Modelling the Dispersion of Harmful Algal Bloom (HAB) in the Coastal Area of Oman Sea

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Abstract The increasingly growing world population and the contamination of rivers and coasts due to human activities have given rise to serious problems in the marine habitats. One of the most recent and challenging issues involves harmful algal blooms also known as red tides. The algal bloom has geographically spread in the entire coastal areas of the world, and the Iranian southern coast is no exception. However, any potential damage in coastal areas can be prevented by accurately predicting the dispersion and advection of the blooming species.

This study intended to examine the dispersion and advection of harmful algal cells through hydrodynamic modules MIKE 3-FM and ECO Lab, which simulated the hydrodynamics and quality of water as well as the distribution of chlorophyll-a across the southeast coast of Iran. After calibration of the model, the results of simulation were adequately consistent with the measured data on variations of chlorophyll-a, i.e. the cause of algal bloom. In fact, the modeling was successful in simulation of currents across the Gulf of Oman in hydrodynamic and quality terms. For validation of model the root mean square error (RMSE) is used. RMSE of calibrated and field data for chlorophyll a values equal to 0.016, obtained under 0.1 indicates that accuracy is very high and also for water level equal to 0.19, which represents the accuracy of hydrodynamic model is good. Since the dispersion of Cochlodinium polykrikoides was first observed at mid-April 2009 in the nearest station to the Strait of Hormuz. The bloom spread toward eastern stations of Chabahar at mid-May and then persisted for two months. The results were consistent with those obtained through software modeling on the dispersion of chlorophyll-a, the major cause of algal boom. The validated model in this study can be employed to provide on-time warning and prevent any adverse social and economic consequences.

Keywords: Harmful algal bloom, Nutrient, Chlorophyll a, Numerical modeling, Distribution

1. Introduction

Harmful algal blooms (HABs) possess potential for extensive negative impacts to fisheries, coastal ecosystems, public health, and coastal economies (Anderson *et al.*, 2015; Van der Lingen *et al.*, 2016). Harmful algae can adversely affect the outputs of seawater reverse osmosis worldwide. This red tide known as harmful algal bloom forced several seawater reverse osmosis SWRO plants in the Oman Sea and Persian Gulf region to reduce or shutdown Operation (Richlen, 2010; Villacorte, 2015). The geochemistry of surficial and core sediments of these regions show various along with flocculation processes have been extensively studied that are indicative of a changing aquatic environment from oxic to anoxic conditions (Biati *et al*., 2012; Vaezi *et al*., 2015).

In the coastal waters of Iran, as in most sensitive coastal regions of the world, phytoplankton blooms have occurred during the past two decades. When the population of phytoplankton exceeds one million cells per liter of water, algal bloom occurs and the high density of phytoplankton in the water changes its color to green, milky, red, brown, or orange. Among the main contributing factors are rising temperatures and the entrance of chemicals such as nitrate and phosphate caused by human activities (Han *et al.*, 1995; Tang *et al.*, 2004; Anton *et al.*, 2008). A harmful algal bloom caused by Cochlodinium polykrikoides happened in September 2008 extending from the south of the Oman Sea to the Strait of Hormuz and the Persian Gulf and lasted for more than nine months (Richlen *et al.*, 2010; Attaran Fariman, 2010; Fatemi *et al*., 2012).

Given that the algal bloom is known as one of the most destructive phenomena in water resources, the environmental engineers have been concerned about when and where the next HAB will disperse. Hence, several models have so far been developed.

Although models are important to understand the effects of harmful algal bloom dynamics, but they should be used carefully. We need thorough data sets around which to formulate models, more interaction between model development and field sampling design, development of data assimilation techniques to improve the predictive power of models and techniques to allow better dynamic interpolation of data by models and the recovery of poorly known parameters (Franks, 1997). Horizontal transport of blooms is also an important feature of many HABs, often over hundreds or even thousands of kilometers. Major toxic outbreaks can suddenly appear at a site due to the

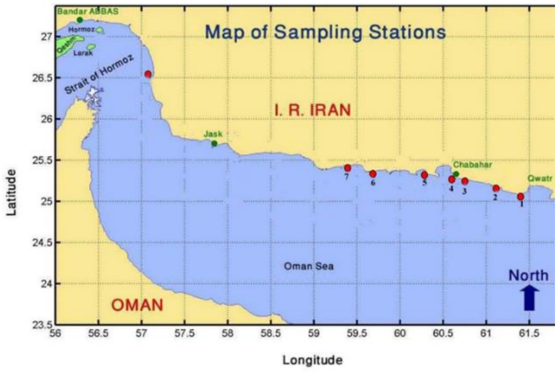

Figure 1. Sampling locations along the South-East coastal area of Oman Sea (adapted from Attaran-Fariman, 2010)

transport of blooms ocean currents. Advance warning of imminent outbreaks is thus possible with the appropriate tools (e.g., satellite optical sensors and numerical forecast models) (Villacorte, 2015).

This study intended to examine the dispersion and advection of harmful algal cells through hydrodynamic modules MIKE 3-FM and ECO Lab, which simulated the hydrodynamics and quality of water as well as the distribution of chlorophyll-a across the southeast coast of Iran. The hydrodynamic processes model is dependent on the wind speed and direction, and wave and tidal characteristics of the region. Additionally, the simulation software included the various physical, chemical and biological factors contributing to the phytoplankton cell density, such as nitrates and phosphates (the most important factors hindering the growth of phytoplankton), chlorophyll-a, salinity, dissolved oxygen and temperature.

2. Material and methods

2.1. Study Area

The Oman Sea is a triangular strait situated between Iran, Oman, and Pakistan. It is surrounded by land on three sides and connected to the high seas on the other hand. The southern coasts of Iran stretches from the Strait of Hormuz to the Gwatar Port on the Oman Sea. The length of the Oman Sea from the Strait of Hormuz

The data used in this research included qualitative parameters along the coasts of the Oman Sea. The sampling Stations were selected in the regions of Passabander (station 1), Bris (station 2), Ramin (station 3), Chabahar (station 4), Pozm (station 5), Kalat (station 6), and Galk (station 7). Samples were taken in the spring and summer of the year 2009.

2.2. Field measurements

Water samples were collected once every two weeks from late April to late September 2009. It is usually not possible to collect samples during the period of monsoon winds due to wind intensity and occurrences of severe storms, therefore, samples could not be taken in July/August (Attaran Fariman, 2010). Modeling in this study involved only the data recorded during one quarter from April to June.

Samples were collected from depths up to 50 cm using Rotner bottles or employing one-liter simple bottles employing the method introduced by Sournia (1978). In each region, three samples were used for studying the phytoplankton, one for examining the chemical factors, and one for measuring chlorophyll a. Salinity, temperature, transparency (Secchi Disk), nitrate, phosphate, silicon, dissolved oxygen, and chlorophyll a were measured. The phytoplankton samples were fixed at the sampling Stations using Lugol's solution and employing the method introduced by Parsons *et al*. (1992). If phytoplankton masses were observed at any Station, another sample was taken but this one was not fixed.

The samples were then sent to the laboratory for measuring the parameters and for studying the phytoplankton. Live phytoplankton samples were examined at the laboratory using a light microscope equipped with a camera. The phytoplankton species in the samples were identified using Internet sources, available identification guides, and various published articles. Chlorophyll a was measured using the method introduced by Regional Organization for the Protection of the Marine Environment (ROPME, 1987) in mg/m3 or µg/l, and pH was determined using a WTW-320 model pH meter. The method introduced by the Manual of oceanographic observations and pollutant analysis methods (MOOPAM, 1998) was used to measure nitrate employing a DR2000 model spectrometer and reading light absorption at 500 nm wavelength. A Hitachi U-2000 model spectrophotometer was employed for measuring phosphate and silicate at 882 and 810 nm wavelengths , respectively (MOOPAM, 1998).

2.3. Model setup

2.3.1. Hydrodynamic model

This study involved the hydrodynamic module of MIKE 3-FM and ECO Lab for the hydrodynamic simulation of the dispersion of chlorophyll-a across the Oman Sea. In fact, it is a numerical modeling system for simulating current in estuaries, bays, coastal areas and oceans. The ECO Lab module is coupled with the hydrodynamic modules. In this procedure, the hydrodynamics data are transferred from the

HD module to the EL module, which simulates several processes including transmission, distribution, deposition and variables chemical and biological interactions in different scenarios, describing how the concentrations are distributed in each scenario (DHI, 2007, 2008 and 2009; Erichsen *et al.*, 2010). In this study, the regional currents were simulated through a three-dimensional hydraulic model coupled with ECO Lab involving flexible triangular mesh. The modeling on the dispersion of chlorophyll-a during algae bloom was conducted in two stages due to the limitations of field measurements in the region as well as the need to reduce the model's runtime. The hydrodynamic model first covered the entire Persian Gulf and Oman Sea according to the available data. Then, the results of the above-mentioned modeling were employed to develop the hydrodynamic model for the dispersion of chlorophyll-a in a smaller area covering Chabahar Bay to Galak Station (Fig. 2). Moreover, the data from the Iranian National Cartographic Center was employed to prepare the numerical model's bathymetry (Fig. 3). Meanwhile, the wind data from Chabahar Synoptic Station at 3-hour time step intervals. There were several advantages to selection of Chabahar Station, including great accuracy of measurements, proximity to the sea and ideal height above sea level. The regional tidal currents model was implemented through the water level data at Pasabandar Station as well as tidal tables provided by the Iranian National Cartographic Center. At one-hour time step intervals (boundary conditions), the data was applied to the only eastern maritime boundary in the regional model as shown in Figure 2a. Since there was no access to the local tidal data, the regional model was first implemented and then calibrated so as to obtain the water level data for three maritime boundaries within the local model (Fig. 2b). The tidal currents in Iran are mixed, i.e. a lunar day experiences a pair of tides, one larger than the other. The results of modeling indicated that the direction of currents in Chabahar Port shifts four times within 24 hours. This can be associated with the mixed tidal currents across the region, where the currents shift direction twice following a pair of tides within 24 hours (Payandeh *et al*., 2015). Since the eastern and western maritime boundaries in the local model are relatively short, the water level data at the central point of each boundary was extended to the entire length of boundary. It was then applied into the model as time series (variable time and fixed along the boundary) at 10-minute time step intervals. Due to the extremely long southern boundary, however, the model was conducted in a way that the southern maritime boundary behaved in variable time and boundary length. In fact, the tidal data for five points along the southern boundary was extracted from the regional model. Then, the five points formed four line segments of identical length. In each line segment, the variations of water level were measured through interpolation of water level data for two adjacent points.

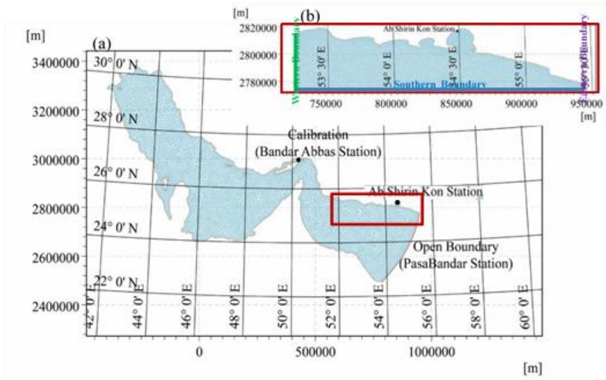

Figure 2. Position of the maritime boundary in the (a) regional model (open), (b) local model (western, southern and eastern boundaries)

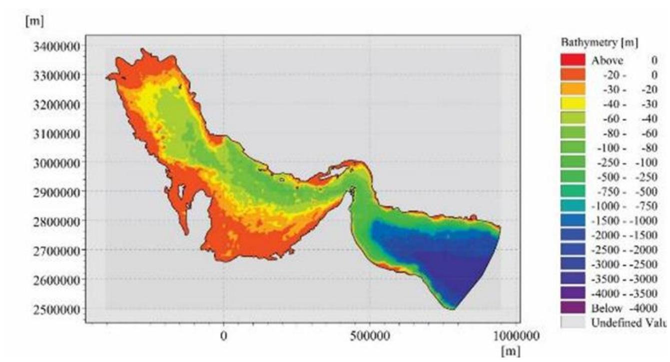

Figure 3. Bathymetry of the region (Persian Gulf and Oman Sea)

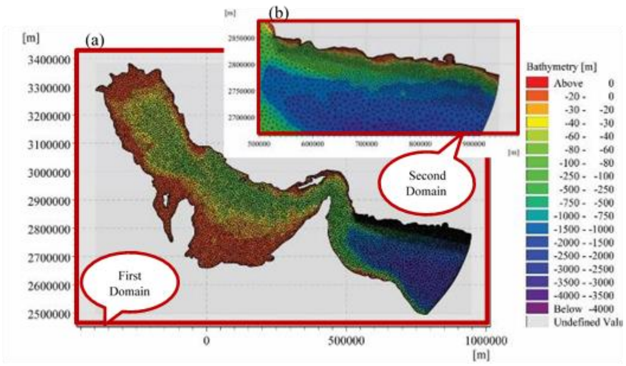

Figure 4. Modeled regions and computational grid in the first and second stages (a) First domain (Persian Gulf and Oman Sea) (b) Second domain (Station 1 to 7)

2.3.2. Qualitative model

The qualitative modeling spanned from April 20 to July 22, 2009 at 7 stations according to Figure (1) focusing on the southeast coast of Iran, where the concentrations of Chlorophyll-a, nitrate, phosphate, water temperature, dissolved oxygen and salinity were measured at 15-day time step intervals. In order to implement the qualitative model, the data from field measurements were employed. Moreover, the data from Stations 1 and 7 were used as boundary conditions at the eastern and western boundaries within the local model. The concentration of each parameter at the southern boundary was obtained by interpolation of the values measured in all stations. This paper mainly aimed to examine the dispersion of chlorophyll-a. Hence, the next section will only discuss the density and dispersion of algal bloom based on chlorophyll-a.

2.3.3. Computational grid

It is critical to build a computational grid so as to obtain reliable results. At first, the bathymetry file was prepared through several measures including the selection of scope and construction of model's boundary, importing the bathymetric data at great accuracy into the modeling scope, and defining the boundary conditions at open and closed boundaries.

The meshing was irregular given the numerical method employed in the model. The bathymetry file was created within MIKE ZERO-Mesh Generator. It should be noted that as the dimensions of the grid are downsized, the accuracy of the hydrometry file and subsequently the computational cost substantially escalate. The computational grid should be selected based on the computational accuracy and cost. The susceptibility tests demonstrated that the outputs of the model were extremely susceptible to the size and resolution of the computational grid. Having performed the simulations under different meshes, the optimum mesh was selected. Any increase in the optimum mesh resolution would not alter the output of the model. The computational grid was composed of 11,693 nodes and 21,869 elements (Fig. 4a). According to project objectives, the mesh resolution in expanded between Station 1 to 7 as illustrated in Figure (4b).

3. Results and Discussion

Since phytoplankton fluctuated similar to chlorophyll-a at all stations during the sampling periods, the phytoplankton were modeled through the simulating the dispersion of chlorophyll-a across the Iranian southeast coast covering longitude 53.2 to 55.5 degrees. The implementation of the numerical model required sufficient data on the region, particularly concerning the boundary conditions. Since the data on boundary conditions was not available beforehand, the regional model (covering the Persian Gulf and Oman Sea) was conducted and calibrated so as to obtain the water level information for the local maritime boundaries. Having obtained the hydrodynamic data and the water quality data in the region, the dispersion of chlorophyll-a was simulated over a time span from April 20 to July 22, 2009. The results of the simulation model were approved by a comparison against the data obtained from sampling of variations in chlorophyll-a at 7 stations. Hence, it can be argued that modeling can be useful to predict the dispersion of algae across coastal areas. It should be noted that the phenomenon of harmful algal bloom in the Oman Sea was first modeled through software.

Since the coastal towns such as Chabahar near the Persian Gulf and Oman Sea are developing as free trade zones, this trend can leave deleterious environmental effects on aquatic ecosystems including the phytoplankton communities. As the industrial, municipal and agricultural wastewater bring in more nutrients, the HABs are not far from expectation. On the other hand, the simulation software applications take into account the nutrients, making it possible to accurately predict the concentration and dispersion of phytoplanktons based on the contaminants and the wastewater leaking into aquatic ecosystems during every red tide.

3.1. Calibration of the hydrodynamic model

Regional model: the numerical model was calibrated by adjusting the parameters and comparing the results of numerical models against the field data. The susceptibility tests showed that the bed friction was the most effective parameter in altering the results of the numerical model. The bed friction was applied to model through with the

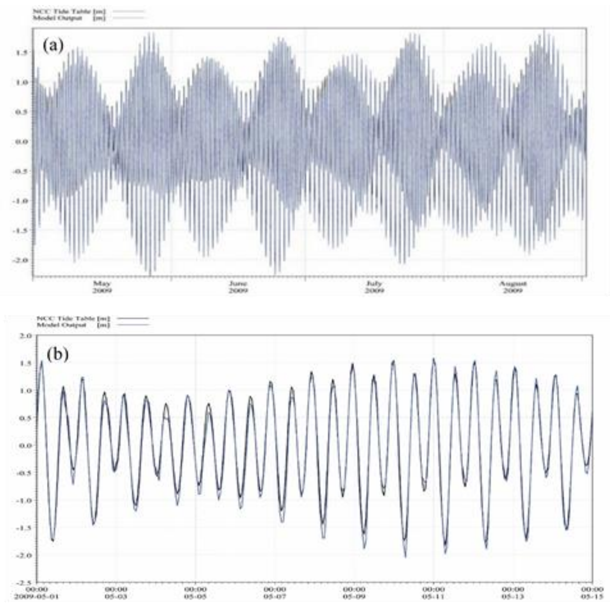

Figure 5. Comparison of the observed and simulated water surface elevation at Bandar Abbas station, (a) for 3 months, from mid-April to mid-July 2009 (model runtime), (b) for fifteen days, from early-May to mid-May 2009

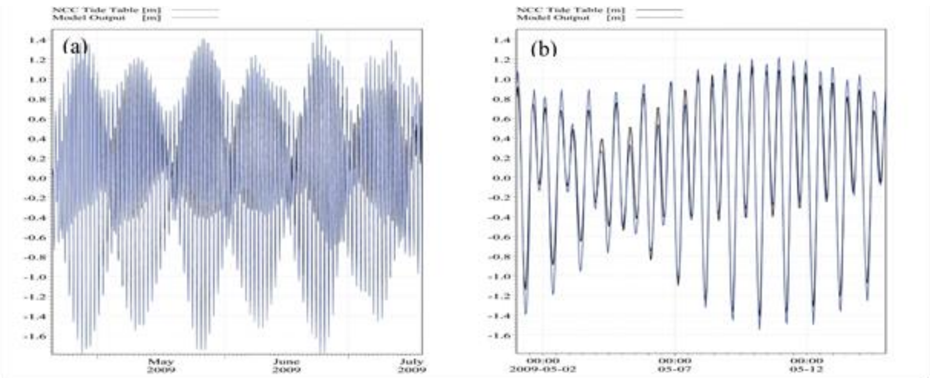

Figure 6. Comparison of the observed and simulated water surface elevation at Ab Shirin Kon station, (a) for 3 months, from mid-April to mid-July 2009 (model runtime), (b) for fifteen days, from early-May to mid-May 2009

Manning formula, which selected 45 m^(1/3)/s as the final option. The calibration of the model involved the water level data in Bandar Abbas Station over a 4-month period (the location of Bandar Abbas Station can be seen in Figure 2-a). Figure (5) compares the water level data from Bandar Abbas Station and the model outputs for a period lasting 105 days. As can be seen, the model after calibration was adequately accurate in predicting the water levels.

Local model: it was calibrated based on the variations in the bed roughness coefficient and comparison of the water level at the Ab Shirin Kon station and model outputs. Having performed several tests, the Manning formula (35 m^(1/3)/s) was selected as the roughness coefficient within the model. As seen in Figure (6), there is an acceptable consistency of between the modeled and measured water levels at the Ab Shirin Kon station over a period lasting 105 days.

For validation of model the root mean square error (RMSE) is used. RMSE of calibrated and field data for water level equal to 0.19, which represents the accuracy of hydrodynamic model is good

3.2. Calibration of the qualitative model

Involving the two parameters of Death rate of chlorophyll-a and Settling rate of chlorophyll-a, the qualitative model was calibrated based on various tests. The selected values for the two parameters were 0.01 (/d) and 0.2 (m/d), respectively. By comparing the results of the numerical model against those of the field measurements for the concentrations of chlorophyll-a, it can be concluded that the numerical model adopted in this study was capable of correctly simulating the dispersion of chlorophyll-a (Fig. 7).

For validation of model the root mean square error (RMSE) is used. RMSE of calibrated and field data for chlorophyll a values equal to 0.016, obtained under 0.1 indicates that accuracy is very high

3.3. Dispersion of chlorophyll-a

Figure (8) schematically displays the results of dispersion and density of chlorophyll-a at different times. Figure 8-a shows the algal bloom at Station 7 in mid-April. As can be seen in in Figure 8-c and 8-b, the chlorophyll-a spreads toward the east coast of Oman according to the modeling of currents, wind and other factors across the Oman Sea. After 3 months in mid-July, the dispersion covers the entire coastal areas of the Oman Sea (Figure 8-d). The concentration of chlorophyll-a and the number of phytoplankton cells diminish near Station 7 by mid-July.

4. Conclusion

Since the dispersion of Cochlodinium Polykrikoides was first observed at mid-April 2009 in the nearest station to the Strait of Hormuz. The bloom spread toward eastern stations of Chabahar at mid-May. As the blooming species spread in mid-May, a 60-km of coastline 200-300 wide turns reddish-brown smelling terribly. Moreover, the bed of the eastern coast suffered the bloom for two months, which was well consistent with the results of hydrodynamic, qualitative modeling and calibration through the simulation software in Oman Sea from mid-April to mid-July, when the concentrations of chlorophyll-a and dispersion of algal bloom were measured. For validation of model the root mean square error (RMSE) is used. RMSE of calibrated and field data for chlorophyll a values equal to 0.016, obtained under 0.1 indicates that accuracy is very high and also for water level equal to 0.19, which represents the accuracy of hydrodynamic model is good. This can validate the modeling to predict the dispersion and concentration of phytoplankton upon first observations. This study demonstrated that modeling could provide a useful tool to predict and develop several scenarios concerning the spread of HABs within aqueous ecosystems.

Given the results and the great eutrophication potential in southern coastal areas of Iran due to the disposal of municipal and industrial wastewater, the phytoplankton are expected to further disperse and concentrate, thus leading to greater algal bloom in the region.

Moreover, the modeling of this phenomenon can provide early warning and prevent any economic and social consequences against aquaculture and desalination systems

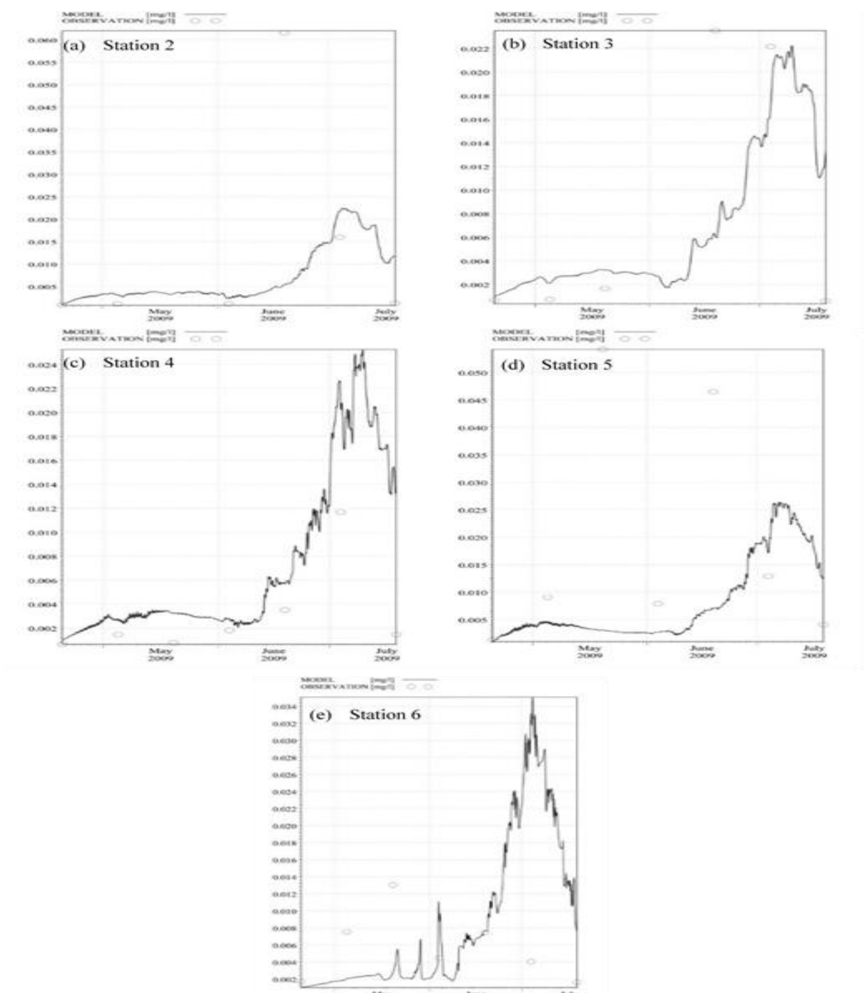

Figure 7. Comparison of the field measurements and simulated concentrations of chlorophyll-a at (a) Station 2, (b) Station 3, (c) Station 4, (d) Station 5, (e) Station 6

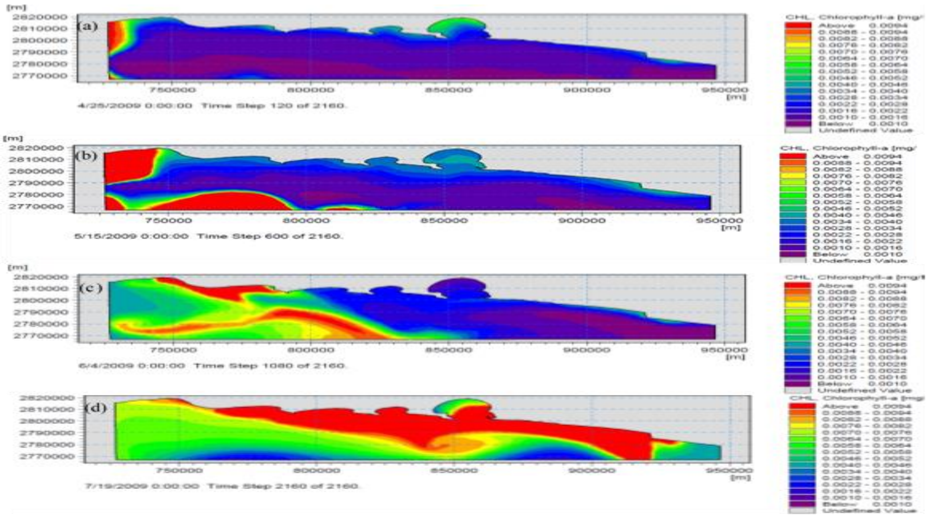

Figure 8. Schematic dispersion of chlorophyll-a through 3-month modeling, (a) late-April, (b) mid-May, (c) early-June, (d) mid-July

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