J. Basic. Appl. Sci. Res., 2(5)4382-4391, 2012
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ISSN 2090-4304
Journal of Basic and Applied Scientific Research
www.textroad.com

Two Dimensional Simulation of Seasonal Flow Patterns in the Gorgan Bay

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ABSTRACT

This study have done by aim of modeling flow patterns and water level fluctuations in during an annual period, separately for four seasons (winter 2009 to fall 2010) in the Gorgan Bay using Mike 21 HD package. The hydrodynamic equations consist of depth-averaged equations of continuity and motion in two dimensional. The equations are solved by implicit finite difference techniques with the variables defined on a space staggered rectangular grid 150×150 meter. The data of water level fluctuations in the Ashoradeh station as an open boundary condition with 2 hours time step, wind stress as a constant in space but varying in time with 10 minute time step, mean daily discharge of Qarahsoo river, evaporation, precipitation and Khozeini waterway are imposed to the model. Model has been calibrated and validated using against current measurements in the Gorgan Bay. The comparisons show that model reproduces the results to a satisfying level. The results of the model represented which, flow pattern is influenced by wind stress, bottom topography and domain geometry, respectively. generally, flow pattern is counter clockwise in the Gorgan Bay. Water surface level in the Gorgan Bay is affected by water fluctuations in the Caspian Sea.

Key Words: Flow Pattern, Gorgan Bay, Mike 21, Simulation.

1. INTRODUCTION

The Gorgan Bay (36°48'N, 53°35'E and 36°55'N, 54°03'E) is a semi-confined triangular-shaped bay, located at the south-east extremity of the Caspian Sea along Iranian coastline in the Golestan province [12] (Figure.1). Gorgan bay is formed during the Newcaspian /Holocene period [15] by a sandy spit which is named Miankaleh coastal barrier system. That is only Iranian bay at the Caspian Sea and has an area of 400 km^2, length is 60 km, average width 12 km, maximum depth of 6.5 m and average depth 1.5 m [2] and also plays a substantial hydrological and ecological role in the functioning of the coastal systems of the southeast Caspian [8].

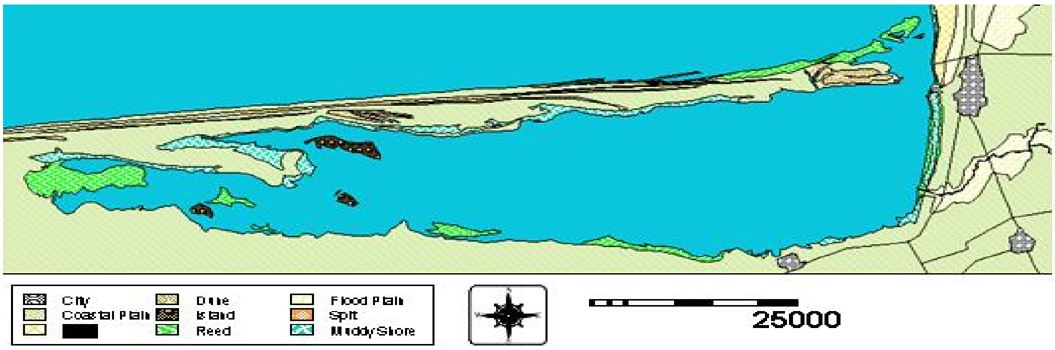

Figure.1. Geomorphological location of Gorgan Bay in the Caspian Sea.

The bay basin is bounded on the west, south and north by Mazandaran Province, Golestan province and Miankaleh peninsula respectively. There are no tides in the Gorgan Bay. It is connected with the Caspian Sea 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 dynamic status of water 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 [9]. 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 [11]. But among them, the Qarahsoo river is the only important fresh water source flowing into the bay. The first step in order to perform all marine studies on modeling is the run of a hydrodynamic model, and it is mainly this investigation which is presented in this paper. Our understanding on

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the hydrodynamic regime in the Gorgan Bay is fairly poor. The limited number of studies and projects were done on the Gorgan Bay. On the other hand, these investigations did not consider the long time simulations 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 duration one year and four seasons. In this work, we simulated flow patterns as a two dimensional using Mike 21 HD in the Gorgan Bay during one year and four seasons. So that this research may be useful for any future studies, the parameters specified for the simulations are detailed as well as the problems that have occurred during this period.

2. MODEL DESCRIPTIONS AND BASIC GOVERNING EQUATIONS

Mike 21 is a professional engineering software package containing a comprehensive modeling system for two-dimensional free-surface flows. Mike 21 is applicable to the simulation of hydraulic and related phenomena in lakes, estuaries, bays, coastal areas and seas where stratification can be neglected. Mike 21 HD forms the basis for calculations in additional Mike 21 modules. Mike 21 HD solves the vertically integrated, fully dynamic equations of continuity and conservation of momentum in two horizontal directions. The numerical model is a finite-difference schema using an A.D.I (Alternating Direction-Implicit) technique to integrate the equation for mass and momentum conservation in the space-time domain. The equation matrices are resolved by a Double Sweep (DS) algorithm. The 2D Shallow Water equations are obtained by means of averaging of the 3D Navier-Stokes Equations over the depth. The new variables obtained are mean values over the depth. The effects of Coriolis force, bottom friction stress, wind friction stress, source and sink, eddy viscosity are included in the equations [4,5 and 6]. The governing equations are written as follows:

Continuity equation:

$$\frac{\partial \zeta}{\partial t}+\frac{\partial p}{\partial x}+\frac{\partial q}{\partial y}=\frac{\partial d}{\partial t} \qquad (1)$$

Momentum equation in x-direction:

$$\frac{\partial p}{\partial t}+\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{pq}{h}\right)+gh\frac{\partial \zeta}{\partial x}+\frac{gp\sqrt{p^2+q^2}}{c^2h^2}-\frac{1}{\rho_w}\left[\frac{\partial}{\partial x}(h\tau_{xx})+\frac{\partial}{\partial y}(h\tau_{xy})\right]$$

$$-\Omega_q-fvv_x+\frac{h}{\rho_w}\frac{\partial}{\partial x}(p_a)=0 \qquad (2)$$

Momentum equation in y-direction:

$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial y}\left(\frac{q^2}{h}\right)+\frac{\partial}{\partial x}\left(\frac{pq}{h}\right)+gh\frac{\partial \zeta}{\partial y}+\frac{gq\sqrt{p^2+q^2}}{c^2h^2}-\frac{1}{\rho_w}\left[\frac{\partial}{\partial y}(h\tau_{yy})+\frac{\partial}{\partial x}(h\tau_{xy})\right]$$

$$+\Omega_p-fvv_y+\frac{h}{\rho_w}\frac{\partial}{\partial y}(p_a)=0 \qquad (3)$$

The following symbols are used in the equations:

$h(x,y,t)$ Water depth $(\zeta - d, m)$

$d(x,y,t)$ Time varying water depth (m)

$\zeta(x,y,t)$ Surface elevation (m)

$p,q(x,y,t)$ Flux densities in x-and y- directions ($m^3/s/m$) = (uh, vh); (u,v) = depth Average velocities in x- and y- directions.

$C(x,y)$ Chezy resistance ($m^{1/2}/s$)

g Acceleration due to gravity (9.81 ms^{-2})

$f(V)$ Wind friction factor

$V,V_x,V_y(x,y,t)$ Wind speed and components in x- and y-directions (m/s)

$\Omega(x,y)$ Coriolis parameter, latitude dependent (s^{-1})

$p_a(x,y,t)$ Atmospheric pressure (pa)

ρ_w Density of water (kg/m^3)

x,y,z Space coordinates (m)

t time

$\tau_{xx},\tau_{xy},\tau_{yy}$ Components of effective shear stress

3. MODEL SETUP

The model was run with 60 second time step intervals separately for four seasons (2009-2010). The initial surface elevation for winter specified as a constant value (0.22 m) for all area based on tide gauge data. At the initial stage, the flow field was assumed to be stationary in first season (winter 2009). The simulated results of the first days were not used as the model was allowed to settle for a few days. Initially, several runs of the model have been carried out to test efficiency in reproducing surface elevations and currents in computational domain. In this investigation, last time step of each seasonal simulations (as a Hot Start file) was used as an initial conditions for next season (spring, summer and fall 2010, respectively). The flood and dry checking is done as a default value for a drying depth of 0.2 meter and a flooding depth of 0.3 meter just for winter [3]. In Mike 21 ngrid cell size and time step are predetermined to ensure a low Courant number is obtained. The grid spacing is linked with the Courant number as follows:

$$C_R = c \times \frac{\Delta t}{\Delta x} \qquad (4)$$

Where c is the celerity, Δt the time step and Δx the grid spacing. For a tidal wave the celerity is

$$c = \sqrt{g.h} \qquad (5)$$

Where g is gravity and h is the water depth. 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.

3.1. TURBULENCE AND EDDY VISCOSITY

The effective shear stresses in the momentum equations contain momentum fluxes due to turbulence and vertical integration. The terms are included using an eddy viscosity formulation. The formulation of the eddy viscosity in the equations is based on Smagorinsky Formula [13]:

$$E = c_s^2 \Delta^2 \left[\left(\frac{\partial U}{\partial x} \right)^2 + \frac{1}{2} \left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right)^2 + \left(\frac{\partial V}{\partial y} \right)^2 \right] \qquad (6)$$

Where U,V are depth average velocity components in x - and y – direction, Δ is the grid spacing and C_s is a constant 0.25.

3.2. BOUNDARY CONDITIONS

Five types boundary are considered in this model such as, land-sea (coastal, island) boundary, air-sea (surface) boundary, sea bottom friction boundary, discharge from river boundary and bay-open sea (open) boundary. Thus the boundary conditions used in Mike 21 HD model include sea surface, sea bottom friction, open boundary and the discharge from river along the Gorgan Bay.

3.2.1. BATHYMETRY DATA

The accuracy of the results of any numerical model is directly impacted by the accuracy of the bathymetric data [10]. Bathymetry data as a dfs2 data file containing the water depths in the Gorgan Bay digitized using the map issued by the National Cartographic Center Islamic Republic of Iran (Scale 1:100 000). In this map, depths are in meters and are reduced to lowest level of Caspian Sea in 1995 which is approximately 26.5 meters below Mean Sea Level of Persian Gulf. 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 model domain, the Gorgan Bay is divided into 121 equal grids in north-south direction and 352 grids in west-east direction. The grid cell used in computations was equal to 150×150 meter.

3.2.2. WIND FRICTION

For the sea surface boundary, 10 minute variations of wind data including speed and direction for the Gorgan Bay were gathered during 21 December 2009 to 21 December 2010 from a meteorological station at the Bandartorkaman, located in the closest town to the bay (less than 2 km). In this investigation we supposed wind speed and direction are varying with time but constant in space. The wind climate has presented visually in the form of seasonal wind rose at 22.5 direction intervals and 2.5m/s speed intervals (Figures.2, 3, 4 and 5).

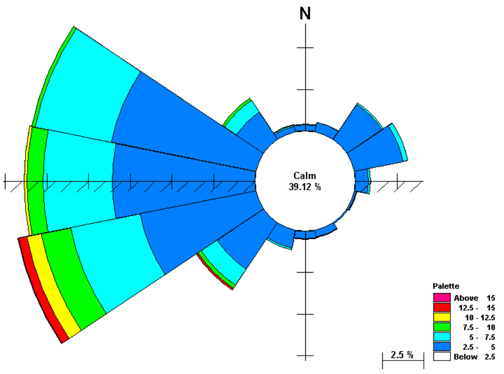

Figure 2. Spring wind rose in the Gorgan Bay.

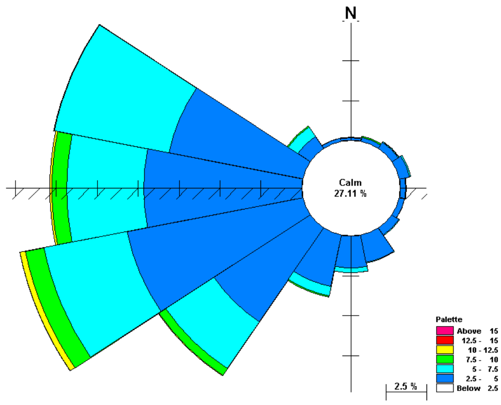

Figure 3. Summer wind rose in the Gorgan Bay.

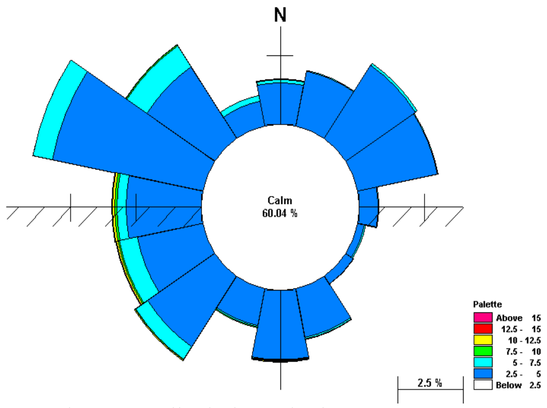

Figure 4. Fall wind rose in the Gorgan Bay.

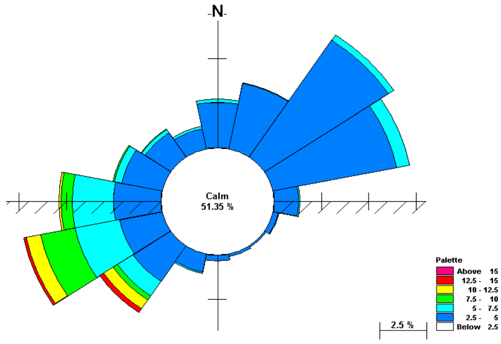

Figure 5. Winter wind rose in the Gorgan Bay.

In broad terms, spring and summer tends to be windier than fall and winter, with less occurrence of calm periods (average wind speed <2.5m/s) and a slightly higher mean wind speed. During warm seasons, winds come predominantly from the northwestern, western and southwestern quarters, while in cold seasons, a greater occurrence of winds from the northwestern, southwestern and western quarters in the fall and southwestern and northeastern quarters in the winter are experienced. The driving force due to wind blowing is calculated from the following quadratic law:

$$f(v)\frac{\rho_{air}}{\rho_{water}}v^2 \qquad (7)$$

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 [14]:

$$f(v)=\left\{\begin{array}{ll} f_0 & for \quad v<v_0 \\ f_0+\dfrac{v-v_0}{v_1-v_0}(f_1-f_0) & for \quad v_0\le v\le v_1 \\ f_1 & for \quad v>v_1 \end{array}\right\} \qquad (8)$$

$f_0=0.00013 \quad , \quad v_0=0 \quad m/s$

$f_1=0.0026 \quad , \quad v_1=30 \quad m/s$

Where

v_1, v, v_0 : Are wind speed

f_0, f_1 : Wind friction parameter

Daily mean rainfall, 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 waterway topography, water exchange through waterway was considered as a linear series.

3.2.3. BOTTOM FRICTION STRESS

The bottom friction in the Mike 21 model can be specified either as a Chezy number or as a Manning number. In both cases the bed resistance used is:

$$\frac{g.u.|u|}{C^2} \tag{9}$$

Where g is gravity, u is velocity and C is the Chezy number. Manning numbers are converted to Chezy numbers as follows:

$$C = M.h^{\frac{1}{6}} \tag{10}$$

Where M is the Manning number and h is the water depth. In this work, a bed resistance number is assigned as a constant value ($32 \quad M^{\frac{1}{3}}/s$) to each grid point in the model area.

3.2.4. OPEN BOUNDARY

A straight boundary line, separating Gorgan Bay from Caspian Sea along the mouth of Ashoradeh-Bandartorkaman is considered as an open boundary. Measured water level recordings with 2 hours time step intervals by tide gauge from Ashoorade station located near the northwestern open boundary at the Ashoradeh is considered as a time series data for open boundary conditions in the model.

4. CALIBRATION AND VALIDATION

The model is valid if it accurately predicts the performance of the marine system. If this is not achieved then it is necessary to examine and change the structure and assumptions of the model. With repeated adjustments to these, a valid model can be developed for future works. In the present study, the Mike 21 simulations has been calibrated and validated using against current measurements data at the monitoring points for separately two seasons (summer and winter, 2002) [7]. The comparisons show that the Mike 21 model reproduces the results to a satisfying level and thus the model is considered adequate for the present purpose in seasonal simulations (2009 to 2010). The main parameters to adjust during the calibration phase were bed resistance, eddy viscosity, bathymetry, boundary conditions and wind friction.

5. CONCLUSION

5.1. CURRENT SPEED DISTRIBUTION AND WATER SURFACE ELEVATIONS IN WINTER

Figure 6 shows the model results of mean surface current velocity distributions in the Gorgan Bay. A counter-clockwise current dominates the circulation in the central parts of the bay with speed of 2 to 4 cm/s. Generally, current speeds are weak (below 4 cm/s) within the Gorgan Bay; they are stronger within mouth of Ashoradeh-Bandartorkaman. The current travels from the mouth of the Gorgan Bay towards inner parts of the bay with the mean maximum speed of 16 cm/s. But this mentioned current, affected just on near parts of the mouth. In the other parts of the bay, currents are affected by wind pattern in this season. Mean currents velocity are weak rapidly by traveling from the mouth to the other parts of the bay. There are currents along the coastal areas in the northern and southern coasts that moving from west to east. The mean sea surface variation in the bay is from 0.16 m to 0.19 m from west to east (Figure.7). In the other hands, water depth in the deepest part of the bay varying from 6.5 m to 7 m in during winter. Generally, water depth increased about 0.18 m in the Gorgan Bay during winter. These subjects represented increasing water depth for the Gorgan Bay in duration winter (Figure.8). Overall, water level gradually increased in the Gorgan Bay in winter.

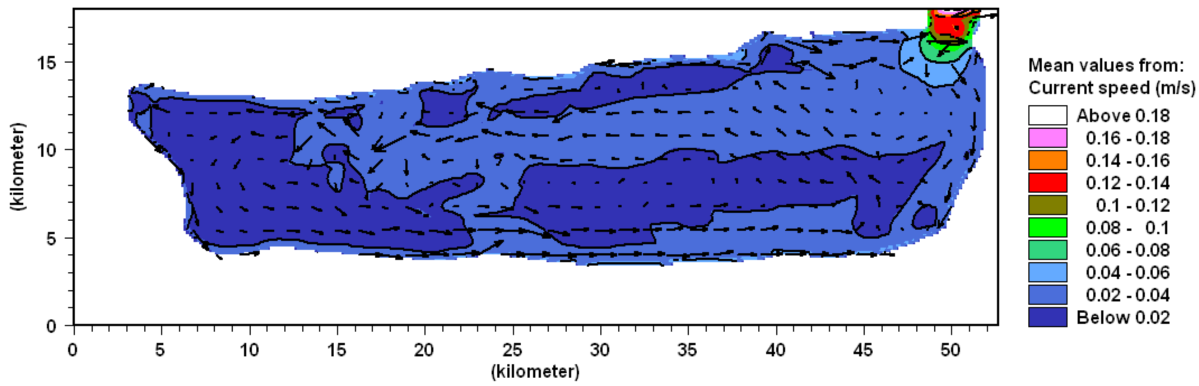

Figure 6. Surface current velocity distribution in winter.

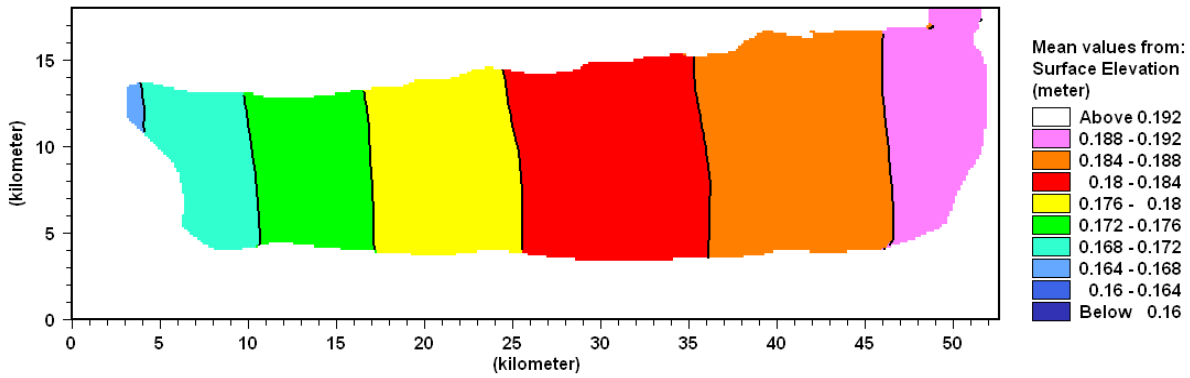

Figure 7. Mean sea surface variations in winter.

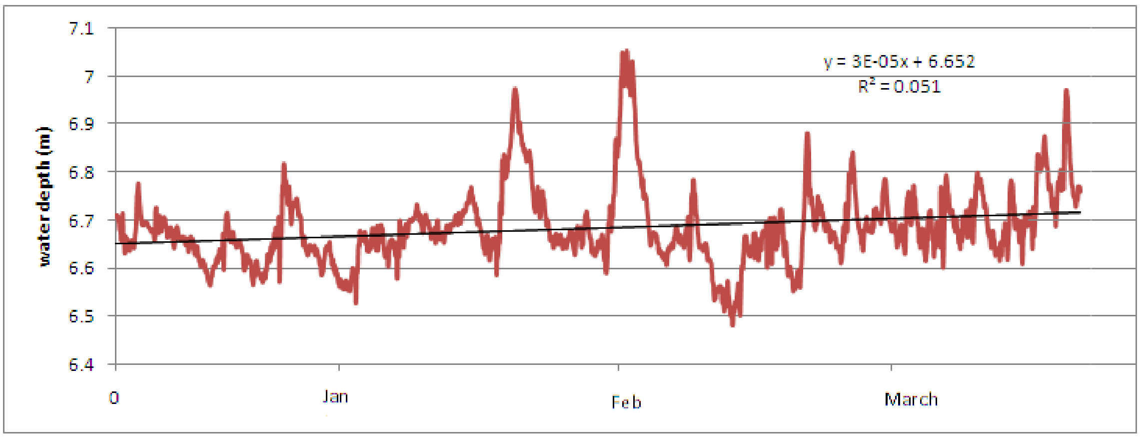

Figure 8. Water depth variations in winter.

5.2. CURRENT SPEED DISTRIBUTION AND WATER SURFACE ELEVATIONS IN SPRING

Figure 9 shows the model results of mean surface current velocity distributions in the Gorgan Bay in duration of spring season. A counter-clockwise current dominates the circulation in the central parts of the bay with speed of 2.5 to 5 cm/s. The current travels from the mouth of the Gorgan Bay towards inner parts of the bay with the maximum speed of 20 cm/s. Generally, mean current velocity increased due to prevailing wind pattern in this season. There are currents along the coastal areas in the northern and southern coasts that moving from west to east. The mean sea surface variation in the bay is from 0.23 m to 0.18 m from east to west (Figure.10). Variations of water depth in the deepest part of the bay are from 6.5 m to 7 m in during spring. Generally, water depth increased about 0.3 m in the Gorgan Bay during this season. But the rising the water level in this season in comparing to winter is so rapidly (Figure.11). These variations are driven mainly by surface elevation changes in the open boundary and represented increasing water surface in duration spring such as winter.

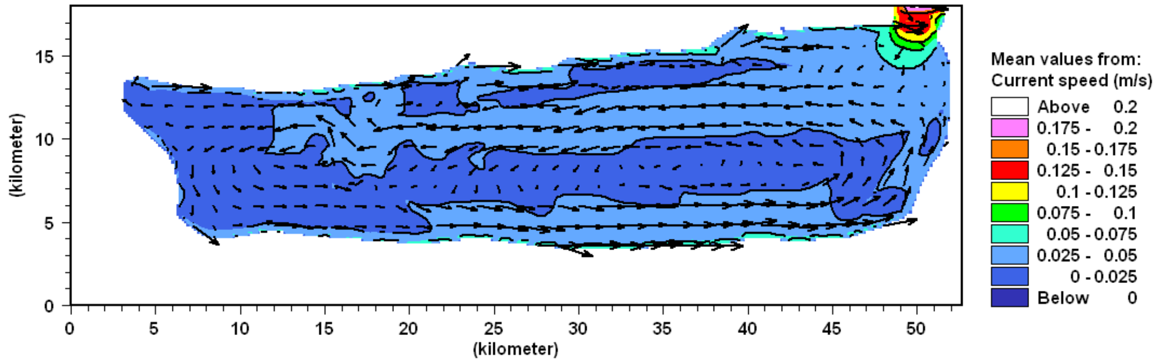

Figure 9. Surface current velocity distribution in spring.

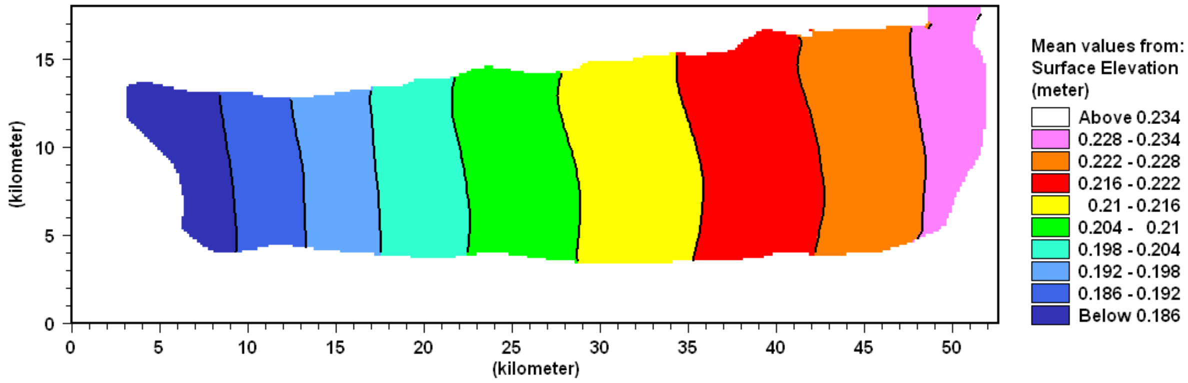

Figure 10. Mean sea surface variations in spring.

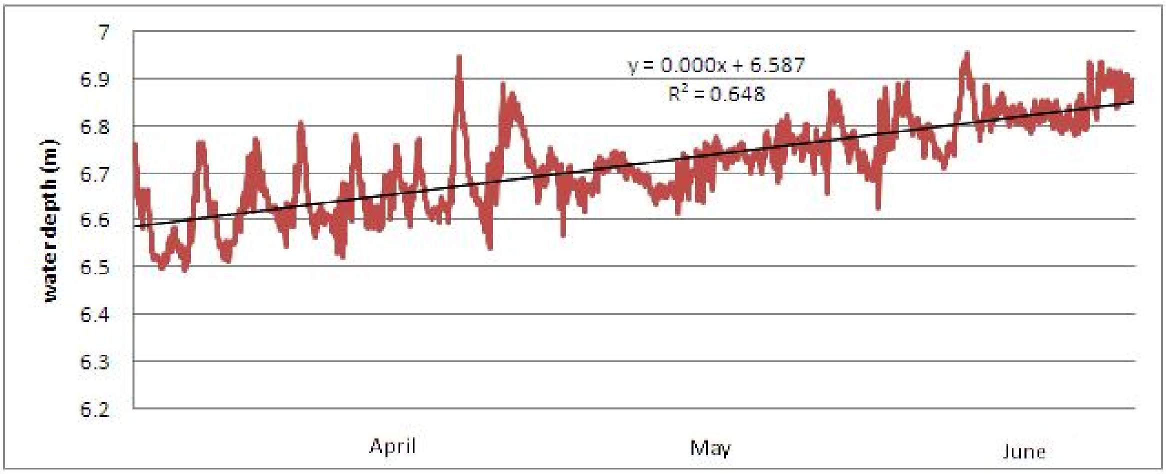

Figure 11. Water depth variations in spring.

5.3. CURRENT SPEED DISTRIBUTION AND WATER SURFACE ELEVATIONS IN SUMMER

A counter-clockwise current dominates the circulation in the central parts of the bay with speed of 2 to 6 cm/s (Figure.12). The current travels from the mouth of the Gorgan Bay towards inner parts of the bay with the maximum speed of 18 cm/s. Generally, mean current velocity increased due to prevailing wind pattern in this season. There are currents along the coastal areas in the northern and southern coasts that moving from west to east. These currents are stronger in comparison with other seasons. The mean sea surface variation in the bay is from 0.3 m to 0.23 m from east to west (Figure.13). Water depth variations in the deepest part of the bay are from 6.5 m to 7.1 m in during summer. Generally, in this season, water level increased till mid-summer (about 0.27 m) but then it decreased slowly (Figure.14). These variations represented decreasing water surface by surface elevation changes in the Ashoradeh-Bandartorkaman mouth for the Gorgan Bay in during summer.

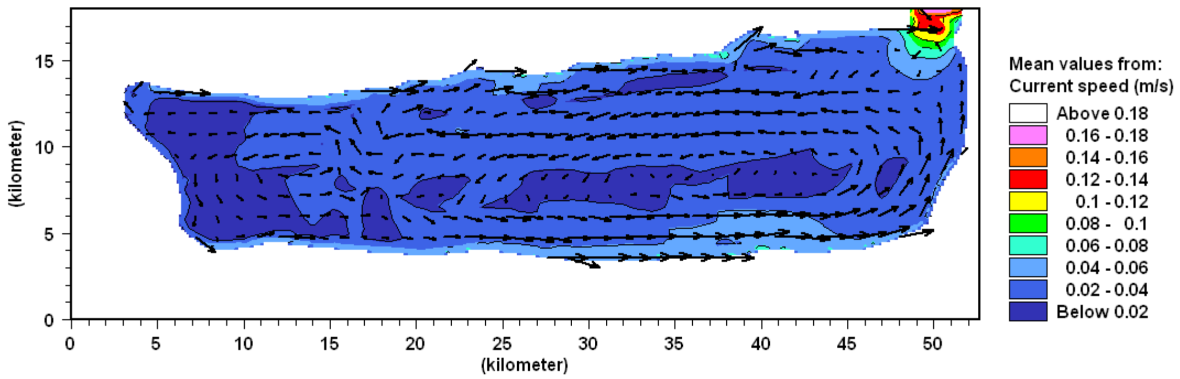

Figure 12. Surface current velocity distribution in Summer.

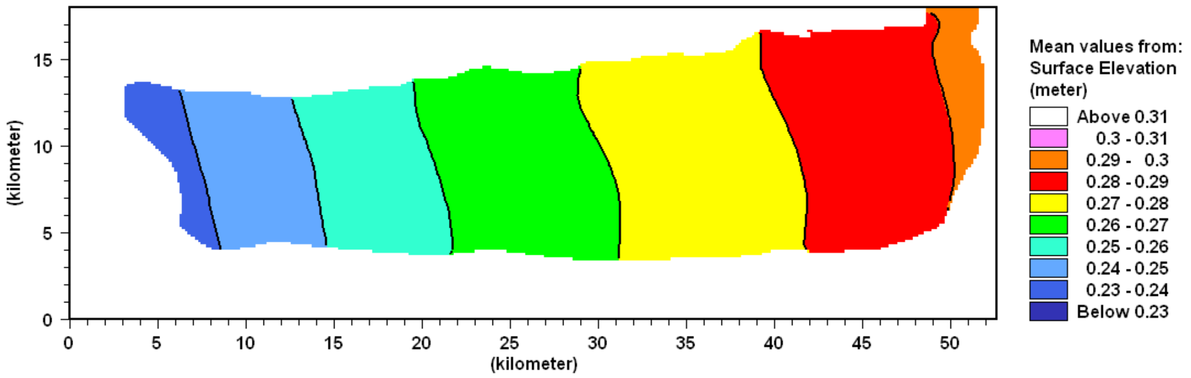

Figure 13. Mean sea surface variations in summer.

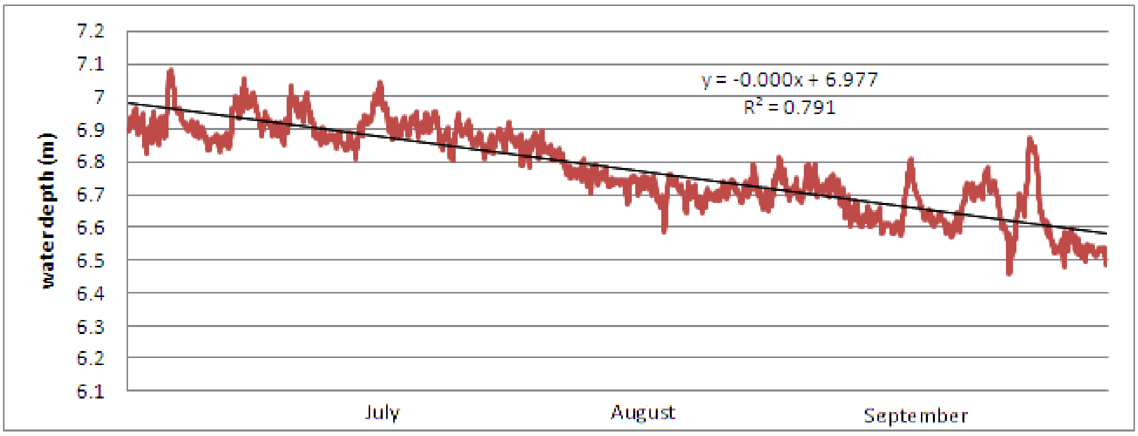

Figure 14. Water depth variations in summer.

5.4. CURRENT SPEED DISTRIBUTION AND WATER SURFACE ELEVATIONS IN FALL

In this season, there is a prominent counter-clockwise current in the central parts of the bay with speed of 1.5 to 3 cm/s (Figure. 15). The current travels from the mouth of the Gorgan Bay towards inner parts of the bay with the mean maximum speed of 10 cm/s. Due to weak wind blowing on the surface bay, mean current velocity decreases in this season. There are currents along the coastal areas in the northern and southern coasts that moving from west to east. However in other seasons, these currents are stronger than fall. The mean sea surface variation in the bay is from 0.169 m to 0.163 m from east to west (Figure. 16). Water depth variations in the deepest part of the bay are from 7.1 m to 6.5 m in during fall. Drop in water level in this season in comparing to other seasons is so faster (Figure.17).

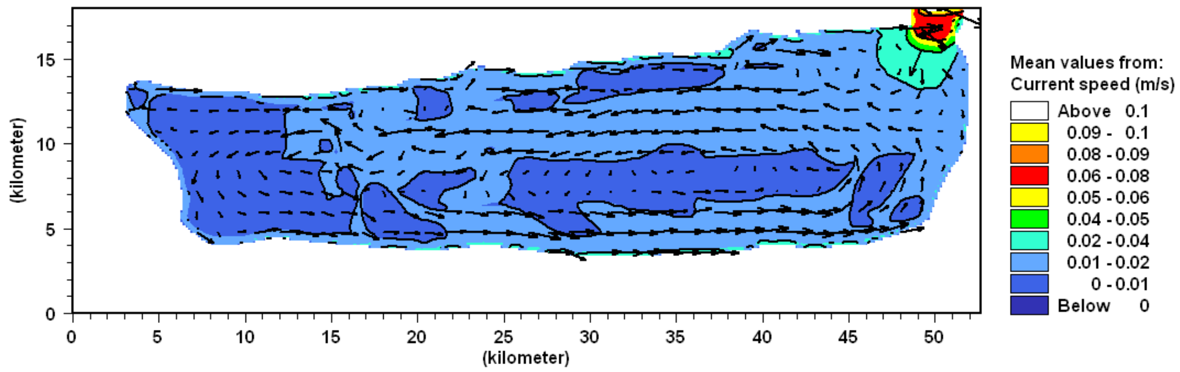

Figure 15. Surface current velocity distribution in fall.

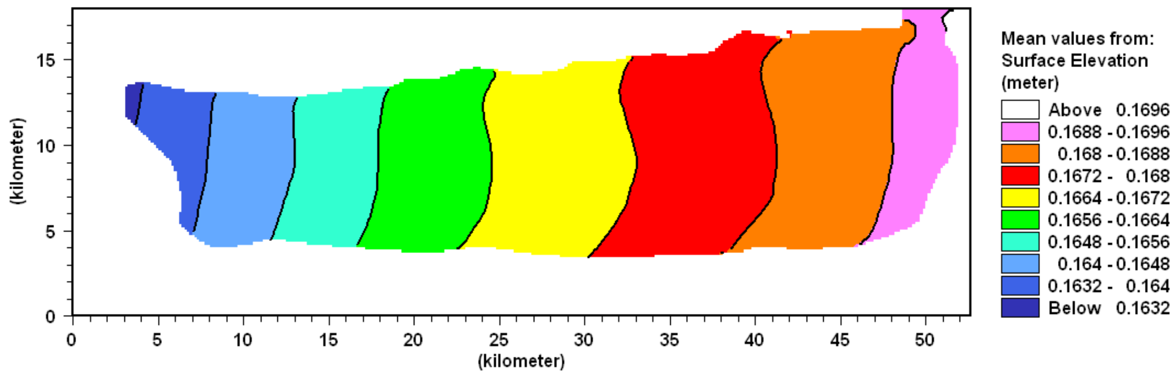

Figure 16. Mean sea surface variations in fall.

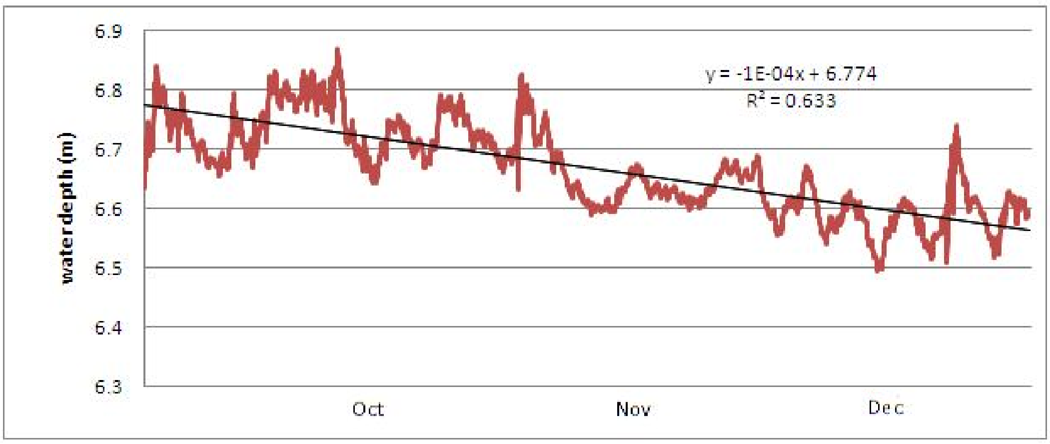

Figure 17. Water depth variations in fall.

6. DISCUSSION

This paper describes seasonal flow patterns and water surface elevation in the Gorgan Bay with a two dimensional model. The results of the model are as follow:

1- Generally, there is a counter-clockwise flow pattern in the Gorgan Bay in four seasons. This current pattern is driven primarily by prominent wind stress and then is affected by bottom topography and domain geometry.
2- In the northern and southern shores, currents are along the coastal areas and moving from west to east by effecting dominant winds.
3- Variations in the magnitude and direction current due to the presence of the complexity of bottom topography are clearly seen in bay.
4- The water surface elevation changes in the open boundary just affected on the current distributions and velocity values on near parts of the Ashoradeh-Bandartorkaman mouth.

5- The water surface fluctuations in the Gorgan Bay are affected by open boundary which is affected by the Caspian Sea.
6- Generally, the bay has a maximum value of water fluctuations in during a year about 0.5 meters.

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