table 3.

Table 3 Average wind velocities (m/s) in 2002 in the main directions

N	NE	E	SE	S	SW	W	NW
7.3	8.4	6.7	4.9	6.6	5.8	4.5	5.5

RESULTS

General setup of simulations

The study is divided into two parts: the first consists of ideal simulations using as input data average values of discharge and of wind speed, separately studying the different wind directions. The second simulates the sediment dynamics and the annual circulation, using as inputs the data measured in 2002, with particular attention to the seasonal differences.

In both groups of simulations the vertical viscosity coefficient is set at the reference value of $10^{-3} m^2/s$. The time step is 300 secs throughout the entire simulation. The data output is daily.

The first group of simulations lasts for one month. The current circulation becomes stationary after 2 days of simulation, while the erosional and depositional phenomena increase with time. The attention is focused on the moment when an erosional or depositional rate higher than 0.5 cm begins to occur and on the situations simulated after one month.

In the second part of the study the circulation varies strongly, with, mainly, the wind speed and direction. The interest is thus focused on current characteristics in moments when there were considerable changes in the bottom elevation. An extra analysis is based on the final maps of erosion and deposition resulting from the singular seasonal simulations, in order to compare them with the seasonal meteorological characteristics.

The data inputs for the model simulations are the Danube discharge and the wind stress. Constant average values are used in the first part, while variable data are used in the second part.

Idealized simulations

This part of the study can be divided into two further parts.

The first studies the current circulation, using only the 3-dimensional hydrodynamic model. The output is represented by circulation maps at different depth levels.

The second part regards mainly the sediment transport. In this case both models are used (the hydrodynamic model is used, nevertheless, in 2-dimensional mode). The barotropic circulation simulated by the 2-dimensional hydrodynamic model is similar to the one obtained by the average circulation at all levels.

The ideal simulations have a constant value of solid and liquid discharges, equal to the average values measured for 2002. These values are shown in Table 4.

Table 4 Liquid discharge (m^3/s) and concentrations (g/m^3) in the different branches of the Danube river

Branch	Liquid discharge	Concentration		
		Sand	Silt	Clay
Stambulu Vechi	1890	13.17	188.85	17.75
Sulina	1386	17.57	188.85	13.17
Sf. Gheorghe	1764	17.57	188.85	13.17

The wind stress is constant for each time step, equal to the average value of the 2002 measured data in the first simulation. Other ideal simulations are made with constant values of wind, increasing gradually to 15 m/s. The simulations are made in the three main wind directions: North, South and North-East.

North

The simulation is done with a constant Northern wind with a speed of 7.3 m/s.

Once arriving at a stationary state in the first (superficial) layer, the current flows Southwards, parallel to the shoreline along the entire coast. Close to the Sulina jetties, a divergence point from which the water flows in various directions is obvious.

At a depth of one meter the current begins to change its shape, revealing the presence of an anticyclonal current, forming an eddy whose diameter is directly proportional to the water depth. This eddy has a diameter of several kilometres, starting near the end of the jetties and extending towards the coast.

In the Southern area there are no differences in the current direction at different depths.

As expected, the current velocity decreases inversely proportional with the water depth, due to the bottom friction increasing influence.

The model allows us to calculate the average current in all the layers. This barotropic current (Fig. 2) seems similar to the one simulated by the 2-dimensional model. It presents an anti-cyclonal current which occupies the Northern area (about 6.6 km) of the coast and a parallel current along the coast in the Southern zone.

The sediment dynamics is simulated under this wind condition.

Most of the sediments discharged through the Sulina mouth settle close to the jetties, at few kilometres from the coast, due to an evident reduction of the current velocity. The remaining is divided into two parts: one carried by the anti-cyclonal current, is moved towards the Northern coast, while the second one, carried by the current parallel to the coast, flows towards the Sf. Gheorghe mouth.

For the assessment of the deposition pattern the simulation has to run for at least 8 days, and after a month it reaches a value of the order of 1 cm. In the immediate proximity of the coast (except for the Northern area) the current speed is too high to allow deposition.

With a wind speed of 13 m/s, the sediments released from the Sulina mouth can be carried closer to the coast, and the deposition is relevant after 3 days of simulation. After a month, the deposition reaches the value of about 3 cm.

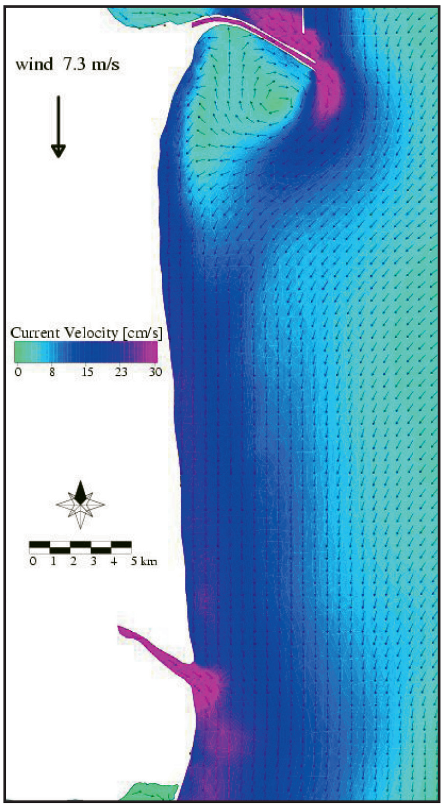

Fig. 2 Barotropic current circulation in the ideal case of constant wind from North with a speed of 7.3 m/s

Deposition was the only phenomenon resulting from this simulation. In order to understand the critical wind speed value that generates erosion, other simulations with higher wind speed values are made. Erosion starts, only in the Southern zone, when the wind speed approaches 13 m/s, and in this case it is higher than 0.5 cm after only one day of simulation. After one month of simulation it reaches an average value of 2 cm, with peaks of 10 cm.

South

The simulation is done with a constant wind from the South with a speed of 6.6 m/s.

The current in the Southern zone flows Northwards, parallel to the coast, for all the considered water depth levels. Its speed decreases with increased depth. When arriving close to the Sulina jetties, the water turns Eastwards, toward the open sea.

At the surface and in the first layer a small cyclonal eddy is formed, due to the wind effect and to the coastal morphology. This eddy disappears in the deeper levels.

It is anyway present in the average barotropic circulation, even if it does not significantly influence the coastal dynamics.

The Northward oriented current carries all the sediments discharged from the Sulina mouth out of the study zone Northwards. Also, the sediments from Sf. Gheorghe mouth are carried by a Northward current and deposited along the coastal area, without reaching the Northern part, due to the slow current speed.

The highest deposition is in front of the Sf. Gheorghe mouth and it has a value of 3 cm.

The study of the erosional threshold is particularly interesting. Increasing the wind speed, the erosion begins at 13 m/s. After a month of simulation it has a slightly smaller value than in the previous case (an average of about 2 cm with peaks of 10 cm).

With this wind speed value, the current velocity in the vicinity of the coast is very high, being thus able to carry the eroded sediments to the Northern zone, where the current slows down to a value of about 15 cm/s. Here this allows the sediment deposition that, after a month, increases the bottom elevation by 1 cm.

This phenomenon is more obvious when the wind has a velocity of 15 m/s. In this case the sediments eroded from the Southern zone are carried close to the jetties allowing an increase of the bottom elevation of about 4 cm.

It must be noted that this is the only case in which the settled sediments are mainly sandy, due to the bottom sediment characteristics near the shoreline.

The erosional process is evident from the first day of simulation. For the deposition the model must run with an average wind speed for at least 6 days, and for 1 day only with a higher value of wind speed.

North-East

The simulation is done with the North Eastern wind with a speed of 8.4 m/s.

The same situation occurs as in the case of Northern wind: an anticyclonal current appears from the 2mnd layer on in the Sulina zone. The diameter of the eddy increases with depth, but in this case it is smaller and further from the shoreline.

In the barotropic circulation, obtained by averaging the levels, the eddy has small dimensions and is far from the shoreline.

In fact, in the Northern area the current flows Westwards, parallel to the jetties, and then parallel to the coast, Southwards for the entire studied area. The current speed in the Northern coast is higher than the one obtained with the Northern wind simulation, due to the absence of the anticyclonal current and to a higher value of the average wind speed.

In this case the sediments discharged by the Sulina mouth are carried by the current parallel to the jetties.

The deposition zone is similar to the one obtained in the case with Northern wind, but moved Northwards, adjacent to the jetties for the first kilometres.

Compared to the simulation performed for Northern winds, even the values are similar, with an increase of the bottom elevation of about 1 cm after a month of simulation. There are differences, though, as the deposition rate amounts to 0.5 cm after 11 days.

The sediments not carried towards the Northern coast are transported Southwards, to the Sf. Gheorghe mouth. Nevertheless these never touch the shoreline due to the high current speed.

Gradually increasing the wind speed, it is possible to notice the erosional phenomenon in the Southern part of the coast when the wind speed approaches 15 m/s. In this case, erosion becomes relevant after only one day of simulation and reaches a value of about 2 cm after a month. Compared to the previous simulations, it has the same average erosion value but with much lower peak values.

The deposition rate in the Northern area is higher, directly proportional with the wind speed. The deposition reaches a value of 6 cm after one month.

SIMULATIONS OF 2002

In this part of the study the wind stress input is once for every 6 hours, using the measured data of 2002. The average annual wind speed is of 6.5 m/s. The wind speed highest value (29 m/s) is reached by the end of winter. The longest storm period (about 4 days) was at the beginning of December, with an average wind velocity of 21.8 m/s.

The discharge input consists of the monthly values measured in 2002.

The highest value is reached in December, with a value of 1790 m^3/s through the Sulina branch. The lowest discharge is in January, with a value of 935 m^3/s.

For the solid discharge also the highest value is in December (1290 kg/s) which strongly differs from all the others (except for December and November, the monthly discharges of other months do not exceed 500 kg/s). The smallest value is in January with a solid discharge of 20 kg/s.

General features

After the entire simulation, the meteorological conditions during relevant changes in the sea bottom were analysed.

It was thus possible to identify the general features that allow deposition or erosion of the bottom sediment.

The deposition in the Northern area was present in different situations: average value of wind speed mainly from North and North-East for a period of at least 2 or 3 days; high values of wind from South; sharp decrease in the wind speed, and therefore in the current velocity, after a period of storm, or equivalently a fast change in the wind direction, which causes a decrease in the current velocity.

The erosional process is mainly due to winds from North and North-East with speeds higher than 13 m/s. The longer the period with winds stronger than 13 m/s, the higher is the erosion rate.

If a high wind event is isolated, i.e. the strong wind lasts for only a few hours, the current does not have the time to increase and erosion cannot develop. Otherwise, if strong winds last longer, erosion can occur from the first day.

Seasonal differences

In order to investigate the seasonal differences in coastal dynamics, it is useful to analyse the differences in the meteorological conditions for the various seasons. In Table 5 the average seasonal solid and liquid discharge values through the Sulina branch are shown. In Table 6, the wind is described through some characteristic values such as the highest velocity, average velocity and main directions, measured in each season. As pointed out in the ideal study, the erosion process is greatly influenced by winds stronger than 13 m/s. For this reason the percentage of wind higher than this value is computed for each season.

Table 5 The main seasonal variation of discharge characteristics

Season	Liquid discharge	Solid discharge
Winter	1190 m^3/s	700 kg/s
Spring	1470 m^3/s	890 kg/s
Summer	1280 m^3/s	450 kg/s
Autumn	1603 m^3/s	2070 kg/s

Table 6 The main seasonal variation of wind characteristics

Season	Max Vel	Aver Vel	Vel > 13m/s	Main dir
Winter	29 m/s	6.6 m/s	10.3%	SW, S
Spring	18 m/s	5.5 m/s	3.9%	N, NE
Summer	17 m/s	5.9 m/s	6.9%	NE, N
Autumn	26 m/s	8.0 m/s	19.1%	N

The highest wind speed value in 2002 is 29 m/s, registered during winter. This value does not strongly influence the coastal dynamics because it is isolated. The storm during which that value was measured lasted for only one day.

During winter the average wind velocity, as the frequency of wind speed higher than 13 m/s, is the second highest. Nevertheless, the erosional rate (about 9 cm decrease in bottom elevation), found after the simulation of the entire season (Fig. 3), is only the third in comparison with the other seasons. This is due to two factors: first, the high wind values are generally isolated, so they are not able to strongly increase the current velocity. Second, the most frequent wind direction is South-West, and from this direction the current speed is slower than the one caused by a wind from either North or South, and the erosional threshold is higher.

The deposition rate is the lowest found in all seasons, and it is situated very far from the coast. This is mainly due to the very low value of solid discharge present in this season, and

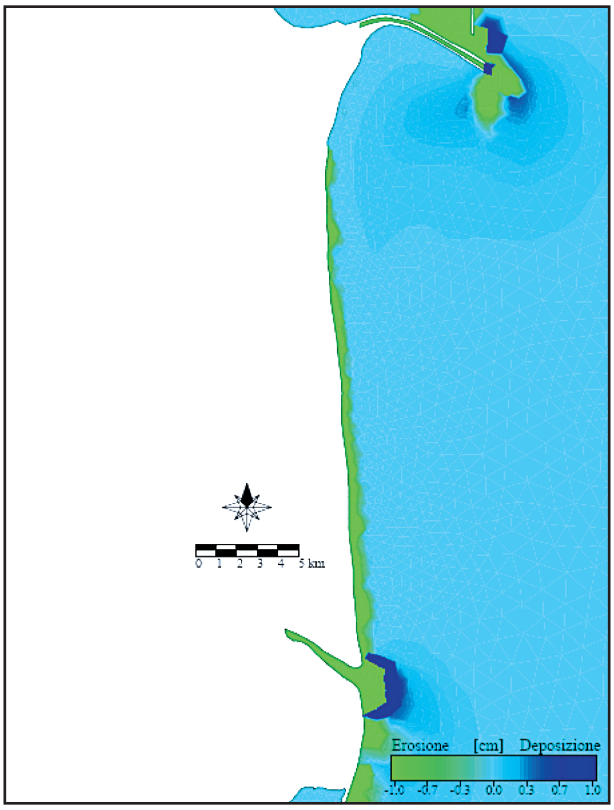

Fig. 3 Final map of bottom elevation after the winter simulation

to the small quantity of eroded sediments available for the current to be carried towards the Northern area.

In spring, the modelling shows the best conditions for a high deposition rate. In fact the wind speed, mainly coming from North and North-East, has small values and the frequency of winds faster than 13 m/s is lower than 4%. There are many periods during which the wind continuously blows from the same directions for more days so it is possible that the sediments are carried to the Northern coast, by the anticyclonal current when the wind is from North, and by the current parallel to the jetties when the wind is from North-East, as it is shown in the ideal simulations.

The simulation of this season is shown in Fig. 4. The deposition rate close to the coast is higher than in all the other seasons, as it reaches the value of about 4 cm. Erosion in the Southern area has a lower value than in all the other seasons, equal to about 5 cm.

In summer, the wind has the 2nd lowest speed, and this produces the 2nd biggest deposition rate (about 3 cm) close to the Northern coast. This was mainly due to the fast decrease in the wind speed after storms (in several cases decreases from more than 15 m/s directly to less than 5 m/s). Many of the sediments suspended during the storm, settled quickly when the current velocity decreased, and this happened mainly in the Northern area due to the presence of the jetties that stopped the water flow. Results are shown in Fig. 5.

When the wind speed is higher, the main directions of wind are from North-East and North. This causes a strong erosion along the Southern coast (about 12 cm after the entire season).

The highest wind speed values in 2002 are in autumn, and the percentage of time during which it was higher than 13 m/s is close to 20%. This is why during autumn the results showed the highest erosion rate. During the first part of the season, the Southern coast was in erosion, whereas the Northern one was in deposition, mainly due to the sediments deposited when the current velocity decreased sharply after a storm.

At the beginning of December the most relevant event of the entire year happened. A storm more than 4 days long affected the zone. The average value of wind speed was 21 m/s, in a range between 18 and 26 m/s, mainly coming from North and North-East.

This caused a current speed higher than 70 cm/s in the Southern coast and of about 30 cm/s in the Northern area protected by the jetties.

In only 4 days the coastal dynamics relevantly changed, as shown in Fig. 6. The deposition zone in the Northern coast disappeared and switched to erosion (10 cm). In the Southern area the higher erosion rate made the bottom decrease by more than 30 cm only during this storm.

The highest deposition rate in December is of 5 cm, positioned far from the coast.

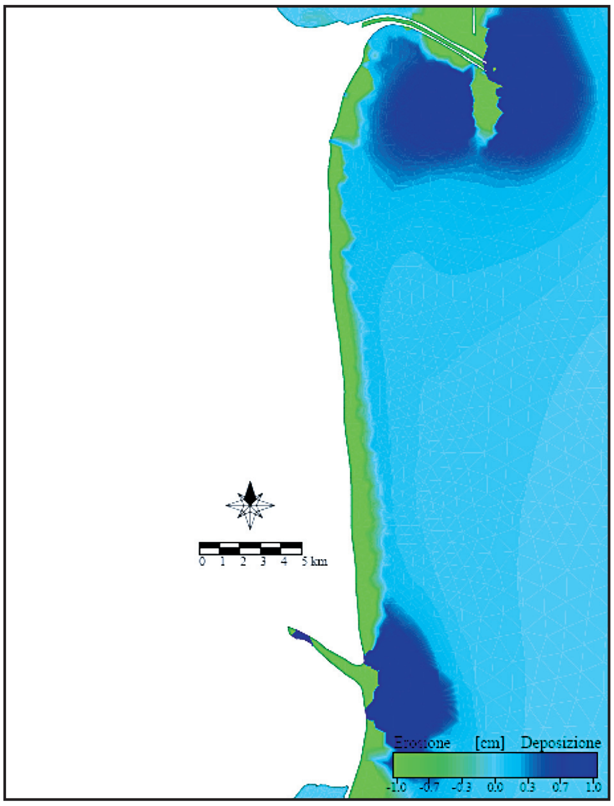

Fig. 4 Final map of bottom elevation after the spring simulation

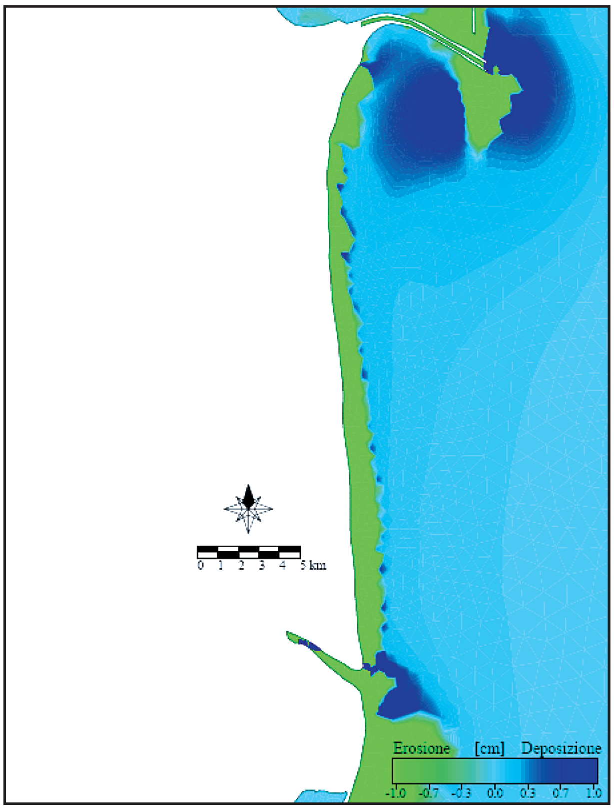

Fig. 5 Final map of bottom elevation after the summer simulation

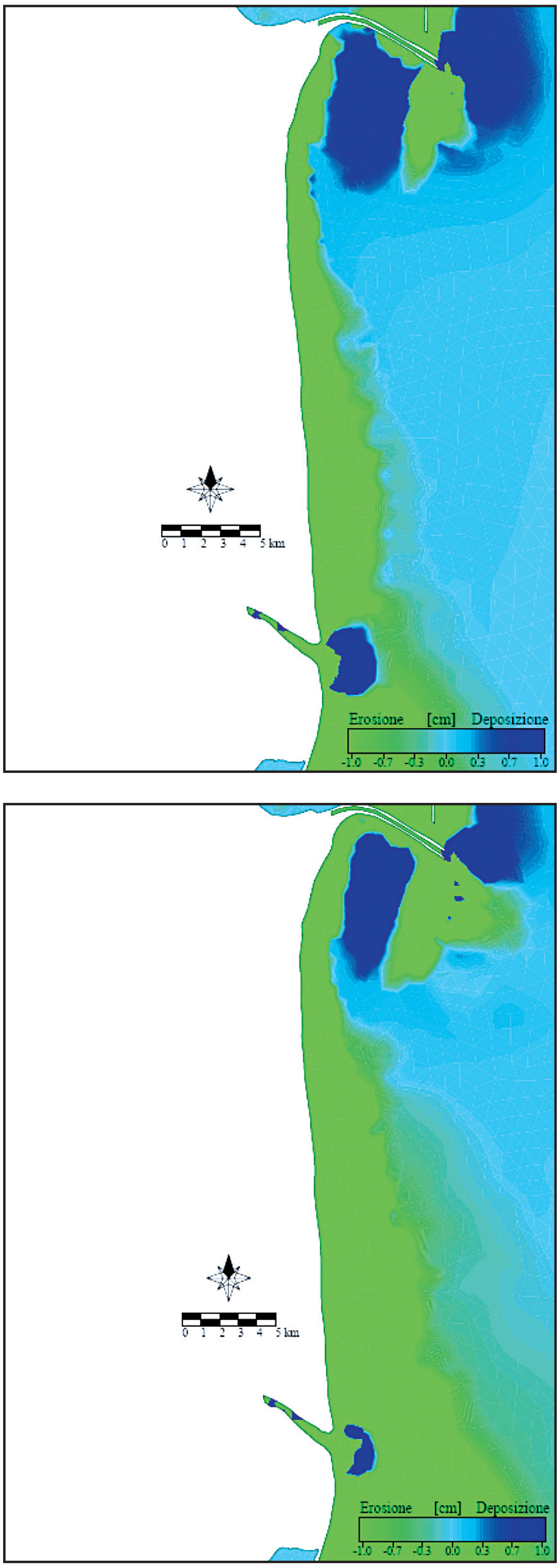

Fig. 6 Maps of the bottom elevation before (top) and after (bottom) the storm of the beginning of December 2002

DISCUSSION AND CONCLUSION

Ideal simulations comparison

Analysing the current circulation, the anticyclonal current, described in literature, was identified under the effect of particular meteorological conditions.

With an average North Eastern wind, the eddy is far from the coast and its diameter has only a few kilometres. With an average Northern wind, the eddy is well defined and its diameter is a little smaller than the length of the jetties. The eddy arrives to its highest dimensions during North Western winds, when its diameter is as long as the jetties and the only current present near the Northern coast is the anticyclonal one.

The bottom sediments characteristics show that the simulated deposition zone situated at several kilometres from the jetties as well as from the coast is mainly composed of silt. This is the main material discharged by the Sulina mouth, being thus in agreement with the simulated data.

It was possible, through the ideal simulations, to identify three different ways of deposition in the Northern area, depending on the wind direction.

With a Northern wind, the sediments discharged by the Sulina mouth are carried by the anticyclonal current. The high current speed at the river mouth allows the transport of the sediments towards a circular area, few kilometres off the jetties and from the coast, where the current speed decreases and the sediments settle. This deposition area increases in width until it reaches the coast.

With a North-Eastern wind, the sediments are carried by a current parallel to the jetties. The deposition zone has a shape similar to the previous one but moved Northward, in contact with the jetties in the first kilometres.

The third way of deposition is during Southern winds stronger than 13 m/s. In this case the deposited sediments are those eroded along the Southern coast and carried by the current toward the Northern area to the jetties, where the current quickly decreases. These sediments are mainly sandy, different from the other case, when they are mainly silty.

The threshold wind speed necessary to generate erosion was also identified. When the wind blows from North or South, the wind speed has to be higher than 13 m/s, while when the wind blows from North-East the speed must exceed 15 m/s.

Annual simulations comparison

The wind is the main factor that influences the coastal dynamics. Except for autumn (8.0 m/s), the average values of wind speed in the other seasons are quite close (winter 6.6 m/s, summer 5.9 m/s and spring 5.5 m/s). It is important to analyse the different wind directions and the period during which the wind is higher than 13 m/s.

During winter, the second highest value of average wind speed was recorded, but the direction, mainly from South-West, causes only the third highest value of erosion.

During the same season, the very low discharge also caused the lowest deposition rate.

During spring, the average wind is from North and North-East. That causes the highest deposition rate close to the coast in the Northern area, mainly due to the transport of the sediments discharged by Sulina through the anticyclonal current and the current parallel to the jetties.

The highest erosion rate is in autumn, strongly increased by the tempest in the beginning of December, as well as the highest rate of deposition far from the coast in the Northern area.

The year's simulation presents a high rate of erosion all along the coast. In the Southern part it is due to the sum of the erosional rates computed for all the seasons, while in the Northern coastal area it is due mainly to the storm from the beginning of December 2002, which induced an erosional rate higher than the sum of the deposition rates computed for all the other three seasons.

From the measured data (presented in Fig. 7) the Northern area is the only one with a tendency of deposition in the first 2 km. Moving southwards, after a stable zone (about 1.5 km), there is an area of about 2 km influenced by an erosional rate between 3 and 4 m/yr (Stanica, in press).

The Southern area, up to 6 km from the Sf. Gheorghe mouth, follows a tendency of erosion ranging between 5 and 7 m/yr of coastline retreat. The highest erosion rate was 23 m in one year (between1997 and 1998).

The area near the Sf. Gheorghe mouth is generally stable.

The tendency shown in this study is qualitatively in agreement with the simulated results. Thus, the Northern part is generally in deposition until the storm of December 2002. The Southern coast is mainly under the effect of erosion.

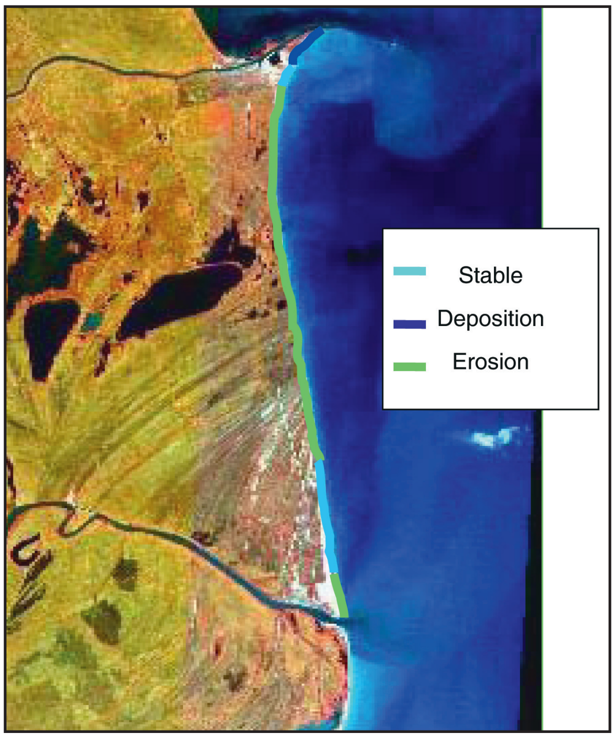

Fig. 7 Coastal dynamics from measured data

A stable zone means that the shoreline changes from deposition to erosion in different years. In 2002 the simulated data show a total tendency of erosion.

It must be noticed that the results cannot be quantitatively compared with the measured ones, because the model outputs differences in the bottom elevation, leaving the position of the shoreline unchanged. However, the measured data gives the movements of the shoreline.

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