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Investigation for hydrodynamic processes of water in Khour Al-Zubair Port using hydrodynamic model

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ABSTRACT

The hydrodynamic model for Khour Al-Zubair port was introduced using the Mike 21 Flow Model FM. 2D numerical model using continuity equations and the Navier-Stokes equation to simulate hydrodynamic characteristics. Field data were collected over two different periods and on a complete tidal cycle (13 h). The model was run from October 15 to December 15, 2020, with a time step (10 sec) based on water levels and wind data. Calibration and validation of the model are evaluated based on statistical criteria (Root Mean Square Error "RMSE", Mean Absolute Error "MAE" and correlation coefficient "R"). Depending on the values of the statistical criteria, it can be said that the results of the model were encouraging as the difference between the measured, and calculated data is not perceptible. Moreover, the results showed the behavior of tidal currents for one day of a complete cycle and the velocity of the flow in the ebb state, causing the accumulation of pollutants in the area more than in the flood state.

1. Introduction

Hydrodynamic modelling is the study of moving fluids; due to interest in the global economy and its remarkable development, it was necessary to expand and develop hydrodynamic studies on the economic facilities in the country, including ports that are an indispensable economic tributary. This development led to an increase in the use of numerical models to simulate the phenomena of nature in a better form and rely on them for decision-making. Ports are exposed to future changes in natural processes that may occur over time; for this reason, simulation models have become so important. One of these programs with the same great potential in numerical models is MIKE 21 Flow Model FM. It's developed by the Danish Hydrodynamic Institute (DHI). MIKE 21 is a valuable tool in future pollutions management such as sediment, oil spill, particle tracking module …etc. [1]. Studying the hydrodynamic characteristics of coastal waters using numerical modelling provides the possibility to examine and analyze problems and hazards with the least amount of error. It also allows them to change the input parameters and observe the consequences [2]. The behaviour of the hydrodynamic processes of coastal waters should be understood in these areas from deposition or erosion. Furthermore, hydrodynamic characteristics control the exchange of water masses along with the vertical and horizontal directions through blending between different water masses and govern the transfer of pollutions, waves, sedimentations, water level ris etc. [3]. Khour Al-Zubair water was a lagoonal environment or a negative estuary because the salinity reaches as much as 47 parts per thousand in summer months [4] Khour Al-Zubair can be considered a hypersaline lagoon according to [5]. Their definition of hypersaline lagoons is salinity higher than 40 −50 parts per thousand. After the opening of the Shatt Al-Basra artificial channel in 1983, freshwater reached Khour Al-Zubair from the Euphrates River through this channel, where the environment of Khor Al-Zubair became a positive estuarine environment. Main Outfall Drain (MOD) was connected to the Shatt Al-Basrah channel at km 10 from the canal head in 1993; the connection with the Karmat Ali River was closed. The MOD canal, which contains the water of the drained regions, is agricultural water with drainage through the Shatt Al-Basrah canal, which is then discharged towards the Arabian Gulf through Khour Al-Zubair [6]. The seawater of Khour Al-Zubair is prevented inter to the Shatt Al-Basrah channel during the flood tide; the flow in the channel was controlled by a regulator (Shatt Al Basrah regulator). In 2003, after the Third Gulf War, the

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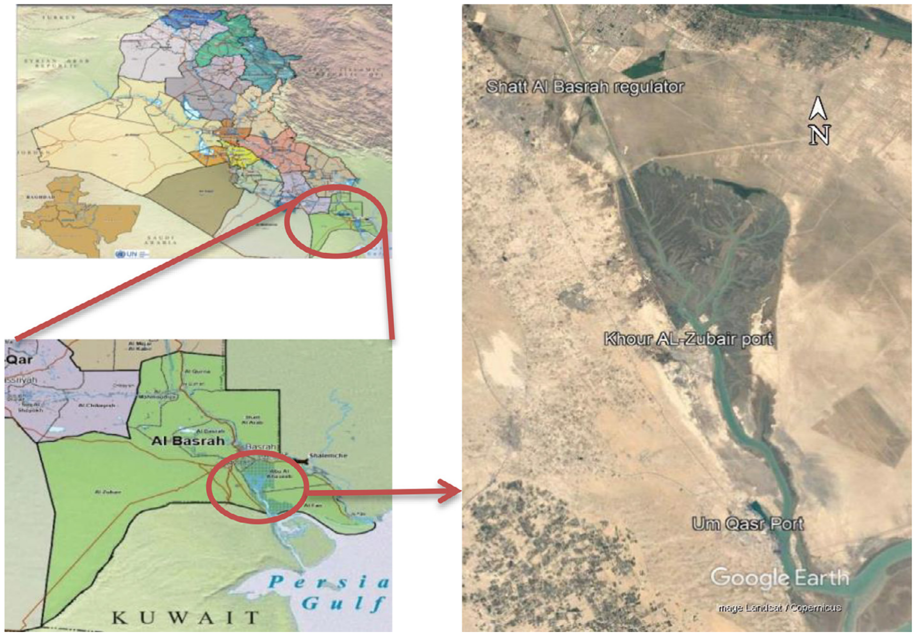

Fig. 1. Study area in reference to the map of Iraq [9,10].

regulator was bombed and became the Shatt Al-Basrah channel, and the MOD is the same environment. In late 2008, the broach was storm-water opening from the Nasiriyah city to the MOD by discharge 60 m^3/s [7]. So, Iraqi ports have special importance; therefore, it was directed the study to solve structural problems related to it, and to analyze these problems, it was necessary to study the hydrodynamic processes at the beginning. The objective of the study is to prepare a hydrodynamic modal for Khour Al-Zubair Port by using Mike 21 Flow Model FM that can be used in investigating the attitude of hydrodynamic characteristics of the port.

2. Study area

Khour Al-Zubair Port lies 60 km to the south of Basrah City centre southeastern Iraq and 105 km from the north end of Arabian Gulf, the port located in Khour Al- Zubair estuary. Khour Al-Zubair Port is the second largest port in Iraq. There are 13 berths and piers in the port that are commercially used. Two open boundary conditions in the study area. The lower boundary is Umm Qasar port about 20 km south of the port and the upper boundary is Shatt Al Basrah regulator about 25 km north of the port (Fig. 1). The depth of water ranges between 10 and 20 m of the navigational channel. The tidal regime in Khour Al- Zubair follows a mixed type, mainly semi-diurnal; there are two low and two high water daily [8].

3. Methodology

The main aim of the study was to investigate the hydrodynamic processes of the water in the Khour Al-Zubair Port using the hydrodynamic model. The performance of the hydrodynamic model can be evaluated in terms of an appropriate fit after a model structure is calibrated using the training time-series and other time-series for validation data set. Statistical criteria (Root Mean Square Error (RMSE) (Eq.1), Mean Absolute Error (MAE) (Eq.2), and correlation coefficient (R) (Eq.3) are used for evaluating the difference between the measured and calculated values [11].

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Xm,i - Xs,i)^2}{n}} \quad (1)$$

$$MAE = \frac{\sum_{i=1}^{n}|Xm,i - Xs,i|}{n} \quad (2)$$

$$R = \frac{\sum_{i=1}^{n}[(Xm,i - \overline{Xm})(Xs,i - \overline{Xs})]}{\sqrt{\sum_{i=1}^{n}(Xm,i - \overline{Xm})^2 \sum_{i=1}^{n}(Xs,i - \overline{Xs})^2}} \quad (3)$$

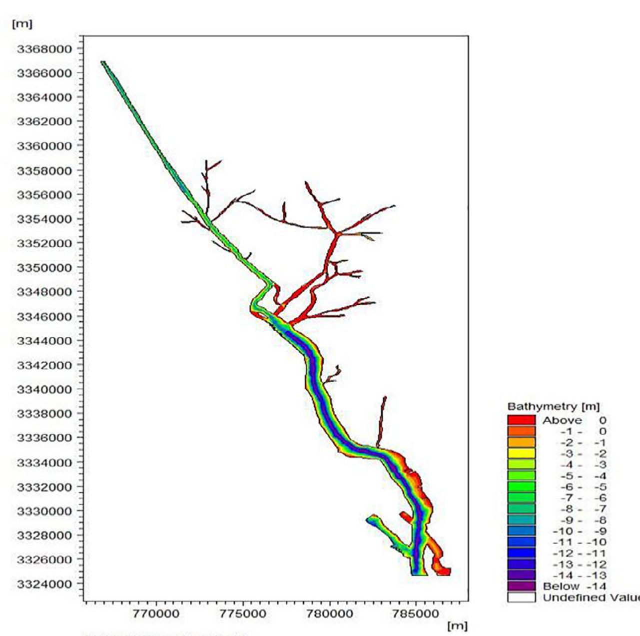

Fig. 2. Bathymetry of Study Area.

Fig. 3. Water level sensor.

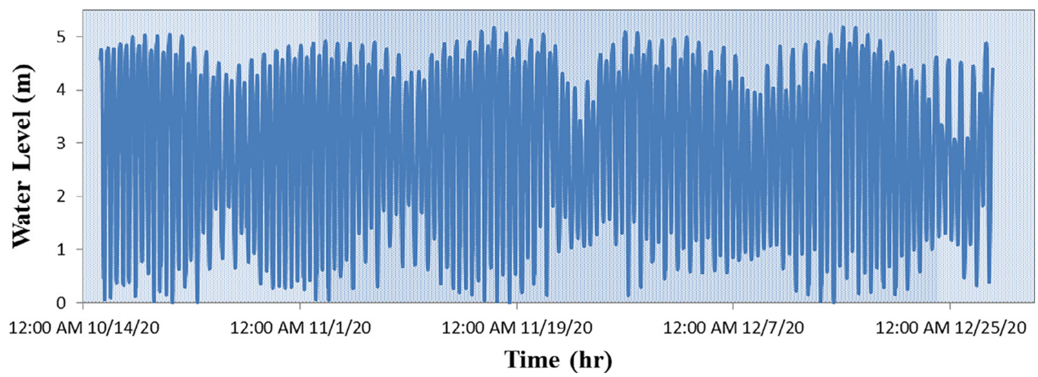

Fig. 4. Water level measurements at Shatt Al Basrah regulator.

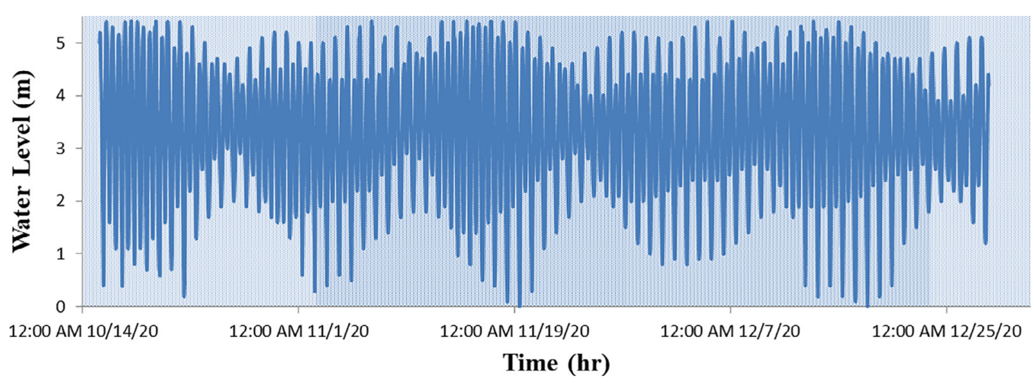

Fig. 5. Water level measurements at Umm Qasar Port.

Where:

Xm and *s* : The measured and simulated values respectively.

$\overline{Xm}$ and $\overline{Xs}$: The mean of measured and simulated values respectively.

n : The number of measured values.

Firstly, many of the data were collected, which include bathymetry, speed, and direction of the wind. And the data were measured which include water level, and flow velocity. Then, the tidal and wind data were used as input to the hydrodynamic model to simulate tidal currents in the Khour Al-Zubair port. Finally, the results of the hydrodynamic model were analyzed.

3.1. Bathymetric data

Preparing the model requires a satellite image map of known geographical dimensions (38 zones), then the map was linked to the survey files (Bathymetric data) obtained from the marine science center - Basrah university surveys conducted in 2006 [12], and the surveyed along Khour Al-Zubair and Shatt Al-Basrah canal that carried out by Tatweer Office to South Oil company Iraq [13] (Fig. 2).

3.2. Water-level data

The water level is measured (as time series) in three locations, the first one is located in the Shat Al-Basrah regulator, the second one at the Khor Al-Zubair port. The water level data are measured by installing a HOBO Water Level (100 feet) data recorder (Fig. 3a) [14], while the third one is located at Umm Qasar port, the water levels data in this site are measured by installing a Valeport Tide-Master Portable Tide Gauge with a pressure sensor (Fig. 3b) [15]. All these data are hourly recorded and referenced to the Lowest

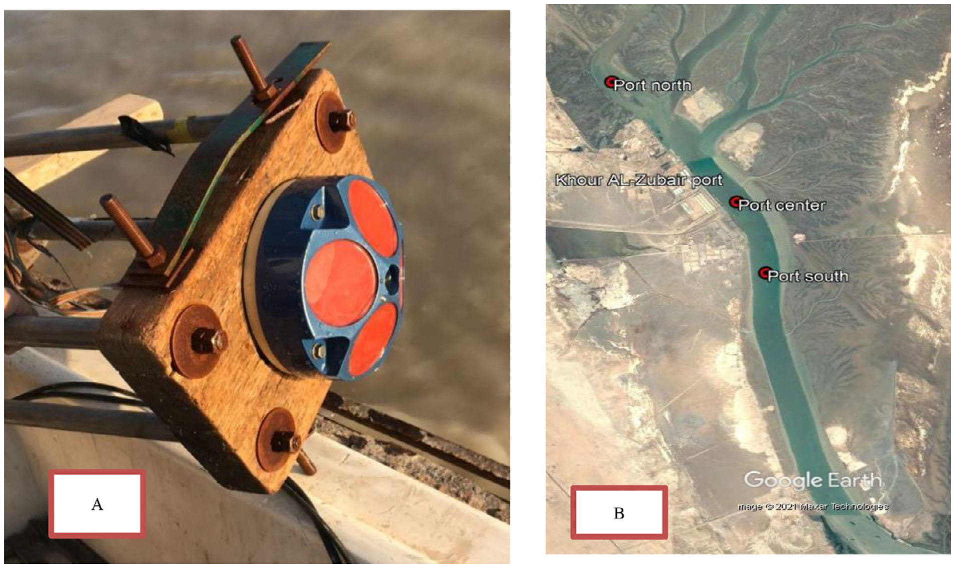

Fig. 6. Flow velocity measurements.

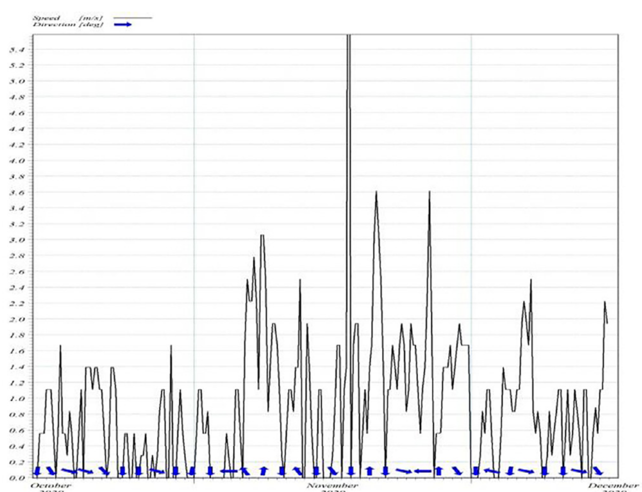

Fig. 7. Wind speeds at Khour Al-Zubair Port.

Low Water (local chart datum) in this region from October 15, 2020 to December 28, 2020. At upstream, a time-series file was created using data measured at the Shatt Al Basrah regulator (Fig. 4). At downstream, a time-series file for downstream water level was created using data measured at Umm Qasar port (Fig. 5).

3.3. Flow velocity data

The flow velocity was measured using the Acoustic Doppler Current Profilers (ADCP) technique, developed specifically to measure water current velocities and discharges based on the Doppler theory (Fig. 6A). This technique is a type of sonar that measures and records water velocities over a range of depths. The ADCP is now considered an essential tool for oceanography, estuary, river, and stream flow current measurement worldwide [16]. The flow velocity measurements were carried out at three stations, the first in the center of the port, the remaining two are north and south of the port with an hourly record on a full tidal cycle (13 h) for the period from 23 to October 25 and the period from November 30 to 4Dec. 2020 (Fig. 6B).

3.4. Wind data

The wind speed and direction were obtained from the Khour Al-Zubair Port authority [17] (Fig. 7).

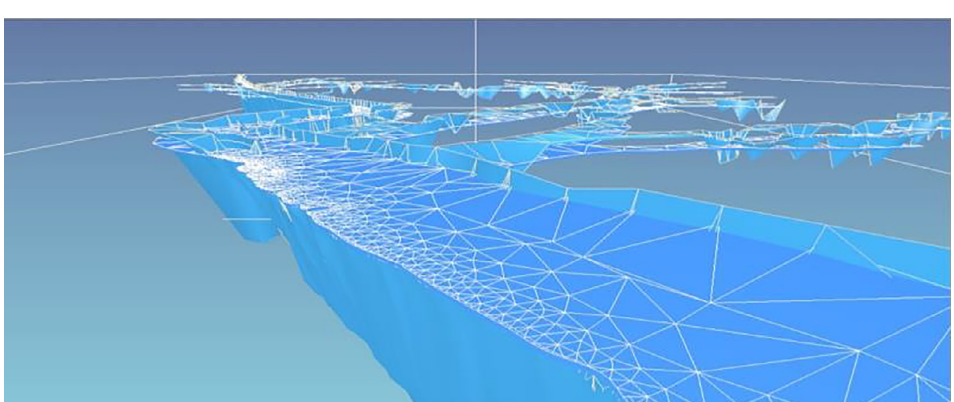

Fig. 8. Mesh generated for Khour Al-Zubair Port.

Table 1
RMSE, MAE, and R of hydrodynamic processes during the calibration period.

Hydrodynamic Processes	RMSE	MAE	R
Water Level at Port	0.452	0.360	0.954
Flow velocity at the center Port	0.422	0.355	0.961
Flow velocity at South Port	0.425	0.352	0.993
Flow velocity at North Port	0.301	0.231	0.967

3.5. Governing equations

The model is based on solving three-dimensional incompressible Navier-Stokes equations (Momentum Equations) and the continuity equation and they are written as follows [18]:

Continuity Equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=S \quad (4)$$

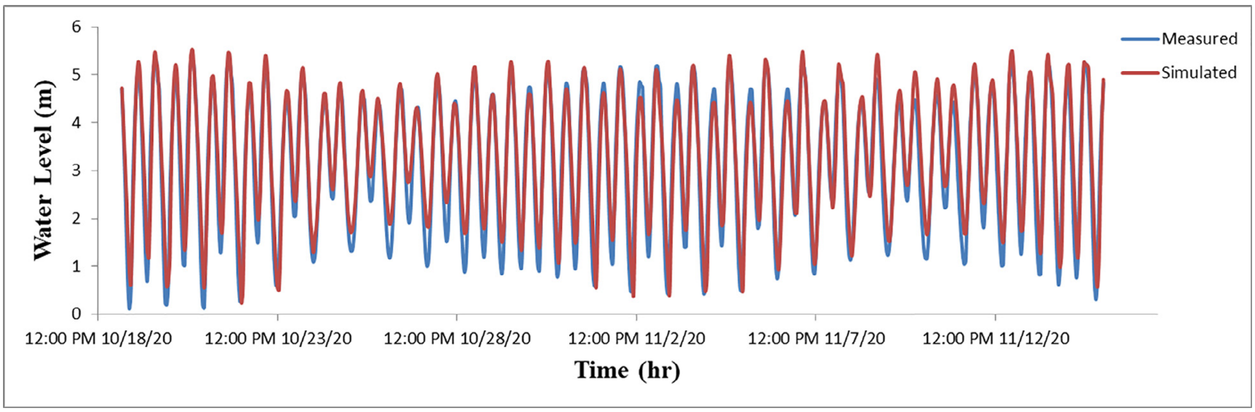

Fig. 9. Water level calibration between measured and simulated at Khour Al-Zubair Port.

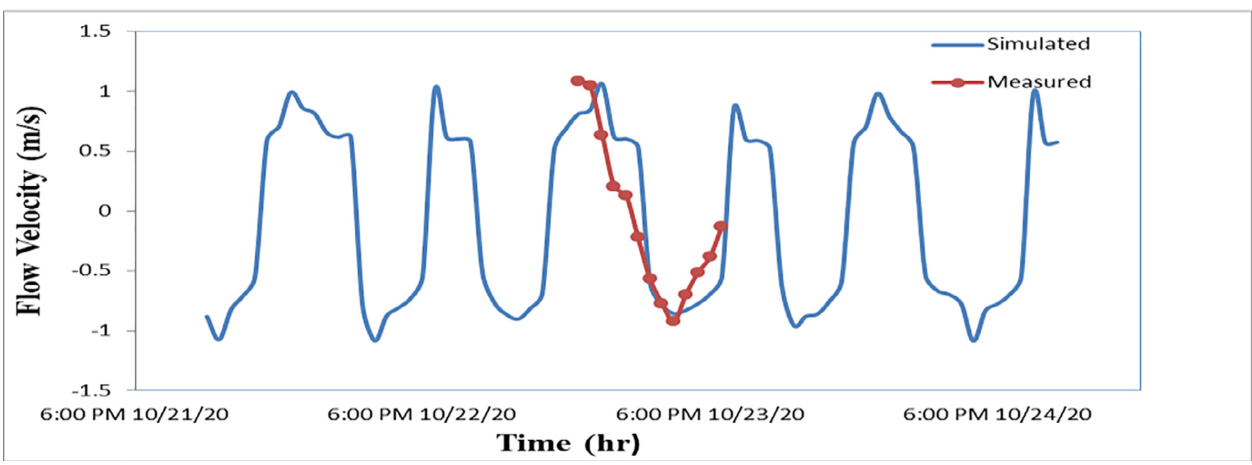

Fig. 10. Flow velocity calibration between measured and simulated at the centre Khour Al-Zubair Port.

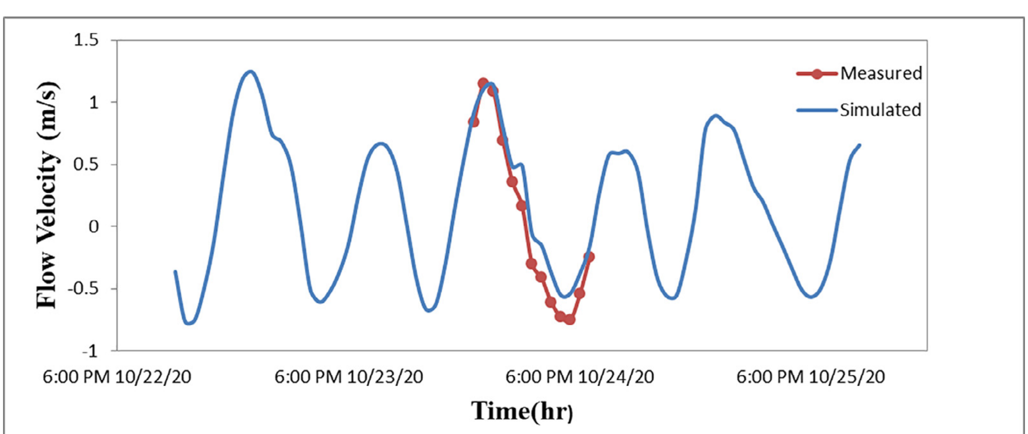

Fig. 11. Flow velocity calibration between measured and simulated at south Khour Al-Zubair Port.

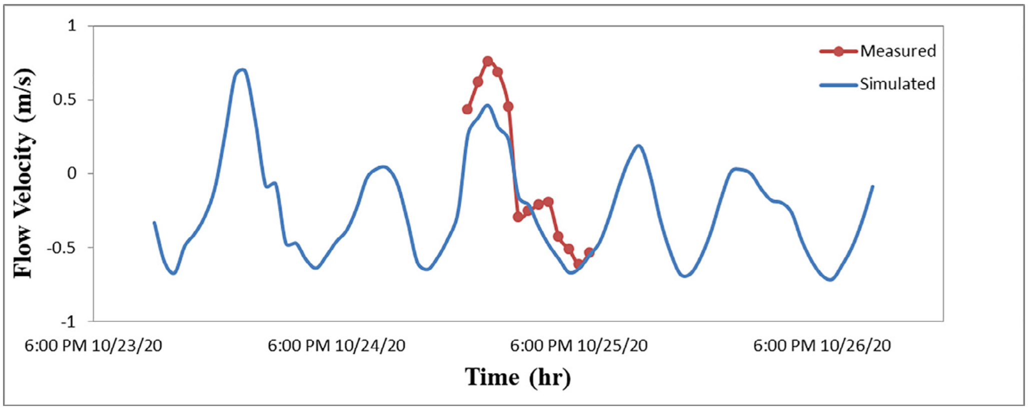

Fig. 12. Flow velocity calibration between measured and simulated at north Khour Al-Zubair Port.

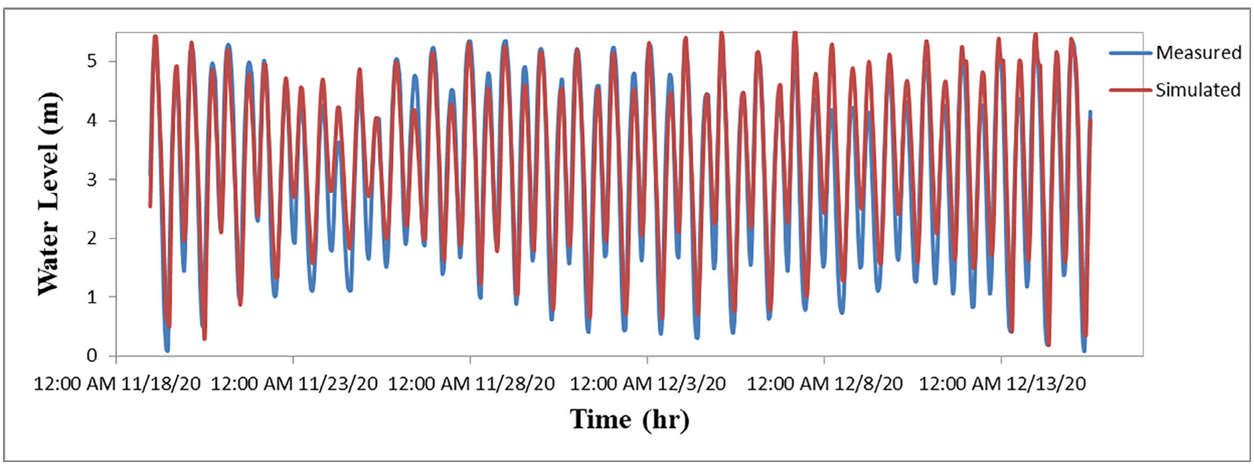

Fig. 13. Water level validation between measured and simulated at Khour Al-Zubair Port.

Table 2
RMSE, MAE, and R of hydrodynamic processes during the validation period.

Hydrodynamic Processes	RMSE	MAE	R
Water Level at Port	0.542	0.444	0.931
Flow velocity at the center Port	0.364	0.327	0.941
Flow velocity at South Port	0.482	0.405	0.952
Flow velocity at North Port	0.295	0.241	0.964

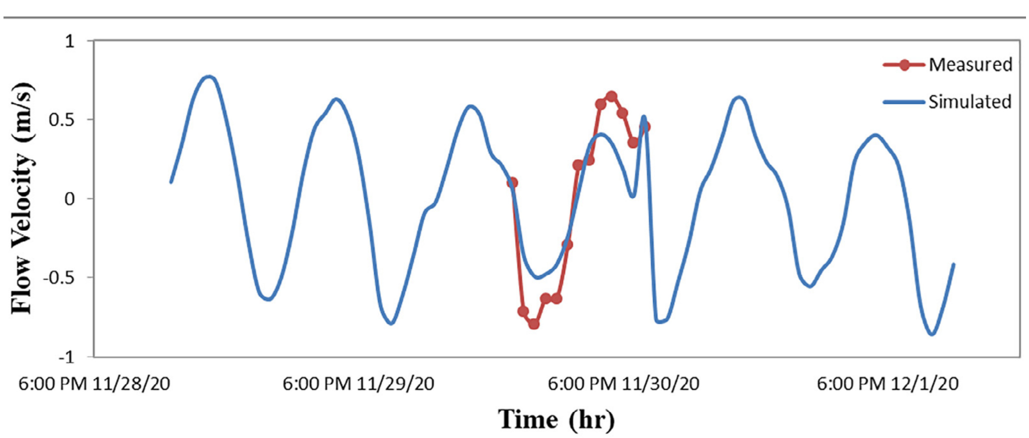

Fig. 14. Flow velocity validation between measured and simulated at the center Khour Al-Zubair Port.

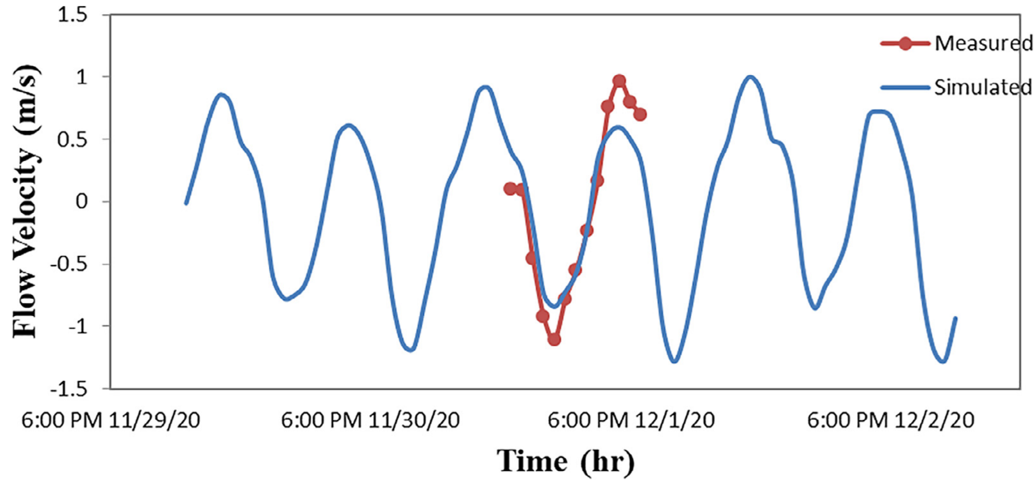

Fig. 15. Flow velocity validation between measured and simulated at south Khour Al-Zubair Port.

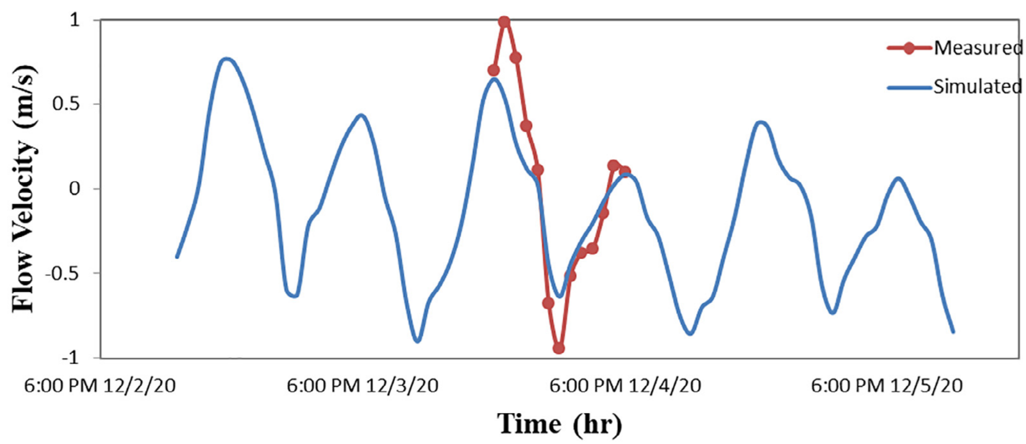

Fig. 16. Flow velocity validation between measured and simulated at north Khor Al-Zubair Port.

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial uv}{\partial y}+\frac{\partial uw}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\mu(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}) \quad (5)$$

$$\frac{\partial v}{\partial t}+\frac{\partial uv}{\partial x}+\frac{\partial v^2}{\partial y}+\frac{\partial vw}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\mu(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}) \quad (6)$$

$$\frac{\partial w}{\partial t}+\frac{\partial uw}{\partial x}+\frac{\partial vw}{\partial y}+\frac{\partial w^2}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \quad (7)$$

Where:
u , , and w : The instantaneous velocities in vertical and horizontal dimensions.
p : The water pressure.
ρ : The density.
μ : The viscosity coefficient.

In the Mike 21 flow model FM, many sorts of simplifications have been proposed, the most popular being the shallow water equations which Mike 21 flow model FM based on it [19].

3.6. Shallow water equations

The two-dimensional shallow water equation is obtained by averaging the three-dimensional Navier-Stokes equations over the depth. The new variables obtained are mean values over the depth which can be written as [19]:

$$U(x,y,t)=\int_{-h}^{z}udz, V(x,y,z)=\int_{-h}^{z}vdz \quad (8)$$

Where:
z : the free surface.
h : the bottom elevation.

The values of U, V, and h are calculated by solving the equations with a given initial and boundary conditions.

3.7. Numerical formulation

The numerical model is a finite volume scheme to the spatial discretization of equations using flexible mesh (FM) technique as an unstructured grid comprising of triangles [20]. An explicit scheme is used for the time integration and an approximate Riemann solver is used for computing the convective fluxes [19]. Fig. 8 refers to mesh generated.

4. Results and discussion

Hydrodynamics of the coastal waters especially the circulation pattern is a prerequisite to estimate the other processes of the

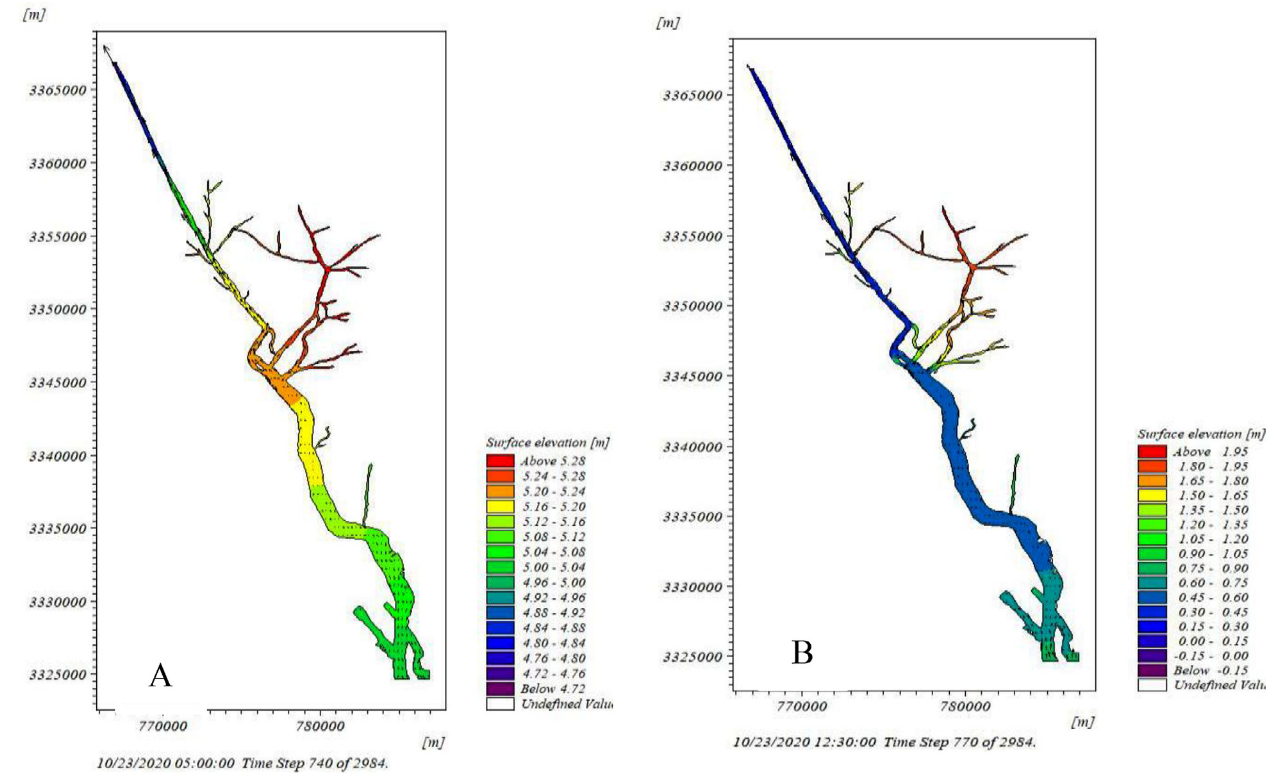

Fig. 17. Snapshots of the Flow conception during A- Ebb, B- Low Tide.

coastal waters. Circulation in coastal waters is subject to many influencing factors such as bathymetry, waves, tides, and wind stress [21]. In Khour Al-Zubair Port, tidal-driven circulation dominates the hydrodynamic processes behavior. For the present study, the hydrodynamic model was set up for two different periods (Spring & Neap). The model was calibrated and validated of water level in Khor Al-Zubair Port and flow velocity at all stations. The accuracy of the model is evaluated by RMSE, MAE, and R.

The model was run for two months covered the period of October 15 to December 15, 2020 with time step (Δt) equal to 10 sec. There are two parameters evaluated in the calibration process, Manning number (M) and eddy viscosity coefficient. The eddy viscosity coefficient νt can be specified by a time-varying function of the local gradients in the velocity field. This equation is based on the called Smagorinsky concept which yields [22]:

$$V_t = {C_s}^2\Delta^2\sqrt{(\frac{\partial U}{\partial x})^2 + \frac{1}{2}\left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x}\right) + (\frac{\partial V}{\partial y})} \quad (9)$$

Where:

Δ : The grid spacing

C_s : A constant between 0.25 and 1.

In the model, the constant is changed to obtain the best eddy viscosity coefficient for the area study. Whereas, there are no measurements for any of these parameters in Khour Al-Zubair Port. Measured data for the period (October 15 to November 15, 2020) was used in calibrating the model; this period represented the neap tide.

In the trial-and-error calibration process, the independent variables (Manning number (M) and eddy viscosity coefficient "constant Cs") of a model are adjusted manually, in successive model runs, to produce a reasonable match between the simulated and measured data. A trial-and-error calibration based on statistical criteria.

The values of Manning number (M) and eddy viscosity coefficient "constant Cs" are 51 $m^{1/3}$ /s and 0.26, respectively. These values representing the best values obtained for the study area, making the calculated values of water levels and velocity very close to the measured one.

The comparison between simulated and measured water levels at the port was referred to in Table 1 and Fig. 9, while Figs. (10 to 12) refer to the comparison between simulated and measured flow velocities at the center, north and south of the port with RMSE, MAE and R shown in Table 1.

The validation process for the water level and flow velocity with the same eddy viscosity coefficient "constant Cs" and Manning number (M) values obtained in the calibration process are used to validate the model. The period used for the validation process extended from November 15 to December 15, 2020. Fig. 13 and Table 2 refer to the comparison between simulated and measured water levels at the port, while Figs. (14 to 16) refer to the comparison between simulated and measured flow velocities at the center, north, and south of the port with RMSE, MAE and R referred to the Table 2.

Figs. 17 and 18 show the behavior of the tidal currents for one day of a complete cycle of ebb, low tide, flood, and high tide using two-dimension current velocity and direction patterns. The patterns show that the flow velocity continues in an ebb duration more than in a flood duration. The reason is that the ebb period is longer than the flood period than it causing the accumulation of pollutants in the area, and taking a long time to clean under the natural cleaning forces may worsen the situation and could make the port pollutants accumulate in the future. Where the ebb period was 7.30 h and the flood period was 5.45 h.

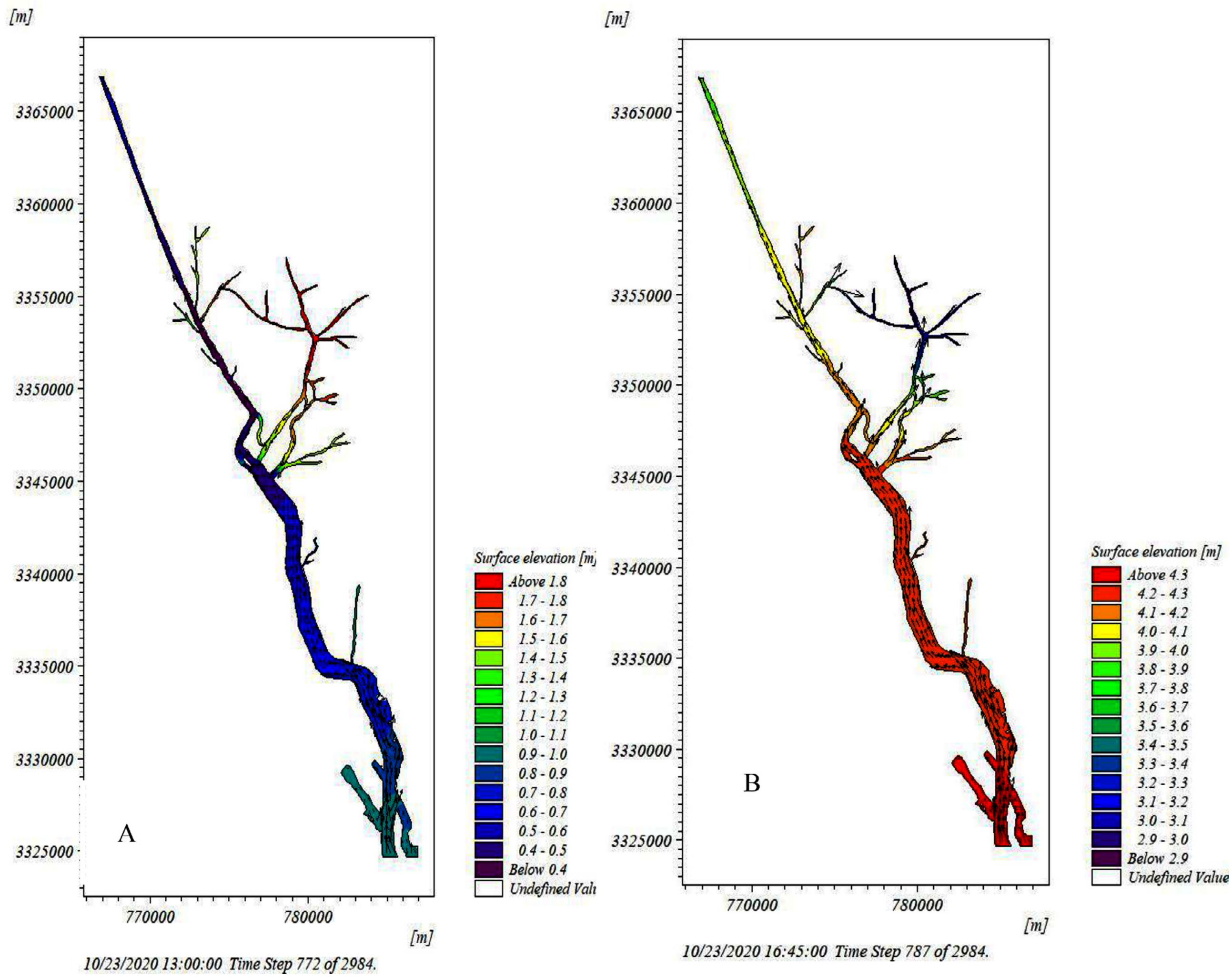

Fig. 18. Snapshots of the Flow conception during A- Flood and B- High Tide.

5. Conclusion

This study reached the following conclusion from the simulations using the Mike 21 Flow Model FM. First, the calibration and validation processes of the model results showed that there was almost no difference between the simulated data and measured data. Therefore, these processes confirmed that the model behaved well and ensured that it also operates on clean, correct, and valuable data. Second, the superiority of the flow velocity in the ebb state to flood state may be due to that the values of a Manning number 51 $m^{1/3}$ s^{-1} and the eddy viscosity coefficient "Cs" 0.26; this is evident even in the practical study.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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