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Simulation of Pollutants Dispersion in the Bay of Tangier (Morocco)

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Abstract: The study is focused on numerical simulation of the process of coastal pollution by wastewater in the Bay of Tangier in Morocco. The process is governed by flows generated by the tide and the large variations of the discharges from the different Wadis (rivers) flowing into the bay. The simulation requires a number of tests and trials, something that is experimentally expensive and sometimes impossible. Hence the idea was developed of a numerical study aimed at tracking the dispersion of pollutants into the bay and determining the level of degradation of its waters. The simulation was done using the computer CFD FLUENT software, first in 2D modeling to track the spread of pollution on the free surface. The results of this step made it possible to visualize the dispersion mechanism and to gain valuable information on the flow generated by the interaction of discharges and high/low tide movements near the beaches of the bay. This area is naturally the most critical in terms of environment. From the perspective of flows, the results were used to locate stagnant water and turbulent areas. These findings were used to adopt a 3D modeling - where the depth of the bay was taken into account to get closer to reality - subject to certain assumptions and including the influences of salinity and thermal gradients between the surface and the seabed, given the gravity and pressure gradients.

Keywords: Pollution, Dispersion, Tide, Turbulence, Modeling.

Nomenclature

a	Fluid Thermal Diffusivity
D	Diffusion Coefficient
C	Specie Concentration

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p	Static Pressure
f_i	Body Forces
u_i	Velocity Component
u_i	Velocity averaged component
u'_i	Velocity Fluctuating Component
Re	Reynolds Number

Greek Letters

ρ	Density
μ	Dynamic Viscosity
ν	Kinematic Viscosity

1 Introduction

The direct discharge of wastewater is one of the major factors of marine environment degradation and that because this water is collected and discharged directly into the sea with high concentrations of pollutants. However, if the discharge area is not controlled properly, the effluent can return along the coast without being sufficiently diluted and may then contaminate fishing grounds, areas for farming or collecting shells and or crustaceans, as well as beaches [Projet SMAP III (2007)]. Incidentally all parts of the Moroccan coast, including the Bay of Tangier, are lined with popular tourist beaches and fishing areas. This bay faces a really critical problem of coastal pollution, a problem the complexity of which is compounded with the involvement of many factors.

There are many systems capable of providing accurate oceanographic (temperature, sea state, current level sea salt), biogeochemical (dissolved oxygen, partial pressure of CO_2, nutrients, turbidity) and ecosystems information. These operational oceanography systems were first developed as global and regional frameworks International (GODAE, GOOS) and with European EuroGoos, Mersea and GMES. They mainly involve observation by satellite and compliance with in-situ buoys and floats (measuring temperature, salinity...). In parallel, these systems are being developed by the use of new computer software often through the concepts of fluid mechanics applied to coastal oceanography.

In the case of models, two processes are important: the tide and wind. Tide induces long-term changes that must be considered in the models. This influence can be direct or indirect [Guérin (2007)]. The direct effect of the tide is caused by nonlinear interactions, including topography, which generate an average circulation known as the tidal residual circulation. The indirect effect is that the tide creates turbulence which has the effect of vertical mixing of ocean layers. The interaction with the topography may also give rise to such mixing through the creation of internal waves. Another consequence of the tide is the rapid movement of sandbanks and suspended particles (pollutants...) in the shallow areas. The high tide spreads more widely than low tide; it brings more particulates than the low tide. From these considerations, it follows that the tide is the main component that must be included in a hydrodynamic model of Tangier bay.

These hydrodynamic models have been the subject of a number of studies through computational models. An example is a tides study of the Belgian coastal area using the SLIM model to establish the boundary conditions of the Scheldt model [De Brye (2007)]. It was a two-dimensional model using the finite element method describing the evolution of water depth and velocity averaged along the vertical. Such studies with finite difference method, were the object of many validated hydrodynamics models [Davies and Furnes (1980); Davies (1983); Davies and Furnes (1986); Flather (1976)].

This study is a new contribution to these hydrodynamic models since it considers the coupling of Navier-Stokes equations with the conservation of energy and species. Equations are solved by the finite volume method by means of the FLUENT software [Fluent 6.2 User's Guide (2005)]. The objective is to carry out numerical modeling of the dispersion of pollutants from wadis that discharge directly into the bay of Tangier. This process is governed mainly by tidal currents, and the pollution dispersion is followed up for a 24-hour cycle, which corresponds to two cycles of high and low tides. The study is performed in 3D, taking into account the depth of the bay. Note that others software such as "MOHID" [Vaz, Dias, Leitao and Nolasco (2007); (2009)] have been developed to study hydrodynamics problems, but they are appropriate for larger regions than that considered in this study and they are less efficient in terms of physical models.

The Bay of Tangier is located in the north-western extremity of Morocco, on the southern border of the Gibraltar Strait, between parallel of 35°46' and 35°48' North and meridians of 5°45' and 5°49' West. It has a dense river network in the form of low wadis flowing through the city from south to north (Fig. 1) [El Arrim (2001)].The intensity of their flow is especially remarkable in their upstream course, while downstream they are almost perennial because of drainage of wastewater from the city. Moreover, these wadis can make a significant contribution in water during rainy seasons, causing severe flooding (CWHL 1971), and often flooding the neighborhoods in low areas (valleys) of the city because of the impermeability of the soil and the steep slopes of surrounding hills. These wadis by order of hydrological and hydraulic importance are: Meghogha wadi, Souani wadi, Lihoud wadi, Mellaled wadi and Chatt wadi (Fig. 1).

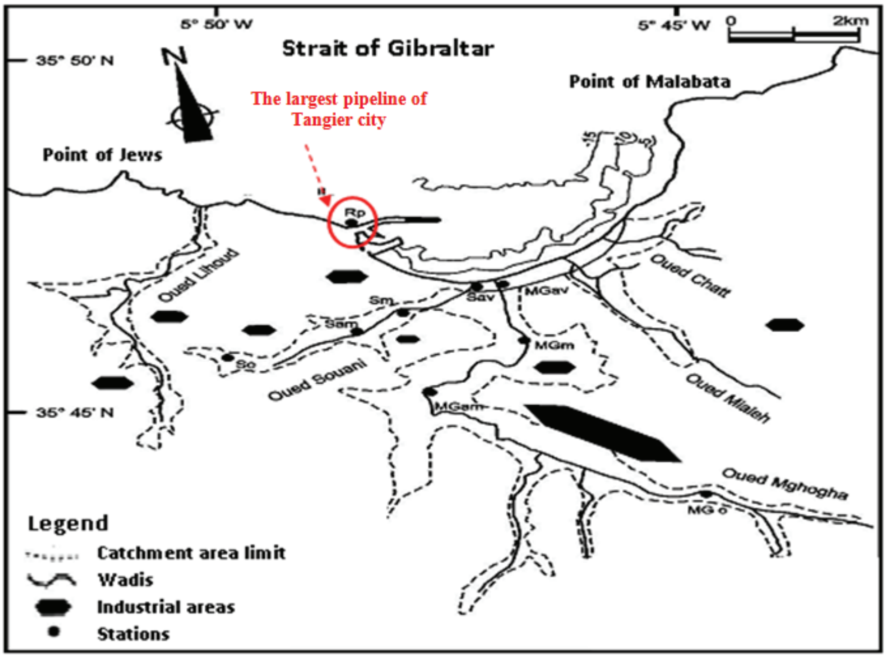

Figure 1: Geographical position and drainage network of the bay of Tangier [Hatimi, Achab and EL Moumni (2002)]

Tangier bay tide is semi diurnal with an average amplitude of 1.8m. The tidal current velocity oscillates between 1.8 to 2.7 m/s during a high tide period and reaches 0.8 m/s during a low tide period (L.C.H.F. 1974 and Long. 1988).

2 Governing equations

The present problem is governed by the unsteady incompressible Navier-Stokes equations, expressing conservation of mass and momentum, together with the conservation of energy and species (pollutant) equations [Padet (2010); Garbe, Handler and Jahne (Eds.) (2007); Wesselingh and Krishna (2000)].

Masse conservation equation

$$\frac{\partial \overline{ui}}{\partial x_i} = 0 \quad i = 1,2,3 \tag{1}$$

Momentum conservation equation

$$\frac{\partial \overline{u_i}}{\partial t} + \overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\upsilon\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right) - \overline{u_i' u_j'}\right] + \overline{f}_i \tag{2}$$

Energy conservation equation

$$\frac{\partial \overline{T}}{\partial t} + \overline{u_i}\frac{\partial \overline{T}}{\partial x_i} = \frac{\partial}{\partial x_i}(a\frac{\partial \overline{T}}{\partial x_i} - \overline{u_i T'}) \tag{3}$$

Species conservation equation

$$\frac{\partial \overline{C}}{\partial t} + \overline{u}_j\frac{\partial \overline{C}}{\partial x_j} = \frac{\partial}{\partial x_j}\left(D\frac{\partial \overline{C}}{\partial x_j} - \overline{u_i C}'\right) \tag{4}$$

These equations have the same general form as the Navier-Stokes equations written using the Reynolds decomposition which refers to separation of the flow variable into the mean (time averaged) component and the fluctuating component:

$$\overline{u} = u + u'; \quad \overline{T} = T + T'; \quad \overline{C} = C + C' \tag{5}$$

But it appears unclosed terms: Reynolds stress tensor $\overline{u_i' u_j'}$, turbulent diffusions $\overline{u_i T'}$ and $\overline{u_i C'}$. Hence, this system requires a closure model, and in this study standard k-ε model is selected [Cousteix (1989); Dumas and Al. (1976)].

When solving the governing equations, appropriate initial conditions and boundary conditions (Fig. 2) needed to be applied. Hence, the following conditions were taken into account:

- The velocity of tidal currents is imposed on Atlantic Ocean side, whereas the five wadis and the largest pipeline of Tangier city correspond to the mean velocity of discharges flow rate. This condition is applied to compute mass flow into the domain and fluxes of momentum, energy, and species through all inlets.
- Flow exits (Spanish and Mediterranean sides) where the details of the flow velocity and pressure are not known prior to solution of the flow problem, are defined as outputs. Latter, are appropriate where the exit flow is close to a fully developed condition, as the outflow boundary condition assumes a zero gradient for all flow variables except pressure.
- On coasts and seabed of the Bay, a zero velocity flow to the waterproof wall is taken.

- On the free surface of the bay, a boundary condition type "Symmetry" is used.

- Finally, at the initial time (t=0), the density of salt water (1030 Kg/m^3) is applied throughout the bay.

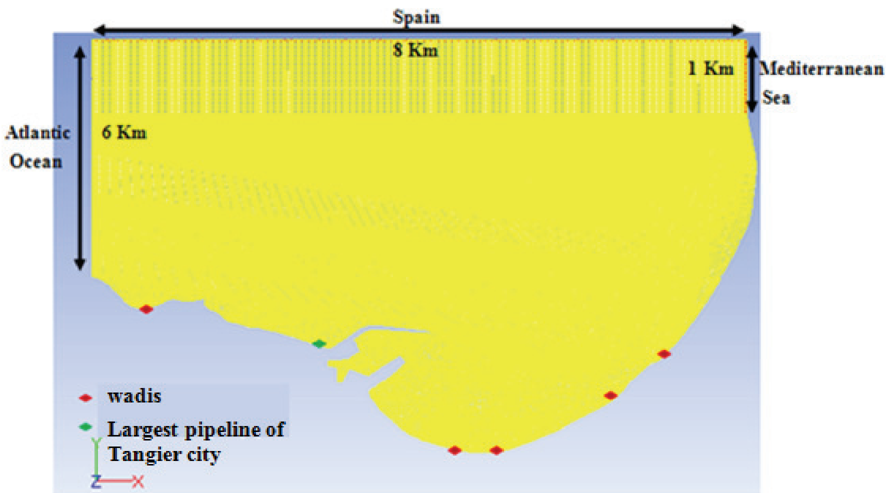

Figure 2: Computational domain: Geometry and Boundary conditions

3 Numerical modeling

The resolution of governing equations is done by the Finite Volume Method. The first step is to divide the domain into a number of control volumes (cells) where the variable of interest is located at the cell center of the control volume. The next step is to integrate the differential form of the governing equations over each control volume. Hence, discretization equations obtained express the conservation principle for the variable inside the control volume. Discretisation is the process of finding a solution for the general variable by considering a set of values of the dependent variable at discrete locations instead of its continuous exact solution (Patankar, 1980). For this, the calculation domain is divided into cells (control volumes) which together make up the computational grid. The solution at any one grid point is assumed to be an algebraic function of the solution at its neighboring grid points. Grid points correspond to cell centers. Algebraic equations for a discrete dependent variable Φ are constructed by integrating the governing equations over the separate control volumes. Hence, the result is given by:

$$A_P\Phi_P = \sum_{nb} A_{nb}\Phi_{nb} + S \tag{6}$$

where indices *nb* refer to adjacent cells to the cell P. A are coefficients including the convection and the diffusion terms of Φ, whereas S is a source term.

Convection terms are interpolated from the cell center values. This is accomplished using an upwind scheme. The diffusion terms are central differenced and this approach is known as the central-difference scheme second-order accurate.

The residual R^Φ is the imbalance in Equation (1) summed over all the computational cells P. This is referred to as the "unscaled" residual. It may be written as

$$R^\Phi = \sum_P \left| \sum_{nb} A_{nb}\Phi_{nb} + S - A_P\Phi_P \right| \tag{7}$$

To scale this residual, a scaling factor representative of the flow rate of Φ through the domain is used. Hence, the "scaled" residual is defined as

$$R^\Phi = \frac{\sum_P \left| \sum_{nb} A_{nb}\Phi_{nb} + \mathrm{S} - \mathrm{A}_P\Phi_P \right|}{\sum_P |A_P\Phi_P|} \tag{8}$$

The latter is a more appropriate indicator of convergence for most problems. This residual is the default displayed by Fluent software.

In the computational domain (Fig. 2), the mesh as shown in Figure 3 has been generated by about three million non-structured tetrahedral cells. The mesh density near the wadis mouths is refined in order to have more precision in the numerical results.

4 Results and discussion

As explained above, simulations of three-dimensional modeling were made only during the winter period. The results presented correspond to a 24-hour cycle alternating between a high tide and low tide every 6 hours, a cycle for which the flow regime within the bay was established.

Below are presented the species contours of this cycle, where the blue color indicates the seawater concentration and the red color indicates the release rivers concentration. So, at the initial point, the entire bay is colored blue. Figures 4a, b, c show the evolution of the pollutant dispersion through the estuaries during the

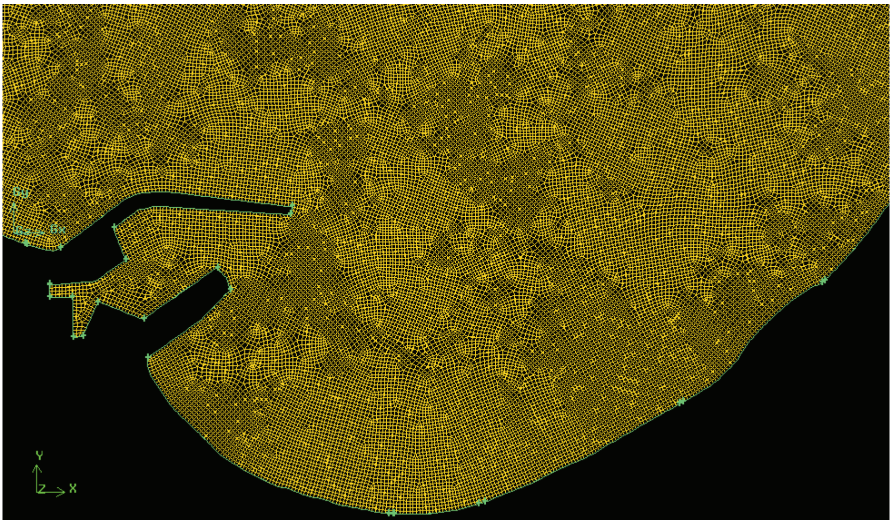

Figure 3: Detailed mesh of the free surface near the coast and estuaries of wadis

first high tide after every two hours. Discharges begin to enter the bay through the mouths of the wadis. The interaction between these discharges, in particular those of the east (Meghogha and Souani), promotes their dispersion to the rest of the bay, while for those to the west (Lihoud and the largest pipeline of Tangier), their discharges interact slowly over the period. The latter, under the effect of tidal currents, join the release from the east and create a common pollution area. The interaction process continues and the pollution area expands and becomes more concentrated towards the last hour of this tide.

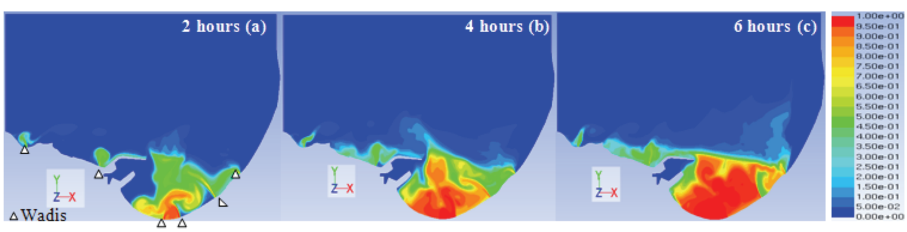

Figure 4: Pollutant concentration at the free surface during the first high tide: after 2 hours (a), 4 hours (b) and 6 hours (c)

The results presented by the velocity vectors colored by the mass fraction of pollutant show that in the first two hours of the simulation, the movement of pollution

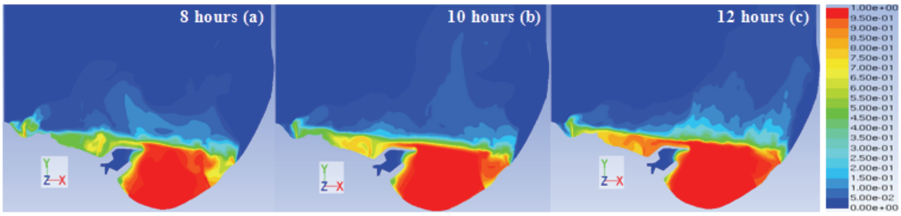

Figure 5: Pollutant concentration at the free surface during the first low tide: after 8 hours (a), 10 hours (b) and 12 hours (c)

dispersion to the east of the port, is in the form of vortices generated by the interaction between the different releases from the wadis, especially from Souani and Meghogha Wadis which exhibit a strong interaction due to the short distance between them (Fig. 6). This interaction creates a vortex of random dispersion and rapid pollution. Unlike to the west of the port, the releases of Lihoud Wadi and the largest pipeline of Tangier city probably have yet to meet because of the great distance that separates them, but the flow direction moves well to the east under the effect of the tidal currents coming from the west to the east.

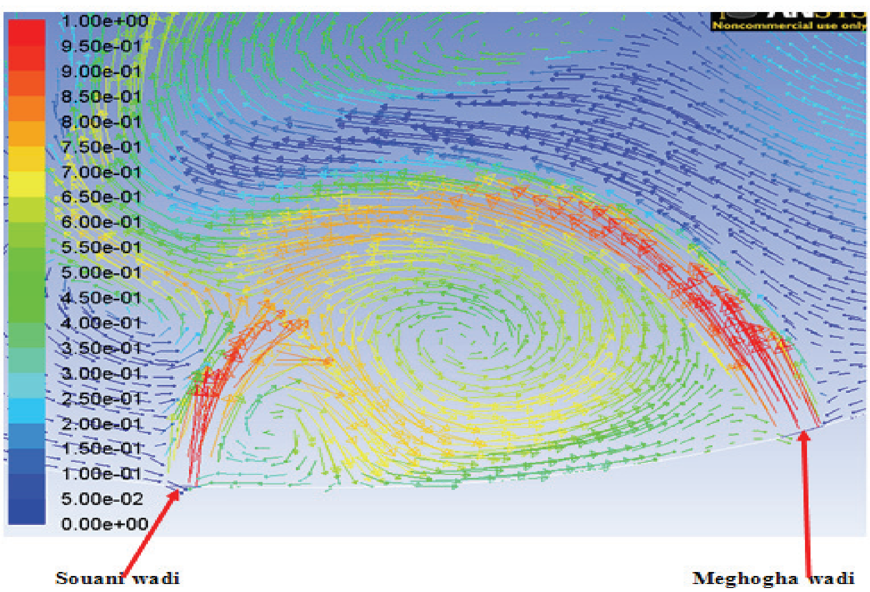

Figure 6: Velocity vectors colored by mass fraction of pollutant

Physically, this interaction is managed by the formation of vortex structures (Fig. 6) caused by high velocity gradients resulting from the inputs of the freshwater wadis. These gradients are an internal force on the water mass, mainly constituted by density differences associated with differences in salinity and temperature between the salt water of the bay and the fresh water of the discharges. These differences are reflected in the weight of the water column, and thus there is a higher pressure downstream than upstream. This pressure gradient causes a displacement of water masses from high pressure to low pressure areas.

Similarly, Figures 5a, b, c show this dispersion during the first low tide, 12 hours from the initial point. At the beginning of the low tide, the discharge dispersion from the wadis is no longer strongly constrained by the tidal currents because the flows arrive at a much higher speed than that of the tide. Hence the pollutant concentration is more important in the pollution area described previously.

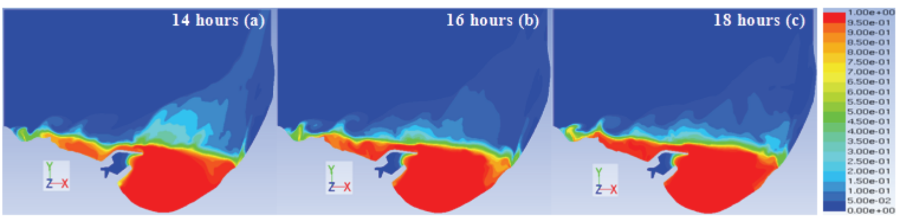

Figure 7: Pollutant concentration at the free surface during the second high tide: after 14 hours (a), 16 hours (b) and 18 hours (c)

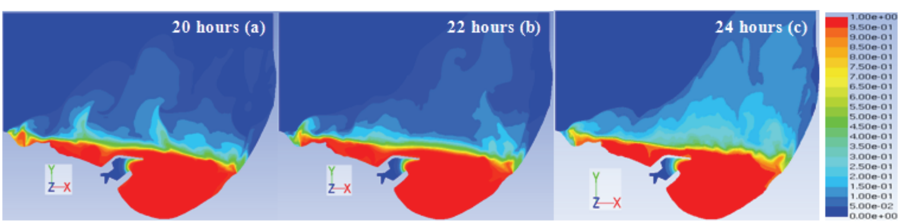

Figure 8: Pollutant concentration at the free surface during the second low tide: after 20 hours (a), 22 hours (b) and 24 hours (c)

On the return of the high tide (Fig. 7a, b, c), its currents curb the discharges to spread to the offshore of the bay and force them onto the coast. These high/low tidal currents push the water mass of discharges, causing it to flow into the port.

Once the low tide comes in with its low speed (0.77 m/s) compared with those of the different wadis (about 3m/s), the spread to the offshore is refreshed and again extends to the exit of the Mediterranean side (Fig. 8a, b, c). Over time, the pollution spread in the bay stabilizes. The flow is then established and the next low and high tides, 24 to 48 hours from the initial time, give approximately the same results and are not presented here. The only difference is the low and gradual pollution of the port because this region is not subjected to turbulent movements.

Figure 9 shows the temperature maps at the free surface of the sea 24 hours from the initial time. It can be seen that the thermal and pollutant dispersion are highly correlated to the flow movements explained above. There are also correlations between them, indicating that the diffusion processes are dominated by convective processes occurring from tidal movements and discharges from the wadis.

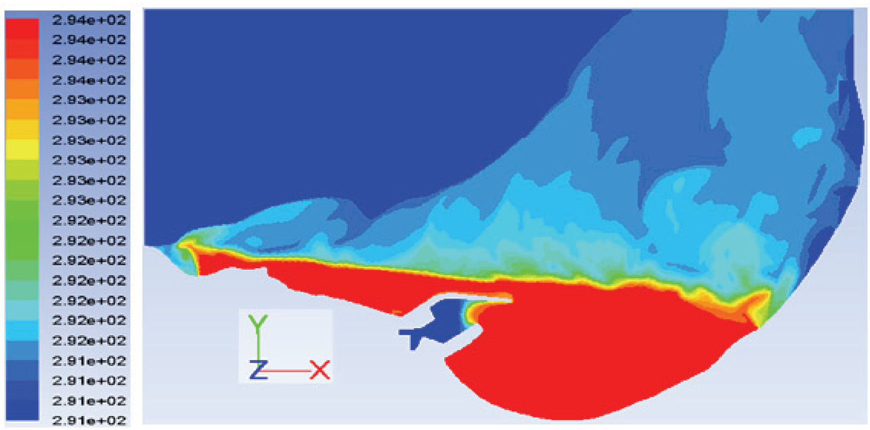

Figure 9: Temperature maps at the free surface of the bay after 24 hours

The numerical simulation describes the hydrodynamics of fresh water propagation from the wadis into the bay. In situ, these discharges contain a number of metals which are used in the industrial units located in the wadi basin slopes of the study zone. The distribution of these metals in the different points of the bay depends heavily on their physical, thermal and chemical properties, in particular the density and the diffusion coefficients.

Hence, the numerical results were qualitatively validated by assimilation with those of the geochemical studies of sea water samples and surface sediments of Tangier bay and its continental emissaries [El Arrim (2001, 2002 &2003), El Hatimi (2002 & 2003), Amendis (2003 & 2005)]. In this paper we refer to the experimental results of a geochemical study about metallic pollution affecting the Bay of Tangier

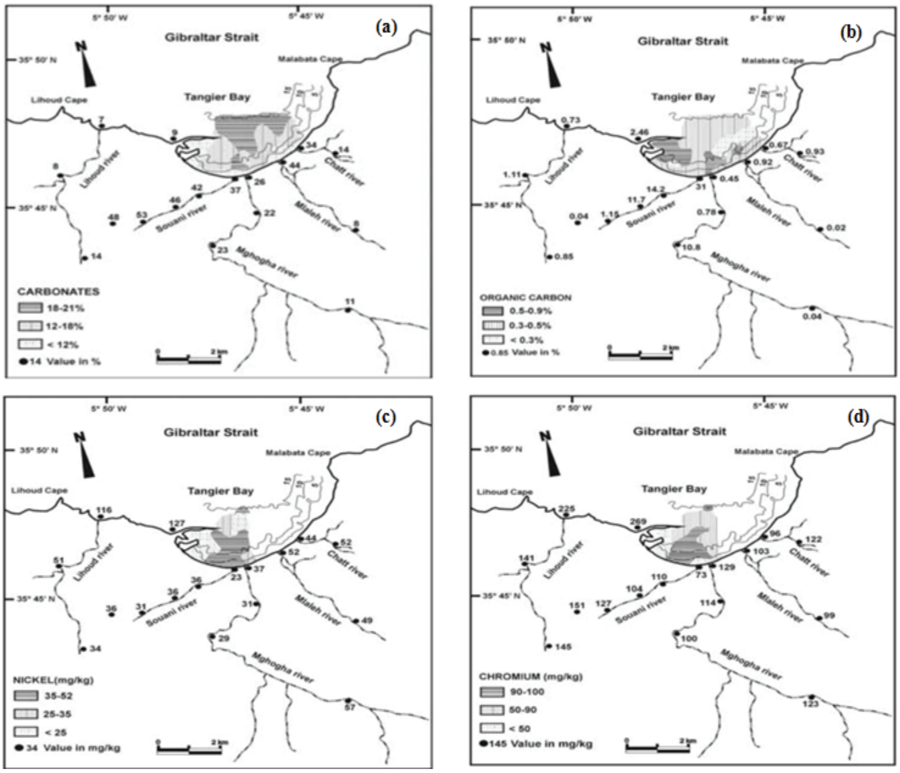

Figure 10: Distribution map of Carbonates contents (a), Organic carbon contents (b), Nickel contents (c) and Chromium contents (d) [Achab and Al. (2007)]

and its continental emissaries [Achab and Al. (2007)], whose principal objective was to evaluate the state of contamination by heavy metals of surface sediments in the Bay of Tangier and its continental emissaries, and to determine their space-time variations.

The comparison shows a good agreement between numerical simulations determining areas affected by discharges and experiment analysis indicating the distribution expressed in mg/Kg of different metals loaded with freshwater exiting from wadis (specially Souani and Meghoga) to the bay (Fig. 10a, b, c,d).

Another validation was done referring to a SPOT XS image [El Abdellaoui (2004)]. The comparison showed an interesting agreement between numerical simulation turbid freshwater flow from wadis into the bay and the same flow detected by SPOT XS imagery (Fig. 11).

On simulation, the turbid fresh water flow from wadis mouths arrives at a more

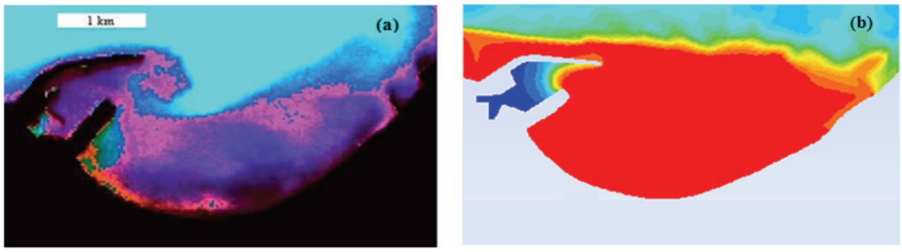

Figure 11: Concentration of turbid fresh water flow into the Tangier Bay, SPOT XS imagery (a), Numerical simulation by Fluent (b) [El Abdellaoui (2004)]

important level within the bay by exceeding the port exit; This is because of the high flows wadis recorded during the rainy season (Winter 2002) adopted, where all the wadis mouths were open to evacuate water excess in the Tangier sewerage system. Although on the SPOT XS image; fresh water flow allows to the rainy season of 1998 where flows wadis are less important and the more high flows were those of Meghogha and Souani, while those of the others wadis and the largest pipeline of Tangier city are low, ie negligible.

5 Conclusion

The results of this study are consistent with the findings of a number of physicochemical and sedimentological studies [Hatimi, Achab and EL Moumni (2002)] which show that pollution in this area is mainly due to discharges from the wadis, the affected areas being identical to those of the current study. This confirms the preponderance of the mechanisms of ebb and flow in the process of spreading pollution, and that is why it is necessary to model these mechanisms as precisely as possible.

The dispersion of pollutants is important, especially during the low tide, owing to the ocean current that takes particulate pollutants into the interior of the strait. This pollution spreads throughout the entire bay and extends along the coast. In the summer period, when rivers are lower, the results show that pollution is less intense than in the winter period. This is mainly due to the ocean currents that prevent the spread offshore. Note that the 3D modelling gives significantly different results compared to 2D modelling [Belcaid (2009)], suggesting greater pollution. Although approximations were made in terms of bathymetry, the results were confirmed by measurement campaigns carried out by a registered inspector on the quality of seawater and, in recent years, swimming has been prohibited in the Bay of Tangier.

To improve the model, the effect of wind will be applied on the free surface and more accurate bathymetric data will be introduced. In this new 3D model, we expect to achieve depth sections in wadis in order to draw curves mapping pollutant concentrations and temperature. This will allow us to describe more accurately the state of pollution in the Bay of Tangier.

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