Ecological characterization and simulation of a coastal industrial area in the United Arab Emirates

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Abstract

This paper presents an overview of the water quality and biological data collected from a coastal industrial site in the United Arab Emirates. Evaluation of the data shows that the area is characterized by high nutrients and low productivity and chlorophyll carbon. Evaluation indicates that further identification of the small-sized phytoplankton is needed. The data is then incorporated in a 3-D ecological numerical model to simulate the lower trophic level prevailing in the area. Hydrodynamic conditions are needed for the model as they were developed in an earlier study. The simulation is done for both the summer and winter seasons utilizing four data sets for parameter stabilization and calibration. Phytoplankton and zooplankton are both simulated with time and space in response to variable effluent fluxes of nutrients and organic matters. Other simulated parameters include nutrients, DOC, POC, COD, and DO. The model proves to be a good tool for evaluating the ecological conditions of coastal areas under different effluent loads.

1 Introduction

The coastal ecosystem of the UAE may experience environmental threats due to the establishment of new industries linked to oil and petrochemicals. The limited
knowledge on the marine biogeochemistry in the Arabian Gulf coastal seas and the level of marine lives vulnerability to the influence of oil-related activity does constrain the exploration of such threats. It is extremely difficult to assess the dynamics of the lower trophic level which is a key indicator of the marine ecosystem health.

The study area is a major industrial zone in the UAE encompassing an oil refinery, petrochemical factory, a fertilizer factory, a sulfur production unit, and a desalination plant. Such facilities discharge their effluent wastewater in the coastal water after applying various levels of physical treatment undertaken onshore before discharge.

The time-dependent distribution of phytoplankton-zooplankton and other water quality variables in the area is a vital requirement for any environmental studies. This can be achieved by unsteady three dimensional modeling that requires extensive field information and enormous computational time. Mathematical modeling of the lower trophic level, which basically comprises phytoplankton and zooplankton in most marine water, is advantageous for understanding the eco-dynamics. This provides an efficient environmental tool to evaluate any possible implications of anthropogenic interference by simulating the spatial and temporal distribution of various biological variables. Sophisticated models with more than 10 state variables were applied in recent years to study the unsteady ecological process [1, 2]. This paper presents a brief overview of the simulation results produced from a Japanese 3-D unsteady model applied on the coastal area after employing 4 sets of ecological field observations collected during four months representing the summer and winter seasons.

2 Theory of ecological modeling

The current study employs a bio-chemical model [3] that has been developed to evaluate the physical-biological interaction in the lower trophic level in terms of nutrients and oxygen cycle. The biological model estimates the standing stock by considering their local changes as a result of biochemical processes and including the advective-dispersive transportation under the hydrodynamic forcing. Discharging loads are incorporated as source terms. Among the thirteen compartments of the model, three compartments, i.e., phytoplankton, picoplankton and zooplankton, constitute the living part.

The biochemical model is fundamentally forced by flow field, temperature and solar radiation. The water temperature plays an important role in regulating the biochemical processes of the model, as the model assumes the well known exponential Arhenius relation to the temperature for most of the biological kinetics. The general description of the coupled physical and biological model is:

\[
\frac{\partial B}{\partial t} + (\nu \nabla) B + (w + w_p) \frac{\partial B}{\partial z} = [\nabla.(K_H \nabla)]B + \frac{\partial}{\partial z} \left( K_z \frac{\partial B}{\partial z} \right) + \left( \frac{dB}{dt} \right) + q
\]
where, \( B \) is the standing stock or concentration of an arbitrary compartment, \( w_p \) is the sinking rate for a particular organic compartment, \( K_h \) and \( K_z \) are the horizontal and vertical diffusivity constants, \( (dB/dt) \) represents the local temporal change of \( B \) according to the biochemical processes. The term, \( q \), appearing last in the equation accounts for the fluxes due to external sources and sinks like nutrient loading, benthic release or bed consumption, etc. The schematic flow diagram of the model processes is shown in Figure 1.

![Schematic view of the ecosystem model](image-url)

**Figure 1:** Schematic view of the ecosystem model [7].

In this model, the well known cell quota approach [4], [5] is used to formulate the photosynthetic growth of phytoplankton where the photosynthetic growth rate is affected by available light and by intracellular nutrient reserves (cell quota) of phytoplankton. The cell quota works as a limiting factor to the maximal growth rate of phytoplankton, and from among the two intracellular nutrients, the phosphorus quota and the nitrogen quota, the most limiting nutrient is determined based on Liebig's law of minimum. Formulation of other
biochemical processes include mortality of phytoplankton, growth and mortality of picoplankton and zooplankton, nutrients uptake and POC mineralization, plus many other processes can be found elsewhere [6].

3 Study area

The coastal study sea is a sheltered zone of the Southern Arabian Gulf with an area of 264 km² (Figure 2). Sin Bani Yas Island is located at the northwest while large tidal flats in the east separate the area from the UAE eastern coastal seas. An amphidromic points for M2 and S2 tides exist at the north of the study area where the area is subject to diurnal tide. Tidal wave enters the Arabian Gulf through the Straights of Hormuz and develops varying tidal pattern along the coastline in combination with the incidental and reflective tides. Earlier studies show that the tide does not create any mean flow in the southern in the central gulf. However spatial density variation caused by high evaporation and influx of fresher water from the Arabian Sea in the east develops residual flows [7].

Figure 2: Study area.

The Arabian Gulf is affected by extra-tropical weather system from the northwest. A NW wind, more well known as shamal, occurs year around [8]. The winter shamal brings some of the strongest winds and highest seas to the gulf region. It seldom exceeds 10 m.s⁻¹ (<5% frequency) but lasts several days
The summer shamal is usually continuous from early June through July. Coastal winds in the UAE are dominant between west and north directions. The landward winds are driven by the intense temperature difference between land and water surface. The salinity and temperature in the Arabian Gulf are highest in the coastal waters of the UAE and Qatar. The temperature is found to vary over the study area between 20 and 34°C while the salinity changes from 44 to 46 psu over one year. The salinity increases up to 50 psu at the west of study area near Qatar peninsula. These figures have been reported from conducted filed measurements to be discussed in the following section.

4 Hydrodynamic characterization

Advection of different compartments is acquired from hydrodynamic simulation that resolves the flow by taking into account the tidal force, wind force and heat flux over a given bathymetry under the influence of proportioned friction and diffusion levels. More details about the hydrodynamic modeling theory can be found elsewhere [10]. Brief description is presented herein.

The hydrodynamics of the studied coastal area is characterized by diurnal tide with maximum tidal range of 1.6 m during the spring tide. The tidal flats and Island A partially shelter the area from the active flow dynamics of the deep seawater. This feature is conducive to forming pockets of low mixing water mass and localized eddies in the study area [10]. The water temperature rises to 35 °C in summer and decreases to 20 °C in winter while the salinity usually ranges between 45 and 46 ppt all around the year. In general, the water in the UAE coastal shelf is more saline than the central gulf [11] and this creates a three dimensional circulation shifting the heavier water down to the deeper section of the sea [9].

5 Field measurements and ecological characterization

Water quality monitoring was conducted in June 2003, August 2003 representing the summer season and in November 2003 and January 2004 representing the winter season. The observations were conducted at 10 stations spread over the basin (Figure 2) covering three depths (top, middle, and top). The acquired data includes DO, TOC, DOC, POC, COD, NO3-N, NO2-N, NH4-N, PO4-P, chlorophyll a, phytoplankton, picoplankton, and zooplankton. More details addressing the collected and ecological characterization of the Ruwais basin are available in another study [12]. A brief overview of such results is presented here.

The phytoplankton concentration was low in the early summer in the north and east but relatively higher in the central part and close to the eastern shoreline. Both POC and DOC were found higher in the shallow water. Most of the nutrient values were lower close to the north and west boundary and this may have happened due to fresher water exchange through these areas. Phytoplankton concentration was higher in the deeper water in winter. Both POC and DOC
were observed higher in the deep areas and along the north boundary. No definite trend is observed for nutrient distribution in the winter.

The ecosystem of Ruwais basin has been classified as HNLC (High nutrients low chlorophyll). Poor productivity at both primary and secondary levels is evident. Reasons for such poor productivity may be related to high salinity, partial limitation of phosphate nutrients, high erratic concentrations of TPH contamination, and possible shortage of secondary nutrients and vitamins. Moderate to poor species diversity index was calculated with the minimum value spotted close to SPM points. It was also shown that grazing controls the food web system after finding no sign or weak contribution of the microbial biomass to the secondary level biomass [12]. As a major part of the industrial effluent data was collected from the refinery, the utility plants, and the polymer industry (Brooj), the effluent loads needed for the simulation were estimated.

6 Model setup and calibration

Numerous water quality parameters are involved in the considered model that do not have unique values due to wide variability of the physiological characteristics of different organism groups, sensitive dependency on meteorological condition and dependency on the ambient features. A stabilization process has been employed in the present study by adopting the ecological parameters from literatures and adjusting them for the local condition so that an ecological equilibrium is attained within reasonable time frame. The computation is done for summer and winter seasons, covering two-month simulation period in each season. In each case, while the initial condition is set according to the field observation, the end results are also compared with measurement. The process parameters are gradually tuned within realistic range to get closer match. Obtained model parameters (one group for both summer and winter conditions) can be found elsewhere [6].

7 Simulation results

Nearly stable seasonal conditions are attained after the stabilization process. Stable condition is attained after about two weeks, when most of the model compartments start to show small changes with time and after the governing kinetic equations reach an equilibrium condition over dominating the influence of the initial conditions. Phytoplankton, picoplankton and their cell quota exhibits diurnal oscillation as light radiation and tidal flows are cyclic events. While the POC concentration tends to decrease throughout the simulation period, the DOC and nutrient levels remain almost unchanged.

Phytoplankton and zooplankton distributions averaged over the 60-day period for the surface layer are shown in Figure 3. Both phytoplankton and picoplankton concentrations are higher near the shore and show a sign of propagation towards north. Such trend is attributed to the mean flow pattern induced by tide, wind and density gradients. Industrial discharges leading to higher nutrient level stimulate higher growth of the phytoplankton community in
this region. However, at the same time, the zooplankton biomass is found lower in the shallow coastal region.

Winter results show that the phytoplankton and picoplankton concentration in the central basin is relatively lower. In the areas near the open boundary, growth is strongly influenced by the input boundary condition. Higher biomass close to the shore line is caused by nutrient loading through industrial discharges. As the summer condition, the zooplankton biomass is found lower close to the shore line. DOC is estimated higher close to the northern boundary with values close to 3000 mg/m³ but relatively lower near the western boundary and in the central basin area.

Results for other water quality compartments in the summer and winter season as well as vertical profiles of selected compartments are further explained in another study [7].

Figure 3: Time-averaged distributions of (a) phytoplankton and (b) zooplankton in summer season. Contours are in mgC/m³.
8 Summary and conclusion

Physical and biological dynamics of Ruwais coastal water in the UAE have been simulated using a 3-D hydrodynamic-ecological coupled model. The model considers thirteen compartments including three living ones, i.e., phytoplankton, picoplankton and zooplankton. The model parameters are identified for both the summer and the winter seasons based on the obtained water quality and ecological data. Compared to the observed compartments, the model produced weak spatial variation during the stabilization process that can be attributed to the large influence from the boundary. The small area of application site (12 km by 10 km) reflects small changes in temperature and salinity and can also explain that phenomena.

The simulated phytoplankton and picoplankton concentrations in the summer are found slightly higher near the shore as a result of industrial discharges containing high nutrients. The concentrations tend to propagate towards the north as a result of mean flow pattern induced by tide, wind and density gradients. Zooplankton biomass is found lower, however, in the shallow coastal region. Winter outputs reflect an overall slow decreasing trend of phytoplankton and zooplankton biomass. Similar trends were observed for the organic carbon and all nutrients except for the phosphate that increased by almost three folds in two-month period brought about by the model generated boundary conditions. Temporal results of the averaged model compartments of stations 1, 9 and 10 reach a steady state after about two weeks. Except for phosphate, the level of nutrients in the water is not changed with the continuous loading from the outfall as a result of oxidation and uptake process. The phosphate level increases steadily due to the boundary influx. However, the growth of the phytoplankton is not influenced by the nutrient variation as the available nutrient does not create a nutrient limiting condition. Growth of the living compartments in the open boundary is strongly influenced by the considered boundary condition. Similar to the summer observation, high biomass close to the shore line is caused by nutrient loading from the industrial discharges while the zooplankton biomass is still lower close to the shore line.

The model proofs to be an efficient tool for evaluating the ecological conditions of coastal areas when subjected to different effluent loads.

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