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Full Length Research Paper

Water circulation modeling study upon the construction of al-Dannat development at the Halfmoon Bay, Saudi Arabian Gulf

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The present study aims to understand the flow field near the coast of Halfmoon Bay located in the Arabian Gulf arising due to creation of an artificial island by al-Dannat. The study was performed using the state-of-art hydrodynamic model, Princeton ocean model (POM), applied for a detailed analysis of flow conditions, temperature and salinity distributions after the creation of this artificial island. These hydrodynamic conditions are felt to be critical in assessing stagnation of water, which may eventually lead to eutrophication process. The computed maximum current speeds are in the order of 0.03 ms^{-1}, which suffices to produce reasonable ventilation to the Arabian Gulf even after the construction activity.

Key words: Ocean circulation, modeling, stagnation.

INTRODUCTION

The Arabian Gulf, in the Southwest Asian region, is an extension of the Indian Ocean located between Iran and the Arabian Peninsula. It is historically and commonly known and referred as the *Arabian Gulf* or simply *The Gulf.* This is a shallow basin that separates the Saudi mainland from Bahrain and has many good fishing grounds, extensive coral reefs, and abundant pearl oysters, but its ecology has come under pressure from industrialization, and in particular, petroleum spillages during the recent wars in the region of which the 1991 Gulf war is quite notable. The Gulf is a semi-enclosed marginal sea that is exposed to an arid subtropical climate. It is located between latitudes 24°N and 30°N and is surrounded by deserts.

The study area is located in the Kingdom of Saudi Arabia having an outlet into the Arabian Gulf. The Halfmoon Bay region, located in the Arabian Gulf where the Dannat development is proposed (Figures 1a to b) is a region of relatively quiet and stagnant water. The development of an island in this region can modify the existing flow field and hence the importance of this study.

It is mandatory to have an environmental impact assessment study to understand the impacts arising due to construction activity. It is expected that the effects due to coastal reclamation can change the flow field in the study domain. The dredging activity is limited to a width of 70 to 80 m without altering the banks. The present study involves a detailed analysis of the flow velocity and the resultant temperature/salinity distribution after the construction activity. The aforementioned conditions will determine the residence/flushing time of water surrounding the island having direct implications on the water quality. This deciphers the fact that residence time resulting from release of contaminants into this body of water from the mainland through near-shore waters into the Gulf can be pre-determined. Hence this study is critical to understanding the water quality and eutrophication process.

The computations were performed for a very small domain (having size of 1.45 × 1.45 km) hereafter referred to as the ‘simulation domain’ (Figure 1b). The focus of this work is to determine the penultimate flow field arising due to the construction activity, and hence details relevant to dredging and dredged sediments are not within the scope of this study. Hence, quantification of physical oceanographic processes including the overall circulation features; temperature and salinity distribution fields were thereby affected due to the fact that this new

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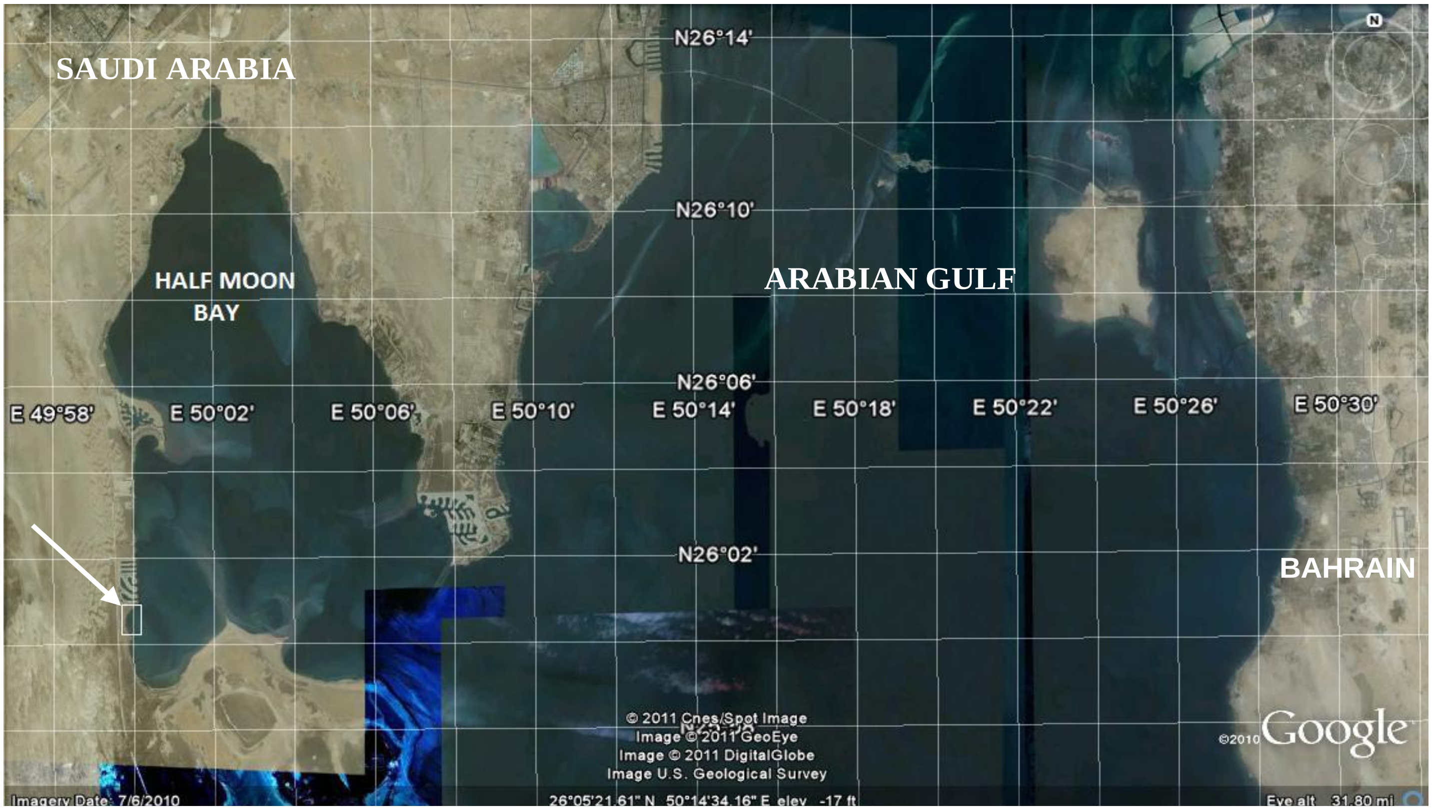

Figure 1a. Location of Halfmoon Bay. The arrow points to the domain of construction and the site for the present study. The coastal water where the island will be constructed is about 4 to 5 m deep. The development of this island is initiated by the Dannat development which involves dredging and refilling the dredged sediments for the island expected off Halfmoon Bay. A comparatively smaller curved island (shown in Figure 1b) is planned for Commercial Township and recreational purposes within close vicinity of Dannat Development Agency.

Figure 1b. Domain for simulation as proposed. 1 cm in x – direction = 242 m; 1 cm in Y- direction = 191 m.

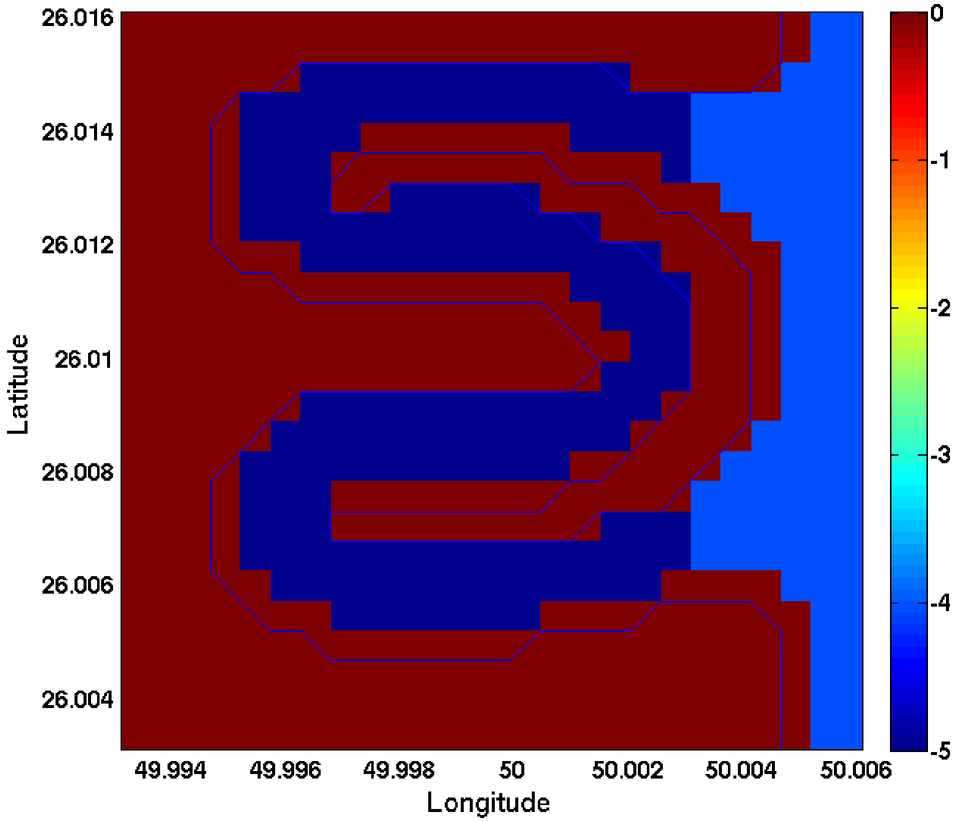

Figure 2a. Bathymetry of the simulation domain for model runs. The deep blue and the sky blue colours indicate depths of 5 and 4 m, respectively and the brown colour indicates zero depth or land acoording to the construction proposal.

construction was given more importance.

METHODOLOGY

Physical background

Bathymetry

The bathymetric details essential for model runs is obtained from the digitized bathymetry map provided by the King Fahd University of Petroleum and Minerals (KFUPM), Kingdom of Saudi Arabia. The simulation domain covers the near shore having water depths less than 6 m. These shallow depths can be modeled using the Princeton Ocean Model (POM, description given under the heading, hydrodynamic model). The bathymetric details are shown in Figure 2a where the water depths are expressed in meters.

Surface winds

The stress resulting from surface wind forcing is an essential pre-requisite for POM runs. In this context, meteorological wind data for the simulation domain was obtained from satellite observations of QuikSCAT (Quick Scatterometer). The final product from QuikSCAT comprises gridded scalar wind speed, zonal and meriodional components of surface winds over the global oceans. In the present study, daily winds for the entire year during 2009 were extracted for the geographic location (50°E, 26°N). As seen, the spatial extent of the simulation domain is very limited in size, hence the extracted wind information from QuikSCAT can be assumed as the representative wind for the simulation domain. The wind vector represented as a polar diagram (wind-rose) for the entire year of 2009 is shown in Figure 2b. The extracted wind field from QuikSCAT for the aforementioned location is then provided as input to force POM model.

The winds in the simulation domain are typically north westerly winds associated with large scale sand-storms. These winds, referred to as ‘Shamal’, by Perrone (1981), prevail throughout the year and are usually stronger during the day than at night. The intensity of these winds is strong during summer months and less common during the winter periods. The wind data used for the present study also show the dominant direction as north-west (Figure 2b) followed by the south-west direction.

Temperature and salinity

The initial conditions required for POM runs require diagnostic fields such as temperature and salinity for the simulation domain. These fields are obtained from the state-of-art World Ocean Atlas (WOA05), which provides fields of temperature and salinity at standard water depths on monthly, seasonal and annual time scales for the world oceans. The WOA05 is a set of objectively analyzed 1° × 1° spatial grid climatology; in the context to this study, the derived temperature and salinity fields for the geographic

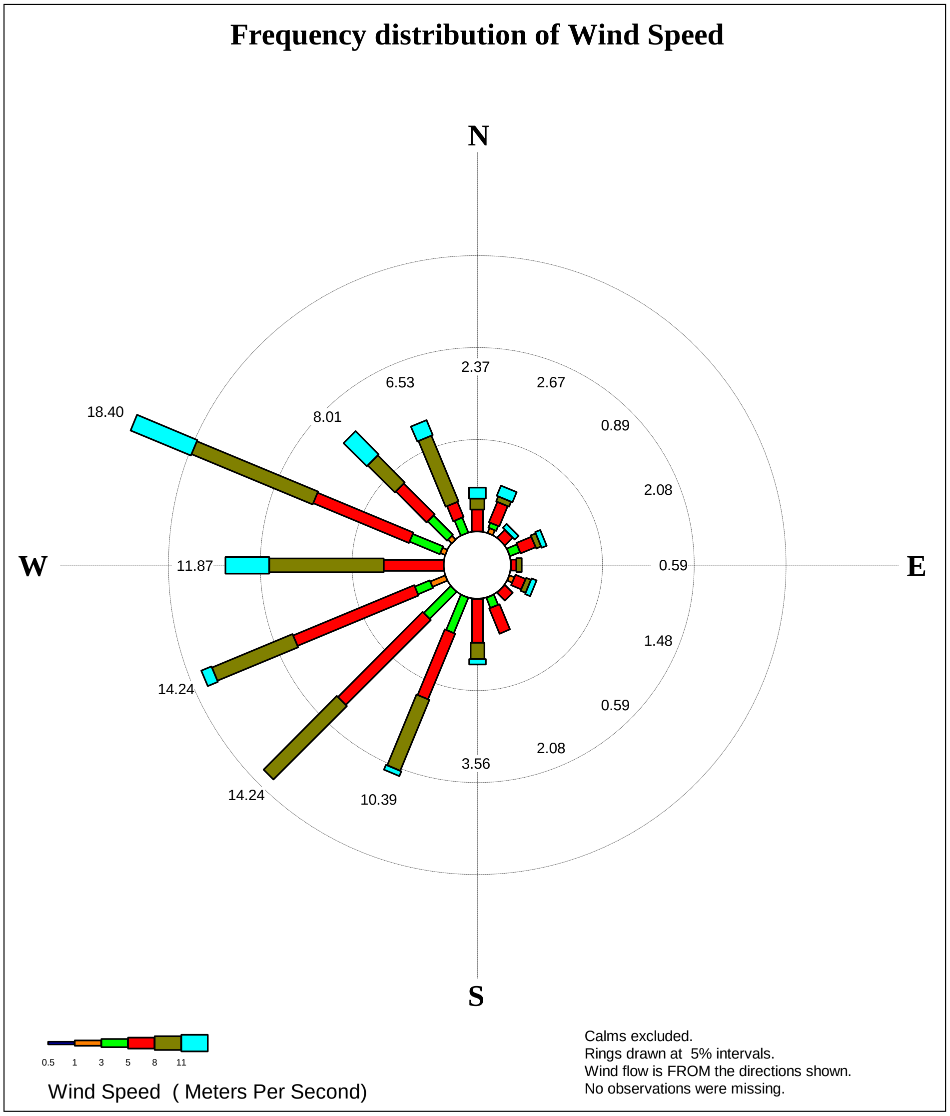

Figure 2b. Annual distribution of wind field in 2009 expressed as Wind Rose over Dannat (simulation domain).

location 50°E, 26°N was used representing the simulation domain. The temperature and salinity data used for the present study is from the monthly climatology of WOA05.

DYNAMICAL ASPECTS

The conservation principles of volume and salinity can be used for the estimation of residence/flushing times in semi-enclosed water bodies. In this context, key parameters such as the flow field, temperature and salinity are essential pre-requisite. An exhaustive study of water circulation at the construction site is also required to understand the water quality characteristics. Since the water depth at simulation domain is limited to less than 6 m, the prevalent currents which control the fluid motion can be attributed due to wind and tides. The depth averaged case for currents can be assumed in the simulation domain due to very shallow depths. In case of wind driven currents, the Ekman depth will be the total water depth (due to depth limitation) and Ekman transport governs the fate of transport mechanism. The intensity and mixing by tidal currents can be pivotal in context to the water quality. Hence, a comprehensive understanding of wind and tidal currents is important to the near-shore dynamics in the simulation domain.

HYDRODYNAMIC MODEL

Model description

The model used for this study is the Princeton ocean model (POM). This model has the capability to simulate three dimensional flow fields relevant for this study. It is a community general circulation numerical model used for nowcasting and forecasting of ocean parameters. The applicability of POM includes wide spectrum of oceanic problems such as circulation and mixing processes in estuaries, semi-enclosed seas, coastal seas and open oceans. The

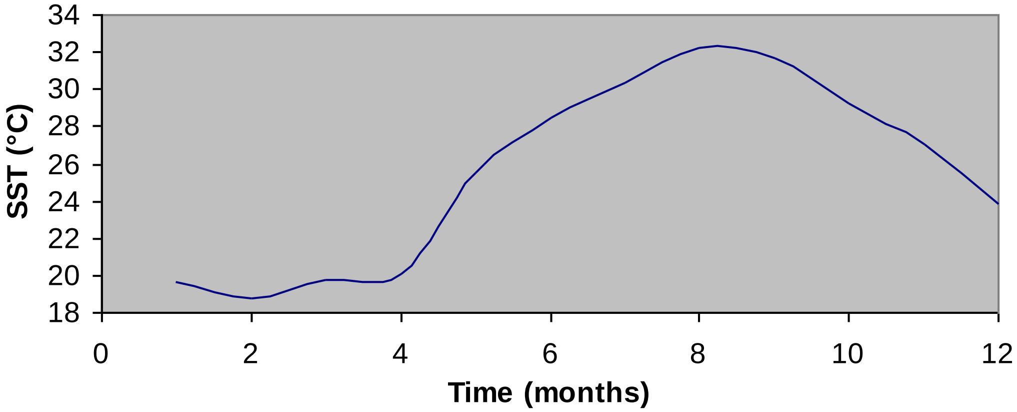

Figure 3a. Time series of SST (°C).

model is based on primitive equations, sigma coordinate system having sophisticated level of turbulence mixing schemes. The recent version also includes an option for wet and dry grids accounted from varying water levels near-shore. The governing equations are discretized in a finite-difference grid. The original version of POM was developed at Princeton University (Blumberg and Mellor, 1987) with collaborative efforts as reported in Herring and Patchen (1994). The version of POM used in the present study is POM2k developed by Mellor (Mellor, 2003). The Blumberg-Mellor model (later termed as POM) includes additional features such as free surface to handle tides, sigma terrain following coordinates to handle complex topographies in shallow regions, curvilinear grids to better represent coastlines, and turbulence scheme called Mellor-Yamada scheme (Mellor and Yamada, 1974) to handle vertical mixing. In the early 1980s, POM model was used for estuarine applications such as the Hudsen-Raritan estuary (Oey et al., 1985a, b) and the Delaware Bay (Galperin, 1990 a, b). The first attempts to use a sigma coordinate model for basin-scale problems started with a coarse resolution model for the Gulf of Mexico (Blumberg and Mellor, 1981).

Governing equations

The model equations are usually expressed in a flux form. This is desirable in terms of computational power to separate the vertically integrated equations (external mode) from the vertical structure equations (internal mode). This method, known as mode-splitting, permits the calculation of the free surface elevation with no priori restriction on computation time. This is achieved by solving the velocity transport separately from three-dimensional estimation of the velocity and thermodynamic variables. The time integration is performed using a leap-frog two level time scheme. This method has been found to be extremely efficient and stable in calculating the surface mixed layer and also rigid boundary layer as in case with land boundaries. The imposed condition of free sea surface in the model permits the dynamic change of water level elevation due to tides.

Model domain and grid resolution

The simulation domain is shown in Figure 2a. The horizontal spatial extent is approximately 1.45 × 1.45 km having depth less than 6 m. The total number of grid points along the horizontal are 26 × 26 with spatial resolution of 56 m. A rectilinear coordinate system is used in the horizontal and 16 sigma levels were specified in the vertical direction.

Initial and boundary conditions

The inputs required to initialize the model are bathymetry, surface winds, temperature and salinity fields with appropriate boundary forcings. In this case study, the forcing at open boundary includes water level variations, temperature and salinity. The free surface forcing is accounted from wind stress, flux of heat and moisture. In the present study, the Blumberg-Kantha radiation type scheme (Blumberg and Kantha, 1985) is used for open boundary condition.

RESULTS AND DISCUSSION

Temperature and salinity

The model computed sea surface temperature (SST) and sea surface salinity (SSS) are shown in Figures 3a and b, respectively. The occurrence of maximum SST is noticed during the month of August (32.2°C) with a net difference of more than 10°C during the winter months (≈ 18.75°C). The sea surface salinity (SSS) is shown in Figure 3b which reveals that maximum surface salinity occurs during the month of January and minimum during June. This temperature and salinity distribution decides the fate of the biological population there. There are about 11 profiling stations (designated from A – K) in the simulation domain (Figure 4a).

Surface circulation

The surface circulation features for different months are shown in Figures 4b to e, respectively for January, April, July and October. As seen from these figures, the surface currents are oriented along eastward and north-eastward directions at various segments of the simulation domain. The color in these Figures indicates the temperature pattern (in °C) and a particular color for each month indicates uniformity of thermal field within the study domain.

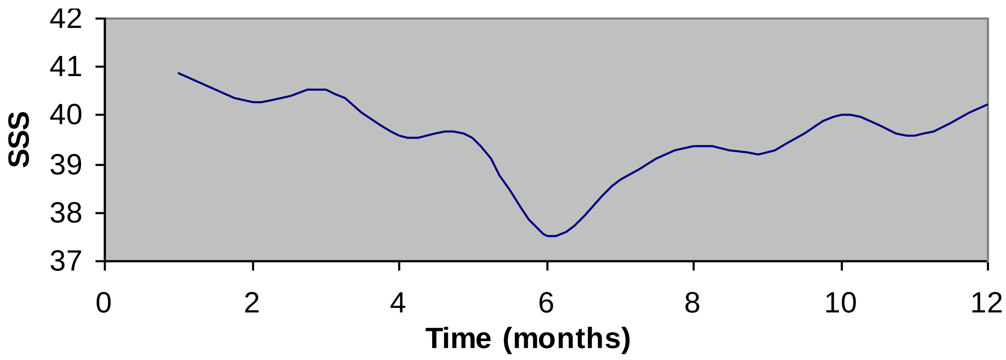

Figure 3b. Time series of SSS (‰).

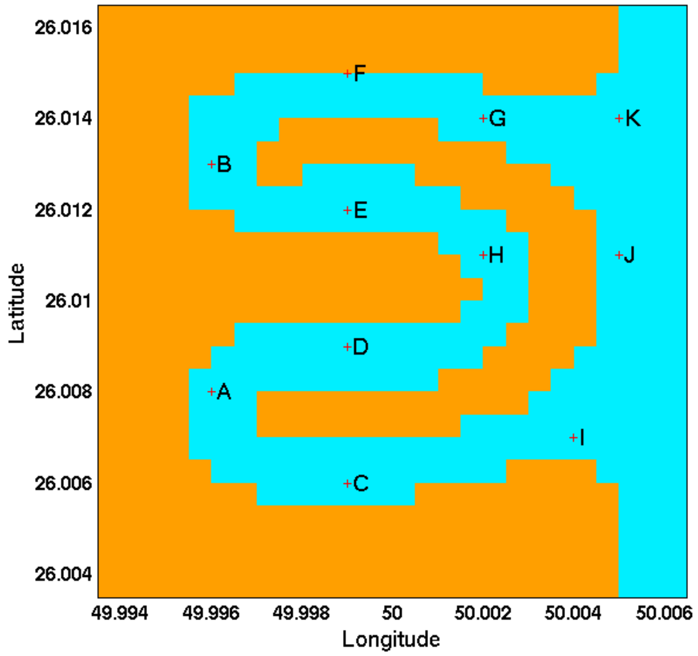

Figure 4a. Locations of the eleven profiling stations.

Vertical velocity profile of currents

The current velocity profiles (magnitudes as a function of water depth) at eleven profiling stations (Figure 4a) near the site are shown in Figures 5a to d. The advantage of such profiling leads to an understanding of the vertical distribution of velocities. As can be seen from these figures, the vertical profiles show difference among the 11 locations.

A comprehensive analysis of the velocity profiles (Figures 5a to d) shows that the domination current directions are either eastward or northward. This may not lead to stagnation of water mass in the construction site. The magnitudes of surface currents are shown as velocity contours for four months in Figures 6a to d. The

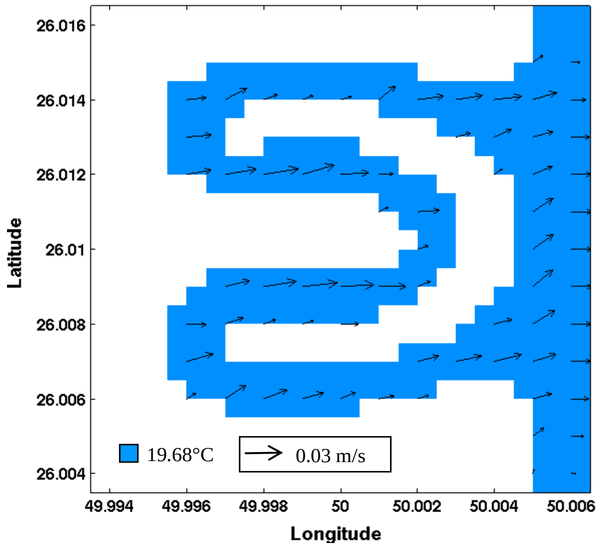

Figure 4b. Surface circulation for the month of January.

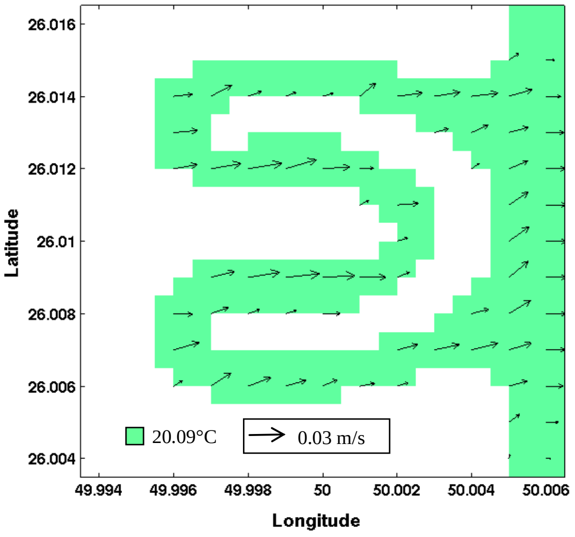

Figure 4c. Surface circulation for the month of April.

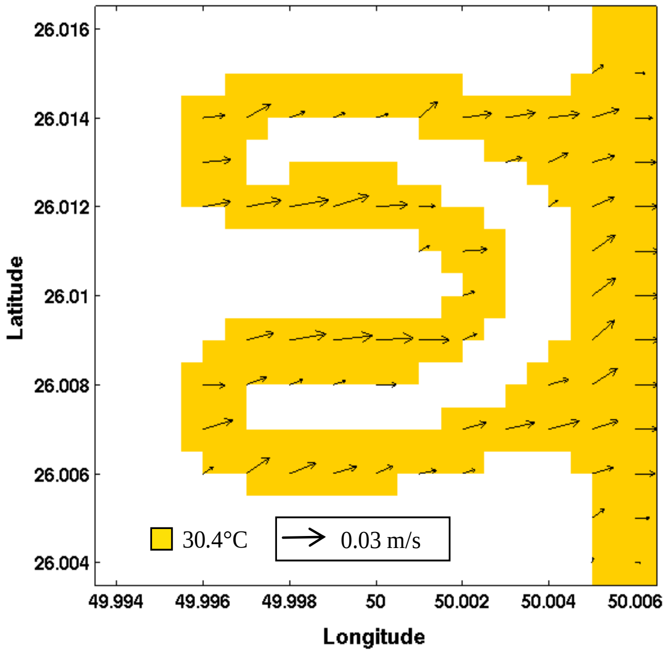

Figure 4d. Surface circulation for the month of July.

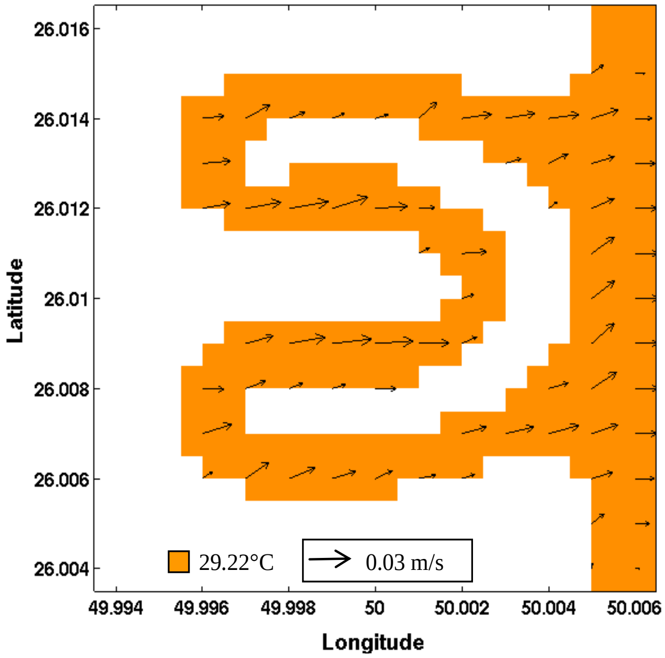

Figure 4e. Surface circulation for the month of October.

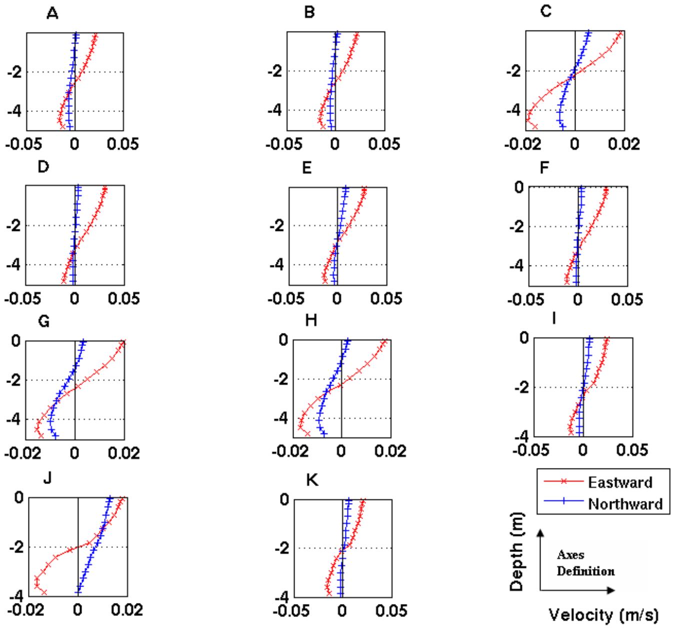

Figure 5a. Vertical velocity profile for the month of January.

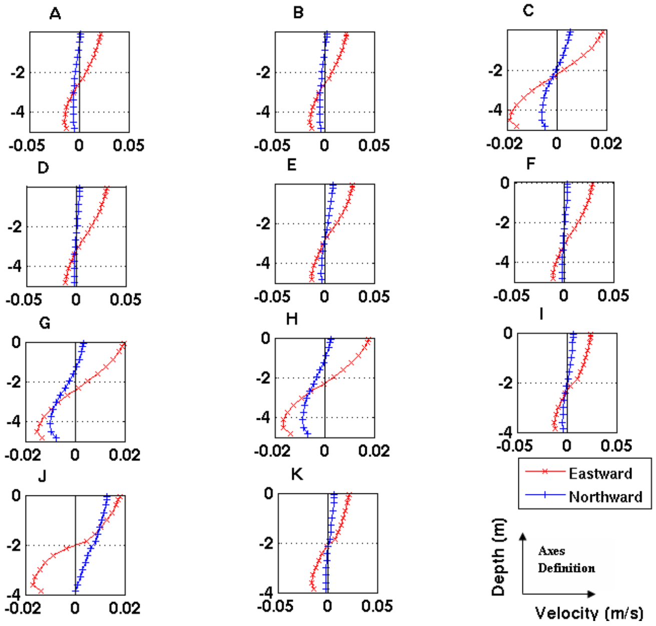

Figure 5b. Vertical profile of velocity for the month of April.

variability of current magnitude are seen along the 11 representative locations, however the seasonal difference is marginal. More details are tabulated and shown in Table 1. The dominance of eastward component is seen compared to the northward component suggesting that the net flow will not result in water stagnation.

Conclusions

The primary goal of the present study was to investigate the net flow field of waters near-shore Dannat area of Halfmoon Bay, Kingdom of Saudi Arabia. After the re-filling process of dredged sediments, an artificial island is expected near the coast for various activities. The circulation aspect relevant to this change of natural

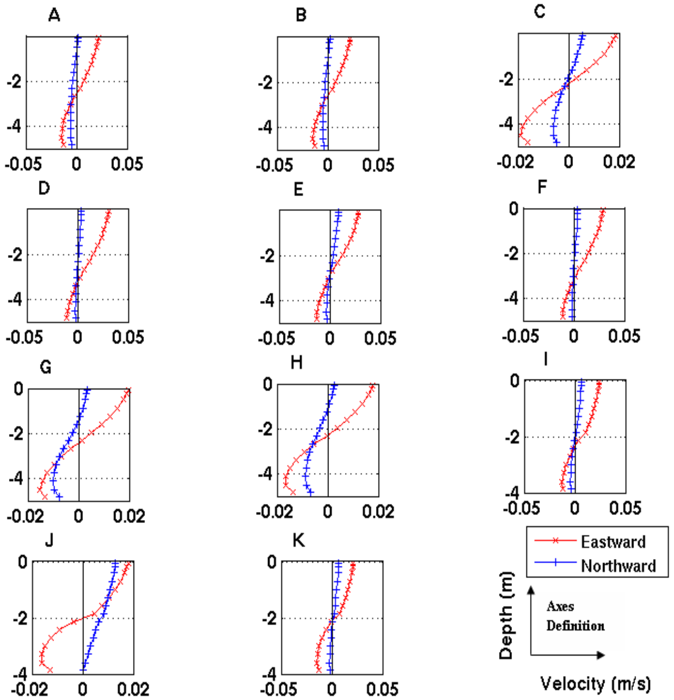

Figure 5c. Vertical profile of velocity for the month of July.

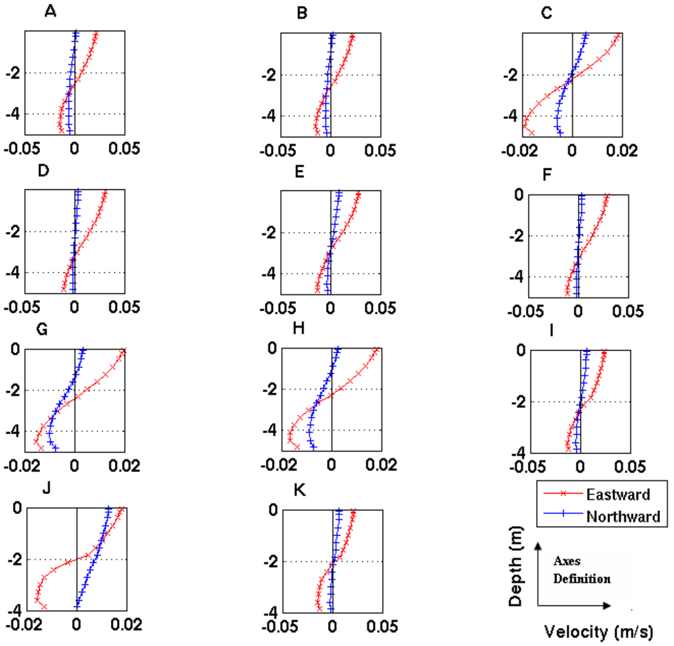

Figure 5d. Vertical profile of velocity for the month of October.

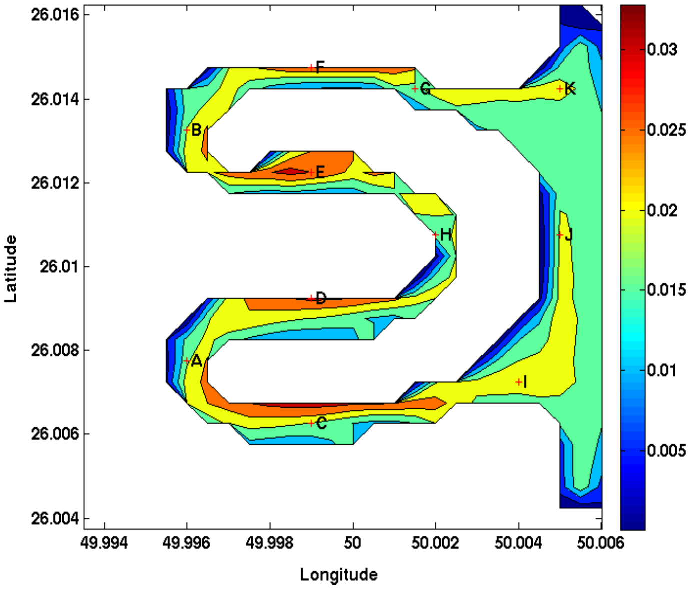

Figure 6a. Magnitude of surface current for the month of January.

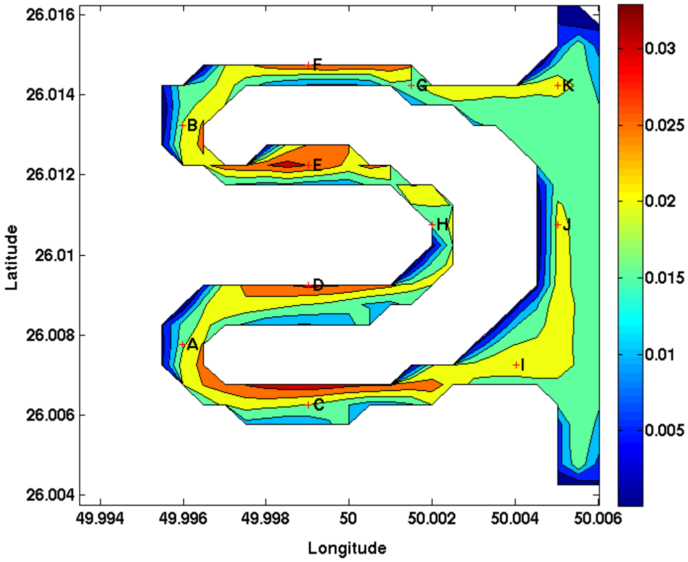

Figure 6b. Magnitude of surface current for the month of April.

system arising from re-filling and construction activity has been studied. The simulated current velocities are in the order of 0.03 m/s. The persistence of such currents along with net eastward transport direction can produce reasonable circulation to prevent water stagnation in the eventuality of construction activity at Halfmoon Bay, Kindgom of Saudi Arabia.

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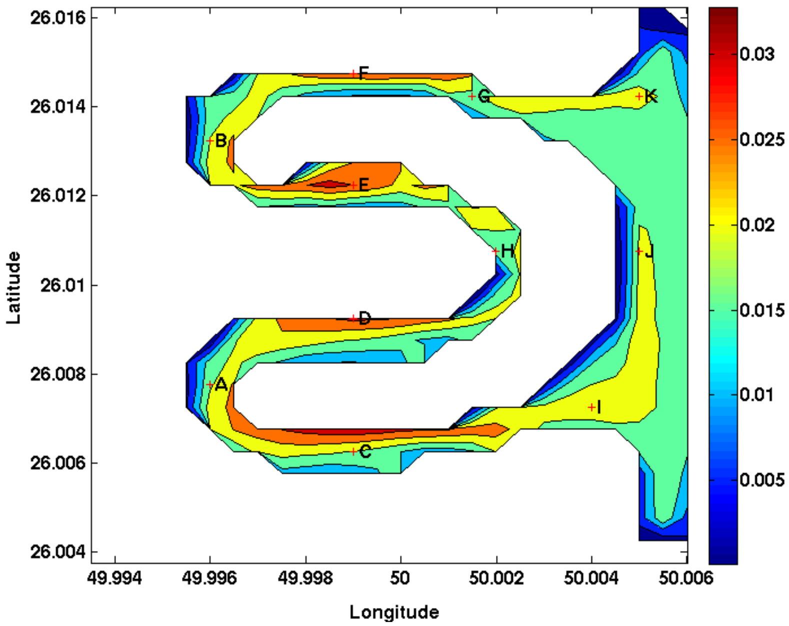

Figure 6c. Magnitude of surface current for the month of July.

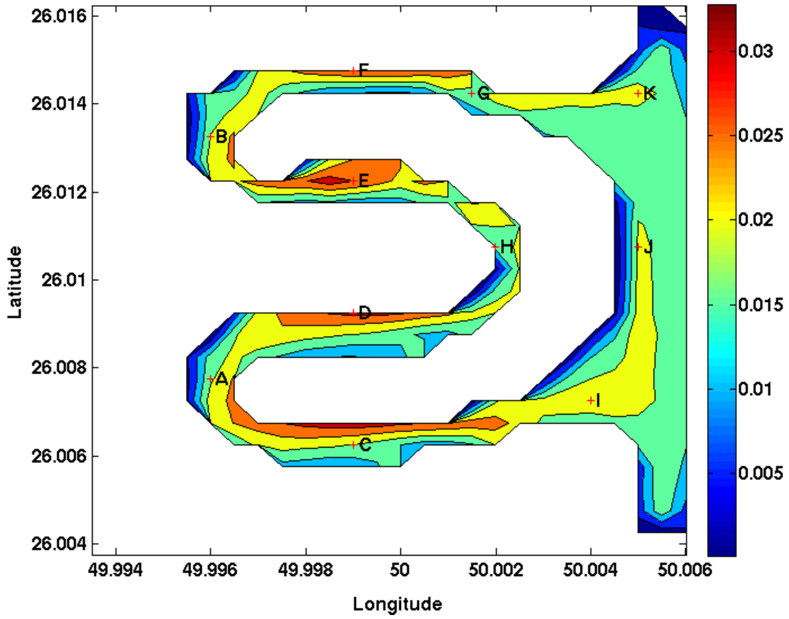

Figure 6d. Magnitude of surface current for the month of October.

Table 1. Computed surface flow field at four different months.

Month	Current-magnitude (m/s)		U-component (m/s)		V-component (m/s)	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
January	0.00	0.0328	-0.0238	0.0322	-0.0126	0.0155
April	0.00	0.0329	-0.0238	0.0323	-0.0127	0.0155
July	0.00	0.0328	-0.0238	0.0322	-0.0127	0.0155
October	0.00	0.0328	-0.0238	0.0323	-0.0126	0.0156

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