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Assessment of Annual Sediment Load Using Mike 21 Model in Khour Al-Zubair Port, South of Iraq

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Abstract

Although estuarine locations provide natural safety and protection for the construction of harbours and other infrastructure, they are prone to natural filling due to sediment settlement. As a result, dredging is required regularly to keep navigation channels and harbours safe and functional. A numerical model has been developed in this study to compute annual sediment load in Khour Al-Zubair Port, South of Iraq, setting up a MIKE 21 FM model. MIKE 21 FM was developed by the Danish Hydraulic Institute (DHI) where provides the capability of simulation of a hydrodynamic model (HD) coupled with the mud transport model (MT). The model operates with an unstructured mesh of triangles and quadrilateral elements of different sizes. Field and experimental data were provided during two periods (Neap and Spring) for calibration and verification process. According to the sensitivity analysis results, it is clear that the settling velocity is an essential parameter. Based on the results of the calibrated model, there is annual sedimentation of 1220500.64 tons/year. The primary deposition took place in the meandering of the Khour Al-Zubair estuary and behind the piers.

Keywords: Khour Al-Zubair Port, Mike 21 flow model FM, Mud transport model, Annual sediment.

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1. Introduction

Given ever-increasing global trade, the international economy is inextricably related to the well-being of critical coastal facilities such as waterways and ports. Coastal areas account for about 70 % of the world's major cities, so it's critical to understand how coastal aquatic environments change due to sediment movement [1]. As a result of waves and tidal currents, harbours are prone to large sediment influxes [2]. The restricted water circulation in semi-enclosed coastal harbours may encourage sediment settling and deposit within the harbour basin [3]. Sediment build-up in harbours creates navigational and ecological issues, needing expensive dredging [4]. As a result, sedimentation in harbours is a severe issue and its assessment is critical for harbour management [5].

Sediment is a fragmented material derived from rocks generated by various physical and chemical processes and transported by water. Sediment transport is usually divided into two primary forms: bedload and suspension (Fig. 1) [6].

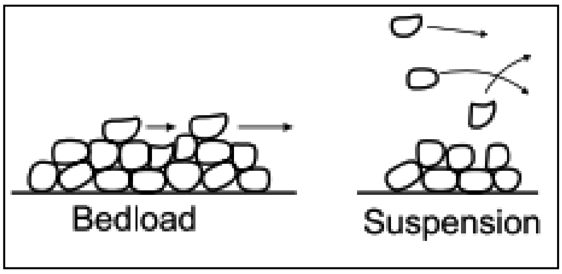

Fig. 1 Types of sediment transport [6].

Bedload transport is defined as the type of transport where sediment grains roll or slide along the bed. Suspended sediment is the fine sediment carried by the water column as suspension. It includes material picked up from the bed of the stream (suspended material) and material washed into the stream from the surrounding land (wash load). The wash load is usually more refined than the suspended bed material [7], [8].

Different researchers succeed to estimate annual sediment based on values of suspended sediment measured using numerical modelling. Thus, the technique shows high accuracy in predicting annual deposition.

Liiv and Liiv (2004) [9] studied sediment transport balance investigations for the Saaremaa harbour (new harbour) with MIKE 21 models. From the field measurement, data proved that the bottom of the harbour area is covered with a layer of sand that is 0.5 to 1.0 meters thick. MIKE 21 models showed the sediment transport in the harbour area is lightly changed by the presence of the quays, and investigations showed that there would be no need for maintenance dredging.

Stephensen (2016) [10] created a numerical model in MIKE 21 FM to determine the annual sedimentation within the Fan marina basin. The marina basin is approximately 21000 m^2. The model was calibrated with field data collected in the summer and autumn of 2015. The annual sedimentation rate was found to be 1980 ton/year.

This study aims to estimate the annual deposition in Khour Al-Zubair port, located in the Khour Al-Zubair estuary tidal area. Numerical modeling was performed using Mike 21 Flow model FM software.

2. Study area

Khour Al-Zubair Port is located in Khour Al-Zubair estuary, Basrah Province, Iraq. Khour Al-Zubair is an extension from the Arabian Gulf into the Iraqi lands (Fig. 2). It is influenced at its downstream boundary by the tidal phenomenon from the northwest of the Arabian Gulf, where the tidal range, during spring tide, reaches about 5 m. The tides in the Arabian Gulf and subsequently in the study area are generally described as mixed type with mainly semidiurnal [11].

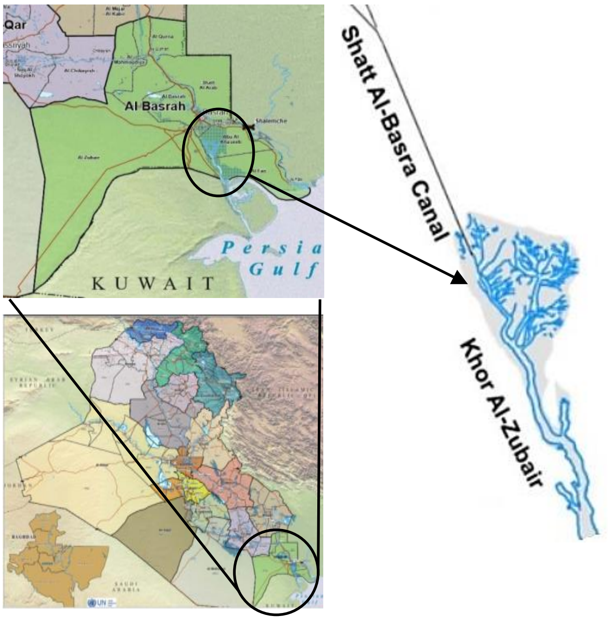

Fig. 2 Study area in reference to the map of Iraq [12], [13].

3. Method and materials

In this study, the MIKE 21 hydrodynamic model (HD) and Mud transport model (MT) are used to investigate Khour AI-Zubair Port. On-site Bed Materials sampling, water samples, water-level data, and geometric and hydraulic data measurements by using the ADCP technology to measure water velocity, discharge, area of cross-sections, top width, and water level during two periods (Spring & Neap) with an hourly record on a complete tidal cycle are gathered. DHI (Danish Hydraulic Institute) MIKE 21 FM models adapt the finite volume method to computational fluid dynamics, automatically satisfying the continuity equation. It has better adaptability for irregular boundaries by using irregular meshes [14]. FM refers to a flexible mesh, which means that the software operates with an unstructured mesh of triangles and quadrilateral elements of different sizes, this makes it possible to optimize the resolution in the area of interest while still holding the computation time on a reasonable level [15].

The inputs to the models can be divided into different groups, and an overview of the various model inputs and the following outputs are illustrated in Fig. 3.

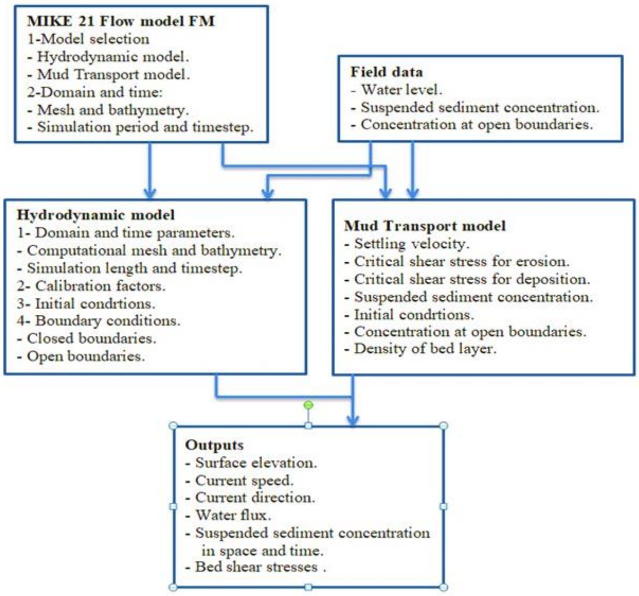

Fig. 3 Model inputs and outputs.

3.1. *Bathymetric Data*

Preparing the model requires a satellite image map of known geographical dimensions (38 zones). The map was linked to the survey files (Bathymetric data) obtained from the marine science center - Basrah University surveys conducted in 2006 [16], and the surveyed along Khour Al-Zubair and Shatt Al-Basrah canal that was carried out by Tatweer office to South Oil Company Iraq [17] (Fig. 4).

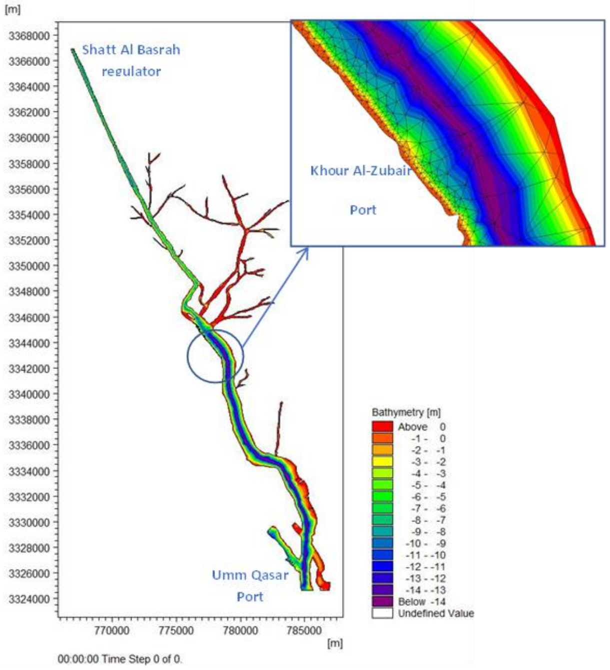

Fig. 4 Bathymetry of study area.

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, while the third one is located at Umm Qasar port. All these data are hourly recorded and referenced to the lowest low water (local chart datum). All these data were hourly recorded from 15 Oct 2020 to 28 Dec 2020.

3.3. Initial and Boundary Conditions

Initial Condition started with zero water level, and velocities called cold start. The study area has two open boundary conditions. The first is the lower boundary of Umm Qasar port, about 20 km south of the Khour Al-Zubair port. The second is an upper boundary of the Shatt Al Basrah regulator about 25 km north of the Khour Al-Zubair port; the rest was all solid. A time-series file was created upstream, using data measured at the Shatt Al Basrah regulator. The measured data at Umm Qasar port is used to create a time-series file for downstream water level.

3.4. Governing Equations

MIKE 21 FM models are based on shallow water equations and numerical solutions in two horizontal dimensions, taking the Reynolds averaged Navier-Stokes equations. Thus, the model vertically integrates continuity and momentum equations in two horizontal dimensions in the HD model. Integration of the horizontal momentum equations and the continuity equation over depth $h = \eta + d$, the following two-dimensional shallow water equations are obtained [18]:

Continuity Equation

$$\frac{\partial h}{\partial t} + \frac{\partial h\bar{u}}{\partial x} + \frac{\partial h\bar{v}}{\partial y} = hS \qquad (1)$$

Momentum Equations

$$\frac{\partial h\bar{u}}{\partial t} + \frac{\partial h\bar{u}^2}{\partial x} + \frac{\partial h\bar{v}\bar{u}}{\partial y} = f\bar{v}\,h - g\,h\,\frac{\partial \eta}{\partial x} - \frac{h}{\rho_\circ}\frac{\partial P_a}{\partial x} - \frac{gh^2}{2\rho_\circ}\frac{\partial \rho}{\partial x} + \frac{\tau_{sx}}{\rho_\circ} - \frac{\tau_{bx}}{\rho_\circ} - \frac{1}{\rho_\circ}\left(\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y}\right) + \frac{\partial}{\partial x}(hT_{xx}) + \frac{\partial}{\partial y}\left(hT_{xy}\right) + h\,u_S\,S \qquad (2)$$

$$\frac{\partial h\bar{v}}{\partial t} + \frac{\partial h\bar{v}\bar{u}}{\partial x} + \frac{\partial h\bar{v}^2}{\partial y} = f\bar{u}\,h - gh\frac{\partial \eta}{\partial y} - \frac{h}{\rho_\circ}\frac{\partial P_a}{\partial y} - \frac{gh^2}{2\rho_\circ}\frac{\partial \rho}{\partial y} + \frac{\tau_{sy}}{\rho_\circ} - \frac{\tau_{by}}{\rho_\circ} - \frac{1}{\rho_\circ}\left(\frac{\partial S_{yx}}{\partial x} + \frac{\partial S_{yy}}{\partial y}\right) + \frac{\partial}{\partial x}\left(hT_{xy}\right) + \frac{\partial}{\partial y}\left(hT_{yy}\right) + h\,v_S\,S \qquad (3)$$

Where:
t: Time.
x, y and z: Cartesian coordinates.
η: Surface elevation.
d: Still water depth.
h: Total water depth ($\eta + d$).
u, v and w: Velocity components in the x, y and z-direction.
f : The Coriolis parameter ($f = 2\ \Omega \sin\emptyset$) ($\Omega$ is the angular rate of revolution and $\emptyset$ the geographic latitude).
g: Gravitational acceleration.
ρ: Water density.
S_{xx}, S_{xy}, S_{yx} and S_{yy}: Components of the radiation stress tensor.
V_t : Eddy viscosity.
P_a: Atmospheric pressure.
$\rho°$: The reference density of water.
S: The magnitude of the discharge due to point sources and (u_S, v_S) is the velocity by which the water is discharged into the ambient water.

The sediment transport formulations are based on the Hydrodynamic module's advection-dispersion calculations. The following equation generally describes the transport of the mud [19]:

$$\frac{\partial \bar{c}}{\partial t} + u\frac{\partial \bar{c}}{\partial x} + v\frac{\partial \bar{c}}{\partial y} = \frac{1}{h}\frac{\partial}{\partial x}\left(h\,D_x\frac{\partial \bar{c}}{\partial x}\right) + \frac{1}{h}\frac{\partial}{\partial y}\left(h\,D_y\frac{\partial \bar{c}}{\partial y}\right) + Q\,C_L\frac{1}{h} - S_M \qquad (4)$$

Where:
$\bar{c}$: Depth averaged concentration.
u and v: Depth averaged flow velocities.
D_x and D_y: Dispersion coefficients.
h: Water depth.
Q: Source discharge per unit horizontal area.
C_L: Concentration of the source discharge.
S_M : Deposition/erosion term.

4. Results and discussions

4.1. Calibration and Verification Procedure

The performance of the Mike 21 FM 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 verification data set, after configuring all the files and sub-models required by the Mike 21 Flow Model FM program. The program was implemented for two different periods (Spring & Neap) and using the default values for the parameters that play an essential role in the calibration process, such as the Bed Resistance (Manning number) parameter and the settling velocity coefficient. Statistical criteria, such as root mean square error (RMSE), mean absolute error (MAE), and correlation coefficient (R) were used for evaluating the performance of the model.

The model has been calibrated and verified using water level, flow velocity, and total suspended sediment concentration in Khour Al-Zubair Port. Since flow velocity is the most affecting factor on sediments transport, for each section. The depth-averaged velocity values were compared with those predicted by running the hydrodynamic model. The model was run for two months covered from 15 Oct to 15 Dec 2020 with time step (Δt) equal to 10 sec.

Measured data for the period (15 Oct to 15 Nov 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 settling velocity coefficient ($W°$)) of a model are adjusted manually, in successive model runs, to produce a suitable match between the simulated and measured data. A trial-and-error calibration based on statistical criteria. The values of Manning number (M) and settling velocity coefficient ($W°$) are 51 $m^{1/3}$/s and 15, respectively. These values represented the best values obtained for the study area, making the calculated water levels, velocity and total suspended sediment concentration (SSC) very close to the measured one. The comparison between simulated and measured water levels, flow velocity, and total suspended sediment concentration at the port was shown in Figs. 5, 6, and 7 respectively, with RMSE, MAE and R referred to the Table1.

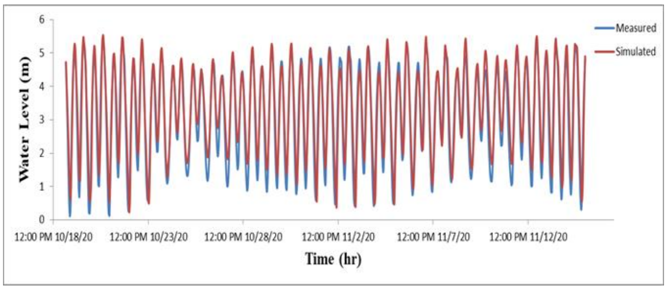

Fig. 5 Measured water level versus simulated water level at Khour Al-Zubair Port during calibration period.

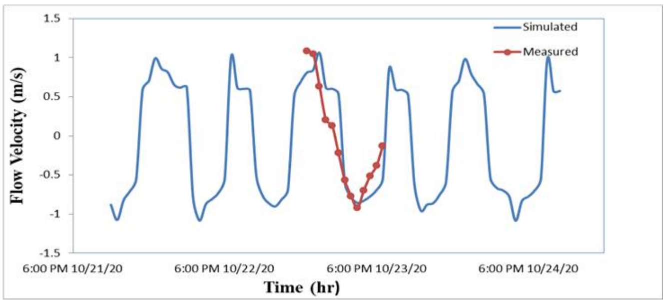

Fig. 6 Measured velocity values versus simulated velocity values at Khour Al-Zubair Port during calibration period.

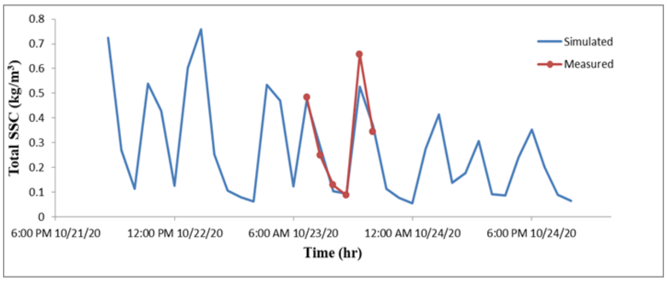

Fig. 7 Measured total SSC values versus simulated total SSC values at Khour Al-Zubair Port during calibration period.

Table 1. RMSE, MAE, and R of MT model during the calibration period.

Processes	RMSE	MAE	R
Water Level at Port	0.452	0.360	0.954
Flow Velocity at Port	0.422	0.355	0.961
Total SSC at Port	0.058	0.04	0.969

The verification process for the water level, flow velocity and total suspended sediment concentration with the same Manning number (M) and settling velocity coefficient (W_o) values obtained in the calibration process are used to verify the model. The period used for the verification process extended from 15 Nov to 15 Dec 2020, this period represented the spring tide. Figures 8, 9, and 10 refers to the comparison between simulated and measured water levels, flow velocity, and total suspended sediment concentration (SSC), respectively at the port center with RMSE, MAE, and R referred to the Table 2.

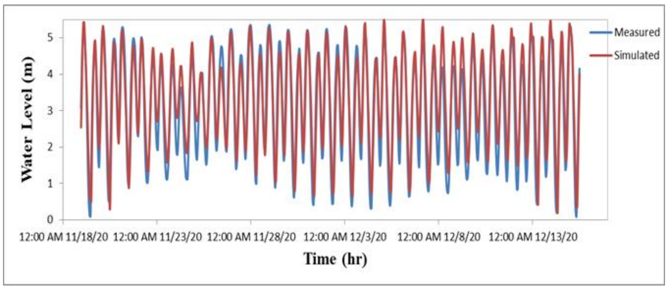

Fig. 8 Measured water level versus simulated water level at Khour Al-Zubair Port during verification period.

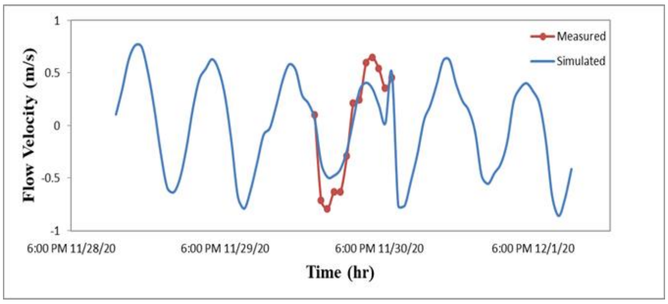

Fig. 9 Measured velocity values versus simulated velocity values at Khour Al-Zubair Port during verification period.

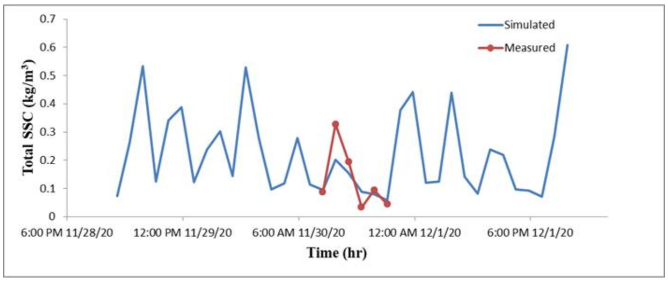

Fig. 10 Measured total SSC values versus simulated total SSC values at Khour Al-Zubair Port during verification period.

Table 2. RMSE, MAE, and R of MT model during the verification period.

Processes	RMSE	MAE	R
Water Level at Port	0.542	0.444	0.931
Flow Velocity at Port	0.364	0.327	0.941
Total SSC at Port	0.058	0.042	0.965

4.2. Sensitivity Analysis

4.2.1. The Effect of Manning Number (M)

The laboratory results of sieve analyses and hydrometer were showed that the soil is mud (silts, clays), and the suggested value to Manning number for this soil is 32 [20]. This value was increased by 25 and 50 percent to show the effects of varying M values on the current velocity and water levels. The effects of varying the Manning number values on the water levels and distribution of flow velocities are shown in the Figs. 11 and 12 respectively. Figure 11 shows that the water level values throughout the study area are insensitive to the variation of Manning number values. Figure 12 shows that there is a slight increase in the flow velocity with increasing Manning number at Khor Al-Zubair Port. The reason is that water depths in Khour Al-Zubair estuary are great; hence, the effect of bottom shear stresses is insignificant. Consequently, the increase of Manning number values will decrease shear stresses and increase flow velocities in the Khour Al-Zubair port. Moreover, the flow velocities with a negative value means that the load is opposite to the direction due to the tidal phenomenon.

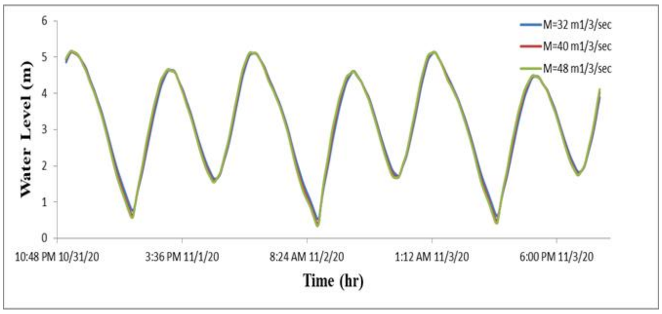

Fig. 11 The water levels at Khour Al-Zubair port were calculated with different Manning number values.

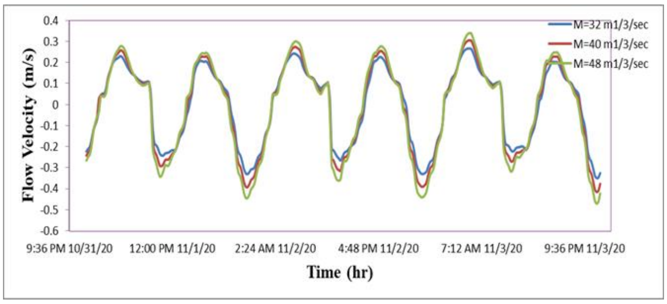

Fig. 12 The flow velocities at Khour Al-Zubair port were calculated with different Manning number values.

4.2.2. The Effect of Settling Velocity

A sensitivity analysis was carried out by running simulations using different settling velocity coefficients (W_o); adding/subtracting a constant value to the default value suggested by the MT model, different coefficient values were produced. The effects of varying settling velocity coefficient values on the suspended sediment concentration are shown in Fig. 13. It is clear that settling velocity is an essential parameter to determine the reliability of suspended sediment concentration results. It is seen that settling velocity will cause determined annual sedimentation quantities.

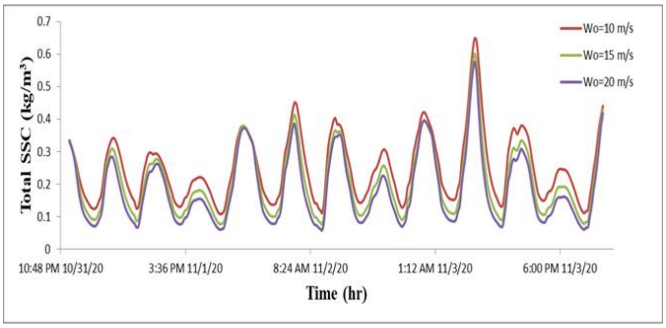

Fig. 13 Sensitivity analysis of different settling velocities coefficients at Khour Al-Zubair port.

4.3. Sedimentation Map

After the expiry of 60 tidal periods from 15 Oct to 15 Nov 2020, the sedimentation map is shown in Fig. 14, it can be seen that the simulated results correspond pretty well with the near areas in the port. Also, it is seen that the primary deposition is taking place in the meandering of Khour Al-Zubair estuary and that the sedimentation decreases gradually towards the north of the port. Furthermore, deposition takes place behind the piers and the branches formed opposite the port. This is also in accordance with local observations. It can be illustrated in Figs. 15 to 18. The sedimentation pattern is relatively complex due to different phenomena, such as the tidal cycle and horizontal circulation as flow separation, which are causing the high siltation. The model's annual sediment in the port is 1220500.644 tons/year.

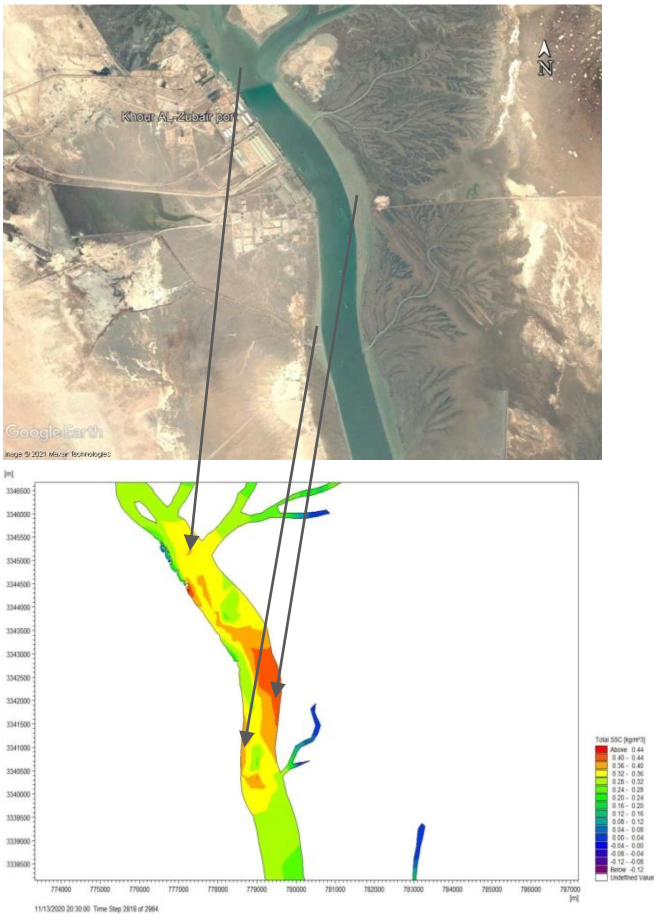

Fig. 14 Sedimentation map compared with Google Earth map.

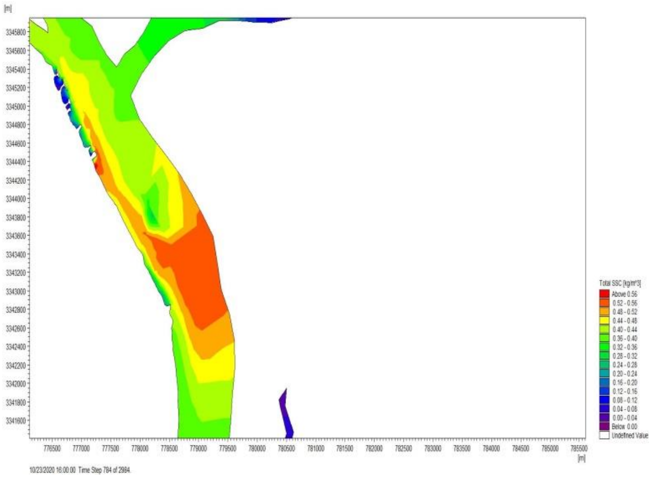

Fig. 15 Suspended sediment concentration +3 hours flood tide.

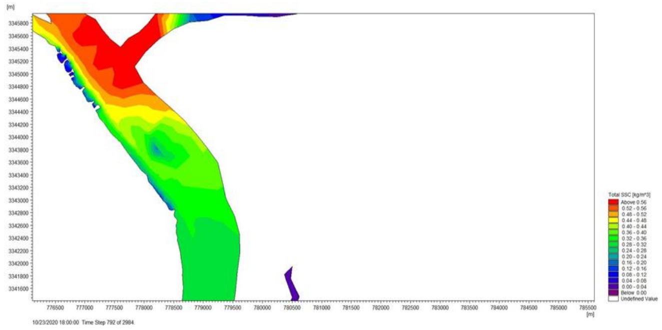

Fig. 16 Suspended sediment concentration +5 hours flood tide.

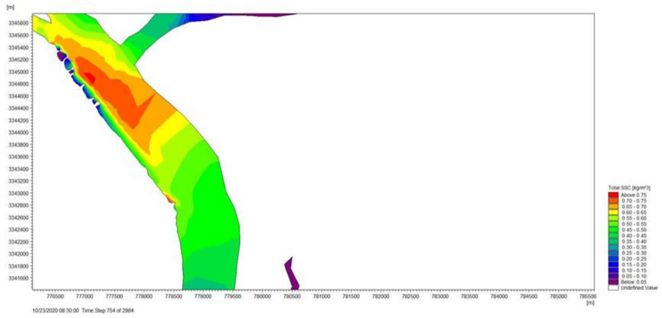

Fig. 17 Suspended sediment concentration +3 hours ebb tide.

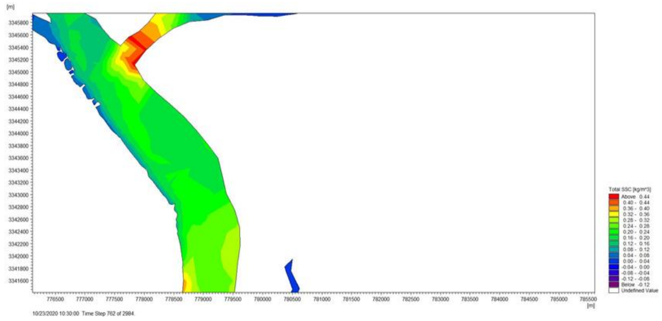

Fig. 18 Suspended sediment concentration +5 hours ebb tide.

5. Conclusions

The hydrodynamics and suspended sediment concentration measurements were conducted in the tidal period of Khour Al-Zubair port. Khour Al-Zubair Port is affected by the suspended sediments load in Khour Al-Zubair estuary, which mostly consists of clay and silt. The following conclusions are extracted through the field measurements and application of the Mike 21 Flow Model FM:

1. There was a good agreement between the measured and computed results by using Mike 21 Flow Model FM for flow velocity, water level, and suspended sediment concentration in the study.
2. A sensitivity analysis of the Manning number and settling velocity showed that the model results highly depend on these parameters.
3. Different phenomena, such as tidal range and horizontal circulation as flow separation, are causing the high siltation at Khour Al-Zubair estuary.
4. The predicted value of annual suspended sediment discharge in the study area is approximately (1220500.64) tons/year.

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