3-D simulation flow pattern in the Gorgan Bay in during summer

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ABSTRACT
The main purpose of this investigation is three dimensional modeling of currents in the Gorgan Bay using MIKE 3 Flow Model in duration summer 2010. The model is based on the numerical solution of the three-dimensional Reynolds-averaged Navier-Stokes equations, invoking the hypothesis of hydrostatic pressure in the vertical direction. Water level fluctuations in the Ashoorade station as open boundary conditions are imposed to the model as well as wind stress as a constant in space but varying in time, mean daily discharge of Qarahsoo river, evaporation, Coriolis force, bed resistance and effects of inflow and outflow of the Khozeini waterway. Horizontal diffusion is calculated using the Smagorinsky formulation and a $k-\varepsilon$ turbulence model is used in the vertical. The grid cell used in computations was equal to 150×150 meters, 6 layers with vertical grid spacing 1 meter and time step interval 60 second. In this study, according to measurement data, the buoyancy effect in the Gorgan Bay has no great influence and stability factor is positive (E>0). The simulations show that the wind-induced flow creates strong currents near the coastal area and along with coastal area from west to east. Totally all the layers, the flow patterns in the Gorgan Bay are influenced by prevailing winds. Depending on the winds regime, speed and direction of the current vary in the Gorgan Bay. The bottom topography and domain geometry have an important role in forming anticlockwise circulation in the Gorgan Bay. The current velocity values in the bay are mostly affected by prevailing winds. Strong currents are also created at the Ashoradeh-Bandartorkaman mouth affected by storm surge or inter annual water level fluctuations in the Caspian Sea.

Keywords - **Flow Pattern, Gorgan Bay, 3-D Simulation, MIKE 3.**

I. INTRODUCTION
The Gorgan Bay with 400 km^2, 60 km length, average width 12 km, maximum depth of 6.5 m and average depth 1.5 m is located at the south-east extremity of the Caspian Sea along Iranian coastline in the Golestan province [2- 11]. That is a semi-confined triangular-shaped that formed during the Newcaspian /Holocene period [15]. This bay plays a substantial hydrological and ecological role in the functioning of the coastal systems of the southeast Caspian [7]. The Gorgan Bay is not a tidal zone. There is only one connection way between the Caspian Sea and bay through mouth of Ashoradeh-Bandartorkaman situated northeastern part of the Gorgan Bay (Approximately; width of 400 m, 3 km long, mean depth of 1.5 m) where intensive water exchange takes place influencing storm surge and inter annual fluctuations in the Caspian Sea. However, this connection is such that the energy of hydrodynamic processes (especially Waves energy) of the Caspian Sea does not receive enough by the Gorgan bay [8].The Khozeini waterway is a seasonal narrow and second connection way to the Caspian Sea. But this waterway has not permanent communication with the sea. This bay more influenced by its processes within the basin. Water balance in the Gorgan Bay is influenced by water intrusion from the Caspian Sea, precipitation, evaporation and a lesser extent by fresh river water. It receives freshwater inflow from a number of small rivers and streams rising on the humid north slope of the Alborz Mountains to the south [10]. But among them, the Qarahsoo river is the only important fresh water source flowing into the bay. Our knowledge about the hydrodynamic regime in the Gorgan bay is fairly poor. The limited number of studies and projects were done on the Gorgan bay. But these investigations did not consider the three dimensional current structure and variations of flow patterns due to some factors such as water level fluctuations in the Ashoradeh-Bandartorkaman mouth, effecting of Khozeini waterway and variations of wind pattern in long term period. In order to better understanding hydrodynamic regime in the Gorgan Bay, we simulated three dimensional flow patterns using MIKE 3 HD duration summer 2010. So this research may be useful for any future studies, the hydrodynamic parameters specified for the simulations are detailed as well as the problems that have occurred during this period.

II. Model Description, Main Equations and Numerical Formulation

The hydrostatic (HS) model in MIKE 3 HD is a general numerical modeling system for simulation of unsteady three-dimensional flow in estuaries, bays and coastal areas as well as in lakes and oceans. It simulates flows taking into account bathymetry and external forcing such as meteorology, tidal elevations, currents and other hydrographic conditions [3]. The mathematical foundation for the standard MIKE 3 HD engine is the mass equation and the Reynolds-averaged Navier-Stokes equation, including an artificial compressibility (ACM) due to the chosen numerical solution procedure. The hydrodynamic module of MIKE 3 makes use of the so-called Alternating Direction Implicit technique to integrate the equations for mass and momentum conservation in the space-time domain. The equation matrices, which result for each direction and each individual grid line, are solved by Double Sweep algorithm. These equations read [5] (only X-direction is shown for 2nd equation):

$$\frac{1}{\rho c_s^2}\frac{\partial P}{\partial t}+\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=S_{MASS} \qquad (1)$$

$$\frac{\partial u}{\partial t}+\frac{\partial uu}{\partial x}+\frac{\partial uv}{\partial y}+\frac{\partial uw}{\partial z}+ 2\omega\left(-v\sin(\phi)+w\sin(\phi)\sin(\lambda)\right)= -\frac{1}{\rho}\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}(2\upsilon_t\frac{\partial u}{\partial x})+\frac{\partial}{\partial y}\left(\upsilon_t(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x})\right)+ \frac{\partial}{\partial z}\left(\upsilon_t(\frac{\partial u}{\partial z}+\frac{\partial v}{\partial z})\right)+u_{ss}S_{MASS} \qquad (2)$$

Where

ρ Density

c_s Speed of sound in water

u,v,w Velocities in x,y,z directions

ω Coriolis parameter

ϕ,λ Latitude, Longitude

υ_t Turbulent eddy viscosity

S_{MASS} Source/sink term with

$$S_{MASS}=\sum_{i_s=1}^{N_s}\delta(x-x_{s,i_s},y-y_{s,i_s},z-z_{s,i_s})Q_{s,i_s}$$

δ Delta function of source/sink coordinates m^{-3}

$x_{s,i_s},y_{s,i_s},z_{s,i_s}$ Coordinates of source/sink NO. i_s

Q_{s,i_s} Discharge at source/sink NO. i_s, m^3/s

The differences between MIKE 3 HS and MIKE 3 ACM are:

A hydrostatic pressure assumption is applied, i.e. the vertical accelerations are assumed to be negligible. The vertical velocity w is assumed negligible, resulting in the removal of the secondary Coriolis term and the last diffusion term. The pressure is split up into two parts, the external pressure and the internal pressure. The external pressure is directly linked to the free surface, and the internal pressure is due to the density differences. The fluid is assumed incompressible, as opposed to the standard version of MIKE 3 HD. Consequently, the compressibility term in the mass equations is discarded.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=S_{MASS} \qquad (3)$$

$$\frac{\partial u}{\partial t}+\frac{\partial uu}{\partial x}+\frac{\partial uv}{\partial y}+\frac{\partial uw}{\partial z}-2\omega v\sin(\phi)= -\frac{1}{\rho}\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}(2\upsilon_t\frac{\partial u}{\partial x})+\frac{\partial}{\partial y}\left(\upsilon_t(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x})\right)+ \frac{\partial}{\partial z}\left(\upsilon_t(\frac{\partial u}{\partial z})\right)+u_{ss}S_{MASS} \qquad (4)$$

The external/internal pressure gradient force is given by:

$$\frac{1}{\rho}\frac{\partial P}{\partial x}=g\frac{\rho(\zeta)}{\rho}\frac{\partial \zeta}{\partial x}+\frac{g}{\rho}\int_z^{\zeta}\frac{\partial \rho}{\partial x}dz \qquad (5)$$

Where

g Acceleration due to gravity

ζ Surface elevation

In the ACM version of MIKE 3, the top horizontal layer containing the free surface is solved separately from, but not independently of, the underlying cells. The top layer is layer-integrated as opposed to the underlying cells. In the hydrostatic version of MIKE 3, the equations to be solved are in their layer-integrated form for both the top layer and the underlying cells. This is due to the solution procedure, where it is convenient to have the same formulation for all cells in each water column. Assuming that the horizontal velocities are constant over the layer thickness. The layer-integrated form of (3)-(4), with the pressure gradient force inserted, is:

$$\frac{\partial uh}{\partial x}+\frac{\partial vh}{\partial y}+w_{top}-w_{bot}=P-E +\sum_{i_s}\delta(x-x_{s,i_s},y-y_{s,i_s})Q_{s,i_s} \qquad (6)$$

$$\frac{\partial uh}{\partial t}+\frac{\partial uuh}{\partial x}+\frac{\partial uvh}{\partial y}+(uw)_{top}-(uw)_{bot}$$
$$-2\omega vh\sin(\phi)=-gh\frac{\partial\zeta}{\partial x}-\frac{g}{\rho}\int_{layer}\left(\int_{z'}^{\zeta}\frac{\partial\rho}{\partial x}dz'\right)dz$$
$$+\frac{\partial}{\partial x}\left(2\upsilon_t h\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}(\upsilon_t h\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right))+\upsilon_t(\frac{\partial u}{\partial z})_{top}$$
$$-\upsilon_t((\frac{\partial u}{\partial z})_{bot}+u_{ss}\sum_{i_s}\delta(x-x_{s,i_s},y-y_{s,i_s})Q_{s,i_s} \quad (7)$$

Where the sums represent all point source/sink in the considered layer, and precipitation and evaporation terms, P and E (m/s), have been expluded from the sum. The precipitation and evaporation terms is only included if the considered layer is the surface layer. The depth-integrated version of (6) is:

$$\frac{\partial\zeta}{\partial t}+\frac{\partial UH}{\partial X}+\frac{\partial VH}{\partial Y}=P-E$$
$$+\sum_{i_s}\delta(X-X_{s.i_s},Y-Y_{s.i_s})Q_{s.i_s} \quad (8)$$

With sum over all point source/sinks.
The turbulence is modeled in terms of an Eddy Viscosity and a bed shear stress. In this study, we used mixed 1D $-\varepsilon$, 2D Smagorinsky Turbulence model for determined horizontal and vertical eddy viscosity. The horizontal eddy viscosity is determined by Smagorinsky formula [12].

$$\upsilon_T=L^2\sqrt{S_{ij}.S_{ji}} \quad (9)$$

$$S_{ij}=\frac{1}{2}(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}) \quad (10)$$

u_i Are the velocity components in the x_i-directions. L Is a length scale and for the vertical direction, a 1D $k-\varepsilon$ model is applied.

$$\upsilon_T=C_\mu\frac{k^2}{\varepsilon} \quad (11)$$

k The turbulent kinetic energy
ε The dissipation rate of turbulent kinetic energy
C_μ Is an empirical constant
The bed stress is specified in terms of a drag coefficient formulation according to the relation,

$$\frac{\tau_{bottom}}{\rho}=C_D u^*\left|u^*\right| \quad (12)$$

τ_{bottom} Is the bottom shear stress
u^* The first computational speed encountered above the bottom.
C_D Is the drag coefficient.
When using the mixed 1D $-\varepsilon$, 2D Smagorinsky closure model, the bed drag coefficient reads

$$C_D=\left[\frac{k(1-\frac{K_s}{30Z_b})}{\log(\frac{30Z_b}{K_s})-(1-\frac{K_s}{30Z_b})}\right] \quad (13)$$

Z_b Is the vertical extent of the bottom grid cell
K Is von karmans constant
c_s Is bed roughness length scale

Temperature and salinity are two properties of marine waters. Together, they govern the density of seawater. Surface seawater that is made denser by cooling and increased salinity, or mixing, sinks to depths where its density is equal to that of the surrounding water. The water then spreads horizontally over great distances, moving between waters of lesser density above and greater density below. It continues spreading outward at a very slow pace compared to surface currents as more water of the same density sinks from the surface [16]. The baroclinic effect by fresh river runoff on the saline water body of the Gorgan Bay can influence on the local zone. The Gorgan Bay has low salinity and it varies little with depth (approximately, 0.12 ppt). The temperature varies with depth only 1^{o}c. Sharp gradients of salinity and temperature occur near the mouths of rivers, mouth of Ashoradeh-Bandartorkaman and Khozeini waterway. Since salinity and temperature variations were not of concern in this study, density driven flow caused from buoyancy force was neglected. The magnitude of the buoyancy effect could be considerable (unstable, E<0) or inconsiderable (stable, E>0) by means of static stability factor [14]. According to measurement data, the density increases from the upper layer to the bottom layer. This yields a stable condition in the Gorgan Bay in which the stability factor is positive (E>0). It could be concluded that the buoyancy effect in the Gorgan Bay has no great influence on water movements in this study.

III. Model Set-Up

MIKE 3 is a finite difference model with constant grid spacing in x, y and z directions, and therefore model area has to be rectangular in horizontal plane. A Cartesian coordinate system was selected with x-axis = 50 km (in west-east direction) and y-axis =

15.45 km (in north-south direction), and the model domain was divided into 335 × 150 square grids with a grid size of 150 m. Before being used in the numerical model, the water depths were corrected to mean sea level from the chart datum. The numbers of vertical layers are 6 and vertical grid spacing is 1 meter. Estimated number of computational points was equaled 82651.in this study, due to 30 cm rising in water level of the Caspian Sea in recent years, this amount was added to all depths of the Gorgan Bay [1]. The Courant number represents stability of model problems. The Courant number, C_R is defined as follows:

$$C_R = c \times \frac{\Delta t}{\Delta x} \qquad (14)$$

Where Δt is the time step Δs is the grid spacing in one of the horizontal directions and c is the celerity of the barotropic wave given by:

$$c = \sqrt{g.h} \qquad (15)$$

As the barotropic information (about surface elevations and velocities) in the computational grid travels at a speed corresponding to the celerity, the Courant number actually expresses how many grid points the information moves in one time step [4]. For the model of Gorgan Bay, a grid spacing of 150 meters and time step of 60 second produced a max Courant number of 3.2. The measurements of water level by tide gauge in north of the open model boundary imposed on the model as a time series. For the sea surface boundary, 10 minute variations of wind data including speed and direction as varying with time but constant in space for the Gorgan Bay were gathered during summer 2010 from a meteorological station at the Bandartorkaman, located in the closest town to the bay (less than 2 km) (Figure 1).

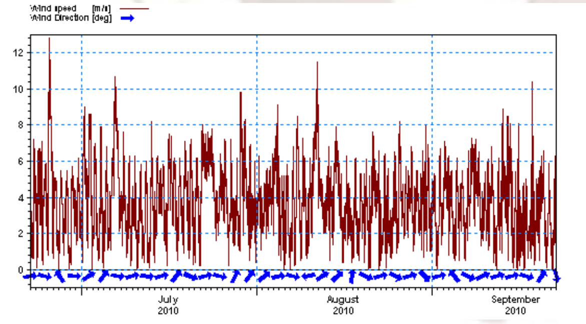

Figure 1. Summer wind speed and direction in the Gorgan Bay.

In broad terms, summer tends to be windier than other seasons, with fewer occurrences of calm periods and a slightly higher mean wind speed. During this season, winds come predominantly from the southwestern, western and northwestern quarters.

The driving force due to wind blowing is calculated from the following quadratic law:

$$f(v)\frac{\rho_{air}}{\rho_{water}}v^2 \qquad (16)$$

Where $f(v)$ is the wind friction coefficient, ρ is the density (the ratio equals 1/800) and v is the wind velocity in m/s 10 m above the sea surface. The wind friction in the sea surface is varying with wind speed, so in order to affect the wind friction factor with wind speed variation we used smith and banks formula [13]:

$$f(v) = \begin{cases} f_0 & for \quad v < v_0 \\ f_0 + \frac{v - v_0}{v_1 - v_0}(f_1 - f_0) & for \quad v_0 \le v \le v_1 \\ f_1 & for \quad v > v_1 \end{cases}$$

$$f_0 = 0.00013 \quad , \quad v_0 = 0 \quad m/s$$
$$f_1 = 0.0026 \quad , \quad v_1 = 30 \quad m/s \qquad (17)$$

Where

v_1, v, v_0 : Are wind speed

f_0, f_1 : Wind friction parameter

Daily mean evaporation and river runoff from Qarahsoo river utilizing as a source and sink parameters in the model. The Khozeini waterway is a seasonal narrow waterway that located in east part of Miankaleh peninsula and its water exchange dependent to water level in the Caspian Sea. This waterway is opened in warm season and water intrusion from the Caspian Sea to the bay (as a source term) but that closed in cold season and water go back to the Caspian Sea (as a sink term until it closed completely). In this investigation, by having maximal and minimal amounts of water level and canal topography, water exchange through waterway was considered as a linear series. The main parameters to adjust during the calibration phase were bed resistance, eddy viscosity, bathymetry, boundary conditions and wind friction [9].

IV. Discussion

Figures 2 to 7 show mean flow pattern and velocity distribution in the different layers in the Gorgan Bay. As seen in figure 2, generally the flow pattern in the surface layer is as an anticlockwise ring. This ring can be seen clearly in central part of the bay in the most time. In western part of the bay that is a shallow part of the bay, there is a small anticlockwise gyre. In the eastern part of the Gorgan Bay and in near parts of the mouth confusion can be seen. It seems that this confusion that is as a result of inflow of the mouth has an important role in forming an anticlockwise pattern in the central part of the bay. So that influenced by the prevailing wind in this season that is the west wind, currents flow along with coastal zone from west to east. After reaching to the east coast, affected by bottom topography in this part is going to be two branches, first branch along the east coast are going toward the mouth and another branch after affected by inflow currents from the mouth (confusion area) go back to the west and make an anticlockwise ring. Shore currents in the northern and southern coasts are along the coast and moving from west to east. But current velocity values in the southern coastal parts are stronger than northern coastal parts. Variations of mean currents velocity in this layer are from 0.01 m/s in middle part of the bay to 0.05 m/s in north and south coastal zone. At the far west part of the bay, because of depth reduction and take a distance from Ashoorade-bandartorkman mouth, current speed is so down. In northeast parts and near the month, current speed will be increase influenced by water intrusion from the Caspian Sea. Mean flow pattern and velocity distribution in second layers in the Gorgan Bay has same results as first layer (figure 3). Such that, an anticlockwise ring in central part of the bay influenced by prevailing wind and inflow of the Ashoradeh- Bandartorkaman mouth can be seen. There is also a small anticlockwise gyre in western part of the bay. It seems that, current speed in central part of the bay is a little stronger than first layer, so that in this area currents with speed of 0.03 m/s can be seen. Mean current speed in this layer is about 0.03 to 0.04 m/s. Velocity values in southern parts are more than northern parts. In third layer (figure 4) that is including the depth with more than 3 meter, an anticlockwise ring with mean current speed of 0.01 to 0.02 m/s is found. Due to the impossibility of observed depths below 3 meter in the western part of the bay in this layer, formation of an anticlockwise gyre starting to appear in this part. Confusion caused by inflowing water from the only open boundary of the model in the near part to the mouth is observable so good. The fourth layer that is characterized in that by the depth of more than 4 meter, only an anticlockwise ring in central part of the bay can be seen. Mean velocity values this part in this layer varying from 0.01 to 0.03 m/s (figure 5). Generally, current speed increasing in middle layers in comparing to upper layers. this subject is approximately consistent to data mesurments in summer 2002 [6]. In most parts of the fifth layer with depth of more than 5 meter, velocity distribution is about 0.03 m/s (figure 6). In the sixth layer that is included the deepest part of the bay with depth of 6 meter, current with speed of 0.03 m/s is found and are from east to west (figure7). Water exchange through Khozeini waterway and river runoff from Qarahsoo river have not effective role on the flow.

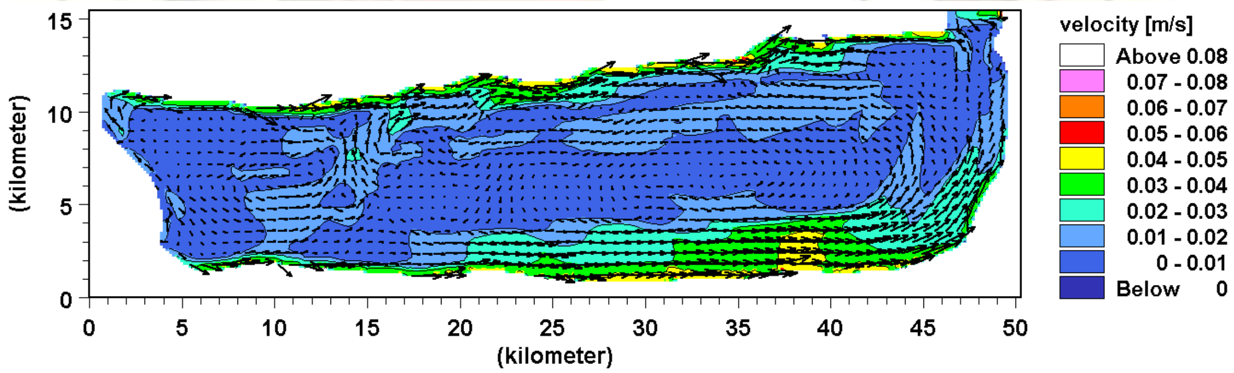

Fig 2. Mean Velocity Distribution in First layer

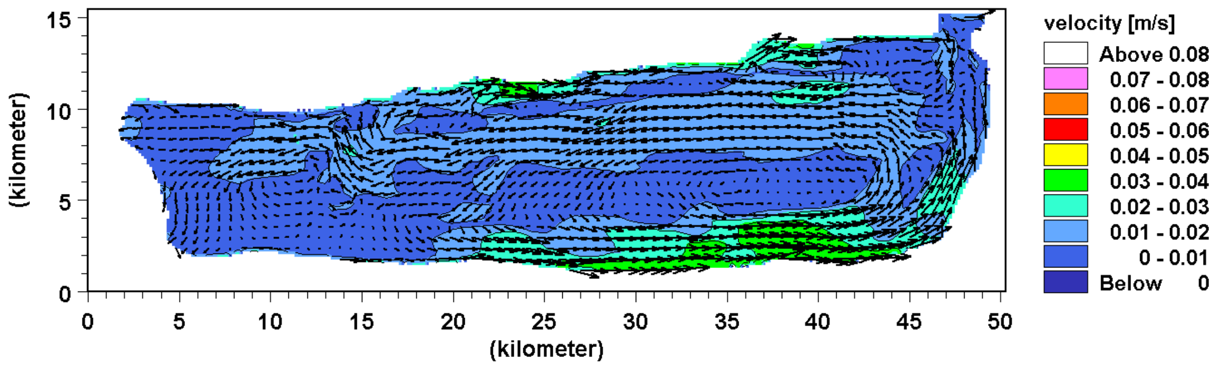

Fig 3. Mean Velocity Distribution in 2 layer

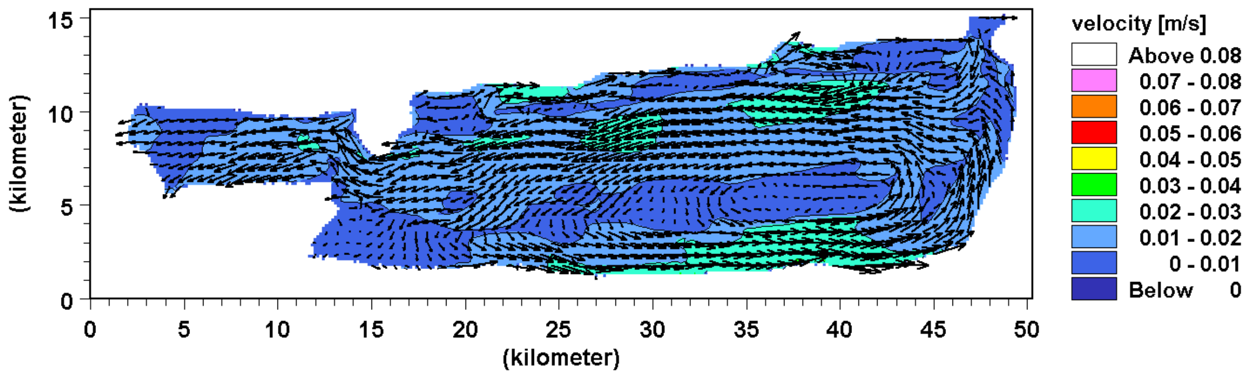

Fig 4. Mean Velocity Distribution in 3 layer

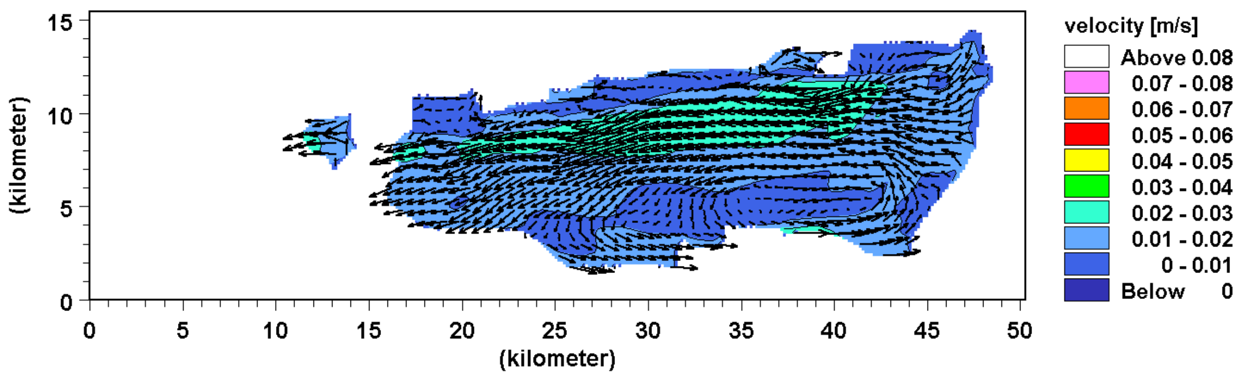

Fig 5. Mean Velocity Distribution in 4 layer

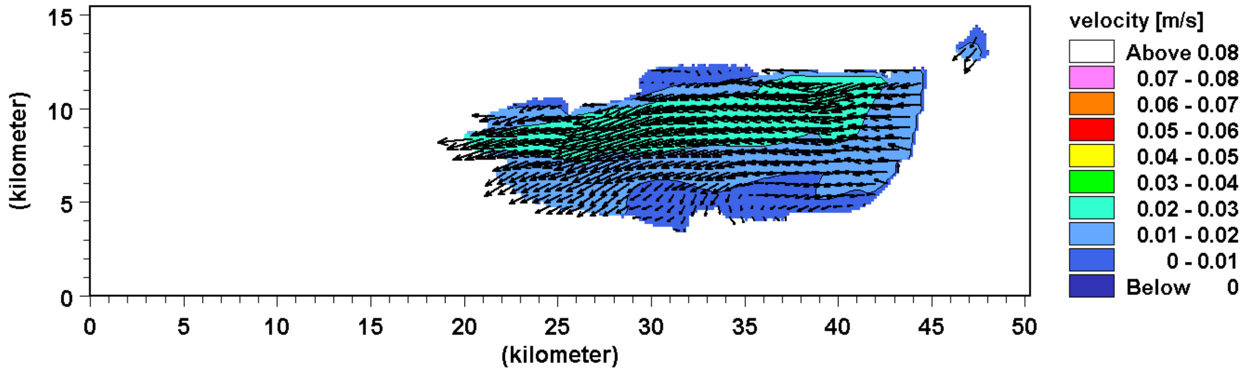

Fig 6. Mean Velocity Distribution in 5 layer

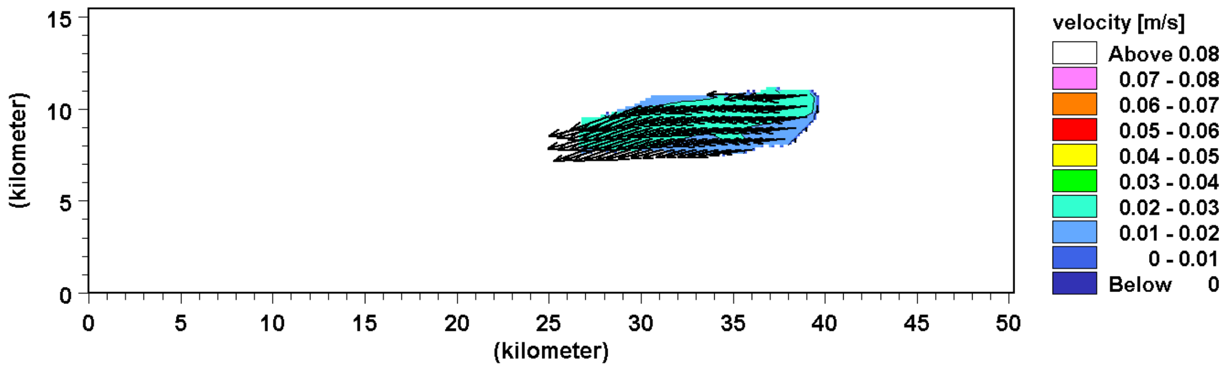

Fig 7. Mean Velocity Distribution in 6 layer

V. Conclusions

3-D Flow pattern modeling in the Gorgan Bay was done using MIKE 3 HD in summer 2010. The pressure supposes to be hydrostatic in this modeling. Simulation results in six layers show that flow patterns in the Gorgan Bay are generally anticlockwise. Velocity values in the Gorgan bay are affecting by wind speed. Along the northern and southern shore strong currents are mostly from west to east. There are strong currents in the Ashoradeh-Bandartorkaman mouth affected by storm surge and inter annual water level fluctuations in the Caspian Sea. The bottom topography and domain geometry have an important role in forming anti-clockwise circulation in the Gorgan Bay. Depending on the speed and direction of the wind, which is forcing the flow, speed and direction of the current vary in the Gorgan Bay. Totally all the layers, the flow patterns in the Gorgan Bay is influenced by bathymetry, bay geometry and prevailing winds; respectively. Bat velocity in the bay is mostly affected by prevailing winds.

Reference

[1] A.A. Ghanghorme and j. Malek, Water fluctuations in the Caspian Sea in (water annual 2008-2009) and environmental effecting factors, *Report Research, Caspian Sea National Research Center, 2010, 96*. (In Persian)

[2] A.R Karbassi and R. Amirnezhad, Geochemistry of heavy metals and sedimentation rate in a bay adjacent to the Caspian Sea, *International Journal of Environmental Science & Technology, Vol.1, No.3, 2004, 191-198.*

[3] Manual of MIKE 3, Coastal Hydraulic and Oceanography Hydrodynamic Module, Scientific Documentation, Danish Hydraulic Institute (DHI Software), 2007.

[4] Manual of MIKE 3, Coastal Hydraulic and Oceanography Hydrodynamic Module, User Guide, Danish Hydraulic Institute (DHI Software), 2007.

[5] Manual of MIKE 3 FLOW MODEL, Coastal Hydraulic and Oceanography Hydrodynamic Module, Hydrostatic Version, Scientific

Documentation, Danish Hydraulic Institute (DHI Software), 2007.

[6] H. Rahimipour Anaraki, Investigation of Hydrodynamic of currents and prediction of Erosion and Sedimentation Pattern in Groan Bay-Iran, *Soil Conservation and Watershed Management Research Institute, 84/322,2005,1-48.* (In Persian).

[7] Ramsar Convention Bureau, Rue Mauverney 28, CH-1196 GLAND, Switzerland, pp.7, 1997.

[8] S. Sharbaty, Simulation of wind-driven waves in the Gorgan bay, *Canadian Journal on Computing in Mathematics, Natural Sciences, Engineering and Medicine, Vol. 3, No. 2, 2012, 40-44.*

[9] S. Sharbaty and S. Hosseini, Simulation of wind driven currents in the Gorgan bay using Mike 21 – HD, *proceeding of 8th Conference of Marine science and technology, Khoramshahr, Iran, 2010, 10.* (In Persian)

[10] S. Sharbaty, S. Hosseini, V. Taghizadeh, M.R. Imanpour and S. Gorgin, Two dimensional modeling in Gorgan Bay Currents influence by sea level changes and wind pattern changes, *Proceeding of first Conference of Caspian sea ecology, Sari, Iran, 2010.* (In Persian)

[11] S. Sharbaty, M.R. Imanpour, S. Gorgin and S. Hosseini, The first phase of simulation studies of short-term sea currents in the Gorgan Bay, Research *Report, Gorgan University of Agricultural Sciences and Natural Resources, 89-2-257, 2010, 41.* (In Persian)

[12] J. Smagorinsky, General circulation Experiments with the primitive equations, *Monthly weather review vol.91, 1963, 91-164.*

[13] S.D. Smith and G. Bank, Variation of the sea drag coefficient with wind speed, Quart. *Journal of Met. Soc. Vol.101, 2007, 665-673.*

[14] R.H. Stewart, Introduction to Physical Oceanography. *Department of Oceanography Texas A & M University, 2006, 315.*

[15] A.A. Svitoch and T.A. Yanina, Holocene Marine Sediments on the Iranian Coast of the Caspian Sea, *Doklady Earth Sciences, 2006, Vol. 410, No. 7, 2006, 1166–1169.*

[16] M. Zounemat-Kermani, and S.R. Sabbagh Yazdi, Conjunction of 2D and 3D Modified Flow Solvers for Simulating Spatio-Temporal Wind Induced Hydrodynamics in the Caspian Sea, *Journal of Ocean Sci. 45(2), 2010,113-128.*