Predicting the Distribution of Harmful Algal Bloom (HAB) in the Coastal Area of Oman Sea

Abdolreza Karbassi*, Elmira Mahin Abdollahzadeh†, Gilan Attaran-Fariman**, Mehrdad Nazariha* and Mahnaz Mazaheri-Assadi***
*Faculty of Environment, University of Tehran, Tehran, Iran
**Department of Marine Biology, Faculty of Marine Sciences, Chabahar Maritime University, Chabahar, Iran
***Biotechnology Center, Iranian Research Organization for Science and Technology, Tehran, Iran
†Corresponding author: Elmira Mahin Abdollahzadeh

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 blooms have 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 modelling was successful in simulation of currents across the Gulf of Oman in hydrodynamic and quality terms. The dispersion of Cochlodinium polykrikoides was first observed at mid-April 2009 in the nearest station to the Strait of Hormuz. The bloom spreads toward eastern stations of Chabahar in mid-May and then persisted for two months. The results were consistent with those obtained through software modelling on the dispersion of chlorophyll-a, the major cause of algal bloom. Given that the Gulf of Oman and the Persian Gulf are linked, the total tidal currents across the region were modelled. The results indicated that tidal currents tend to be stronger in the Persian Gulf than the Oman Sea. Additionally, the tidal range widens in the Persian Gulf, which can be associated with the lower depth of the Persian Gulf and its semi-enclosed environment. Given the results and the great eutrophic 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. The validated model in this study can be employed to provide on-time warning and prevent any adverse social and economic consequences.

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 operations (Richlen 2010, Villacorte 2015). The geochemistry of surficial and core sediments of these regions shows a changing aquatic environment from oxic to anoxic conditions (Karbassi 1998, Karbassi et al. 2010, Biati et al. 2012, Vaezi et al. 2015, Parang et al. 2013).

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 litre of water, algal bloom occurs and the high density of phytoplankton in the water changes its colour 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. 2004a, 2004b, 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).
Coastal waters are being deteriorated by the negative effects associated with the development of societies and industrial activities. Untreated discharge of urban and industrial wastewaters are among the main sources of pollution in coastal waters (Attaran-Fariman 2010). One of the natural factors in the occurrence of red tide is the rising of warm currents that are rich in nutrients. Based on Herrings theory, winds that blow in the various seasons are one of the main causes of harmful algal blooms. These winds cool surface waters and raise the level of the deeper and warmer waters, which is followed by the transfer of nutrients together with large volumes of dinoflagellates to the surface of the water. The reaction of ecosystem to eutrophication in coastal waters is complex and depends on the concentration of nutrients, the chemical form of nutrients (organic vs inorganic), and the ratio of the nutrient supply (Anderson 2015). Therefore, it is crucial to predict HABs as long as human factors are involved.

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 the 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 kilometres. Major toxic outbreaks can suddenly appear on a site due to the transport of bloom’s 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-α across the southeast coast of Iran. The hydrodynamic process 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-α, salinity, dissolved oxygen and temperature.

**MATERIALS AND METHODS**

**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 stretch from the Strait of Hormuz to the Gwatar Port on the Oman Sea. The length of the Oman Sea from the Strait of Hormuz to Deccan is about 610 kilometres. It covers an area of 9.03 × 10⁵ km². This sea is relatively deep (as deep as about 3500 meters). Its depth decreases on its western part and declines to 72 meters near the Strait of Hormuz. Since the Tropic of Cancer passes through this sea, it is considered one of the warm seas of Southwestern Asia. The waves generated in the Oman Sea are mostly influenced by monsoon winds. Small ports like Jask, Chabahar and Gwatar are located in the coastal region of this sea and are used for trade and sea transportation. The important cities bordering this sea are Chabahar and Jask in Iran and Muscat in Oman.

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 Pasabander (station 1), Bris (station 2), Ramin (station 3), Chabahar (station 4), Pozm (station 5), Kalat (station 6), and Galk (station 7) (Fig. 1). Samples were taken in the spring and summer of the year 2009.

The reasons for choosing these ports are: Pasabandar is open coast a place that HABs events happen regularly (Attaran-Fariman 2007). In Bris and Ramin ports discharge of Tuna fishing industry has been observed. Station 4 located in the Chabahar bay along the Chabahar port almost in the middle of the southeast coast of Iran near the town of the Chabahar and is the main fishing ground for lobster in the region and in the past 5 years has been berth construction in port. Station 5 located in the Pozm port near the fishing harbour. Station 6 is also near the fishing harbour and station 7 there are no berths in this area, but is under construction (Attaran-Fariman et al. 2007). Samples were taken in the spring and summer of the year 2009.

**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). Modelling 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-litre 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 Parson et al. (1992). If phytoplankton masses were observed at any station, another sample was taken, but this one was not fixed.

Winkler bottles were used for determining dissolved oxygen. 3 mL of manganese chloride and the KI NaOH indicator were added to each sample at the sampling stations to fix the samples (MOOPAM 1998). Salinity was measured...
using an MT110 model salinity meter with the accuracy of 0.1. The temperature was measured by a thermometer with the accuracy of 1°C. Finally, the transparency of waters was determined by Secchi disc.

The samples were then sent to the laboratory for measuring the parameters and for studying the phytoplankton. Live phytoplankton samples were examined in 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-α 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).

Model Setup

Hydrodynamic model: This study involved the hydrodynamic module of MIKE 3-FM and ECO Lab for the hydrodynamic simulation of the dispersion of chlorophyll-α across the Oman Sea. In fact, it is a numerical modelling 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 variable chemical and biological interactions in different scenarios, describing how the concentrations are distributed in each scenario (DHI 2007a, 2007b, 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 modelling on the dispersion of chlorophyll-α 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 modelling were employed to develop the hydrodynamic model for the dispersion of chlorophyll-α 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 were collected from Chabahar Synoptic Station at 3-hour time step intervals. There were several advantages to the 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 were applied to the only eastern maritime boundary in the regional model as shown in Fig. 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 modelling 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 were extended to the entire length of boundary. It was then applied in 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 were 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.

Qualitative model: The qualitative modelling spanned from April 20 to July 22, 2009 at 7 stations, according to Fig. 1, focusing on the southeast coast of Iran, where the concentrations of Chlorophyll-α, 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-α. Hence, the next section will only discuss the density and dispersion of algal bloom based on chlorophyll-α.
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 modelling 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 escalates. 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 is expanded between station 1 to 7 as illustrated in Fig. 4b.
Fig. 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.

Fig. 6: Comparison of the observed and simulated water surface elevation at AbShirinKon 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.
RESULTS AND DISCUSSION

Since phytoplankton fluctuated similar to chlorophyll-\(a\) at all stations during the sampling periods, the phytoplankton were modelled through simulating the dispersion of chlorophyll-\(a\) across the Iranian southeast coast covering longitudes of 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 were 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 modelling 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 modelled through software.

In order to examine the observations from the dispersion of phytoplankton in the Oman Sea and the Persian Gulf during every red tide over the last few years, the next section will explore the entire tidal currents across both the gulfs, thereby to predict the dispersion rate of algal bloom.

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 brings 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. Moreover, it can serve as a strategy to prevent any types of possible damages to aquaculture and desalination systems by providing solutions at the right time in the southern coast of the country.

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 the Manning formula, which selected \(\frac{45}{s}\) as the final option. The calibration of the model involved the water level data in Bandar Abbas Station for over a 4-month period. The location of Bandar Abbas Station can be seen in Fig. 2a. Fig. 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 AbShirinKon station and model outputs. Having performed several tests, the Manning formula \(\frac{35}{s}\) was selected as the roughness coefficient within the model. As seen in Fig. 6, there is an acceptable consistency between the modelled and measured water levels at the AbShirinKon station over a period lasting 105 days.

Calibration of the qualitative model: Involving the two parameters of the 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 (m/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).

Dispersion of chlorophyll-\(a\): Fig. 8 schematically displays the results of dispersion and density of chlorophyll-\(a\) at different times. Fig. 8a shows the algal bloom at station 7 in mid-April. As can be seen in Fig. 8c and 8b, the chlorophyll-\(a\) spreads toward the east coast of Oman, according to the modelling 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 (Fig. 8d). The concentration of chlorophyll-\(a\) and the number of phytoplankton cells diminish near station 7 by mid-July. The results of modelling in Fig. 8 are consistent with the field measurements. In their research, Karbassi et al. (2016) identified the eutrophication of the region through the trophic index in the same period. The average six-month value of TRIX varies from 4.9 to 6.2 and decreases (on average) as we approach the eastern part of the Oman Sea. The average value of this index is indicative of a mesotrophic state at the Pasabandar Station. Unfortunately other stations showed eutrophic conditions due to discharge of wastewaters from urban and industrial sectors into the coastal waters. Statistical analysis revealed a good correlation amongst the identified species of phytoplankton that are responsible for algal...
Fig. 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.
bloom with nitrate, phosphate and chlorophyll-a content of coastal waters. It can be inferred that nutrients and chlorophyll-a can be very influential in the occurrences of algal blooms in coastal waters of the Oman Sea.

Therefore, the results of modelling in this study under the same physical and chemical parameters effective in the regional trophic can confirm the eutrophication and algal bloom across the region.

Development of the hydrodynamic model for Persian Gulf: The results of studying the dispersion of phytoplankton in the coastal waters of Oman revealed that the red tide happening in the Persian Gulf could be extended in various ways to the Iranian coast in the Oman Sea. The Red tide disaster across the Persian Gulf and Sea of Oman during 2008-2009 caused tremendous social and economic damage to the coastal towns and marine ecosystems. Although this study mainly intended to simulate the dispersion of chlorophyll-a across the southeastern region of Oman Sea, the tidal currents of the Persian Gulf and Oman Sea were briefly examined (the line a tide travels from the Oman Sea down the Persian Gulf), as shown in Fig. 9. In Fig. 9a, as a tide occurs in Chabahar Bay area, the currents in Persian Gulf were faster despite the fact that the tide initiated within the Oman Sea. In Fig. 9b, as the tide occurs within the Strait of Hormuz, the currents meet their maximum intensity. In Fig. 9c, as a tide occurs in the Strait of Khoran, the maximum tide throughout the modelling was ongoing in the region. Figs. 9d and 9e display the tidal currents in the Persian Gulf and Oman Sea when a tide occurs at the center and end of the Persian Gulf, respectively.

According to Fig. 9, the results indicated that tidal currents tend to be stronger in the Persian Gulf than the Oman Sea. Additionally, the tidal range widens in the Persian Gulf, which can be associated with the lower depth of the Persian Gulf and its semi-enclosed environment.
Fig. 9: The tidal currents across the Persian Gulf and Oman Sea as a tide occurs within the region, (a) Chabahar Bay, (b) Strait of Hormuz, (c) Strait of Khoran, (d) Persian Gulf, and (e) Oman Sea.
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 towards the 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 and 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 modelling and calibration through the simulation software in the Oman Sea from mid-April to mid-July, when the concentrations of chlorophyll-a and dispersion of algal bloom were measured. This can validate the modelling to predict the dispersion and concentration of phytoplankton upon first observations. This study demonstrated that modelling could provide a useful tool to predict and develop several scenarios concerning the spread of HABs within aquatic ecosystems.

Given that the Oman Sea and the Persian Gulf are linked, the total tidal currents across the region were modelled. The results indicated that tidal currents tend to be stronger in the Persian Gulf than the Oman Sea. Additionally, the tidal range widens in the Persian Gulf, which can be associated with the lower depth of the Persian Gulf and its semi-enclosed environment. Given the results and the great eutrophication potential in southern coastal areas of Iran, due to the disposal of municipal and industrial wastewater, the phytoplanktons are expected to further disperse and concentrate, thus leading to greater algal bloom in the region.

Moreover, the modelling of this phenomenon can provide early warnings and prevent any economic and social consequences against aquaculture and desalination systems.

ACKNOWLEDGEMENTS

This research is a part of the Ph.D programme carried out in University of Tehran. Thanks are due to Chabahar Maritime University for providing us with several useful data (The data used in this research are financially supported by environmental office in Sistan and Baluchestan Province). We also thanks MAPNA GROUP, grant no. RD-THD-91-06 for their financial support. We gratefully acknowledge all the stake-holders.

REFERENCES


DHI (Danish Hydraulic Institute) 2008. ECO Lab-Short Scientific Description. MIKE by DHI. DHI Water Environment Health, Horsholm, Denmark.


Abdolreza Karbassi et al.


