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Flushing Characteristics of a Marina Using a 2D Hydrodynamic Model: Case Study of The New Extension of Al-Wakrah Port, Qatar

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ABSTRACT

This study presents the hydrodynamic flushing modeling of the new extension marina at Al-Wakrah Port, Qatar. The planning of the extension must be carefully designed to guarantee the adequate circulation of clean water. So, water flushing problem concerns must be assessed. A 2D numerical model was utilized to simulate water circulation in the port under the natural forces of tide and wind. The model should assure that the extension plan of the port would not result in the development of stagnant water areas, besides ensuring efficient water exchange throughout the entire water system. Based on a flexible mesh model of the study area, the hydrodynamic and advection/dispersion modules of MIKE 21 have both been used to the investigation. The constructed model was applicable for the analysis of free-surface flows, hydrodynamic forces, and dispersion in the proposed marina layout. The hydrodynamic module used tidal and wind data to generate tidal currents in the marina basin. The results were used as input to run the advection/dispersion module that simulated the spread and movement of conservative tracer material. After 30 hours, the tracer concentration approaches 10% of its initial concentration. This indicates excellent flushing due to the higher exchange with the Arabian Gulf.

Keywords: Hydrodynamic model, Advection/Dispersion, Water renewal, Flushing time, Tidal flushing.

1 INTRODUCTION

The number of marinas has grown dramatically in recent years, since they are essential infrastructure for the recreational boating industry, a key activity of worldwide marine tourism that is in great demand. At local and national levels, the sailing sector has a significant positive impact on employment and economic growth [1]. Man-made maritime water areas such as harbors/ports/marinas must be carefully designed for their long-term development to guarantee natural water renewal and adequate tidal flushing. Activities related to sea ports, such as cargo loading/unloading, handling and storage, ship repairs, quay operations, the supplement of oil and fuel, etc., could be a source of multiple pollutants that could have a negative impact on the marine environment [2, 3].

Flushing in marinas and coastal lagoons are naturally powered by the tides and waves. The topography of the study area, as well as the regional wave and tide conditions, dictate their relative influence. The flushing will be mostly caused by the tide, and the level of the water system will oscillate within the range of the tide if the marina or coastal lagoon has broad entrances that are deep in comparison to the wave height and tidal range. On the other hand, the sea level elevation driven on by wave motion, such as wave breaking, is a key factor at shallow and narrow entrances.

During the planning and design stages, they should consider water quality issues in harbors/ports/marinas basins. Water exchange and circulation between port basins and surrounding coastal water are critical aspects of port design. Understanding the pattern of water circulation or flushing based on hydrodynamic processes could also be used for effective water renewal and self-cleaning [4, 5].

The flushing capacity of semi-enclosed aquatic environments, such as marinas, is influenced by water flow governed by tides, wind, wave climate, and ship movements. These parameters may predominate flushing mechanisms, one or more of them. Therefore, it may be represented using transport time scales definitions that explain physical transport and mixing processes [6]. Transport time scales have been extensively studied in ports (e.g. [7, 8]) by numerically modeling the transport of a hypothetical tracer.

Numerous research studies have been conducted regarding the hydrodynamic circulation and the timing of waters renewal in ports and coastal areas. This time, which range from time periods of less than a day to 10 days or even more, was determined for a wide variety of ports and harbors across the world. For example, water flushing of the inner basin of Boston's Harbor in the USA is achieved in 2 to 10 days [9], while it was achieved in 6 days for the port of Cabreras in Spain [10]. By using mathematical models and field observations, it was estimated that the renewal time for the waters of Nea Moudania Harbor (in the NW Aegean Sea) is 0.70 days [11]. A study of the tidal recirculation characteristics of a marina located in Kuwait Bay was found that the calculated flushing time of this marina was 6 days [12]. Furthermore, a hydrodynamic model Ahmed, 2022 [13] established to study the flushing characteristics within Al-Ain El-Sokhna Port Extension under the tide effect. Results showed that water exchange between the port and the Suez Gulf is not good as per available standards.

Water quality in ports has been explored in the literature using numerical models to achieve a sustainable marine and coastal environment. The creation and use of such models aid scientists and engineers in their search for alternate approaches to prevent or lessen unpleasant and detrimental environmental effects. The following are examples of the most relevant studies. Fountoulis et al., 2005 [14] developed a mathematical model to investigate the impact of establishing openings through breakwaters on port basin water quality. The flushing characteristics and effectiveness of Augusta Port, Italia, were analyzed by Lisi et al., 2009 [5] using a two-dimensional hydrodynamic model to explore the function of hydrodynamic action in self-cleaning the port basin from any pollutants. The effect of tide, current, and wave actions on the circulation pattern within a fisheries port was studied using a two-dimensional mathematical model to discover the optimal port layout by Jha et al., 2015 [15]. The hydrodynamic behavior of a Civitavecchia harbor, Italy, was studied by Bonamano et al., 2018 [16] to enhance water quality deterioration using the numerical model. Tolba et al., 2017 [17] used a numerical model to simulate the flow circulation patterns and tracking the pollutants transport in the Damietta port, Egypt. Galal et al., 2020 [18] carried out a comprehensive parametric analysis to provide a specific guideline for Improving water flushing in ports and marinas using numerical simulation.

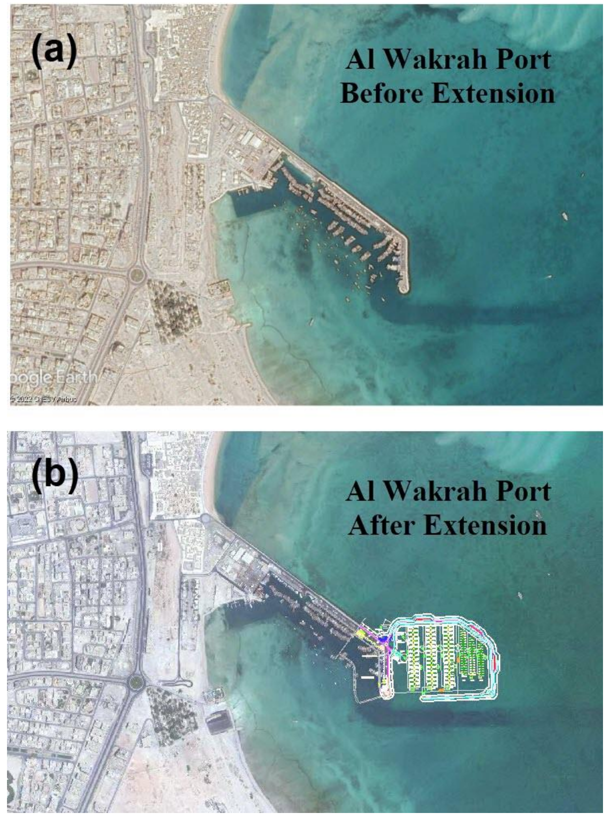

Figure 1: Study area of Al- Wakrah Port before and after the extension works.

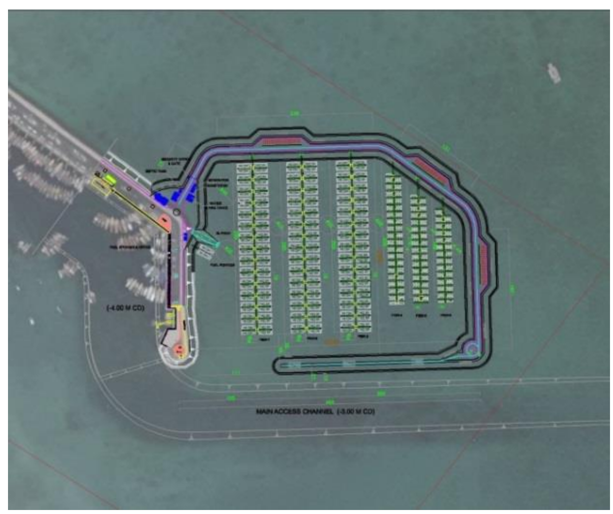

Figure 2: AL- Wakrah Port Extension Layout

Sharaan et al., 2022 [19] studied the tidal-induced water circulation pattern within EL-Burullus fishing harbor, Egypt, using CMS-PTM numerical modeling. Finally, Ahmed, 2022 [13] established a 2D hydrodynamic model to study the circulation patterns which were then used to estimate the flushing characteristics within Al-Ain El-Sokhna Port extension, Egypt, under the tide effect.

In this study, a new extension works for Al-Wakrah port, Qatar, has been carried out which occupies a total area of approximately 150000 square meters. Figure 1 shows the plan of the port before and after the extension development works, while Figure 2 shows the layout of the extension development works. The purpose for the extension works is to provide berthing facilities that shall meet to increase the public demand for the berthing facilities of small boats. It was required that the marina be designed so that flushing the water system using tidal forces alone is enough for cleaning the water system inside the marina with the highest possible efficiency. In these circumstances, it must be guaranteed that the proposed plan won't result in the formation of stagnant water areas, maintaining water exchange and circulation throughout the water system and preventing the creation of traps for floating debris and seaweed.

In order to avoid problems with water circulation and flushing during the Al-Wakrah Port extension works, a study will be conducted. Therefore, in this study, a numerical model will be constructed and utilized to simulate water circulation in the port under different conditions. The model should assure that the plan of the new extension would not result in the development of dead water areas.

2 THE STUDY AREA

The project is located at Al-Wakrah city in the Qatar peninsula at (25° 09' 37" N, 51° 37' 13" E). Port of Al-Wakrah is located, approximately 15 km south of Qatar's capital Doha. The port is located on a shallow and mild slope tidal beach located on the Arabian Gulf, known also as the Persian Gulf, as shown in Figure 3.

The Qatar Ports Gulf Management Company (MWANI) is carried out the extension works for Al-Wakrah port including the design, construction, install of berthing facilities (floating Pontoon), inclusive of all associated facilities and services in the Al-Wakrah Port. The objective of the project was to provide berthing facilities that shall meet to increase the public demand for the berthing facilities of small boats/dhow boats.

The new extension project occupies a total area of approximately 150000 m^2. The project consists mainly of the construction of approximately 1050 m of breakwaters with Armor rocks, which will be required to accommodate 450 boats. The dredging and reclamation works were needed to reach the seabed level with a depth of 2.0 m below the (CD) chart datum in the new marina.

3 METEOROLOGICAL CONDITIONS DATA

The present section aims to describe in detail the data of meteorological conditions and specify the dominating meteorological and oceanographic factors at the project site such as bathymetry, wind, and water levels. The baseline data collected from different sources including the purchased data from relevant agencies and data from previous studies and literature.

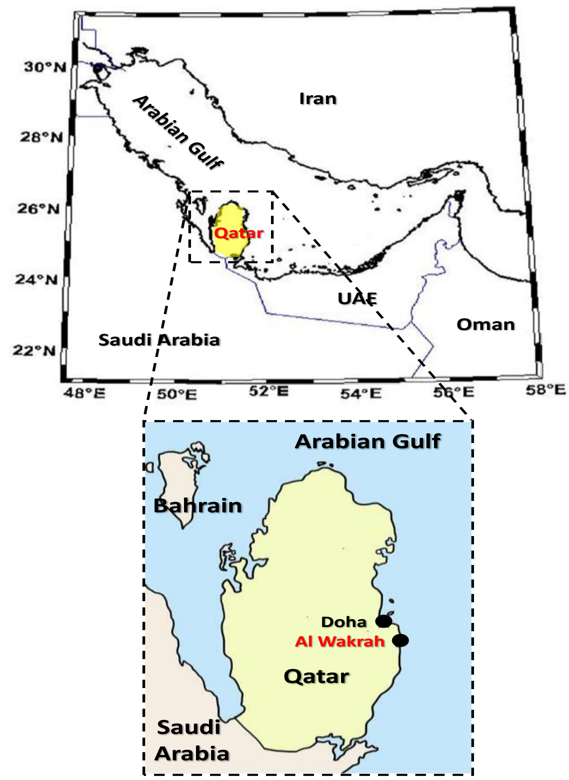

Figure 3: Location of the study area at Al- Wakrah Port, Qatar.

3.1 Bathymetric Data

The bottom topography of the Gulf is relatively shallow, with a maximum depth of 90~100 m in the Strait of Hormuz, and a mean depth of about 35 m. The deeper topographic features (> 50 m) in the region are found along the Iranian coast while the shallower areas (< 20 m) are found along the southwestern coasts as shown in Figure 4 [20 - 22]. The most important job in a modeling technique is to set up the bathymetry model [23]. Therefore, in this study, the seabed bathymetric data covers an approximate total area of 3.8 Km^2. The offshore bathymetry data utilized in this study was taken from Admiralty Chart No. 3950 for the Eastern Coasts of Qatar, which covers offshore region of the port and it was then digitized using the Mike21 bathymetry wizard. While, the nearshore seabed bathymetry at the port site was developed from bathymetry survey works carried out for the port extension works. All the bathymetric data mentioned above are gathered to get the final product of the 3D seabed with a resolution of 10 m in both directions was created in Grid Editor Wizard, as shown in Figure 5.

3.2 Water level Variations Data

Determination of the maximum and minimum expected water levels during the lifetime of the project is essential for both the construction and the operation of the project.

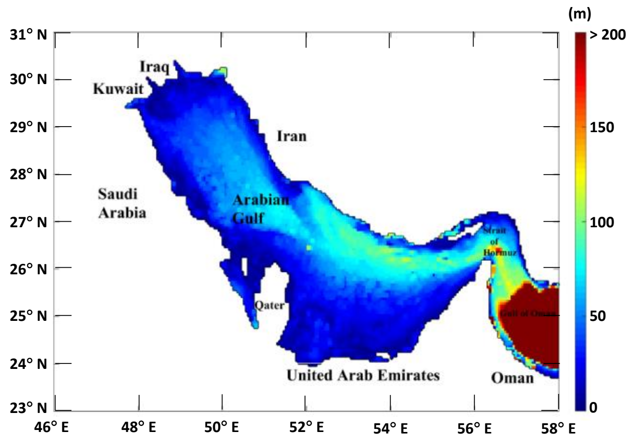

Figure 4: Map of the Arabian Gulf based on 'GEBCO_2021' global bathymetry datasets [22].

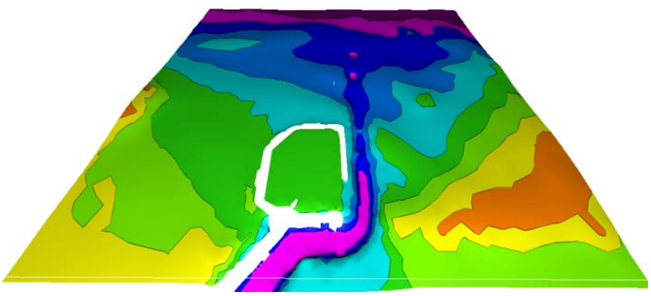

Figure 5: 3D Representation of the bathymetry of the modeled area

Tides in the Arabian Gulf are an important driving and it is to be oscillating at a period of 22.6 or 21.7 hours. Several studies were carried out in the Arabian Gulf to study the tidal conditions using tide gauge data [20, 22]. Tidal levels data at the project site was based on the time series of water levels variation obtained from the Admiralty Tide time series in year 2017 as shown in Figure 6 (The designs for this project were made in 2017, and at that time this was the latest data). It was found that the tide at the location of Al-Wakrah Port is mixed semi-diurnally. Table 1 summarizes the major historical tidal level characteristics at Al-Wakrah Port as calculated from the Admiralty Tide time series related to Admiralty Chart Datum (ACD).

Table 1. Historical tidal Levels at Al-Wakrah Port, Qatar

Tide Level	Level to ACD (m)
Highest Astronomical Tide (HAT)	+2.10
Mean Higher High Water (MHHW)	+1.50
Mean Lower High Water (MLHW)	+0.95
Mean Sea Level (MSL)	+0.90
Mean High Low Water (MHLW)	+0.80
Men Lower Low Water (MLLW)	+0.50
Lowest Astronomical Tide (LAT)	+0.00

1.1 Wind data

Wind data in this study was obtained from the database of Qatar Meteorological Department at the location of Al-Wakrah Port from two filed buoys. One of the buoys is located north of Qatar in open conditions with a long fetch at a depth of around 54 m. The other buoy has been deployed further south in the lee of the Qatar peninsula, in water depth of approximately 16 m.

The wind-speeds estimated at the 10 m elevation [21]. The recent study used the wind measurements which were obtained from January to December 2017 in time series-based data [24]. Figure 7 shows the time series wind speed and direction plot for the period from January to December 2017 at Al-Wakrah Port.

While Figure 8 provides the wind rose plot measured clockwise from the North direction. It can be seen that the predominant wind direction is coming from NNW. The average wind speed of about 4.0 m/s, while the wind gusts may reach a maximum of 14.4 m/s.

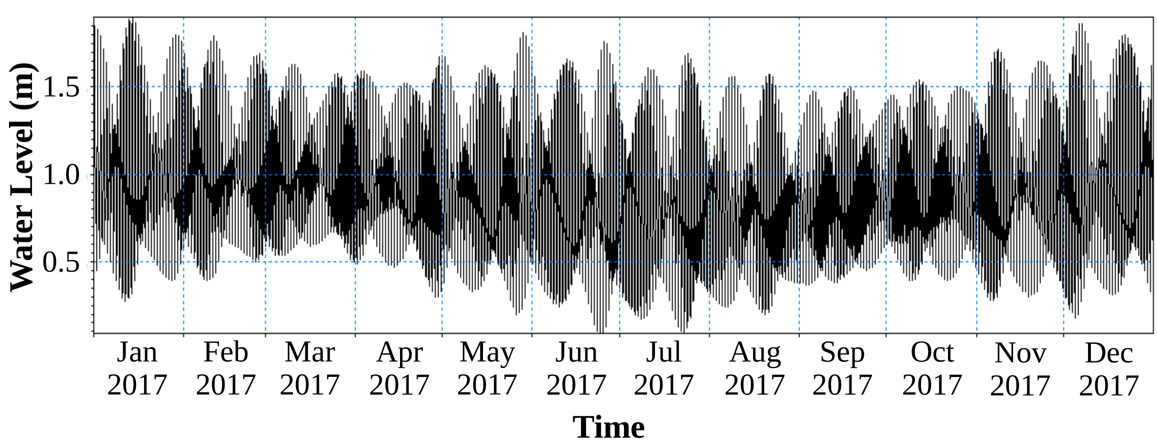

Figure 6: Measured tide levels provided from Admiralty Tide Time Series recorded from Jan. to Dec. 2017

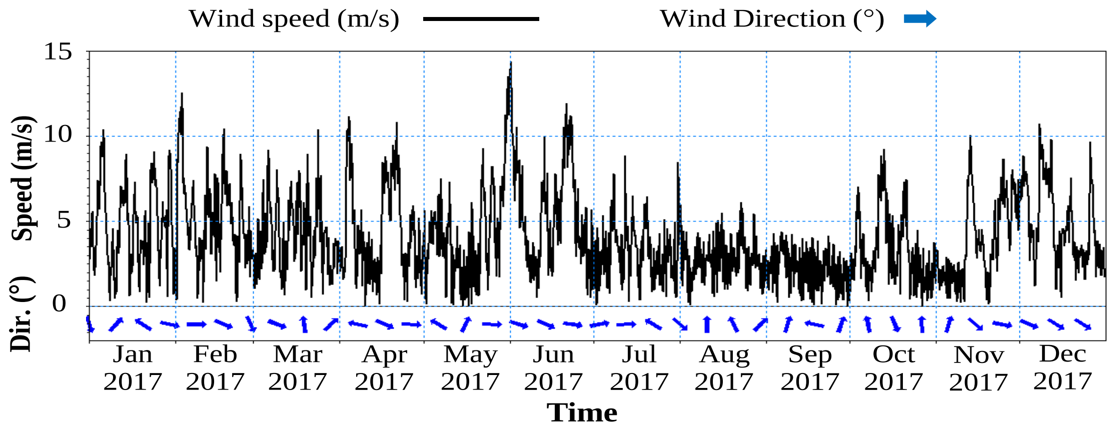

Figure 7: Wind conditions (speed and direction) at Al Wakrah Port measured from January to December 2017.

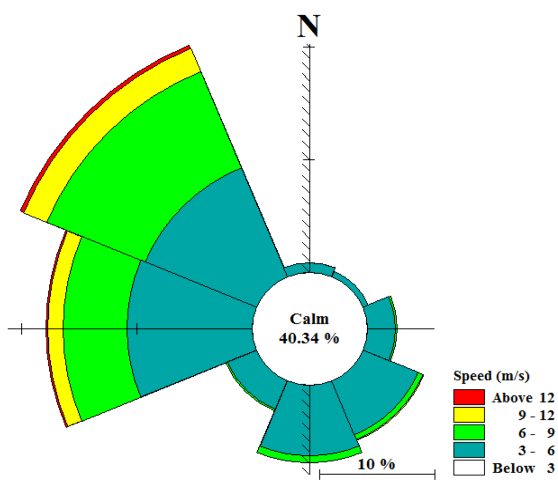

Figure 8: Wind Rose at Al Wakrah Port (measured clockwise from the North direction).

2 FLUSHING TIME CRITERIA

The physical exchange of a predetermined volume of seawater between the connected or surrounding open seawater body and the basin water body is known as port flushing. Time scales for water transport such as the term "residence time," which is frequently used synonymously with "flushing time," is used to describe how long water remains in a given volume. In other words, quicker flushing of a water body is associated with shorter residence times [13].

According to Fisher et al., 1979 [4], the flushing time T_f is equal to the ratio of the mass of a scalar in a reservoir and its rate of renewal, which could be re-expressed as:

$$T_f = \frac{M}{F} \tag{1}$$

where M is the scalar's mass in the reservoir, T_f is the flushing time, and F is the scalar's mass flow rate through the reservoir. The above equation might now be written as [25]:

$$T_f = \frac{V}{Q} \tag{2}$$

where Q is the volume exchange rate inside the system and V is the total volume of water in the coastal system. Estimates of the system volume (and its contained mass) and system exchange rate are required for the application of this term (flow or mass flux). T_f is occasionally computed under the assumption that a water body functions as a Continuously Stirred Tank Reactor (CSTR) and that flushing time may be approximated from measurements of outflow concentration over time since the parameters V (or M) and Q (or F) are commonly unknown. For instance, Eshleman, and Hemond, 1988 [26] predicted alkalinity in a reservoir using a CSTR model and compared the results to the alkalinity that was observed at the outflow spillway. The primary assumption of the CSTR model is that any mass input instantly and uniformly mixes throughout the domain, resulting in the concentration of a constituent that exits the system being equal to the concentration everywhere inside the CSTR. Thomann, and Mueller, 1987 [27] used the well-known exponential Continuously Stirred Tank Reactor (CSTR) to represent the change in concentration (mass/volume) over time as follows:

$$C(t) = C_0^{-(Q/V)t} = C_0^{-t/T_f} \tag{3}$$

where C_o denotes the initial concentration and C_t denotes the concentration at a certain time t. Q stands for continuous flow rate, V for water volume, and T_f for residence/flushing time. By rearranging Equation 3, one may get the e-folding flushing time by solving for T_f using a linear regression of recorded exit concentration time series described by Eq. 4 as:

$$\ln C(t) = -\left(\frac{1}{T_f}\right) t + \ln C_0 \tag{4}$$

The effectiveness of tidal flushing in ports is frequently evaluated using the mean flushing exchange coefficient E, which measures the proportion of water within the marina exchanged with the sea outside during each tidal cycle. Each location I inside the port basin can have its exchange coefficient determined using the formula below [28]:

$$E_i = 1 - \left(\frac{C_i(n)}{C_{t,0}}\right)^{\frac{1}{n}} \quad (5)$$

where $C_{i,o}$ is the initial concentration and $C_i^{(n)}$ is the concentration of a conservative (non-decaying) tracer at point i after n tidal cycles. Larger exchange coefficients imply a quicker resupply of water. By averaging throughout the whole marina, the average flushing exchange coefficient E for the basin is determined. Higher mean exchange coefficients are associated with shorter residence periods.

3 FLUSHING MODEL

3.1 Model Description

The present study utilizes MIKE 21, a commercially available software package developed by DHI [29] for simulating a variety of processes, including tidal circulation and tides, the transport and dispersion of pollutants and/or tracers, and other processes essential to coastal engineering and oceanography [17, 18].

Both MIKE 21 HD (hydrodynamic model) and MIKE 21 AD (Advection-Dispersion model) have been applied to this study. All models are based on a flexible mesh representation of the model area, which allows differentiated triangular mesh cell's sizes throughout the model area, giving the most accurate physical description of the port basin. HD model is considered the basic module of the entire MIKE 21 system. It performs as the hydrodynamic groundwork for most other modules' mathematical calculations. It is applicable for the analysis of free-surface flows, hydrodynamics, and dispersion in coastal areas and seas. While AD model calculates the spread of the floating, suspended, and dissolved substance in natural water bodies due to fluid transport and related dispersion mechanisms.

This study will be conducted using a simulation model which takes into consideration the features governed by the combined effects of bathymetry, tide, and wind. These natural forces will be the input to the HD model to simulate the tidal currents in the port basin. The results of the HD model will be used as input to the AD model to simulate tracer material's spread and movement.

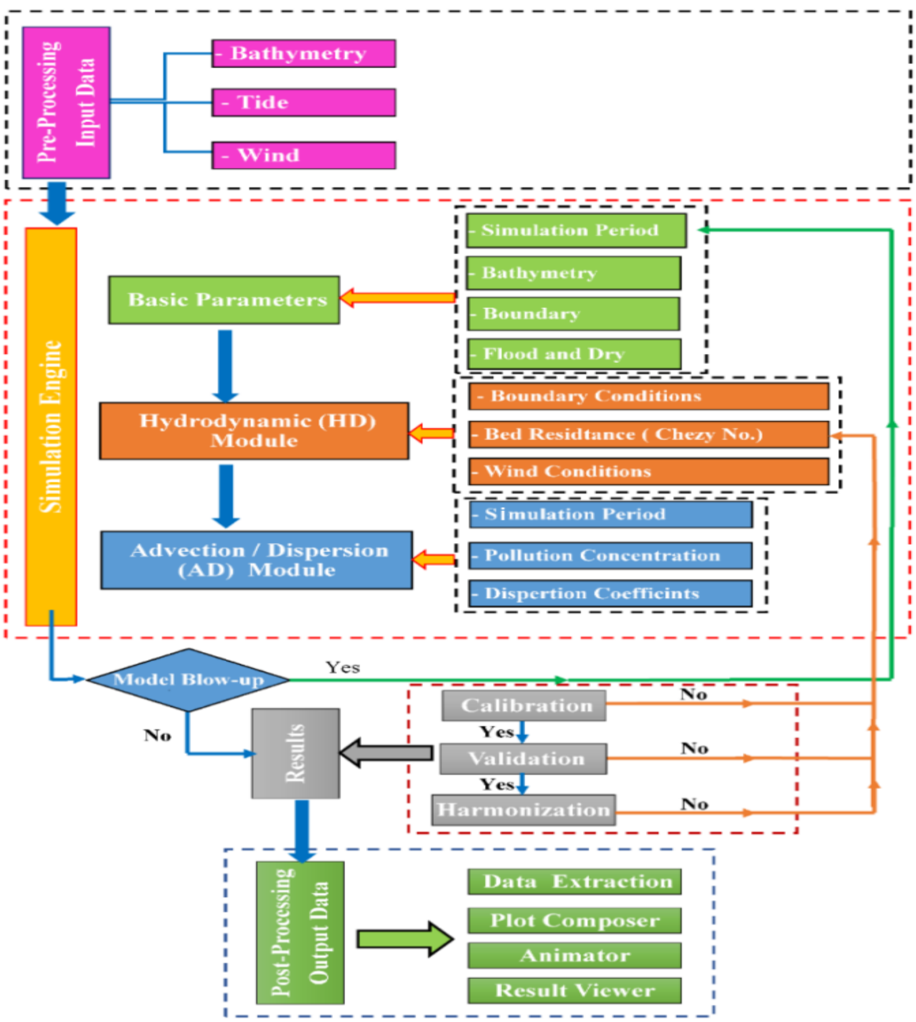

Figure 9: Overall modeling simulation flow chart [17]

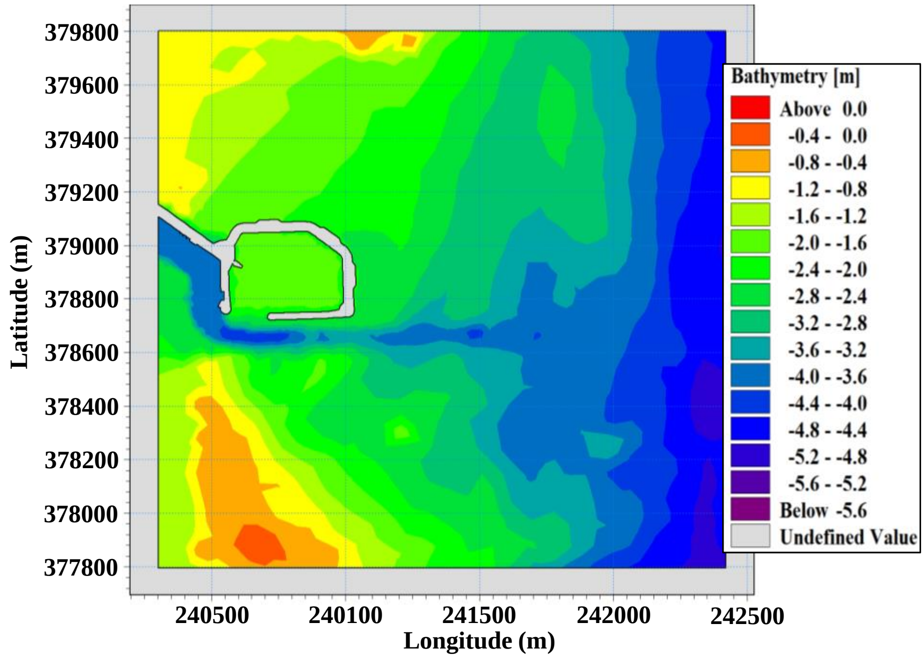

Figure 10: Created model bathymetric map used for Al-Wakrah Port study area.

The main outcomes of the study simulations will help to simulate the flow circulation patterns and the distribution of pollutants concentrations in the port basin system. Finally, the flushing time of the port basin could be estimated. Figure 9 shows the modeling simulation flowchart.

3.2 Model setup

In this study, a 2D numerical model was used in order to simulate and generate a basic HD model that can be used to configure the AD model according the modeling simulation flowchart shown in Figure 9. The seabed bathymetry, without a doubt, is the most significant duty in the modeling process. It describes the water depths in the model region for the hydrodynamic model HD. The data from the survey, Admiralty Nautical Charts and Global Bathymetry Datasets GEBCO_2021 was gathered to build the final bathymetric model that covers the model area.

The final produced bathymetry will be used in the hydrodynamic studies at the Al-Wakrah port. Figure 10 shows the final bathymetric map of the modeled research area which will be used in the hydrodynamic studies at the Al-Wakrah port. Providing the HD model with a suitable mesh file is essential for obtaining reliable results from the model simulations. To correctly reflect the critical hydrodynamic processes at Al-Wakrah port, a coarse spatial resolution was established for the port's unimportant surrounding zone. While, as shown in Figure 11, a high-resolution boundary and depth adaptive mesh (fine mesh) is employed to precisely characterize

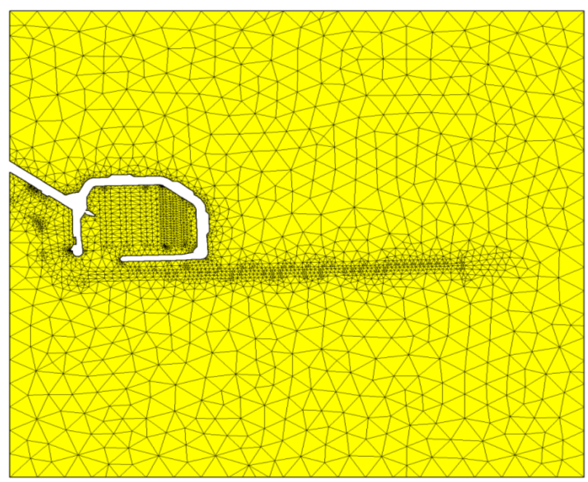

Figure 11: Spatial resolution mesh used for Al-Wakrah Port study area.

the approach channel, the nearby area of the old port, and the planned port expansions. The mesh generator tool was employed to create unstructured overall computational flexible mesh that includes information about the node connectivity of the triangular elements. It was created with 4611 elements and 2501 nodes for obtaining reliable results from the model simulations.

This study was conducted to represent a total simulation period of 7 days, from the 11^{th} to the 18^{th} of December 2017, with time step of 3600 sec to determine the hydrodynamic characteristics and the flushing time rate of the water system based on an hourly basis simulation. The time step for the HD simulation is the same as the one used for the AD simulation as the two models are fully coupled.

If the most important part of the modeling process is to characterize the bathymetry, the second most fundamental duty is to describe the sea levels at the open boundaries. The good the boundary conditions, the good the outcomes, and the fewer issues with model instability. There are four boundaries of the modeling area (East, West, North, and South Lines) defined to represent the open water boundary of the Arabian Gulf. The water elevations along the open boundary line were prepared as a function of time depending on the time series data, and then it was entered as boundary conditions input.

A simulation period of 7 days was chosen to run the mathematical model in order to determine the hydrodynamic characteristics of the water system in this area. Figure 12 (a) provides the tidal water levels for the simulation period. These data of tidal water levels will be used later to run and calibrate the hydrodynamic model as explained later. Figure 12 (b) provides the wind data time for the continued changes in wind speed and direction with time in the study area during the simulation period from the 11th to the 18th of January, 2017.

For this study, it was sufficient to specify a constant turbulent viscosity for the whole flow field. However, different numbers of Smagorinsky coefficients [23] were specified through the calibration process until obtaining the best value of the model area was. Meanwhile, the bed resistance has been entered as a constant value applied to all mesh elements.

A 100% tracer concentration was introduced into the port basin's water system. Open seawater concentration is considered to be 0%. The simulated water elevation and velocity field in the port basin are used as input data for the AD model for the simulation period (7 days). Figure 13 depicts the initial concentrations map inserted into the model to limit the concentration of a suspended conservative tracer component (no decaying or settling) with concentration set to 100% in the whole port water system just at the start of the AD simulation.

Specifying the dispersion coefficients is required whenever there are moving components. The values of the tidal mean dispersion coefficient cited in the literature range over three orders of magnitude, depending on the size as well as the tidal characteristics of a coastal system, and vary spatially and temporally within a given coastal system [4]. In this study, the dispersion coefficients were specified as constant in space, as a coefficient for the x-direction and a coefficient for the y-direction.

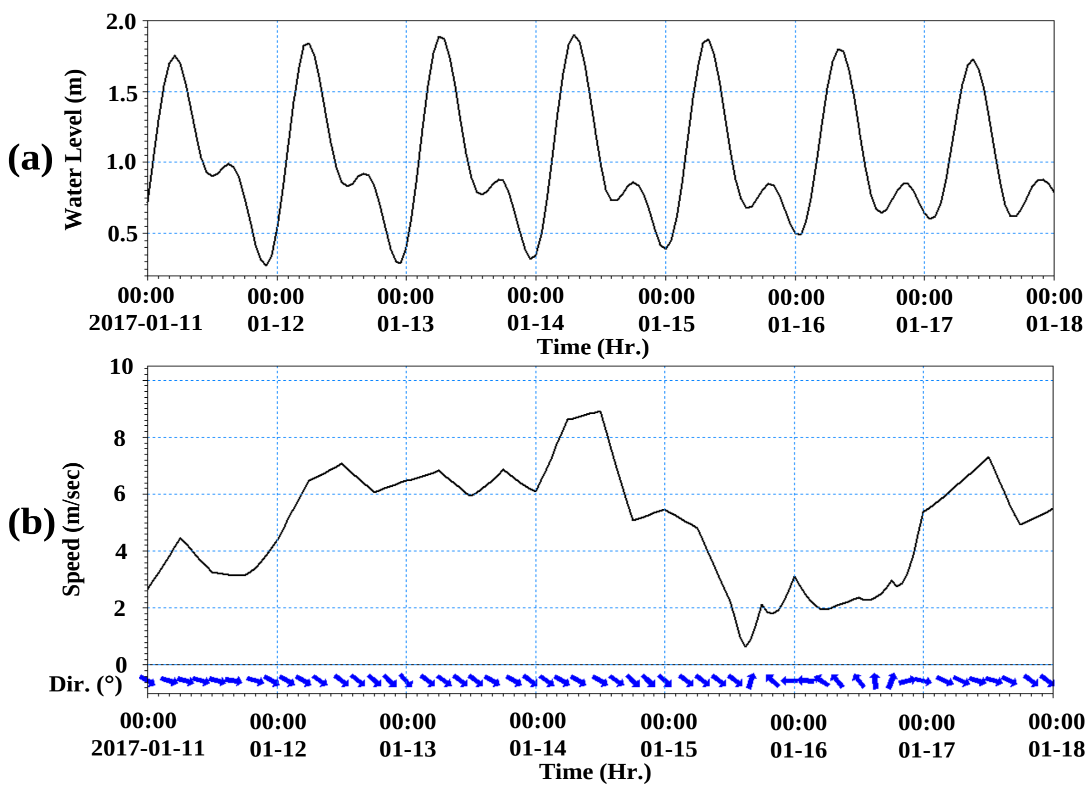

Figure 12: Time series variations of the computed data for the simulation period from 11 to 18 January 2017, a) Tidal water levels, and b) Wind speed and direction.

Finally, in order to monitor the variation of the hydrodynamic characteristics with time along the simulation period, six monitoring points (P1, P2, P3, P4, P5, and P6) were positioned in the main parts of the water system to be used for recording the variation of the water surface elevation and current characteristics with time as shown in Figure 14. Furthermore, the same monitoring points were used to monitor and record the variation of the tracer material concentration with time throughout the simulation period under tidal flushing.

3.3 Model Calibration and Validation

3.3.1 Model Calibration

The calibration process is used to adjust the model to obtain satisfying results that match well with observed parameters in real conditions over a specific period known as the calibration period. The initial simulations are rarely successful because model instability might cause the simulation to stop unexpectedly, a concept known as a blow-up.

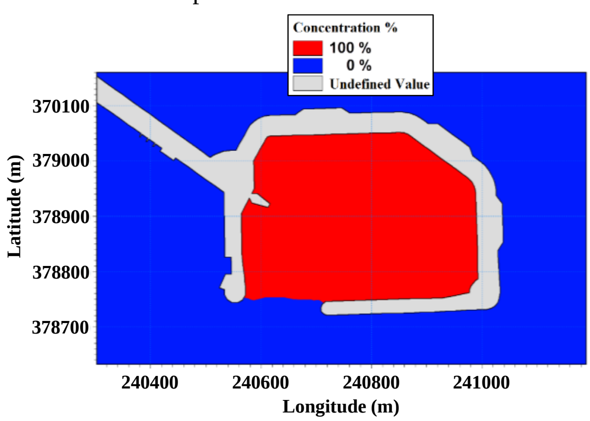

Figure 13: Initial tracer concentrations map used for Al-Wakrah Port study area

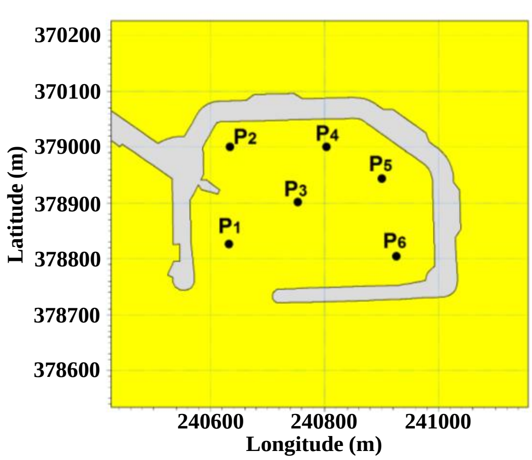

Figure 14: Location of the selected monitoring points of hydrodynamic characteristics in Al-Wakrah Port study area.

The main parameters to be adjusted during the calibration phase are the eddy viscosity, and bed resistance. Many simulations with different eddy viscosity values through changing the Smagorinsky constant were run to get the required smoothened results. Similar to this, an iterative technique was used to assess a variety of constant bed roughness values represented by Manning numbers for the model's tidal water level calibration, and the calibration that produced the best results was adopted [4]. A comparison between the computed water levels and measured water levels obtained from the Admiralty Tide time series at the entrance of the water body are used for the model calibration as shown in Figure 15. The comparison carried out during the 7 days simulation period. The results show that the model is well-calibrated.

3.3.2 Model Validation

The validation process's goal is to certify that the product model performs correctly and that it operates on clean, correct, and valuable data. After calibrating the model, the same eddy viscosity and bed resistance were employed to validate the HD model. The model is validated using water level and wind data from the 1st to the 10th of May, 2017. Figure 16 shows that the model's computed water elevation final result is excellent. There was almost no difference between the computed and input data once the model was verified. As a consequence, we may infer that the model for water level elevation is well-validated.

4 RESULTS AND DISCUSSION

Mike21 numerical software has been applied to develop the HD model to provide a quantitative illustration of hydrodynamic characteristics for the water system of the new extension of Al-Wakrah port. The purpose of the simulated exchange between the water system of the port and the Arab Gulf seawater is to produce a basic HD model that can be used for the set-up of a water quality AD model. It can also give an idea of the current velocities and directions of the water system.

In general, in semi-closed port basins, you may need to examine several individual plots of time series of current speeds, since the tide will alter at different locations. Therefore, in order to monitor and record the variation of the water surface elevation, and current with time under tide and wind forces, Figure 17 shows a comparison between the computed current speed at the six locations (P1, P2,….,P6) which cover the port basin area. The results show that the current magnitudes inside the port area typically in the range of 0.001 m/s to 0.03 m/s. The highest values were recorded at monitoring point P1, which represents the port entrance, while the lowest values were found at monitoring points P5, and P6, which represent places along the breakwater boundary in the inner sectors. Furthermore, this plot clearly indicates that the current speed briefly drops to zero when the current switches direction, where tides are mixed semi-diurnally [30], and the currents reverse about every 4-6 hours.

In this study, the new marina's entrance functions as a source during the flood phase of the tide and as a sink during the ebb phase; that is, the sink and the source are in the same position. The tidal phenomenon has a significant impact on the currents pattern in the port basin because during ebb tide, sea water is quickly attracted to the open seawater of the Gulf, causing sea levels to drop dramatically and quickly. Otherwise, Gulf seawater will enter the port area during a flood tide. This phenomena has formed a pattern of current flow in the new marina. It indicates that tidal conditions have a significant role in the transport of aquatic contaminants. Therefore, to illustrate the current pattern spatial distribution during different tidal stages of the port basin, the current speed and direction pattern were selected as indicators.

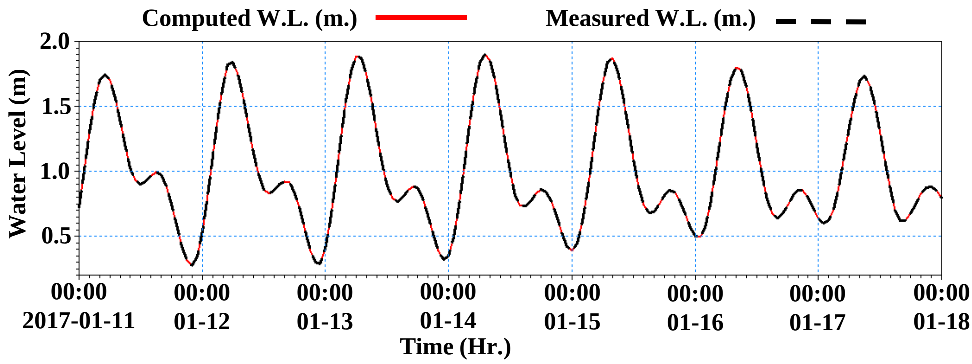

Figure 15: Comparison between the model simulated results and measured water levels for the calibration process.

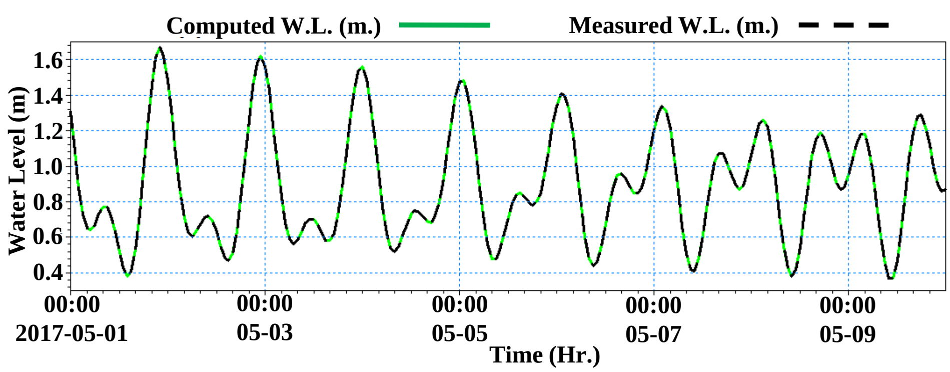

Figure 16: Comparison between the model simulated results and measured water levels for the validation process.

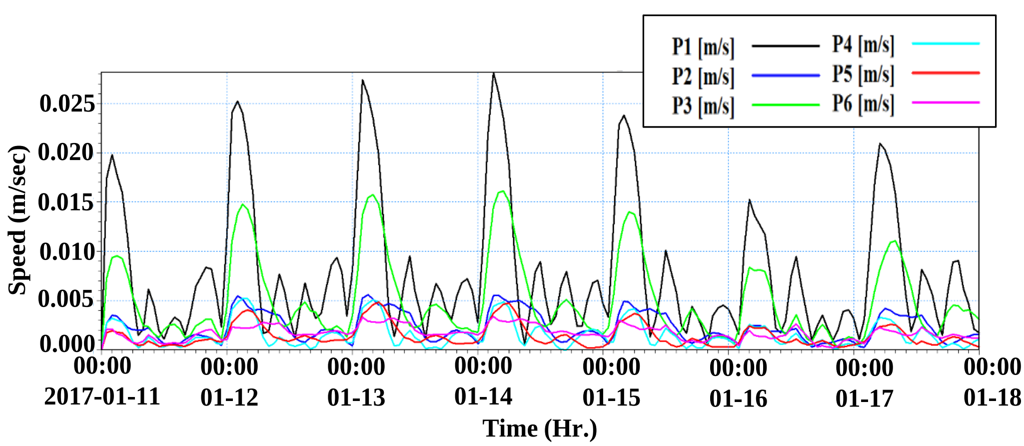

Figure 17: Comparison between the model simulated results of current speeds at the location of the selected monitoring points.

The 2D pattern distribution of the surface current velocity and direction during the Ebb tide (outflow) and Flood tide (inflow) phases, respectively, is shown in Figure 18(a) and (b). The results show that at the port entrance, the current speeds are faster compared with the other parts current speeds, and it decreases as we head to the closed ends of the water body bordered by breakwater. The general trend of the ebb-flow distribution is opposite to that of the flood current. During the ebb condition, the flow did not maintain the same path and eventually developed an anti-clockwise circulation. In general, the results demonstrate that the current speeds at the port basin are suitable to accommodate the boats without accumulating pollutants or floating trash in dead areas and it takes a short time to clean the basin under natural flushing forces.

In this section, we study the possibility of the water renewal of the port basin, induced by natural tidal phenomena, from the impact of the spread of the trace moving material. Therefore, to study the tidal flushing characteristics of the new marina water system; an AD simulation was conducted to cover a period of 7 days.

At the beginning of the AD simulation, a suspended conservative tracer with a concentration of 100 % was applied in the port basin as pollution. The concentration of seawater outside the marina was applied to be 0% as shown before in Figure 13. So, Figure 19 presents snapshots of the pollutant concentration within the port water system from the beginning and along the simulation. The tracer concentration decreased rapidly near the port's entrance, but gradually in the center and inner areas of the port basin. The rapid decrease in concentration indicates that the flushing time at the port's entrance is shorter than in the interior portions. In general, two factors are considered when determine the flushing of water systems: time and pollutant concentration level.

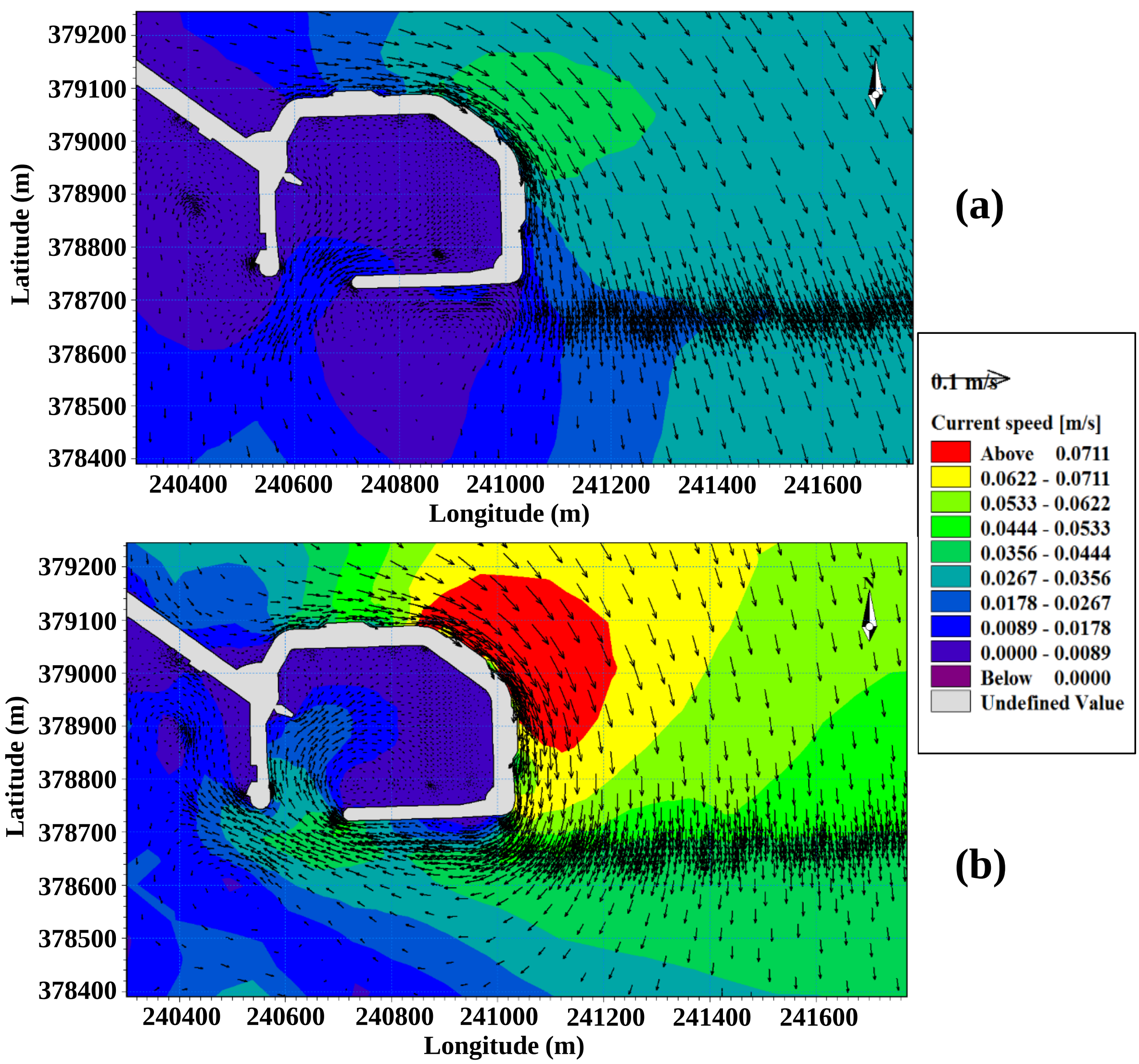

Figure 18: Snapshot of the flow visualization during; a) Ebb tide, and b) Flood tide.

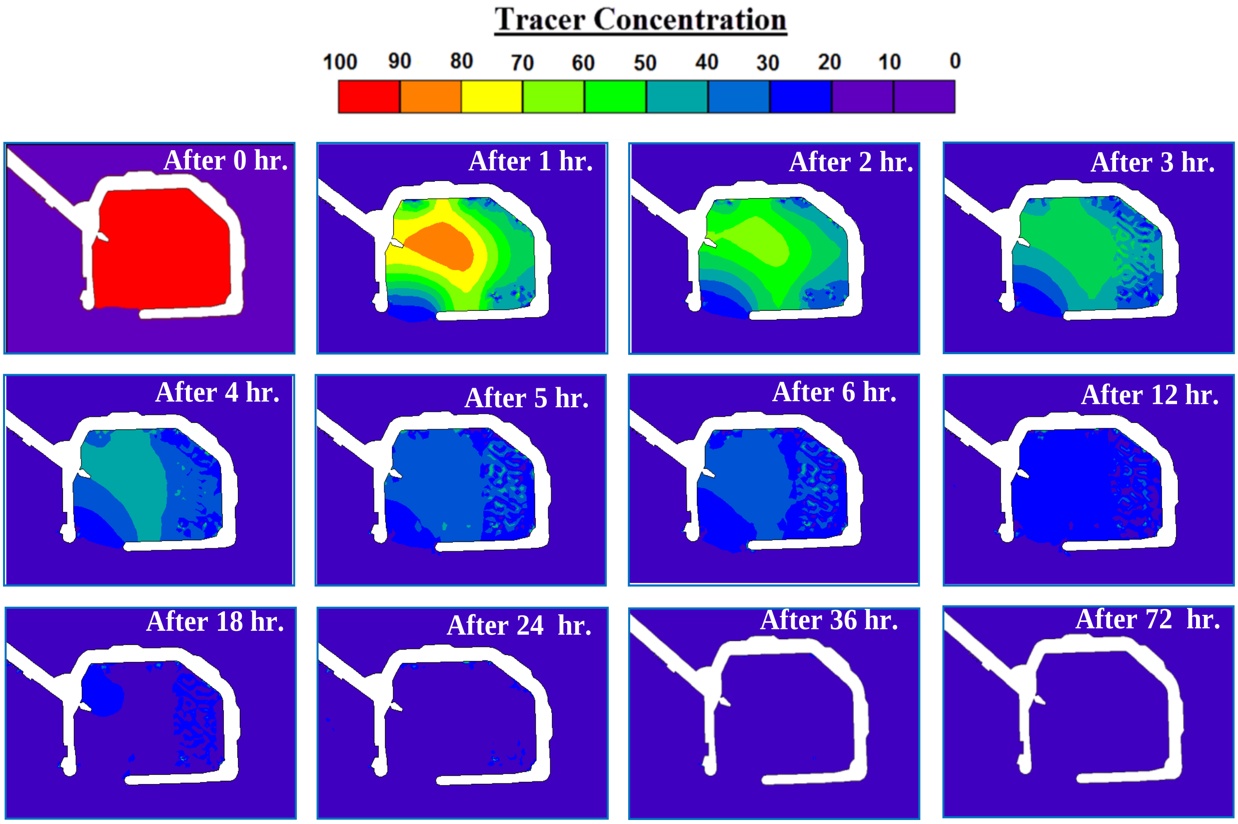

Figure 19: Tracer material concentration at different times during the simulation period.

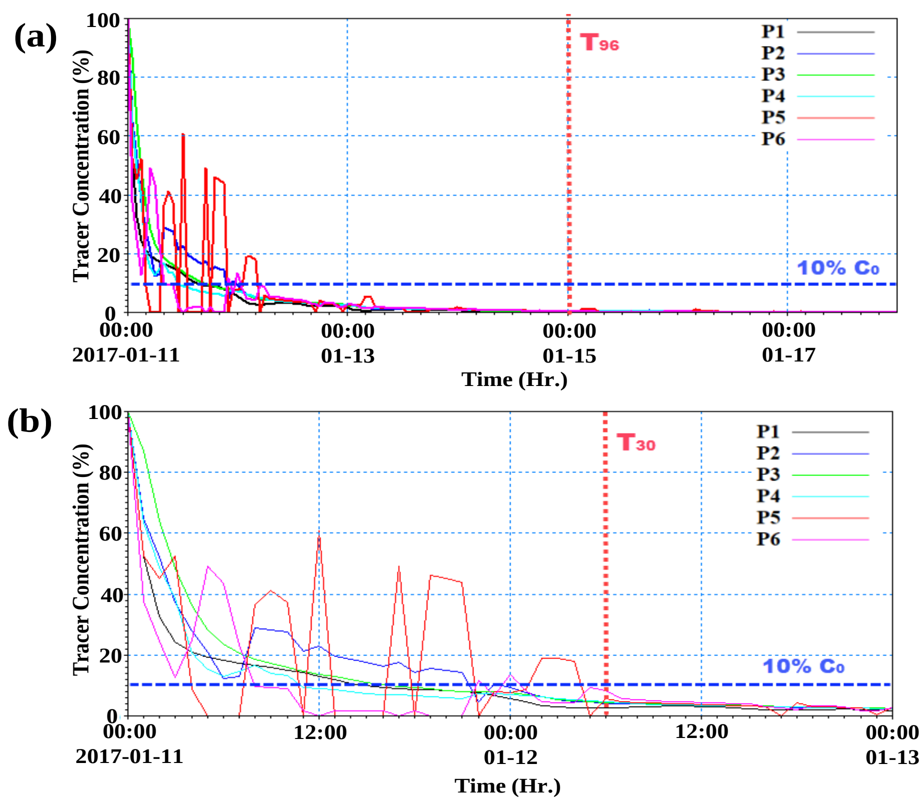

Figure 20: Change in the tracer concentration at the selected monitoring points with time: a) after 7 days, and b) after 2 days.

The concentration of a given tracer will decrease exponentially with time in the ideal mixing conditions case where the inflowing water is mixed (dispersed) with the volume of water, where the tracer instantly forms a homogeneous solution of concentration C_O. This relationship is expressed as in Eq. (3) previously mentioned in section 4. For water sports activities or bathing, according to the US Environmental Protection Agency recommendations guidelines [31,32], the flushing time T_f is defined here as as the time that the tracer material concentration needs to reach 10% of the initial concentration (i.e, $C = 0.10\ C_O$) over a period of 96 hr (T_{96}).

Figure 20 (a and b) shows that the concentration of tracer in the water system at the preselected monitoring points from the beginning of the simulation of the flushing time at 10% of the initial concentration at T_{96}. The results show that after 30 hours, the tracer concentration approaches 10% of its initial concentration. Therefore, under these conditions, natural water circulation by tidal effect is more than sufficient to ensure the flushing of water in the port basin.

5 CONCLUSIONS

A 2D MIKE 21 hydrodynamic coupled with an advection/dispersion modules were used the hydrodynamic flushing modeling of the new extension marina at Al-Wakrah Port. The modeling results show that surface currents during tide phases demonstrate that the current speeds at the port basin are suitable to accommodate the boats without accumulating pollutants or floating trash in dead areas and it takes a short time to clean the basin under natural flushing forces. In addition, the surface current velocity and direction during the Ebb tide (outflow) and Flood tide (inflow) phases show that at the port entrance, the current speeds are faster compared with the other parts of the water body. The general trend of the ebb-flow distribution is opposite to that of the flood current. It is clear from the results that the flushing of the port basin is better due to the higher exchange with the Arabian Gulf Sea.

The rapid decrease in concentration indicates that the flushing time at the port's entrance is shorter than in the interior portions. After 30 hours, the tracer concentration approaches 10% of its initial concentration. Therefore, under these conditions, natural water circulation by tidal effect is more than sufficient to ensure the flushing of water in the port basin.

Credit Authorship Contribution Statement

Elsayed M. Galal: Generating the idea, collecting data, methodology, editing, and reviewing;
Hesham Zaki: Conceptualization, software, and formal analysis Validation; Original draft preparation

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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