Numerical Modelling of Turbulent Coastal Processes

LALE BALAS, ALP KÜÇÜKOSMANOĞLU
Civil Engineering Department
Gazi University
Faculty of Engineering and Architecture, Maltepe, 06570, Ankara
TURKEY
http://www.mmf.gazi.edu.tr/insaat/hocalar/lalebalas.htm

Abstract: A numerical model HYDROTAM-3, is developed that simulates turbulent coastal transport processes due to tidal or nontidal forcing. Model includes four sub model components; hydrodynamic, turbulence, salinity and temperature transport, suspended sediment transport. The only simplifying assumption used in the model is Boussinesq approximation, i.e. the density differences are neglected unless the differences are multiplied by the gravity. It is a composite finite difference finite element model. Model has been applied to Fethiye Bay located at the Mediterrenean Sea. At three Stations in the Bay, continuous measurements of velocity throughout the water depth and water level, were taken for 27 days. Model well simulates the measurements.

Key-Words: 3-D modeling, hydrodynamics, transport, sediment, coastal, finite difference, finite element.

1 Introduction

The activities around enclosed or semi-enclosed coastal areas that have limited water exchange should be carefully planned and detailed researches to understand water circulations and transport processes should be performed. Since field measurements are usually costly and some times impossible due to physical inabilities, application of numerical models becomes more and more important in the simulations of coastal water bodies. Use of three-dimensional models is unavoidable in all cases where the influence of density distribution, or the vertical velocity variations can not be neglected and in the simulation of wind induced circulation [1],[2],[3]. The detailed knowledge of the water motion is very crucial for a reliable prediction of suspended sediment transport [4],[5].

An unsteady three-dimensional baroclinic circulation model ((HYDROTAM-3) has been developed to simulate the transport processes in coastal water bodies[6],[7],[8]. The model consists of four components: hydrodynamic, turbulence, salinity and temperature transport and suspended sediment transport models. Sediment model component is able to predict the distribution of suspended sediments and the locations of erosion and re-suspension.

2 Theory

The governing model equations in the three dimensional Cartesian coordinate system are as follows:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=fv-\frac{1}{\rho_o}\frac{\partial p}{\partial x}+2\frac{\partial}{\partial x}(\nu_x\frac{\partial u}{\partial x})$$
$$+\frac{\partial}{\partial y}(\nu_y(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}))+\frac{\partial}{\partial z}(\nu_z\frac{\partial u}{\partial z}) \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-fu-\frac{1}{\rho_o}\frac{\partial p}{\partial y}+2\frac{\partial}{\partial y}(\nu_y\frac{\partial v}{\partial y})$$
$$+\frac{\partial}{\partial x}(\nu_x(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}))+\frac{\partial}{\partial z}(\nu_z\frac{\partial v}{\partial z}) \tag{3}$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho_o}\frac{\partial p}{\partial z}-g+\frac{\partial}{\partial y}(\nu_y(\frac{\partial w}{\partial y}+\frac{\partial v}{\partial z}))$$
$$+\frac{\partial}{\partial x}(\nu_x(\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z}))+\frac{\partial}{\partial z}(\nu_z\frac{\partial w}{\partial z}) \tag{4}$$

where, x,y: Horizontal coordinates; z: Vertical coordinate; t: Time; u,v,w: Velocity components in x,y,z directions at any grid locations in space; ν_x, ν_y, ν_z: Eddy viscosity coefficients in x,y and z directions, respectively; f: Coriolis coefficient; $\rho(x,y,z,t)$: In situ water density; ρ_o: Reference density; g: Gravitational acceleration; p: Pressure.

The numerical model includes thermohaline forcing. Temperature and salinity variations are calculated by solving the three dimensional convection-diffusion equation which is written as:

$$\frac{\partial Q}{\partial t}+u\frac{\partial Q}{\partial x}+v\frac{\partial Q}{\partial y}+w\frac{\partial Q}{\partial z}=\frac{\partial}{\partial x}\left(D_x\frac{\partial Q}{\partial x}\right)+\frac{\partial}{\partial x}\left(D_y\frac{\partial Q}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_z\frac{\partial Q}{\partial z}\right) \tag{5}$$

where, D_x,D_y and D_z : Turbulent diffusion coefficient in x,y and z directions respectively; Q: Temperature (T) or salinity (S).

The three dimensional conservation equation for suspended sediment where the vertical advection includes the particle settling velocity can be written as:

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}+w\frac{\partial C}{\partial z}-w_s\frac{\partial C}{\partial z}=\frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial x}\left(D_y\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_z\frac{\partial C}{\partial z}\right) \tag{6}$$

where C: Suspended sediment concentration; w_s: Settling velocity.

The settling velocity is calculated by;

$$w_f=10\frac{\nu}{D_s}\left\{\left[1+\frac{0.01(s-1)gD_s^3}{\nu^2}\right]^{0.5}-1\right\} \tag{7}$$

Where ν: viscosity of water, s: ratio of densities of sediment particles and water $\left(s=\frac{\rho_{askı}}{\rho_{su}}\right)$, D_s: representative particle diameter.

The two equation k-ε turbulence model is used for the turbulence modelling [6],[7]. To consider the large scale turbulence caused by the horizontal shear, horizontal eddy viscosity is simulated by the Smagorinsky algebraic subgrid scale turbulence model :

$$\nu_h=0.01\,\Delta x\,\Delta y\sqrt{\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2+\frac{1}{2}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial y}\right)^2} \tag{8}$$

Horizontal eddy diffusivities are approximately equal to the horizontal eddy viscosities. On the other hand, the vertical diffusivity, D_z, is expressed as:

$$D_z=\frac{\nu_z}{P_r} \tag{9}$$

where, P_r is the turbulent Prandtl or Schmidth number and ν_z is the vertical eddy viscosity coefficient.

Solution scheme is a composite finite element-finite difference scheme [6]. The governing equations are solved by Galerkin Weighted Residual Method in the vertical plane and by finite difference approximations in the horizontal plane, without any coordinate transformation. The water depths are divided into the same number of layers following the bottom topography. So, the vertical layer thickness is proportional to the local water depth.

3 Model Application to Fethiye Bay

Developed three dimensional numerical model (HYROTAM-3) has been implemented to Bay of Fethiye. Water depths in the Bay are plotted in Fig.1. The grid system used has a square mesh size of 100x100 m. Wind characteristics are obtained from the measurements of the meteorological station in Fethiye for the period of 1980-2002. The wind analysis shows that the critical wind direction for wind speeds more than 7 m/s, is WNW-WSW direction.

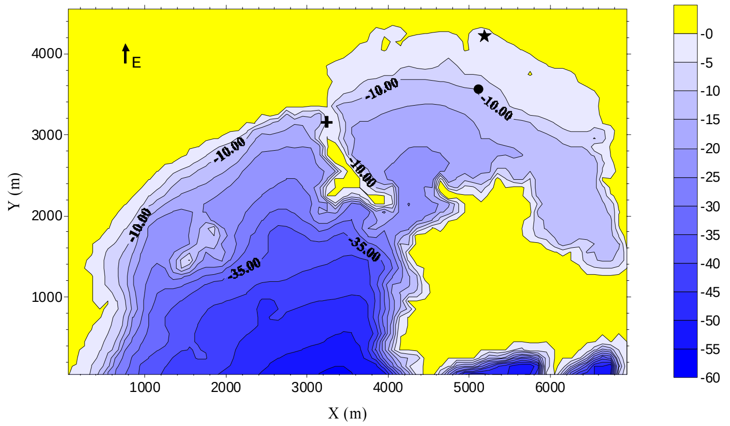


Fig.1. Water depths of Fethiye Bay where +:Station I, •:Station II,∗ : Station III .

Some field measurements have been performed in the area. The current pattern over the area is observed by tracking drogues, which are moved by currents at the water depths of 1 m., 5 m and 10 m.. At Station I and at Station II shown in Fig.1, continuous velocity measurements throughout water depth, at Station III water level measurements were taken for 27 days. A sensitivity study of model predictions to bottom friction coefficient is performed and C_f=0.0026 provided the best match with the measurements. In the application measurement period has been simulated and model is forced by the recorded wind as shown in Fig. 2.

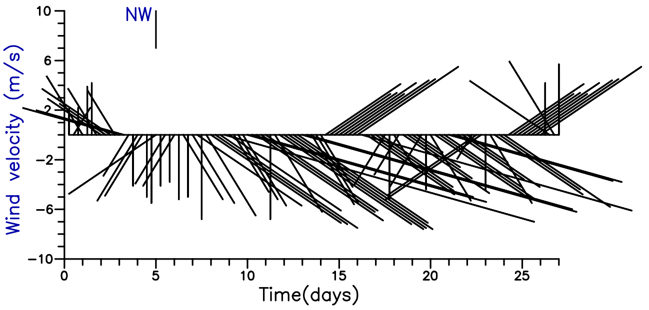


Fig. 2. Wind speeds and directions during the measurement period.

No significant density stratification was recorded at the site. Therefore water density is taken as a constant. A horizontal grid spacing of $\Delta x = \Delta y = 100$ m. is used. Horizontal eddy viscosities are calculated by the sub-grid scale turbulence model and the vertical eddy viscosity is calculated by k-ε turbulence model. The sea bottom is treated as a rigid boundary. Model predictions are in good agreement with the measurements. Simulated change of water level at Station III throughout the measurement period is depicted in Fig. 3 and compared with the measurements. Root mean square error in the water level is 2.235 cm and bias is 0.0178 cm. Flow pattern at the surface and near the bottom at the end of 8.5 days of simulation are sketched in Fig. 4. Simulated velocity profiles over the depth at the end of 8.5 days are compared with the measurements taken at Station I and Station II and are shown in Fig.5.

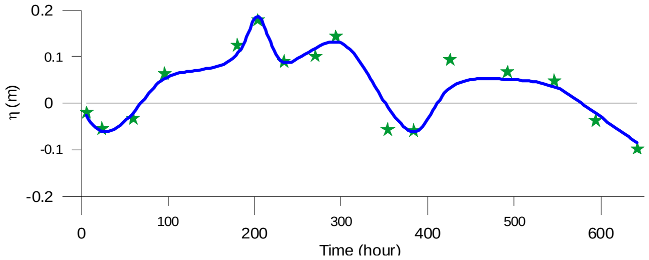
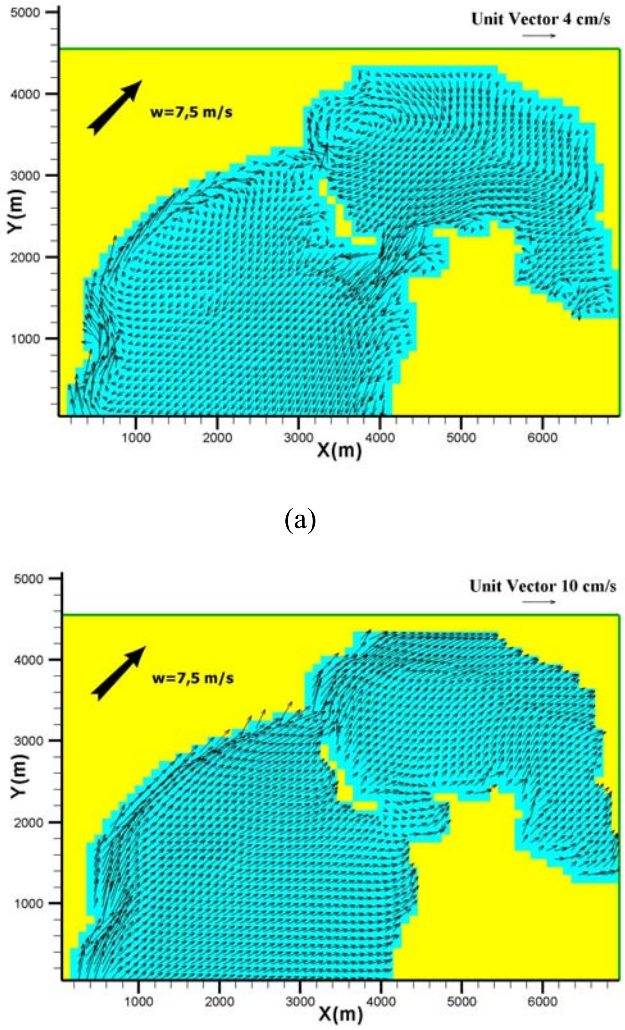


Fig.3. Water level change at Station II (line:model predictions;*:measurements)

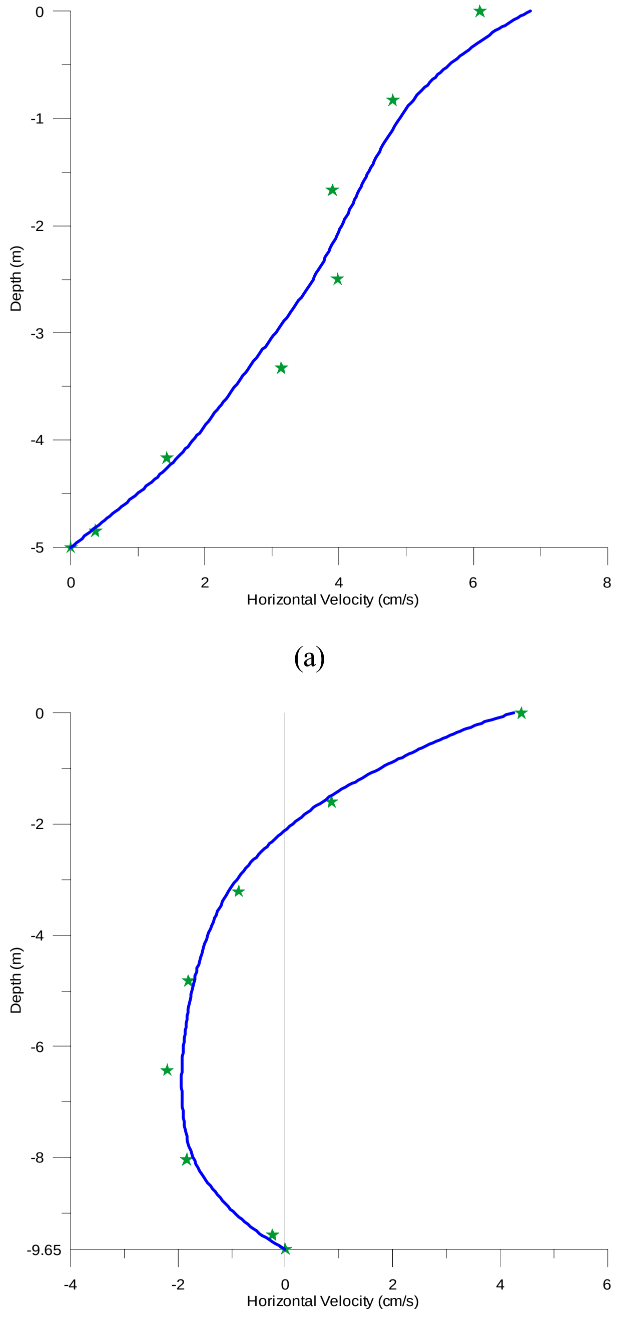
At the end of 8.5 days of simulation, for Station I, the root mean square error is 0.417 cm/s and bias is –0.095 cm/s. and for Station II, the root mean square error is 0.182 cm/s and bias is –0.027 cm/s. Comparison of results is encouraging. Model well simulates the measurement period.



(a)

(b)

Fig. 4. Current pattern at the end of 8.5 days of simulation a) near the bottom b) at the surface.

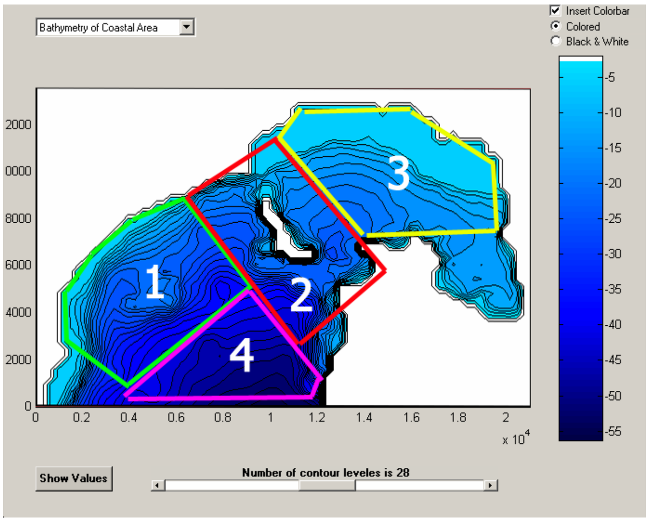


(a)

(b)

Fig. 5. Velocity profiles over the water depth at the end of 8.5 days of simulation, at Station I b) at Station II where solid line: simulation,

Fethiye Bay has been divided into four main regions with respect to sediment transport based on site investigations (Fig.6). In Region I sediment deposition occurs and Region II is the region where suspended sediment concentration is the highest. Region III and Region IV are rather dynamic regions that depending on blowing wind direction there may occur sediment deposition or resuspension. Predicted sediment distributions in the Bay are given in Fig.7. and Fig. 8 at the end of 8.5 and 15 days of simulation, respectively.


Bathymetry of Coastal Area

☑ Insert Colorbar
● Colored
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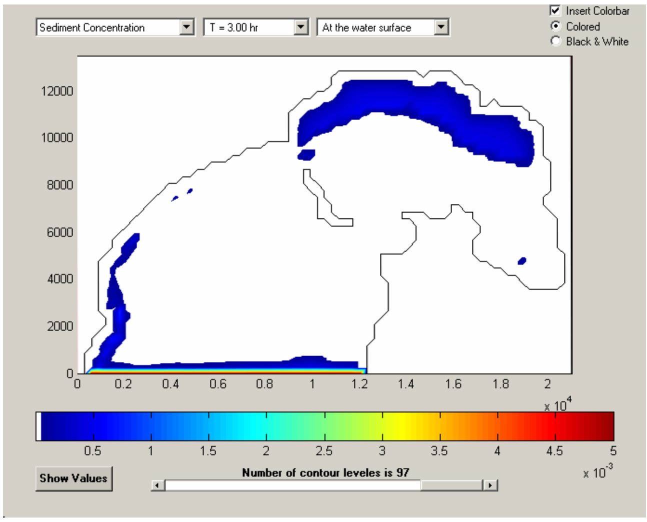
Number of contour leveles is 28

Fig.6. Suspended sediment transport regions in Fethiye Bay


Sediment Concentration

T = 3.00 hr

At the water surface

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Number of contour leveles is 97

Fig.7.a. Distribution of suspended sediment concentration at the end of 8.5 days of simulation at the sea surface.

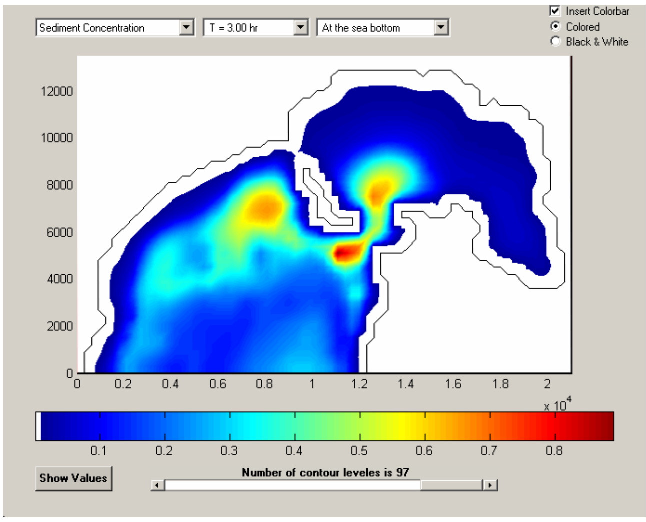

Fig.7b. Distribution of suspended sediment concentration at the end of 8.5 days of simulation at the sea bottom.

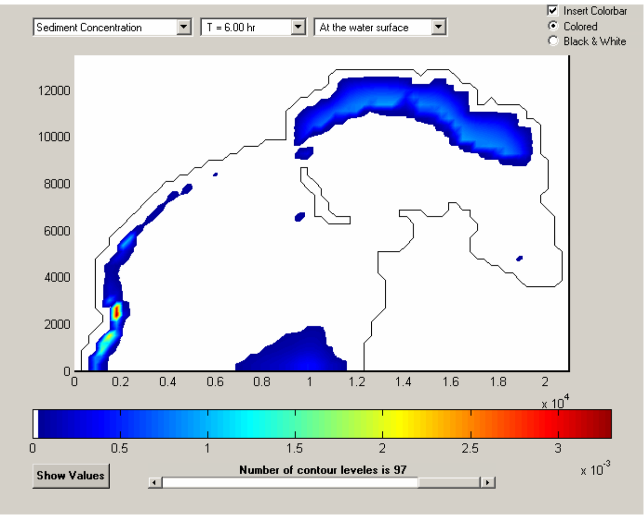

Fig. 8a. Distribution of suspended sediment concentration at the end of 15 days of simulation at the sea surface.

(a)

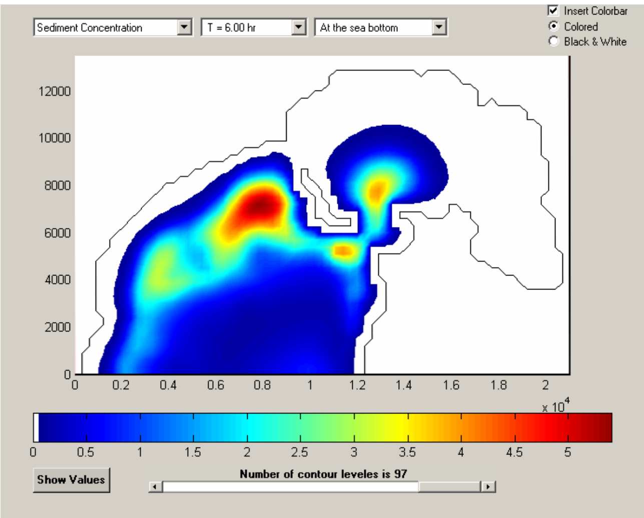

Fig. 8b. Distribution of suspended sediment concentration at the end of 15 days of simulation at the sea bottom.

Model simulations well agree to the observed regions at the site. Regions I and II have been correctly predicted by the model. Sediment sampling studies are still in continuation at the site.

4 Conclusions

A baroclinic three dimensional numerical model of transport processes in coastal areas has been presented. The model consists of four components; hydrodynamic, turbulence, salinity and temperature transport and suspended sediment transport. The developed model is able to predict suspended sediment concentration profiles, re-suspension of bottom sediments, equilibrium and deposition sites of the coastal area and determines changes in sea bed morphology quantitatively. Model has been applied to Fethiye Bay where there exist some field measurements. Model implementation to Fethiye Bay has provided realistic results and has shown the capability of model to predict complex circulation patterns. Model needs to be further verified by appropriate sediment sampling and concentration measurements, since the parameters that show the effect of settling velocity and bed roughness coefficient can strongly vary in time and space.

References:

[1] Olsen, N. R. B., Two-dimensional numerical modelling of flushing processes in water reservoirs, Journal of Hydraulic Research,Vol 37, No 1, 1999, pp. 3-16.

[2] Inoue, M., Wiseman Jr. W. J., Transport mixing and stirring processes in a Louisiana Estuary: a model study, Estuarine Coastal and Shelf Science, Vol. 50, 2000, pp. 449-466.

[3] Li,C.W, Gu, J., 3D Layered-Integrated Modelling of Mass Exchange in Semi-Enclosed Water Bodies, Journal of Hydraulic Research, Vol. 39, 2001,pp. 403-411.

[4] Lin, B., Falconer, R.A., Tidal Flow and Transport Modelling Using Ultimate Quickest Scheme. Journal of Hydraulic Engineering, Vol. 123, 1997,pp. 303-314.

[5] Garcia-Martinez, R., Saavedra, C. I., De Power B. F., Valera E., A two-dimensional computation model to simulate suspended sediment transport and bed changes, Journal of Hydraulic Research Vol.37,1999,pp. 327-344 .

[6] Balas, L., Özhan, E., An implicit three dimensional numerical model to simulate transport processes in coastal water bodies, Int.Journal of Numerical Methods in Fluids, Vol. 34, 2000, pp.307-339.

[8] Balas, L., Özhan, E., Applications of a 3-D Numerical Model to Circulations in Coastal Waters, Coastal Engineering Journal, Vol. 43, 2001, pp. 99-120.

[7] Balas, L.,Simulation of Pollutant Transport in Marmaris Bay, Chineese Ocean Engineering Journal, Vol.15, 2001, pp. 565-578.