Assessment of the Effect of desalination Brine Waste on Marine Water Quality in Ruwais Area: A Numerical Modeling Application

Samer Jouda Al Nahhal

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ASSESSMENT OF THE EFFECT OF DESALINATION BRINE WASTE ON MARINE WATER QUALITY IN RUWAIS AREA: A NUMERICAL MODELING APPLICATION

By

Samer Jouda Al Nahhal

B.Sc. in Civil Engineering
Birzeit University, Palestine (2001)

A Thesis Submitted to the Faculty of Graduate Studies. United Arab Emirates University in Partial Fulfillment of the Requirement for the Degree of Master of Environmental Science

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A Thesis submitted to the Deanship of Graduate Studies
United Arab Emirates University

In Partial Fulfillment of the Requirements for
M.Sc. Degree in Water Resources

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January 2005
To All Whom I Love
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ABSTRACT

This thesis aims to investigate the fate and transport of the effluents discharged from the desalination plant as well other facilities located in the Ruwais Industrial Complex (RIC) in the United Arab Emirates. These effluents are discharged into the Ruwais coastal marine waters. The effluents from the desalination plant are characterized by warm water with high salinity, whereas one other effluent is characterized by high nutrient loads. The characterization of the Ruwais environment and such effluents are addressed through comprehensive field surveys of the Ruwais coastal water over one full year.

In order to investigate the impacts of such effluents on the coastal marine water quality, a coupled physical-biochemical model is employed to study the hydrodynamics and the water quality of the Ruwais coastal water. Hydrodynamic simulation for the entire basin of the Arabian Gulf is developed as regional model, and the mean currents and the circulation phenomenon in the Gulf is described. Subsequently, a local model for the Ruwais coastal water is nested inside the regional model area with three open boundaries across the Gulf basin, to investigate the mean currents of the coastal area in addition to the spatial and temporal variation of temperature and salinity.

To investigate the quality of the Ruwais coastal waters, the water quality model “EUTROP” is used. This model takes into consideration several water quality compartments, i.e., phytoplankton, zooplankton, particulate organic matter, dissolved organic carbon, phosphate, ammonium, nitrite, nitrate, dissolved oxygen, and chemical oxygen demand. The investigation of water quality covers up to 4 future years and employs two different boundary conditions. The study evaluates the present conditions and the future conditions, where the expansion of existing facilities in the Ruwais area is considered.

It is found that the effects of the effluents in the currents conditions is limited and restricted to the outfall area. It is characterized by slight increase in the temperature and salinity without major problems related to the water quality. Moreover, the influence of the future expansion in connection with increase in temperature and salinity extends up to 10 km offshore without major impacts related to water quality beyond that limit.
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<td>20Q-Desal</td>
<td>Expansion scenario for the desalination plant only by 20 times</td>
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<td>Boundary Condition</td>
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<td>COD</td>
<td>Chemical Oxygen Demand</td>
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<td>CTD</td>
<td>Salinity, Temperature, and Density</td>
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<tr>
<td>DO</td>
<td>Dissolved Oxygen</td>
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St. 3  Third observation station near Sir Bani Yas Island
UAE   United Arab Emirates
Z     Zooplankton biomass
CHAPTER ONE
INTRODUCTION

The marine environment is a primary resource in achieving the social, economic, and strategic objectives of the Arabian Gulf region. The discovery of oil in the region increased the importance of the Gulf due to the dominant economic role of oil all around the world. The fishery industry also represents great social significance for the Gulf people due to the wide diversity of the existing fish species. Nowadays, due to the scarcity of freshwater resources in such arid areas, the Gulf is considered as a main source of water for the desalination plants scattered around its coast that cater to the needs of most of the population and to the industries in the Gulf countries.

The United Arab Emirates (UAE) is a federal country consisting of seven Emirates located along the western coast of the Arabian Gulf. These Emirates are Abu Dhabi, Dubai, Sharjah, Ajman, Um Al-Quwain, Ra’s Al-Khaymah and Al-Fujerah. The country has 700 kilometers of coastline, 100 kilometers of which are on the Gulf of Oman and the rest is on the Arabian Gulf. UAE is bounded on the east by the Gulf of Oman and Oman, on the south and west by Saudi Arabia, and on the north by Qatar and the Arabian Gulf. Most of the population in the UAE lives in a few coastal towns or inland oases. The majority of the country’s territories are sandy. The climate of the UAE is characterized by extremely hot and humid weather in the summer with average temperature exceeding 40° C, while the winter is mild; the average annual rainfall is very low (78-152 mm).

The massive development of the UAE and its demographic growth is associated with evolution of desalination technology. Desalinated water has the highest share in the water budget of the country, where the desalination plants supply water for domestic use in addition to industrial and agricultural purposes. The desalination plants supply 98% of the freshwater demand from either seawater or brackish water; for instance, the population of Abu Dhabi, the capital of the UAE, has increased to 2,262,309 in 1997 compared to 200,000 in the early sixties (Sommariva and Syambabu, 2001). In spite of the natural water resources scarcity in the UAE, Abu Dhabi Emirate is considered to have one of the highest per capita water consumptions in the world due to the high standard of life style (Sommariva and Syambabu, 2001). According to Abu Dhabi Water Authority reports, the consumption
per capita exceeds 500 l/d. The supplying of the freshwater from the desalination plants is not limited for the domestic use, but it also extends to the agricultural sector, where the enormous desert greening programmes undertaken by the UAE government increased the agricultural demand of freshwater considerably. In Abu Dhabi Emirate, over 120 million trees have been planted in recent years (Sommariva and Syambabu, 2001); which prompted the government to implement desalination plant projects in a fast track to meet the urgent needs of freshwater.

The robust growth of coastal communities in the UAE is putting a massive stress on the costal marine environment, since all the 7 Emirates of the country along with main cities, ports and most industrial zones are located at the coast.

Ruwais Industrial Complex (RIC) which is the subject of the current study is one of the most important and economical coastal zones as it contains the biggest oil refinery in the UAE and it is considered as the main port for exporting the oil and petrochemical products to the rest of the world. A number of other facilities are also along the coast of Ruwais. This includes a petrochemical factory, a power plant, a fertilization factory, and a gas production plant. A small township is attached to the RIC with amenities and municipal facilities. In order to cater to the needs of the town and these industries, a desalination plant was established.

All of these industrial facilities in addition to the desalination plant discharge their effluents after some treatment to the marine water. These effluents may contain some chemicals, warm waters and a high concentration of brine due to desalination processes. Continuous dumping of such effluents may threaten the ecosystem of the area, and may have many implications on the marine water quality in general and on fauna and flora and eventually the marine life in particular.

Ecologically, marine life in Ruwais coastal area has a wide diversity of marine habitats; i.e. scattered colonies of mangrove in the north along the coast of Sir Bani Yas Island, salt marches in the east and spots of coral reef in the west. This diversified environment is considered as a great wealth for the UAE and the conservation of such resources is of inevitable necessity.

In the present study, a three-dimensional hydrodynamic model is employed to investigate the hydrodynamic conditions of the Ruwais marine waters, and to investigate the fate and transport of the brine discharged from the desalination plant and the warm water released from other facilities. In order to evaluate the brine and the warmer water effects on the marine fauna and flora at the current situation, and for
long term effects, a biochemical three-dimensional model coupled with the hydrodynamic model will be used to simulate the biological and chemical dynamics of the Ruwais coastal water.

1.1 Problem Statement

The desalination plant and cooling lines for other industrial setups in the Ruwais Industrial Complex are generating significant amount of brine and warm waters. Moreover, the effluents from the other facilities have different types and concentrations of chemicals and are also dumped in the coastal water. Continuous discharge of such wastes into the marine environment should have considerable threat to the prevailing balance of the ecosystem, particularly for the protected areas such as Sir Bani Yas Island in the north.

1.2 Objectives

The overall objectives of this thesis can be summarized in the following points:

1. To investigate the fate of the brine water released from the desalination plant located in Ruwais area and to determine the impact of future extensions of these plants on marine environment.

2. To estimate the influence of releasing warmer waters disposed from the desalination plant and the nutrient loads from the other industrial facilities located in the area upon the marine water quality of the Ruwais coast in general and on Sir Bani Yas Island in particular.

3. To understand consequent implications of the disposed brine and warmer waters on microbiological community using a system of hydrodynamic and water quality models and thereby predicts the probable consequence on future coastal ecology.

1.3 Study Area

The objective of the study as mentioned before is to investigate the fate transport of brine and warm water on Ruwais coastal marine environment. In order to achieve this goal, the regional modeling for the entire gulf area is performed then a local model for the Ruwais area is nested from the regional gulf. The following section describes the
environment of the Arabian Gulf as well the Ruwais area. A more detailed description of the water quality and ecological conditions is further presented in Chapter 4.

1.4 Physical Description of the Arabian Gulf

As the modeling work of Ruwais coastal area is based and nested from the Arabian Gulf, this section briefly describes the physical environment of the Arabian Gulf as well the Ruwais area.

The Arabian Gulf is considered as one of the most important water bodies in the world due to its strategic location. It overlooks many countries including United Arab Emirates, Qatar, Bahrain, Saudi Arabia, Kuwait, Iraq, Iran and Oman. These eight states sit atop the largest hydrocarbon reservoirs on earth, with about 76 billion metric tons of recoverable oil distributed over the gulf. The natural gas reservation is about 32.4 trillion cubic meters (Reynolds, 1993).

Other than the significance of the Arabian Gulf as the main way to export the oil and gas production to the world, it has a special significance for all Arabian Gulf countries as it is considered as the main source of the distilled water for these counties, due to lack of the rainfall and other water resources in the area.

Bathymetry

The Arabian Gulf is located between latitudes 24° N and 30° N and longitudes 48° E and 57°E (Fig. 1.1). It is a semi-enclosed sea, stretches 1,000 kilometers from the Shatt Al-Arab waterway in the southern Iraq to the Strait of Hormuz, and varies in width from 75 to 350 kilometers. It is bordered by the Arab Peninsula in the south (United Arab Emirates, Qatar, Saudi Arabia, and Kuwait), by Iraq in the north, and by Iran on the east. The gulf extends over an area of about 239,000 km² with an average depth of about 36 meters. The maximum depth is about 100 m along its axis, and the average volume is about 8630 km³ (Reynolds, 1993).

The Gulf has a northwest-southeast axis. It connects with the Gulf of Oman and the Arabian Sea from the east by a waterway called Strait of Hormuz. The strait touches Iran in the north and Oman in the south. Its length is about 280 km, and the width is only 56 km at its smallest level, while the average depth is about 100 m. The Strait of Hormuz has a great strategic importance, as it is the only sea route through which oil from Kuwait, Iraq, Iran, Saudi Arabia, Bahrain, Qatar, as well as most of
United Arab Emirates can be transported. From hydrological point of view, it is a unique path for the water exchange between the Arabian Gulf and the Gulf of Oman. This process keeps the salinity level of the gulf almost constant over the years. This phenomenon was studied by several scientists, among which Hughes and Hunter (1979) and Hunter (1983) who estimated the residence time of the Arabian Gulf basin to be 2 to 5 years, while John and Olson (1998) proved by their measurements that the residence time ranges between 350 to 500 days. The complex circulation pattern prevailing in the Gulf (to be discussed later) makes the calculation of the residence time difficult and explains the large discrepancy in its estimation by different studies.

The Arabian Gulf bathymetry is characterized by an increasing depth from south to north. A shallower shelf extends in front of United Arab Emirates coast; where the average depth is about (20 m). The depth increases toward the Iranian coast where the maximum depth there is about (80 m).

Rivers

Most of the river discharges into the Arabian Gulf concentrate at the northern part; primarily from Iraq and Iran. Shatt Al-Arab is considered as a confluence of three major rivers: Tigris, Euphrates and Karun. The annual average flow of Tigris and Euphrates is 708 m$^3$.s$^{-1}$, and the Karun outflow is 748 m$^3$.s$^{-1}$. Ninety percent of the Tigris and Euphrates rivers' flow is lost in evaporation and agricultural activities. Hence, the main discharge into the Gulf comes from Karun River. Some recent investigations estimated the outfall into the Shatt Al-Arab approximately 1000 m$^3$.y$^{-1}$. Other major rivers discharge into the Arabian Gulf are; the Hendijan (203 m$^3$.s$^{-1}$), the Hilleh (444 m$^3$.s$^{-1}$) and the Mand (1387 m$^3$.s$^{-1}$). The sum of these averages amounts to an annual runoff of 110 km$^3$.y$^{-1}$ (Britannica.com, 2001).

Climate

The climate components are considered the main driving forces in the hydrodynamic processes. The gulf region and the Arabian Peninsula are known to be one of the hottest areas in the world (ROPME, 1999). The main reason of the dryness of the area is due to the coastal mountain series that separating the Arab Peninsula from the sea. The eastern zones of the gulf are an exception to these conditions, where they are affected by the Indian Ocean monsoon causing some sparse rainfalls.
The winds have a great influence on mixing and circulation of the Arabian Gulf. As the Gulf region is located between latitude 24-30° N, this zone is classified as north-temperate tropical margin. Most of the world's deserts lie in this area. The Gulf is situated between the tropical trade-wind circulation and the synoptic weather system of mid-latitudes, where the sinking dry air produces a clear skies and arid conditions (Perrone, 1979).

The "Shamal" winds blow from the northwest during the year. They have a clear effect at the gulf area. In summer it is occasionally calm and rarely becomes strong (Murty and El-Sabh, 1984); while in winter, it abruptly blows with high speed reaching up to 10 m.s⁻¹ once or twice a year. They are accompanied by strong winds and produce the highest waves of the season (Fig. 1.2).

The Arabian Peninsula coast line is exposed to strong sea breeze. During the day time, the intense heating of the land relative to the water leads the air to rise up, so the sea breeze blows toward the beach; while during the night, when the land cools,
the process reverses; and the land breeze blows toward the sea. The sea breeze speed can reach up to 10 m.s\(^{-1}\), while the land breeze does not exceed 2 m.s\(^{-1}\).

**Precipitation**

The Arabian Gulf is characterized by low rainfall and is categorized as an arid region. The annual rainfall in the gulf area varies between 78 mm and 152 mm (ROPME, 1999), which represents a negligible amount in the freshwater budget of the area. In the winter season extending from November to March, the rainfall intensity generally increases toward the north and the east.

![Typical wind pattern in the Gulf region all around the year](image)

**Figure 1.2**: Typical wind pattern in the Gulf region all around the year. The arrows and the numbers indicate the direction and the speed of the winds respectively. The Shamal winds pattern is represented for the month of January (Reynolds, 1993).
Radiation

The intense evaporation over the Arabian Gulf surface leads to highly saline water in the basin. Increasing the salinity of the Gulf causes the surface water to be denser hence to sink in the bottom of the gulf, and move toward the Strait of Hormuz to exit from the bottom. Less saline water enters from the Arabian Sea to the Gulf from the top of Strait of Hormuz to compensate for the evaporated and the exited part of the Gulf water.

The annual net heat loss over the entire Gulf is about 21 W.m\(^{-3}\) (Table 1.1) (Ahmed and Sultan, 1991).

<table>
<thead>
<tr>
<th>Source</th>
<th>Max/Month</th>
<th>Min/Month</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar radiation</td>
<td>275/ June</td>
<td>136/ December</td>
<td>212</td>
</tr>
<tr>
<td>Long wave (heat)</td>
<td>-92/ January</td>
<td>-42/ May</td>
<td>-66</td>
</tr>
<tr>
<td>Sensible heat flux</td>
<td>-30/ January</td>
<td>42/ June</td>
<td>1</td>
</tr>
<tr>
<td>Evaporative</td>
<td>-299/ July</td>
<td>-85/ February</td>
<td>-168</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>-21</td>
</tr>
</tbody>
</table>

Evaporation

Different studies were carried out to estimate the evaporation from the Arabian Gulf. Some of these studies were in harmony with each other and some of them were at odds with each other. Privett (1959) estimated the mean evaporation in open surface of the Arabian Gulf by 1.44 m per year, where maximum evaporation occurred in December as a result of the strong winds while the minimum was in May. Hastenrath and Lamb (1979) estimation coincided with Privett’s trend. Meshal and Hassan (1986) estimated the mean evaporation in the coast of the Gulf around 2 m per year. An extreme estimation was done by Ross and Stoffers (1978) where they estimated the evaporation as 5 m per year.

Salinity and temperature

Many studies were conducted to estimate the salinity and the temperature of the Arabian Gulf. Emery (1956) and Dryssen (1985) made some efforts in this field, as
Emery studied the summer time and Dryssen investigated the winter time. More comprehensive study was achieved later by Reynolds (1993). Reynolds utilized the data from NOAA vessel Mt Mitchel to carry out his study. These data were acquired using several types of measurements such as, CTD measurements, current meter mooring, buoy tracking and observation of metrological and oceanographic variables. The period of the study was 4 months, extended from the end of winter to the early summer in year 1992. The results for salinity and temperature for both summer and winter are presented in Figure 1.3. A recent study (Elshorbagy et al., 2004a) provided the missing salinity and temperature data in the southern shelf of the Arabian Gulf.

The temperature maps show that the temperature of the northern parts of the Arabian Gulf is usually cooler than the southern parts in both summer and winter. The average temperature in summer reaches up to 35° C and decreases in the winter up to 15° C. Through the Strait of Hormuz, warmer waters enter to the Gulf during the winter season to compensate the evaporated water and to preserve the energy balance as mentioned before, which keeps the temperature of the strait almost unchanged.

Figure 1.3: Distribution of salinity and temperature in the surface water of the Arabian Gulf in summer and winter (Reynolds, 1993)
Ruwais industrial complex officially inaugurated in 1982. It has been developed to be a major contributor to the national economy of the UAE. It is located along the coast of the UAE, 240 kilometers west of the capital Abu Dhabi (Fig. 1.4).

The complex comprises the most important petrochemical industries in the UAE (www.takrear.com, 2004). The refinery plant is the major establishment there. Several petrochemical utilities integrated with it; mainly, the fertilizer manufacturers. The refinery plant and the other facilities discharge their effluent after some treatment to the near coastal water. The effluents can possibly carry high chemical concentrations, in addition to warmer water. To cover the need of freshwater for the manufacturing activities and municipal use, a multi-stage flash desalination plant is present with a capacity of 150,000 m³/d. A large amount of residual brine and warm water is continuously discharged into the marine water by the plant. The effluent water temperature from the plant reaches up to 45º C, and its salinity around 70 ppt. (Elshorbagy et al., 2004b). These values are somewhat high compared to the ambient coastal waters, and may threaten the water quality of the area. This will be investigated in the present study.

![Figure 1.4: Locations of Ruwais Area and Sir Bani Yas Island along the UAE Coast.](image)

The average daytime temperature in the summer within the Ruwais area exceeds 41º C, with extreme maximum reaching up to 50º C. In the winter months, the lowest daytime mean temperature does not usually go below 20º C. The relative humidity is
high throughout the year, averaging about 70% and reaching 95% or more in the early morning hours and late night in the summer. In winter, the relative humidity may temporarily fall below 50% during the Shamal winds (Shamal wind occurs in June-July). The rainfall at Ruwais is not accurately known; but ranges approximately between 0 to 100 millimeters, averaging around 20 millimeters per year (Elshorbagy et al., 2004a). Most of the rainfalls occur during the period of November to March in the form of showers or thunderstorms. In an average year, measurable rain may fall on about 10 - 15 days.

The coastal water of Ruwais is characterized by high temperature and salinity all around the year. In the summer, the water temperature rises up to 35°C, while in winter it decreases up to 20°C. The surface salinity has slight variation over the year, where it fluctuates between 45 and 46 ppt. (Elshorbagy et al., 2004a).

The Ruwais port is one of the most vital ports in the UAE due to its import-export activities of oil and other petrochemical products. The movement of ships and tankers is continuous day and night, all around the year. Loading and unloading activities of oil and petrochemical products may produce some oil spilling and other wastes. Such contaminants move with the currents and may damage the marine environment in the Ruwais area in general. Its effects may also extend to harm the ecosystem at Sir Bani Yas Island in the north.

Sir Bani Yas Island is one of the largest wild life reserves in the Middle East (Vine, 1999). It is 15 km in the north offshore from Ruwais Industrial Complex (Fig. 1.4). The island extends 17.5 km from north to south and 9 km from east to west. A range of bare volcanic mountains are located in the center of the island with height of 148 m. The climate in the island is similar to the Ruwais area presented in the previous section.

The island is major wild life resource. Abdullah bin Zayed Al Nahyan, the Minister of Information and Culture in the UAE declared that “the island, Sir Bani Yas, has been developed with the priority of the nature in mind. His Highness Sheikh Zayed, Ruler of Abu Dhabi and the President of the UAE, has made it a personal mission to rescue as much as possible of Arabian’s wild life as well as threatened species from Africa and Asia, and to provide them with a secure and peaceful home. The success of this project is immediately evident to everyone who visits the island.” (Vine, 1999)
In the last two decades, most of the lands in Sir Bani Yas Island have been planted with different types of fruits and wild trees. 200,000 fruit trees were planted there (Vine, 1999). The eastern coast of the island has been planted with the mangrove. The coastline of Sir Bani Yas has been transformed by landfill operation and dredging ever since 1981, and the earlier maps no longer reflect the present geographic reality (King, 1998).

The marine life around the island is widely diversified. The rich and secure environment attracts several kinds of marine creatures to seek shelter in it. The most important marine species which stamp the marine ecology of Sir Bani Yas shore line are the colonies of coral reefs spreading along the southern east of the island. There are less than 20 km away from the disposal outlets of the Ruwais Industrial Complex. Coral reefs have a fiscal and biological value, where they are important for fishery and nursery. Moreover, the commercial types of them can potentially contribute to the national income in addition to their tourism significance. As the coral reefs sensitivity to temperature and salinity of the surrounding environment is very high, it is very crucial to investigate the effect of the effluents disposed from the Ruwais compound on the ambient water.

1.5 Methodology

In order to study the current and future impact assessment of the brine discharging from the desalination plant and the warm water effluents from other facilities located in the Ruwais coastal area upon the marine water, two numerical models are employed. The first is a 3-D hydrodynamic model and the second is a 3-D ecological model coupled with the hydrodynamic one.

Study of the hydrodynamics of Ruwais coastal water is conducted using a three dimensional multi-level rectilinear grid model called “COSMOS”. This model was used by Elshorbagy et al. (2004a) to study the hydrodynamic characterization of the Arabian Gulf, and was used again by Elshorbagy et al. (2004d) to study the salinity and temperature for Ruwais coast. In the current work the model used to study the dynamics of currents in the Ruwais marine water, in addition to the spatial and temporal distribution of the salinity and temperature. In order to simulate of the Ruwais area, the hydrodynamic model is first run for the entire Arabian Gulf as a regional model to simulate the different hydrodynamic conditions and to provide such conditions at the boundary of the local Ruwais model to be nested inside the regional
model with finer grid size. Several types of data have been collected for the regional model. The bathymetry of the Gulf and the tidal constituents for the considered boundary are obtained from the Admiralty Tide Tables (ATT, 2001). The salinity and the temperature for the boundary as well as for the whole model at time = 0 (initial condition) are based on the data of Mt Mitchell’s campaign (Reynolds, 1993). The wind conditions are based on Hellarman monthly wind data and records from three offshore metrological stations in the southern part of the UAE coast. Other model parameters were turned via comparison with some cited measurements to be performed later. The simulation has been done for the whole year by considering the change of solar radiation and variation of wind pattern in summer and winter seasons. After that, the boundary conditions for the local model are extracted and the model is run again with a finer grid size considering the effluents from the different sources located along the Ruwais coast. The simulation is also done over one whole year with the same previous considerations.

In order to simulate the water quality conditions of the Ruwais coastal water, a three-dimensional biological model called “EUTROP” is used. This model has been used in different studies; Nakata and Taguchi (1982), Nakata et al. (1983, 1985), Taguchi and Nakata (1998), Taguchi et al. (1999) and Elshorbagy et al. (2004b). The model used advection-dispersion scheme to simulate the lower-trophic ecological processes in the physically active regime. Information on all possible potential sources of nutrient disposed into the sea and other biological parameters of the Ruwais marine ecosystem are obtained from Elshorbagy et al. (2004b). Elshorbagy’s data mainly consisted of four groups of survey covering the summer and winter seasons in the years 2003 and 2004. It included phytoplankton biomass (P), zooplankton biomass (Z), particulate organic matter (POC), dissolved organic matter (DOC), phosphate concentration (P), Ammonium concentration (NH4), nitrite concentration (NO2), nitrate concentration (NO3), dissolved oxygen concentration (DO) and chemical oxygen demand concentration (COD). The model employs and considers the temperature, salinity, and flow dynamic data provided by the resolved hydrodynamic model. In the beginning, the model compartment parameters are stabilized in order to match the observed and calculated values of the different compartments. After that, the model is run to simulate the current situation for one whole year by considering the summer and winter variations. After that, the model is run for several years to predict the effects of the future expansions of the desalination
plant and the other facilities upon the water quality of the Ruwais as well on the aquatic life. Figure 1.5 shows a simplified diagram of the modeling process along with the different types of involved data.

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**Data Required**

**Geographical data:**
Location, Topographic data (bathymetry and land boundary)

**Metrological Data:**
Wind (speed & direction), Solar radiation, Humidity, Cloud cover, Precipitation, Evaporation

**Hydrographic Data:**
Water Temp., Salinity, Tides, Density, Inflow rivers (Quantity, Temp., Salinity)

**Water Quality Data:**
Zooplankton biomass, Phytoplankton Biomass, NO₂, NO₃, NH₄, PO₄, POC, DOC, DO, COD.

**Hydrodynamic Model**

- Grid Generation: Making rectilinear grid data
- Depth Generation: Making bathymetry data on the grid
- COSMOS: Hydrodynamic calculations

**Water Quality Model “EUTROP”**

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Figure 1.5: Simplified diagram showing the steps of water quality modeling process.
CHAPTER TWO

LITERATURE REVIEW

Arabian Gulf represents the main artery for its encompassing countries. It is considered as their window to the rest of the world to share civilization and prosperity. Beneath it, huge reservoirs of oil exist, and inside it, enormous wealth of fishes lives. Most capitals and vital cities of the Arabian Peninsulas' countries are located along its coasts. Moreover, each country has several ports and industrial areas on the shore, aside from the recreational and tourism areas that spread along the coast. Over and above, the Gulf importance extends to be the major source of the desalinated fresh water in these arid regions.

United Arab Emirates is one of countries that overlook the Arabia Gulf. Expanding and developing of communities in the UAE coast increased the pressure on the coastal marine environment due to major industrial zones mostly constructed on the coastal line. Most of these zones discharge their effluents into the coastal water increasing the nutrient supply in the marine water. Moreover, the oil import/export petrochemical activities in the different ports of the country produce a lot of pollutants which may deteriorate the water quality of the coast. In addition to the desalination and power plants which are scattered on the UAE coast discharge huge quantities of hyper saline and warm water increasing the salinity and temperature of the coastal waters; as may severely threat the fauna and flora of the UAE marine ecosystem.

In the current chapter, an intensive literature preview will be performed in order to address the main topics discussed in this thesis. These topics will cover the importance of the desalination as the main source of the fresh water in the UAE, the brine and thermal discharged effluents from the desalination plants. Different types of models utilized to assess these pollutants in the world in general and in the UAE in particular will be briefly survey, and finally the impact assessment of such contaminants on the marine biota will be discussed.
2.1 Desalination in the UAE

Water is a limited finite resource. It is essential for the life existence on the planet. Moreover, it is required to satisfy the economic and social development for the mankind. Water is becoming scarce commodity due the population growth and the change of lifestyle (Tsiourtis, 2001). Desalination of seawater is considered a suitable solution to meet the deficit of the potable water both at the present and in the future (Einav et al., 2002). Desalination is used on a large scale in many arid regions in the world where the rainfall and the fresh water resources are limited (Morton et al. 1996). The growing technology of desalination is currently providing enormous quantities of water to meet the escalating needs for domestic and industrial sectors in many water scarce countries (Al-Weshah, 2002).

UAE is an arid country. Its natural water resources of the fresh water are very limited. It is considered as one of the most dependent countries on the desalinated water because it has the second rank of utilizing the desalinated water in the Arab countries after the Saudi Arabia (ACSAD, 1997; ESCWA, 1999; Khouri, 2002). 98% of the country’s supply comes from the desalination of seawater or brackish water (Sommariva and Syambabu, 2001).

There are three main techniques of desalination; multi-stage flash desalination (MSF), multi-effect desalination (MED), and membrane processes mainly reverse osmoses (RO); (Semait, 2000).

The MSF procedure is the most common technique used in the Arabian Gulf region (Awerbuch, 1997). It requires large amounts of energy, so it is suitable for the areas that are rich in cheap fuel (Einav et al., 2002). All large size desalination plants (above 5 MIGD) in the UAE are based on MSF technology (Sommariva and Syambabu, 2001). MSF desalination plant requires an input of seawater around 8 to 10 times the production of its fresh water for cooling and feed backup (Morton at al., 1996).

The MED technique has a limited usage in the world. Even though it produces a good water quality, it mostly used for the remote area, resort locations, islands, etc. (Semait, 2000). MED technology has been applied in some of the UAE projects, where two units of Umm Al Nar desalination plant in Abu Dhabi Emirate were constructed and being used since the year 2000 (Sommariva and Syambabu, 2001).
The RO technology is widely used nowadays and it is considered as the fastest developing technique in the water desalination (Semait, 2000). It is considered as the most efficient desalination process both in terms of energy and costs (Winston and Sirkar, 1992; Altman, 2000). RO desalination plants are used to serve small and large communities in the UAE (Ahmed et al., 2001). RO desalination plant requires seawater feeding about 2.5 to 3 times its fresh water production (Morton et al., 1996).

MSF desalination plant has been constructed in the RIC to cater to the need of fresh water for the population, manufacturing, and the agricultural purposes. It produces 15,000 m$^3$/day. The aim of the current work is to study the effluent impacts of the Ruwais desalination plant and the other facilities; mainly the brine and temperature on the Ruwais marine water quality. In the beginning, a brief description of MSF desalination process will be introduced; later most of the effluent components from the MSF desalination plants will be addressed. The hydrodynamic models as a tool to investigate the temperature and salinity dispersion in the marine coastal water will be presented. Moreover, the effect of the brine and warm water on the marine ecology will be discussed.

### 2.2 Multi-Stage Flash (MSF) Desalination Plant

Semait (2000) stated that “The MSF distillation is currently the most common and simple technique in use”. Commercially, the MSF has operated since 30 years ago (Awerbuch, 1997). Figure 2.1 shows a simple schematic diagram showing the main part of the MSF desalination plant. The seawater is fed into the system under high pressure passing through closed pipes to exchange the heat with vapor, it also be used to condense the vapor in the upper section of flash chambers. The seawater water is heated to a certain initial temperature to be flushed along the lower part of the chambers under low pressure. The seawater transforms to a vapor state. This vapor passes from chamber to another, through that, it passes through a mist eliminator to condense over the condensing tubes in the upper part of chambers. The heat of this vapor transfers to the feed from the seawater to be heated before entering the steam heater, so a part of energy is saved. The condensate drips into collectors and pumped out as distilled water. The brine water in the lower part of chambers pumped again into the system to increase the water recovery. After that, the exhausted brine with high salt concentration is rejected out to dump into the sea after some treatment to
reduce its salinity and temperature. The energy consumption by this technique is very high, so increasing the energy efficiency can be achieved by increasing the number of stages (chambers), raising the temperature of the preheated seawater, enhancing the heat transfer at the condensing vapor, utilization the heat rejected by the distilled water product and the disposed brine, and other factors (Semait, 2000).

![Diagram of a Multi-Stage Flash desalination plant](image)

**Figure 2.1:** Schematic diagram of a Multi-Stage Flash desalination plant (Semiat, 2000)

### 2.2.1 Disposals from the MSF Desalination Plants

Several studies were conducted to investigate the effluent characteristics of the MSF desalination plants. Most of these studied concentrated on the brine and thermal discharging as the most important components of such effluents.

ESCWA (1993) reported that the cost is the main key in disposal method selection, where the disposal cost ranges from 5% to 33% of the total cost of desalination. Many factors are controlling the disposal cost, such as, the characteristics of the rejected brine, the level of treatment before disposals, means of disposal, volume of disposed brine, and the nature of the disposed area.

Ahmed *et al.* (2001) mentioned that all the desalination plants in the UAE dispose their effluents in the sea, although some of them discharge their effluent in nearby creeks linking to the sea.
The Ruwais desalination plant is one of such plants disposes its effluents directly to the coastal water after some treatments (Elshorbagy et al. 2004).

Morton et al. (1996) reported that the most important effluents discharging from the MSF desalination plants are the concentrated brine with high temperature, in addition to some chemicals which can be grouped into three main categories; biocides which is used for disinfection. Traditionally chlorine compounds are used to disinfect the intake systems and associated downstream plant, to prevent the bio fouling or settle down the microorganisms. Later tri halo methane compounds were used to achieve the same purpose, and due to its harmful for the human health they replaced it by copper salts which can accomplish the task without harmful on the human but it has some environmental impacts if the metal accumulates. The second category of the chemicals used is the scale control which is used early as polymeric phosphates at low levels. This component led to problems of bacterial production in the dosing system which caused contamination through the plant. Later, polymeric additives based on maleic anhydride were used to avoid the proliferation problems. The third category is the anti-foams components which are used to prevent the foam to take place especially where the demisters in the desalination plant are close to the surface of brine stream. Ethoxylated with long chain aliphatic hydroxyl compounds are used, where their discharging into the sea have negligible effects on the environment.

In the current study, not all the discharging components will be taken in consideration, because some of them can not be calculated by the water quality model used in the study, even due to their slight effects or their impacts are taking place on very long period which not be easily to be recognized by the model. The main components which were taken in consideration in the hydrodynamic model were the brine disposal and the temperature increments due to the different discharges, whilst, phosphate (PO₄), nitrite (NO₂), nitrate (NO₃), ammonium (NH₄), dissolved organic matter (DOC), particulate organic carbon (POC), and chemical oxygen demand (COD) were taken in account for the water quality model as discussed in details later in chapters 5 and 6.
2.3 Hydrodynamic Models

Al Hajri (1990) reported that, every 6 minutes, one ship passes the Strait of Hormuz, and 60% of the world's marine transports come from this area.

In spite of the economical and strategic importance of the Gulf itself, in addition to the incredible development of the coastal communities in the Gulf area, the oceanographic observations from this region is very scarce, and most of them were carried out by individual efforts of few countries (Reynolds, 1993).

Since the last two decades, the oceanographic hydrodynamic models have been widely used to simulate the Arabian Gulf. Two types of modeling are common, tidal models and circulation models. Several studies were carried out to identify the tides in the Arabian Gulf (e.g. Lardner et al., 1982; Galt, 1983; Galt et al., 1983; Blain, 1998; Blain et al., 2002). Others separate studies investigated the circulation in the Gulf (e.g. Lardner et al., 1987; Lardner et al., 1988; Lardner et al., 1991; Horton et al., 1992; Lardner et al., 1993; Reynolds, 1993; Proctor et al., 1994; Azzam et al., 2004). The third group of studies discussed both tides and circulation (e.g. Chao et al., 1992; Elshorbagy et al., 2004a).

As a general idea, numerical computational models in the past were based on two dimensional (2-D) and depth-averaged equations (Cheong et al., 1992; Shankar et al., 1997). In these 2-D models, the velocities of the currents at different depths are unified and the average value is considered. These calculations gave misleading values for the current velocity, as the current velocity at the surface layers differs from its velocity at the bottom layer due to friction force at the seabed. Moreover, in order to track the oil spill and the fate transport of the contaminants, the vertical distribution of the currents have to be well defined (Zhang and Gin, 2000). Therefore, a three dimensional (3-D) hydrodynamic model became a necessity for realistic simulation of the flow field.

There are two main categories of 3-D hydrodynamic models; multi-layer and multi-level ones. The difference between these two types refers to the construction of the interference layer. In a multi-layer model, the interfacial layers deals independently, without mass transport across the layers and can be displaced vertically to maintain continuity. However, the multi-level model assumes that the interfacial layers are fixed in space and continuity is maintained through the vertical transport between layers (Zhang and Gin, 2000).
2.4 Water Quality Models

In this part of the study, a brief literature will be introduced to describe miscellaneous three-dimensional water quality models which are used in different parts of the world in general and in the Arabian Gulf region in particular.

Three-dimensional ecological modeling has been used when the computer power has been developed enough to recognize the complex finite element processes; hence a desired combination of spatial and temporal resolution with the necessary trophic resolution could be perform (Moll and Radach, 2003). The first appearance of three-dimensional ecological models was in Japan and USA in about 1986, where the large scale ecological models were utilized to deal with dynamics and circulation of the oceans (Maier-Reimer and Bacastow, 1990). They have been used to investigate the climate change problems. Whereas, most of the shelf seas ecological models were used to investigate the eutrophication problems (Zevenboom, 1994).

Several three-dimensional ecological models were used around the world. Earlier, the models addressed pelagic habitats only (Skogen, 1993). After that, they included a simple bottom detritus compartments (Moll, 1995). Later, more sophisticated models were developed to treat all chemical and biological compartments at once (Baretta et al., 1995). The following paragraphs describe some of these ecological models.

NORWECOM (Norwegian Ecological Model System) is a three-dimensional model. It was developed in 1993 by Skogen (Skogen, 1993). The first use of the model was documented by Aksnes (1995) when he simulated the mesocosm experiments in the North Sea. Then it was widely used by several scientists to assess different water quality parameters (Eriksord and Svendsen, 1997; Skogen et al., 1995; Skogen et al., 1998; Moll, 2000).

ERSEM (European Regional Seas Ecosystem Model) is considered as one of the most famous ecological models in the world. The model was developed within a MAST project over 7 years (1990-1996). Several studies where carried out in Europe by using ERSEM model. Varela et al. (1995) and Ebenhöh et al. (1997) utilized the model to calculate the primary production in the North Sea. A microbial dynamics with carbon assimilation and nutrient uptake were simulated by using a modified version of the model (ERSEM-II) by Baretta et al. (1997). The dynamics of the North Sea meso-zooplankton was modeled by Broek-Huizen et al. (1995). Blackford (1997)
modeled the benthic biological dynamics in the North Sea, whereas, Bryant et al. (1995) modeled the production, predation and growth of fish. Patsch and Radach (1997) used ERSEM model for long-term simulation to cover the period 1955-1993 in order to study the effects of eutrophication on the North Sea. Moreover, the model was used by Radach and Ruardij (1997) and Lenhart (1999) to investigate reduced nutrient loads from the major rivers around the North Sea with different scenarios.

POL3dERSEM (Proudman Oceanographic Laboratory 3d ERSEM Model) was utilized by Allen et al. (2001) to simulate the North Sea ecosystem. It is considered as advanced extension for ERSEM and ERSEM-II models, where it could use finer grid size hence, it gave more accurate results for modeling north coast European continental shelf to investigate the spatial and temporal variation of physical and chemical factors which cause the spring blooms in the North Sea.

FINEST is a three-dimensional coupled hydro-ecosystem model. It was used by Tamsalu and Ennet to simulate the Gulf of Finland. Later, some tunings were done to be valid to use in the Mediterranean Sea, so it was utilized by Hamza et al. (2004) to simulate the Egyptian coastal ecosystem functions. In both cases, the model gave acceptable results.

EUTROP is Japanese water quality simulation software. It uses a three-dimensional coupled physical and biological model. It specialized to quantify and evaluate the physical and biological interactions in an estuarine lower-trophic ecosystem in terms of the cycles of carbon, nitrogen, phosphorous and oxygen. It takes in consideration twelve compartments, among which two living compartments; phytoplankton and zooplankton. It was used by Nakata and Taguchi (1982), Nakata et al. (1983, 1985), Taguchi and Nakata (1998), and Taguchi et al. (1999) to simulate different water bodies in Japan coastal marine water and lakes. EUTROP was modified and stabilized to be valid for using in the Arabian Gulf region. Elshorbagy et al. (2004b) used the model to simulate the ecology of the Ruwais marine water in the UAE coast.

Taguchi and Nakata (1998) utilized the EUTROP water quality model to study the mechanism of water pollution in Japanese Hamana Lake which is considered one of highly eutrophicated semi-enclosed estuarine. They adopted chemical oxygen demand (COD) as a water quality index. COD average concentration of summer in the period between 1988 and 1991 was simulated. They concluded that COD flux due to the primary production is 10 times larger than the external loading flux. Moreover,
they verified that the phosphorous is the limiting nutrient in the lake, and the benthic generation is the major source of it in the estuarine.

Elshorbagy et al. 2004b also employed the EUTROP water quality model to investigate the impact of the effluents discharging from the Ruwais Industrial Complex (RIC) on the Ruwais coastal water in the UAE in both summer and winter seasons. The model was used after some calibration for the parameters of the compartments was done to be adapted for simulating such subtropical regions like the Arabian Gulf. Elshorbagy reported that the Ruwais water characterized by NHLC (high nutrients-low chlorophyll) condition, which was caused due to the excessive discharging of the nitrogen nutrients (NH₄, NO₂, and NO₃) from the different facilities locating at the coast and lacking in the phosphate (PO₄) which was considered as a limiting nutrient in the area. He concluded also that the harsh environment at such area mainly the high pollution due to oil and industrial activities reduced considerably the zooplankton biomass. Where the pollution is considered as one of the main factors reduce the zooplankton biomass in the coastal waters (Uriate and Villate, 2004).

2.5 Effects of the MSF Desalination Plants on the Marine Ecosystem

There are many impacts associated with the MSF desalination processes on the marine ecosystem. Theses impacts are mainly caused by the elevated temperature and high concentration of brine disposing into the coastal water (Morton et al., 1996). Many studies dealt with these issues to explain the influence of such effluents on the marine ecology and habitats.

Morton et al. 1996 mentioned that the typical recovery effluent based on feed is 10%. That means the salinity of the effluent is 1.1 times the salinity of raw seawater, while the actual discharge salinity from the RO desalination plants range from 1.3 to 1.7 and from MSF desalination plants decreases to be from 1.1 to 1.5 times the salinity of the feed water. Whereas, Hoepner 1999 remarked that the effluent of brine is usually diluted twice with cooling water before being discharged, so the concentration factor becomes 1.05 times the salinity of the raw seawater.

Ecologically, it is widely accepted that the marine biocoenosis tolerates the salinity variation of plus/minus 1 ppt, so a conservative discharge recommendation follow this line (Del Bene et al., 1994).

Semait (2000) mentioned that the brine disposal problem is mild in small operation scales, and there is no serious damage may occur for the marine
environment, whereas, at large scale operations the problem becomes little more severe. He suggested dilution and spreading of such brine plumes to overcome such problem.

Einav et al. (2002) declared that the main effects of salinity increase on marine biota occur near the discharge pipe, where increasing salinity may influence the benthic and planktonic organisms by different ratios. So, she suggested 4 alternatives of discharging techniques, which are; discharging the brine by long pipe far into the sea, discharging the brine directly to the coastal line after good treatment, discharging the brine through the outlet of the attached power station, and sending the brine directly to a salt production plant. And she commented that the sensitivity to increase in salinity varies from species to other. Some species like planktonic algae can tolerate to variations in salinity, another can tolerate the raising of salinity after a period of acclimatization, whereas most of the species may die.

Einav and Lokiec (2003) indicated according to Dawes (1998) and Levinton (1995) as professional studies that there is no specified salinity limit above which definite damage will occur to benthic population. They also mentioned also that the effects of high salinity discharge are limited to the local environment of the discharging area and it has no accumulated damage of the sea.

Hoepner (1999) mentioned that in the hot and arid regions, the extensive evaporation of the seawater produces variation difference in salinity exceeds plus/minus 1 ppt, that referring to the bathymetry of the region, solar radiation, wind, tidal regime, water exchange between shallow and offshore waters and other influences. So he suggested studying such those zones regarding to their local conditions. He claimed also that the effluent effects on the coastal water are usually little or even absent.

Hoepner and Windelberg (1996) argued that, for the Gulf entire basin, brine discharge is absolutely intangible because the natural evaporation is by magnitudes higher. This conclusion is valid also regionally since the salinity increases by evaporation are highest with in the shallow coastal zones where the brine discharge takes place.

Hoepner (1999) stated that “Thermal desalination plants discharge the concentrate usually with a temperature 10 to 15 °C above ambient seawater temperature.” He elaborated according to Altayran and Madany (1992) investigations about the thermal effects of some desalination plant in Bahrain that in shallow water
regions with hot climate, the spatial and temporal variation of temperature is usual and often exceeds the effluents effects by far, so he concluded that the effluent temperature is a minor problem in the southern part of the Arabian Gulf.

Generally, Morton et al. (1996) reported that increasing the seawater temperature and salinity due to desalination schemes, power stations, and industrial facilities reduces the overall concentration of the dissolved oxygen in the water, which restricts the life forms to those able to live in low oxygen levels. This phenomenon becomes more pronounced if residual chemical concentrations that are used for de-aeration are present such as sodium metabisulphite. Moreover, at the level of the individual organisms, extreme temperature may result in death, whereas, sublethal temperature may influence the biological rates of the different processes in the organisms such as the movement, the onset of maturity, life stage development, growth and size. At the species level, excessive temperature may influence the individual abundance and population diversity. Moreover, the desalination process has a potential threat on the phytoplankton and zooplankton due to pass concomitant with the inflow of seawater into pretreatment processes which usually use a chlorination method for disinfection which almost causes a complete death for all the biological activities in such inflow waters. The temperature differentials across the distiller in addition to the shear stresses and rapid pressure throughout the system enhance significantly the disinfection and prevent most of the biological organism to keep alive.
CHAPTER THREE
PHYSICAL SIMULATION

The United Arab Emirates (UAE) is located in the northeastern part of the Arabian Peninsula. It has 600 kilometers of coastline on the Arabian Gulf. Rapid development during the last two decades; propagated the need for evaluating the marine hydrodynamics, the ecosystem, and the fate transport of oil and other contaminants dumped at the Arabian Gulf water. In order to do that, different studies were achieved, among which Azzam et al., 2004.

In the present study, a sophisticated three dimensional multi-level rectilinear grid model “COSMOS” was employed to simulate the hydrodynamics of Arabian Gulf as a regional model, and then a local model was nested for the Ruwais area in the UAE coastal waters. This hydrodynamic model was developed and used by Nakata and Taguchi (1983), Nakata et al. (1983, 1985), Taguchi and Nakata (1998) and Taguchi et al. (1999) in order to simulate the Japanese coastal waters. COSMOS hydrodynamic model was developed to simulate the hydrodynamic processes in the estuaries and coastal bays, especially for mesoscale (1-100 km) semi enclosed regions.

The hydrodynamic investigations of the Arabian Gulf were restricted to study water currents in the basin, with brief description about its general pattern of circulation. The present study is based on a comprehensive field survey of the Ruwais area to identify the effect of the local discharge effluents from the RIC on the coastal water temperature and salinity. Then 3-D physical model and a biological model “EUTROP” are employed together to investigate the water quality of the Ruwais coastal area, as will be discussed in chapter 6.
3.1 Theoretical Background

3.1.1 The Model Features

COSMOS employs a series of equations which describe the fluid motion, flow continuity, sea surface fluctuation, heat and salt transfer, in conjunction with equation of state. The driving forces of the flow field are tide, river discharge, sea surface wind, heat exchange with the atmosphere and horizontal density gradient. The sea water is considered as incompressible fluid, and the Coriolis parameters which govern the motion of the current due to earth rotation are considered as constant over the entire simulation region.

According to the previous conditions, the main basic equations of the numerical model are shortly listed as follows with respect to the Cartesian coordinate system shown in Figure 3.1:

**Horizontal Fluid Motion**

*In x-direction*

\[
\frac{\partial u}{\partial t} + \frac{\partial}{\partial x} (uu) + \frac{\partial}{\partial y} (vu) + \frac{\partial}{\partial z} (wu) = -f_0 \cdot v - g \cdot \frac{\partial \zeta}{\partial x} - \frac{g}{\rho} \int_0^h \frac{\partial \rho}{\partial x} \, dz - \frac{1}{\rho} \frac{\partial P_x}{\partial x} \\
+ \frac{\partial}{\partial x} \left( A_x \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left( A_y \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \left( A_z \frac{\partial u}{\partial z} \right)
\]

*In y-direction*

\[
\frac{\partial v}{\partial t} + \frac{\partial}{\partial x} (uv) + \frac{\partial}{\partial y} (vv) + \frac{\partial}{\partial z} (wv) = -f_0 \cdot u - g \cdot \frac{\partial \zeta}{\partial y} - \frac{g}{\rho} \int_0^h \frac{\partial \rho}{\partial y} \, dz - \frac{1}{\rho} \frac{\partial P_y}{\partial y} \\
+ \frac{\partial}{\partial x} \left( A_x \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left( A_y \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial z} \left( A_z \frac{\partial v}{\partial z} \right)
\]

**Flow Continuity**

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]
\[
\frac{\partial \zeta}{\partial t} = -\frac{\partial}{\partial x} \left( \int_{-H}^{H} u \, dz \right) + \frac{\partial}{\partial y} \left( \int_{-H}^{H} v \, dz \right)
\]  

(4)

Conservation of Heat and Salt

\[
\frac{\partial T}{\partial t} + \frac{\partial}{\partial x} (uT) + \frac{\partial}{\partial y} (vT) + \frac{\partial}{\partial z} (wT) = \frac{\partial}{\partial x} \left( K_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial T}{\partial z} \right)
\]

(5)

\[
\frac{\partial S}{\partial t} + \frac{\partial}{\partial x} (uS) + \frac{\partial}{\partial y} (vS) + \frac{\partial}{\partial z} (wS) = \frac{\partial}{\partial x} \left( K_x \frac{\partial S}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_y \frac{\partial S}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial S}{\partial z} \right)
\]

(6)

Equation of State

\[\rho = \rho (S, T)\]  

(7)

Where, the right hand side was described by the Knudsen’s expression that relates seawater density to water temperature and salinity:
\[
\rho = \frac{\sigma_i}{1000} + 1 \quad (g \cdot cm^{-3})
\]  

(8)

\[
\sigma_i = \Sigma_i + \left( \sigma_0 + 0.1324 \right) \cdot \left\{ 1 - A_i + B_i \left( \sigma_0 - 0.1324 \right) \right\}
\]  

(9)

\[
\Sigma_i = \frac{(T - 3.98)^2}{503.570} \cdot \frac{T + 283.0}{T + 67.26}
\]  

(10)

\[
\sigma_0 = -0.069 + 1.4708 \cdot Cl - 0.001570 \cdot Cl^2 + 0.0000398 \cdot Cl^3
\]  

(11)

\[
A_i = T \cdot \left( 4.7869 - 0.098185 \cdot T + 0.0010843 \cdot T^2 \right) \times 10^{-3}
\]  

(12)

\[
B_i = T \cdot \left( 18.030 - 0.8164 \cdot T + 0.01667 \cdot T^2 \right) \times 10^{-6}
\]  

(13)

In the previous equations, \( u, v \) and \( w \) are the velocity components \((cm \cdot s^{-1})\) in the x, y and z direction, respectively, \( \xi \) the sea-surface level \((cm)\), \( H \) the still-water depth \((cm)\), \( \rho \) the seawater density \((g \cdot cm^{-3})\), \( f_0 \) the Coriolis parameter \((s^{-1})\) which is given as \( f_0 = 2 \cdot \omega \cdot \sin \varphi_0 \) with the angular velocity \( \omega \) \((s^{-1})\) of the earth rotation and the mean latitude \( \varphi_0 \) of the estuary, \( g \) the gravitational acceleration \((980 \ cm \cdot s^{-2})\) and \( P_a \) the atmospheric pressure \((g \cdot cm^{-2} \cdot s^{-1})\). \( T \) and \( S \) denote water temperature \(^{\circ}C\) and salinity \((ppt)\), respectively; but here chlorinity \( Cl \) \((\%)\) is adopted as the state variable instead of salinity. \( A_x, A_y \) and \( A_z \) represent the coefficient of eddy viscosity \((cm^2 \cdot s^{-1})\) in the x, y and z directions, respectively, and similarly \( K_x, K_y \) and \( K_z \) stand for the coefficients of eddy diffusivity \((cm^2 \cdot s^{-2})\).

**Depth Integration**

As shown in Figure 3.1, the water column is divided into \( K \) number of computational levels, where \( h_k \) represents the thickness of each level \( k \), and the level boundary is defined from \( z = -H_{k-1} \) to \( z = -H_k \); i.e. \( h_k = H_k - H_{k-1} \). The depth-integrated velocity components are described as:

\[
M_k = \int_k u \ dz, \quad N_k = \int_k v \ dz \quad (k=1,2, \ldots, K)
\]  

(14)
The basic equations from (1 to 8) are vertically integrated within each level in the model as the following regime.

Equation of Motion in the X-Direction

\[
\frac{\partial M_k}{\partial t} + \frac{\partial}{\partial x} \left( M_k u_k \right) + \frac{\partial}{\partial y} \left( M_k v_k \right) - (uw) \bigg|_{-H_{k-1}} + (uw) \bigg|_{-H_k} = f_0 N_k + \frac{h_k}{\rho_k} \left\{ \left[ \frac{\bar{P}}{x} \right]_k - \frac{1}{2} g \cdot h_k \frac{\partial \rho_k}{\partial x} \right\} 
\]

\[+ \frac{\partial}{\partial x} \left( A_x \frac{\partial M_k}{\partial x} \right) + \frac{\partial}{\partial y} \left( A_x \frac{\partial M_k}{\partial y} \right) + \frac{1}{\rho} \cdot \tau_{k-1,k} - \frac{1}{\rho} \cdot \tau_{k,k+1} \] (15)

Equation of Motion in the Y-Direction

\[
\frac{\partial N_k}{\partial t} + \frac{\partial}{\partial x} \left( N_k u_k \right) + \frac{\partial}{\partial y} \left( N_k v_k \right) - (vw) \bigg|_{-H_{k-1}} + (vw) \bigg|_{-H_k} = -f_0 M_k + \frac{h_k}{\rho_k} \left\{ \left[ \frac{\bar{P}}{y} \right]_k - \frac{1}{2} g \cdot h_k \frac{\partial \rho_k}{\partial y} \right\} 
\]

\[+ \frac{\partial}{\partial x} \left( A_y \frac{\partial N_k}{\partial x} \right) + \frac{\partial}{\partial y} \left( A_y \frac{\partial N_k}{\partial y} \right) + \frac{1}{\rho} \cdot \tau_{k-1,k} - \frac{1}{\rho} \cdot \tau_{k,k+1} \] (16)

Equation of Continuity

For the top-level (k=1), depth integration of the flow distribution of equation (3) becomes:

\[
\int \left\{ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right\} \, dz = \frac{\partial M_1}{\partial x} \left( \int_1^1 u \, dz \right) + \frac{\partial}{\partial y} \left( \int_1^1 v \, dz \right) - u \bigg|_\zeta \frac{\partial \zeta}{\partial x} - v \bigg|_\zeta \frac{\partial \zeta}{\partial y} + w \bigg|_\zeta \frac{\partial \zeta}{\partial z} - w \bigg|_{-H_1} 
\]

\[= \frac{\partial M_1}{\partial x} + \frac{\partial N_1}{\partial y} + \frac{\partial \zeta}{\partial t} - (v_p - v_E) - w \bigg|_{-H_1} \] (17)

\[w \bigg|_\zeta , \text{ is precipitation rate } v_p \text{ and the evaporation rate } v_E \text{ for the vertical flow velocity at the sea surface. Moreover, the depth integration for the inter-layer } k \text{ (2<k<K) represented as:} \]

\[
\int \left\{ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right\} \, dz = \frac{\partial M_k}{\partial x} + \frac{\partial N_k}{\partial y} + w \bigg|_{-H_{k-1}} - w \bigg|_{-H_k} \] (18)
And for the bottom level \((k=K)\), becomes:

\[
\begin{align*}
\int_{k} \left\{ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right\} \, dz &= \frac{\partial M_{K}}{\partial x} + \frac{\partial N_{K}}{\partial y} + w \bigg|_{-H_{k-1}} \\
\end{align*}
\]  

(19)

**Equation of Heat Transport**

For the top-level \((k=1)\), the local change and the advection terms of the heat transport equation (5) are integrated as:

\[
\begin{align*}
\frac{\partial}{\partial t} (h_{1} T_{1}) + \frac{\partial}{\partial x} (M_{1} T_{1}) + \frac{\partial}{\partial y} (N_{1} T_{1}) - (wT) \bigg|_{\zeta} &= \frac{\partial}{\partial x} \left( h_{1} K_{x} \frac{\partial T_{1}}{\partial x} \right) + \frac{\partial}{\partial y} \left( h_{1} K_{y} \frac{\partial T_{1}}{\partial y} \right) - \frac{Q_{s}}{\rho \cdot c_{p}} \left( K_{z} \frac{\partial T}{\partial z} \right) \bigg|_{-H_{1}} \\
\end{align*}
\]

(20)

And for the level \(k \ (2 < k < K)\) the equation becomes:

\[
\begin{align*}
\frac{\partial}{\partial t} (h_{k} T_{k}) + \frac{\partial}{\partial x} (M_{k} T_{k}) + \frac{\partial}{\partial y} (N_{k} T_{k}) + (wT) \bigg|_{-H_{k-1}} - (wT) \bigg|_{-H_{k}} &= \frac{\partial}{\partial x} \left( h_{k} K_{x} \frac{\partial T_{k}}{\partial x} \right) + \frac{\partial}{\partial y} \left( h_{k} K_{y} \frac{\partial T_{k}}{\partial y} \right) + \left( K_{z} \frac{\partial T}{\partial z} \right) \bigg|_{-H_{k-1}} - \left( K_{z} \frac{\partial T}{\partial z} \right) \bigg|_{-H_{k}} \\
\end{align*}
\]

(21)

Where \(T_{1}\) represents the mean water temperature defined by \(T_{1} = \int_{k} T \, dz\), and \(Q_{s}\) represents the heat exchange flux with the atmosphere.

**Equation of Salt Transport**

The depth integration equation for salt transport does not account for the exchange flux with the atmosphere through sea surface but the change in the surface water volume is taken into account through the processes of precipitation and evaporation.

The integration expression ends up as follows for any level \(k\):

\[
\begin{align*}
\frac{\partial}{\partial t} (h_{k} S_{k}) + \frac{\partial}{\partial x} (M_{k} S_{k}) + \frac{\partial}{\partial y} (N_{k} S_{k}) + (wS) \bigg|_{-H_{k-1}} - (wS) \bigg|_{-H_{k}} &= \frac{\partial}{\partial x} \left( h_{k} K_{x} \frac{\partial S_{k}}{\partial x} \right) + \frac{\partial}{\partial y} \left( h_{k} K_{y} \frac{\partial S_{k}}{\partial y} \right) + \left( K_{z} \frac{\partial S}{\partial z} \right) \bigg|_{-H_{k-1}} - \left( K_{z} \frac{\partial S}{\partial z} \right) \bigg|_{-H_{k}} \\
\end{align*}
\]

(22)
3.2 Regional Model (Arabian Gulf)

3.2.1 Model Setup

The hydrodynamic model “COSMOS” was employed to simulate the entire basin of the Arabian Gulf as a regional model. The area of simulation is shown in Figure 3.2. The computational conditions of the model are summarized in Table 3.1, where, the grid interval is 5 km, with model size 123 x 214 grid steps. The vertical dimension of the model is dividing the water column into 6 layers; 4, 6, 10, 20, 30, and 40m from the top to the bottom respectively. Four main rivers are taken into consideration (Fig. 3.2). These rivers are Shat Al-Arab rivers (Tigris and Euphrates), Hindijan, Hilleh and Manad, those have different flows, but same temperature and salinity as listed in Table 3.1. The boundary conditions of the model are at the Strait of Hormuz. The tidal constituents for the boundary are collected from the Admiralty Tide Tables (ATT, 2001), while, the salinity and the temperature for them are based on the data of Mt Mitchell’s campaign (Reynolds, 1993). The wind conditions are based on Hellarman monthly wind data and records from three offshore metrological stations in the southern part of the UAE coast. Other model parameters are identical to those used in the model employed by Elshorbagy et al. (2004a).

Due to the wide difference of the metrological conditions for the summer and winter in the Gulf region, the model is run for two separate periods, summer and winter, each covered 60 days. The data of the metrological conditions are shown in Table 3.1 too.

Figure 3.2: The simulated regional model, (*) indicates the rivers location.
Table 3.1: Computational conditions of the hydrodynamic model for the Arabian Gulf

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Selected value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>Entire basin of the Arabian Gulf (Fig. 3.2).</td>
</tr>
<tr>
<td>Grid size</td>
<td>5 km</td>
</tr>
<tr>
<td>Number of horizontal meshes</td>
<td>123 (north-south) x 216 (east-west)</td>
</tr>
<tr>
<td>Vertical layer locations</td>
<td>6 vertical layers</td>
</tr>
<tr>
<td></td>
<td>Level 1: from surface to -4, Level 2: from -4 to -10, Level 3: from -10 to -20, Level 4: from -20 to -40, Level 5: from -40 to -70, Level 6: from -70 to the bottom</td>
</tr>
<tr>
<td>River conditions</td>
<td>4 rivers at the north (Fig. 3.2)</td>
</tr>
<tr>
<td></td>
<td>River 1: Q= 1.26 * 10^8 m^3.day^{-1}, T = 15°C, Salinity = 0 ppt</td>
</tr>
<tr>
<td></td>
<td>River 2: Q= 1.75 * 10^7 m^3.day^{-1}, T = 15°C, Salinity = 0 ppt</td>
</tr>
<tr>
<td></td>
<td>River 3: Q= 3.84 * 10^7 m^3.day^{-1}, T = 15°C, Salinity = 0 ppt</td>
</tr>
<tr>
<td></td>
<td>River 4: Q= 1.20 * 10^7 m^3.day^{-1}, T = 15°C, Salinity = 0 ppt</td>
</tr>
<tr>
<td>Tidal constituents for the boundary conditions at Strait of Hormuz</td>
<td>M2, S2, K1, O1; obtained from Admiralty Tide Table (ATT, 2001)</td>
</tr>
<tr>
<td>Temperature and Salinity for the boundary at Strait of Hormuz</td>
<td>Collected from Mt Mitchell data (Reynolds, 1993)</td>
</tr>
<tr>
<td>Wind condition</td>
<td>Records from three offshore metrological stations in the UAE</td>
</tr>
<tr>
<td>Model parameters</td>
<td></td>
</tr>
<tr>
<td>Coriolis parameter</td>
<td>6.376 * 10^{-5} s^{-1}</td>
</tr>
<tr>
<td>Friction coefficient for seabed</td>
<td>0.0026 (assumed)</td>
</tr>
<tr>
<td>Wind friction coefficient at the sea surface</td>
<td>0.001</td>
</tr>
<tr>
<td>Horizontal and vertical eddy viscosity and diffusivity</td>
<td>1.98 * 10^6 m^2.s^{-1}</td>
</tr>
<tr>
<td>Metrological conditions</td>
<td></td>
</tr>
<tr>
<td>Global solar radiation</td>
<td>Summer 1500 cal.cm^2.day^{-1}</td>
</tr>
<tr>
<td>Day length</td>
<td>Winter 970 cal.cm^2.day^{-1}</td>
</tr>
<tr>
<td>Empirical coefficient of solar altitude reflection</td>
<td>0.57</td>
</tr>
<tr>
<td>Cloudiness</td>
<td>0.35</td>
</tr>
<tr>
<td>Daily mean temperature</td>
<td>0.01</td>
</tr>
<tr>
<td>Reliability</td>
<td>20 °C</td>
</tr>
<tr>
<td>Empirical constant of the cloudiness reflection</td>
<td>0.65</td>
</tr>
<tr>
<td>Calculated period</td>
<td>60 days</td>
</tr>
</tbody>
</table>

3-8
3.2.2 Model Development

To run the COSMOS model, some data files have to be prepared in a special digital format. This can be done by using number of subroutines included in the CENESIS suite. The procedure is summarized in the following three steps:

1) A rectilinear grid is developed for the study area. This is done by tracing a digitized map prepared earlier by a digitizer. Such grid generation process is carried out by using GUI software titled “GRDGNR”. The grid size and the depth levels are determined in this step and used as a part of the control data for COSMOS.

2) The next step is to create the model bathymetry. “DEPGNR”, is software used along with grid information to interpolate the depth data in three dimensional schemes. In this process, the depth of each point of the grid is determined. The output files obtained are used as input conditions for COSMOS.

3) Having developed the grid and bathymetry for the model, the next step is to develop the initial and boundary conditions. Two small softwares are used to create the initial and boundary conditions for COSMOS, they are “CSMINT” and “CSMBND” respectively.

3.2.3 Results and Discussion

The main goal of the regional hydrodynamic model is to study the current dynamics across the Gulf basin, hence to extract the boundary condition for the local Ruwais model. As a result, the regional Gulf model was run for 60 days period to simulate both summer and winter hydrodynamics. The model was fairly calibrated in a similar way to the study made by Elshorbagy et al. (2004a) and the simulated water level is compared with the same field measurements. The water level measurements are collected at three stations at UAE coast; Abu Dhabi, Dubai and Ruwais. Comparison the measured and calculated results show a good agreement with slight mismatch for the amplitude at Abu Dhabi during the spring tide as shown in Figure 3.3.

Figure 3.4 shows the time-average currents for the summer season at the surface layer. It is obvious that the dominating residual currents directed southward perpendicular to the gulf axis. At the UAE eastern coast in the south, the currents are stronger and tended to be eastward parallel to the coast while the currents circulate
counterclockwise around Bahrain Island. At Strait of Hormuz, the currents tend to be inward the Gulf basin.

In winter (Fig. 3.5), the current flow patterns in the center of the Gulf tend to be perpendicular to the Gulf axis toward the south. At the Iranian and Arabian Peninsulas’ coasts, the currents direct toward the southern east. At the eastern southern part of the Gulf, the currents incline toward the northeast heading to the Strait of Hormuz as they exit to the Oman Gulf.

Figure 3.3: Comparison of predicted and simulated water levels at (a) Abu Dhabi (b) Dubai and (c) Ruwais (Elshorbagy, 2004a)
Figure 3.4: The mean currents and circulation in the Arabian Gulf during the summer season.

Figure 3.5: The mean currents and circulation in the Arabian Gulf during the winter season.
Several surveys were done to investigate the Arabian Gulf at the last few decades (Emery 1956, Brewer and Dryssen 1984, Reynolds 1993). All these studies did not cover the southern shelf of the Gulf due to the strict restrictions and security implications of the existing oil routes. An extensive study conducted by Elshorbagy et al. (2004d) investigated the southern shelf especially the Ruwais coastal area.

The study was concentrated on the salinity and temperature spatial distribution over 80 km offshore of the UAE. Salinity and temperature values were measured using CTD instrument at 24 representative points which were distributed over the southern shelf. The summer salinity ranged between 39 and 46 ppt and the winter salinity ranged between 41 and 46 ppt. The highest salinity was detected near the Ruwais coast in both seasons. The temperature was found to fluctuate from 31 to 32.5 °C in the summer, and from 20 to 23 °C in the winter.

The southern shelf of the Arabian Gulf is considered as salinity water generation, due to the high evaporation rate at this shallow area which makes the coastal water more saline. This water sinks to the bottom thereafter to exit from the Strait of Hormuz, and less saline water enters from the Strait to substitute this water and keep the circulation continuously taking place.

The general circulation of the gulf has been studied by several scientists, as mentioned in the preface of the current chapter. Several authors have reported that the Arabian Gulf has a cyclonic motion inside it (Schott, 1918; Emery, 1956; Sugden, 1972; and Brewer et al., 1978). Through the Strait of Hormuz, relatively low-salinity and cool water enters the Gulf freshening its hyper-saline water. This flow moves northward against the prevailing winds then sinks to the bottom and moves out of the Gulf as deep counter current (Chao et al., 1992). The inflow from the Gulf of Oman was detected in April 1977, 200 km inside the Arabian Gulf and 50 km from the Iranian shoreline (Sonu, 1979).

A schematic diagram (Fig. 3.6) was produced by the U.S. Hydrographic Office (1960) as a sailing guide down the Arabian Gulf. As shown in the figure, there is inflow from the Strait of Hormuz into the Gulf during the summer characterized by broad width and reaches at the far north of the Gulf. While, the inflow in winter is narrower and almost half of the summer one and the southeastward flow along the Arabian coast is wider.
A more comprehensive study about the circulation in the gulf was achieved by RSMAS (2000). The study classified the Arabian Gulf into two regimes; northern and southern or eastern. The northern regime is governed by the winds which blow to the south along the Gulf axis and with the fresh waters discharged from the rivers at Shatt Al-Arab in the head of the Gulf (Tigris and Euphrates) and at high land of Iran (the Hindijan, Hilleh and Manad), (Fig. 3.7). The downwind flow in the Gulf is a result of the low pressure field at the southern part. This produces down-willing at the western coast and upwelling on the coast of Iran (Reynolds, 1993).

The flow along the Kuwait and Saudi Arabia coast in northern regime is increased by the rivers inflow from Shatt Al-Arab and Iran. The center of the northern Gulf appears to be fairly stagnant (Reynolds, 1993). In the southern regime, the downflow along the Iranian coast continues along the coast to reach the Strait of Hormuz. The northern and southern regimes are singled out by a front that is found off Qatar (Fig. 3.7). This front is characterized by the highest surface temperature in summer and lowest in the late of winter and spring. The location of the front associates with fresh water inflow into the Gulf from the Strait of Hormuz. Most of this inflow ends in a counter-clockwise cyclonic flow to the coast of mid-Gulf front (Fig. 3.7). The intensive evaporation over the Gulf causes an inverse circulation with hyper-saline water leaves the Gulf through the Strait. The High salinity water zones extend from Qatar to the Emirates coast (the hatched region in Figure 3.7). The salinity of water in this region may reach up to (>42 ppt) (RSMAS, 2000).
Figure 3.6: A schematic illustration of the general circulation in the Arabian Gulf and vicinity. The top panel is for summer and the bottom is for winter. (The U.S. Hydrographic Office, 1960)

Figure 3.7: Circulation schematic for the Arabian Gulf (RSMAS, 2000)
3.3 Local Model (Ruwais Coastal Water)

Ruwais coastal water is a part of the southern shallow shelf of the Arabian Gulf. The area has an average depth of about 20 m, while the eastern part of it is shallow (less than 2 m) and contains salt marshes (Sabkha). The dynamics of the coastal water in the Ruwais shore line is characterized by well mixing due to the shoal of the region in addition to sinuosity of the bottom which leads to tidal flat in the eastern side. This mixing process keeps the water unstratified over the whole year (Elshorbagy *et al.*, 2004c). The effluents from the Ruwais Industrial Complex are the most influential at the coastal water, by reason of the relatively high temperature and salinity of these discharges. Continuous dumping of these effluents in the coastal water, may threat the marine biochemistry and water quality in general, and their effects may extend to a cultivated Sir Bani Yas Island in particular.

In the last few years, several numerical modeling studies were carried out to investigate the hydrodynamic characterization of the Ruwais region. Azzam *et al.* (2004) and Elshorbagy *et al.* (2004d) are considered as the most relevant of these studies due to the comprehensive levels of measurements conducted and results obtained. The studies produced considerable detail about the bathymetry, tides, temperature and salinity of the region. They used the Japanese modeling software mentioned earlier (COSMOS) with a resolution of 200m x 200m to resolve the area hydrodynamics. A comparison between the simulated water level, temperature, and salinity and their respective measurements produced fair and reasonable agreement. The average summer temperature and salinity ranged from 32.0 °C to 32.7 °C and from 45.5 to 46 ppt, respectively, whereas, the winter values ranged from 20.5 °C to 21.2 °C and from 45.5 to 46.0 ppt, respectively.

In this part of the study, the coastal water of the Ruwais is simulated using COSMOS hydrodynamic model but with different setup specifications. In addition to discussing the tides and currents at the Ruwais water, the salinity and the temperature will be addressed in more detail.

3.3.1 Model Setup and Calibration

The numerical model of the Ruwais is nested inside the regional model of the entire Arabian Gulf to adopt the boundary flow data. The regional model has its boundary at the Strait of Hormuz. The grid size of the local model was selected to be 1km, so that
long term ecological simulations can be conducted using the same model within reasonable times. The sea surface area used in the local modeling is 374 km$^2$. The horizontal distributions of the grids are 26 east-west and 22 north-south grid steps (Fig. 3.8). The water column consists of 6 layers having the same distribution used in the regional model, i.e. 4, 6, 10, 20, and 30m. Tidal constituents, temperature and salinity for the three open boundaries are nested from the regional Gulf model using the sub-model software, COSBND while the initial values of same variables are nested using the sub-model software, COSINIT. Other computational conditions used in the modeling are also listed in Table 3.3.

Since the outfalls of these facilities are close to each other, they are categorized into three outlets. Outfall (1) includes an oil refinery and gas production plant. Outfall (2) includes desalination plant, power plant, sulfur and fertilization units. Outfall (3) includes only the effluent of the petrochemical factory (Borooj). Each group of these discharge sources has different flow rates with different temperature and salinity values as summarized in Table 3.2.

Figure 3.8: Map of Ruwais coast. The dotted line shows the model boundary and the stars (★) indicates the location of the observation stations.
Table 3.2: Inflow sources in the Ruwais coastal water

<table>
<thead>
<tr>
<th>Utility</th>
<th>Q (m$^3$ day$^{-1}$)</th>
<th>T Summer ($^\circ$C)</th>
<th>T Winter ($^\circ$C)</th>
<th>Salinity (ppt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outfall 1 Oil Refinery (TAKREER)</td>
<td>243600</td>
<td>30.0</td>
<td>23.0</td>
<td>46.0</td>
</tr>
<tr>
<td>Gas Production Plant (GAZCO)</td>
<td>600000</td>
<td>45.0</td>
<td>35.0</td>
<td>46.0</td>
</tr>
<tr>
<td>Total</td>
<td>843600</td>
<td>40.7</td>
<td>31.5</td>
<td>46.0</td>
</tr>
<tr>
<td>Outfall 2 Desalination and Power Plant</td>
<td>192000</td>
<td>45.0</td>
<td>40.0</td>
<td>70.0</td>
</tr>
<tr>
<td>Fertilization Factory</td>
<td>120000</td>
<td>40.0</td>
<td>35.0</td>
<td>46.0</td>
</tr>
<tr>
<td>Total</td>
<td>312000</td>
<td>43.1</td>
<td>38.1</td>
<td>60.8</td>
</tr>
<tr>
<td>Outfall 3 Petrochemical Factory (Borooj)</td>
<td>840000</td>
<td>45.0</td>
<td>35.0</td>
<td>50.0</td>
</tr>
</tbody>
</table>

The local model of Ruwais is calibrated using the measurements of the water level conducted near Sir Bani Yas Island during the period between June 23rd, 2003 and June 29th, 2003. Figure 3.9 shows a comparison of the measured and the simulated values. It shows fair agreement in the amplitude and the phase during the considered period with some deviations in the amplitude at the first few days within the neap-tide period. This may be due to the coarse grid used in the model, where the finer grid (200m x 200m) employed by Elshorbagy et al. (2004d) produced better match between the measured and simulated water levels.

Figure 3.9: Comparison of measured and simulated water levels at Sir Bani Yas Island at the period from 23rd, June, 2003 to 29th, June 2003.
Table 3.3: Computational conditions of the hydrodynamic model for the Ruwais coastal water

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Selected value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>Ruwais coastal water with sea surface area = 374 km² (Fig. 1).</td>
</tr>
<tr>
<td>Grid size</td>
<td>1 km</td>
</tr>
<tr>
<td>Number of horizontal meshes</td>
<td>26 (east-west) x 22 (north-south)</td>
</tr>
<tr>
<td>Vertical layer locations</td>
<td>6 vertical layers</td>
</tr>
<tr>
<td>Level 1: from surface to -4, Level 2: from -4 to -10</td>
<td></td>
</tr>
<tr>
<td>Level 3: from -10 to -20, Level 4: from -20 to -40</td>
<td></td>
</tr>
<tr>
<td>Level 5: from -40 to -70, Level 6: from -70 to the bottom</td>
<td></td>
</tr>
<tr>
<td>Inflow conditions</td>
<td>Three inflow sources at the south, they are listed in Table 3.2</td>
</tr>
<tr>
<td>Tidal constituents for the boundary conditions</td>
<td>Nested from the regional Gulf model</td>
</tr>
<tr>
<td>Temperature and Salinity for the boundary</td>
<td>Nested from the regional Gulf model</td>
</tr>
<tr>
<td>Wind condition</td>
<td>Records from offshore metrological station in the Ruwais</td>
</tr>
<tr>
<td>Model parameters</td>
<td>Coriolis parameter: 6.376 * 10⁻⁵ s⁻¹</td>
</tr>
<tr>
<td>Friction coefficient for seabed</td>
<td>0.0026 (assumed)</td>
</tr>
<tr>
<td>Wind friction coefficient at the sea surface</td>
<td>0.001</td>
</tr>
<tr>
<td>Horizontal and vertical eddy viscosity and diffusivity</td>
<td>1.98 * 10⁶ m².s⁻¹</td>
</tr>
<tr>
<td>Metrological conditions</td>
<td>Summer</td>
</tr>
<tr>
<td>Global solar radiation</td>
<td>1500 cal.cm⁻².day⁻¹</td>
</tr>
<tr>
<td>Day length</td>
<td>0.57</td>
</tr>
<tr>
<td>Empirical coefficient of solar altitude reflection</td>
<td>0.35</td>
</tr>
<tr>
<td>Cloudiness</td>
<td>0.01</td>
</tr>
<tr>
<td>Daily mean temperature</td>
<td>30 °C</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>53 %</td>
</tr>
<tr>
<td>Empirical constant of the cloudiness reflection</td>
<td>0.65</td>
</tr>
<tr>
<td>Calculated period</td>
<td>60 days</td>
</tr>
</tbody>
</table>

3.3.2 Mean Current Results

The aim of the local Ruwais simulation is to use output result files of currents, temperature and salinity spatial distribution as initial conditions to the water quality numerical model (EUTROP). This should allow studying the effect of temperature.
and salinity on the coastal water at present time and its long term impacts in the future.

Figure 3.10 shows the mean currents calculated over the 2-months of summer simulation period. The mean currents are very weak in the southern part of the Ruwais coast (<3 cm/s), as the water there is almost stagnant whereas relatively strong currents exist at the northern eastern side of the area and move outside the model boundary as the velocity may exceed 7 cm/s. In general, the water enters the area from the western boundary and the northern part of the eastern boundary while flow exchange (inflow/outflow) takes place at the northern boundary. The mean flow field produced from the winter simulation is fairly close to the summer one.

Figure 3.10: Mean currents in the Ruwais coastal water during the summer season.

3.3.3 Salinity and temperature horizontal distributions

Salinity Distributions

As shown in Figure 3.11, the salinity values range between 44.5 to 46.3 ppt during the summer season. Such distribution is attained at the end of 2-month simulation over the period of June 1<sup>st</sup> to August 1<sup>st</sup>, 2003. It's noticeable that the salinity increases toward the shoreline, this refers to shoal of the water at the shore, which causes more
evaporation, hence higher salinity. The most saline zone concentrates near the outlets of the Ruwais Industrial Complex, where the salinity there reaches up to 46.3 ppt; this refers to the high saline water which discharges from the desalination plant increasing the salinity of water near the outlet area. The salinity near Sir Bani Yas Island is about 45.0 ppt, this value coincides with other investigations (Elshorbagy et al., 2004c). The dark blue areas with zero salinity value at the figures refer to tidal flat zones.

During winter season (Fig. 3.12), salinity distribution is almost similar to summer trend where the salinity increases toward the shoreline and decreases offshore. The salinity ranges between 43 to 45.3 ppt. Also, the most saline water concentrates near the Ruwais outlets, where the salinity reaches up to 45.3 ppt. Three stations were selected on the modeled area; St.1, St.2, and St.3 (Fig. 3.8), to trace the salinity and temperature temporal variation. The first of these stations (St.1) is in the vicinity to the Ruwais Complex outlets, the second (St.2) is in the middle of the modeling area, and the third (St.3) is near Sir Bani Yas Island. Figure 3.13-a shows the time series for the three stations during the summer. It is quite clear that the salinity concentration increases at station (1) and decreases toward station (3).

Figure 3.13-b shows significant differences in salinity among the three stations, indicating that the sea water is more homogeneous in the area during the winter season. This may refer to the stronger currents during the winter, which causes higher mixing for the Ruwais coastal water.
Figure 3.11: Salinity spatial distribution during the summer season.

Figure 3.12: Salinity spatial distribution during the winter season.
Temperature Distribution

Distribution of the summer temperature in the surface Ruwais coastal water is shown in Figure 3.14. The temperature ranges between 31.5 °C to 33.4 °C, where it increases toward the shoreline and decreases gradually offshore. The maximum temperature in summer is found near the outlets of the Ruwais Industrial Complex that is about 33.4 °C. This may refer to the warmer water discharged form the desalination plant and other utilities in the area. The temperature near the Sir Bani Yas Island was about 33.2 °C. Temperature time series during summer season for the three stations selected earlier are shown in Figure 3.16-a. The chart shows that the temperatures for the three locations fluctuate around 33.3 °C and 33.8 °C with the maximum prevailing at St.1. These values are close to the values reported in the other studies (Elshorbagy et al., 2004c), where the results ranged between 30.5 °C and 33 °C.
Figure 3.14 shows the distribution of the temperature for the Ruwais area during winter season. The temperature ranges between 21 to 22 °C. The narrow range of the surface temperature variation for the area shows that the temperature distribution is quite homogenous over the modeled zone. It is worth mentioning that the highest water temperature is near the outlets of the Ruwais Industrial Complex, where the temperature there reaches up to 21.7°C. Figure 3.16-b shows the temperature time series for the three stations during winter where it shows a very slight difference with temperature variation at the stations.

Table 3.4 summarizes the average temperature and salinity for the three observation stations. It shows that there are about 12 °C differences between summer and winter seasons, and about 0.5 ppt. differences for the salinity.
Figure 3.15: Temperature spatial distribution during the winter season.

Figure 3.16: Temperature temporal variation during the summer and the winter seasons. (St.1: in the vicinity of the Ruwais Complex outlets. St.2: in the middle of the modeling area. St.3: near Sir Bani Yas Island).

Table 3.4: Average temperature and salinity in summer and winter at the three selected stations.

<table>
<thead>
<tr>
<th></th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>Salinity (ppt.)</td>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>Station 1</td>
<td>33.78</td>
<td>45.83</td>
</tr>
<tr>
<td>Station 2</td>
<td>33.39</td>
<td>45.00</td>
</tr>
<tr>
<td>Station 3</td>
<td>33.25</td>
<td>44.71</td>
</tr>
</tbody>
</table>
CHAPTER FOUR
RUWAIS ECOLOGY

Arabian Gulf is characterized by extreme conditions of high temperature and salinity due to the extensive evaporation rate taking place along the year. The Gulf is located between the temperate and tropical zones. The marine biota of the Gulf reflects the climate pattern with strong seasonality in the north, where the air temperature varies from 0-50 °C to a more constant tropical environment in the south (Sheppard et al., 1992). In addition to the arid conditions of the Gulf region, the riverine fresh water inputs are limited and the evaporation rate exceeds these inputs. Moreover, the exchange through the Strait of Hormuz is also limited and does not cover the southern shelf of the Gulf, where the circulation at the southern coast is very weak and it is considered dynamically as stagnant zone (Reynolds, 1993). The water enters from the Strait of Hormuz with a salinity ranged between 36.5 ppt to 37.0 ppt (Sheppard et al., 1992), where the salinity reaches 42 ppt at the Bahraini coast in the west and the maximum salinity value is detected by Basson et al. (1977) in the Gulf of Salwah near the Bahraini too where it was 70 ppt. Given the conditions introduced above, it is clear that the marine biota in the Gulf is exposed to harsh salinity and temperature regimes. This type of regime produces a wide diversity of the marine fauna and flora that can adapt with such extreme salinity values and water temperature fluctuations; hence, the primary production in the Gulf is often higher than for the other seas in the same latitude (Sheppard, 1993; Sheppard et al., 1992; Price et al., 1993).

The salinity in the Ruwais marine water in the present study is found to range between 43.0 ppt and 46.3 ppt along the year and temperature ranges between 31.5 °C and 33.4 °C in the summer and between 21 °C to 22 °C in the winter. This implies that the temperature difference between the summer and winter season is about 11 °C.

In order to use the water quality modeling software “EUTROP”, different water quality parameters from the Ruwais marine water are needed. These data include phytoplankton biomass (mgC/m³), zooplankton biomass (mgC/m³), particulate organic mater (POC), dissolved organic matter (DOC), phosphate concentration (PO₄), ammonium concentration (NH₄), nitrite concentration (NO₂), nitrate concentration (NO₃), dissolved oxygen concentration (DO) and chemical oxygen demand concentration (COD). The model employs the temperature, salinity,
and flow dynamic data provided by the hydrodynamic model resolved earlier. In the present chapter, the field sampling and in situ measurements are briefly described, followed by the laboratory analysis methods employed to quantify the different parameters. The second part of the chapter will describe the marine ecology of the Ruwais in the light of the measurements and the experimental results. It is worth mentioning that the ecological description here will be only limited to lower trophic level in the water column as it will be the case for the numerical simulation introduced later.

4.1 Field Sampling

Observation of coastal water quality in the Ruwais marine water was performed from June 2003 to January 2004. Sampling campaigns were carried out by a team from the UAE University using different boats provided by the local marine authorities. The work was part of an externally funded research project conducted in the UAE University. The water quality and ecological data described here are all obtained from scientific papers that are now revised and processed by international journals after received the necessary approval and publication release from relevant sponsors; mainly TAKREER oil company. Four field sampling expeditions were done. Three of them were at the beginning of spring, summer and autumn season (June, August and November, respectively), and the last one at the end of winter (January).

Water sampling and in situ measurements were done at 10 selected locations scattering near the coastal line in the Ruwais study area. Figure 4.1 shows the station locations numerated from S1 to S10. In situ measurements carried out for salinity and temperature whereas the water samples for phytoplankton, zooplankton, dissolved oxygen (DO), nutrients (Nitrate, Nitrite, Ammonia, and Phosphate), total organic carbon (TOC), and dissolved organic carbon (DOC) were collected, preserved and later sent back to the laboratories of UAE University for analysis. The sampling methods employed during the field work can be summarized as the following.
Figure 4.1: Ruwais coast and locations of measurement stations (⊙) (Elshorbagy et al., 2004d)

4.1.1 Water Quality Sampling

For nutrients, TOC and DOC analysis, three water samples for each analysis were collected in every station at three depths; surface, middle and bottom. The sampling was done using a Niskin water sampler with closing mechanism. Samples for TOC and DOC were filled in a dark glass bottles and preserved in ice after lowering its pH to less than 2.0 using Hydrochloric acid, whereas the nutrient samples were collected in clean glass bottles and preserved in ice too.

4.1.2 Biological Sampling

Sampling for phytoplankton pigments and community structure was done by Niskin water sampler at three levels; surface middle and near bottom. Samples for phytoplankton cell count were preserved by adding a calculated amount of Lugol’s solution to the samples. Whereas, samples for phytoplankton pigment estimation were preserved in ice boxes to be transported later to the laboratories.

Sampling for zooplankton was carried out by collecting zooplanktons by oblique hauls using a Horon Tranter net (mesh size 300 microns and mouth area of
0.25 m²). The net was dragged with the boat with speed 2 knots for ten minutes across each of the sampling point. The collected zooplankton was preserved in 5 % buffered formaldehyde solution.

4.2 Analytical Techniques

All the laboratory analysis was performed in the Central Laboratory Unit (CLU) in the UAE University. The analytical methods have followed the standard methods of analysis. The procedures which were used are summarized below.

4.2.1 Water Quality Parameters

Temperature and Salinity

Temperature and salinity were measured in the field by using CTD instrument. A heavy weight was tied with the CTD sensor to keep the cable almost vertically; hence the measured depths are around the actual depths mentioned at Admiralty charts. Temperature and salinity were recorded at three levels; surface, middle and bottom.

Dissolved Oxygen

DO was determined using Winkler methods described in Standard Methods, 1995, APHA. Many measurements were also made in-site using DO probe and cross-checked with the analytical results.

Nutrients

The nutrients which are, Nitrate-nitrogen, Nitrite-nitrogen and Ammonia-nitrogen were estimated by using HACH DR/4000 spectrophotometer in the light of the instrument manual procedures (HACH company, 1999) and Phosphate-phosphorus is measured by using ICP equipment in the Central Laboratory Unit (CLU) of UAE University.

TOC and DOC

In order to measure the organic carbon (TOC) concentration in sea water, total organic carbon analyzer (Shimadzu V_cohs) was used. It was used to measure the total
carbon (TC) first and then the inorganic carbon (IC). The difference between them is called total organic carbon (TOC). The measurement procedure by using total organic carbon analyzer (TOC-V<sub>ch</sub>) can be summarized as the following:

- Five standard solutions were prepared with different known TC and IC concentrations (100 ppm, 50 ppm, 20 ppm, 10 ppm, and 5 ppm) per each.
- The calibration curve was constructed at the instrument (TOC-V<sub>ch</sub>) using the solutions mentioned in step 1.
- After the calibration curve was prepared, the measurement of the samples was made. The results obtained were TOC values which were (TC - IC) in ppm.
- To measure dissolved organic carbon (DOC), the same procedure was followed as step 1 and 2 but the samples were pre-filtered using glass filter papers (GF 6, Glasfaser Rundfilter, Dia 70 mm) soaked in deionized zero-organic water for 48 hours.

4.2.2 Biological Parameters

**Phytoplankton Pigments**

Absorbance of acetone extract at wavelength 665 and 750 nm method was used to determine phytoplankton pigments (Chlorophyll-a). The sample was treated earlier by 0.1N HCL acid (Standard Methods, 1995, APHA).

**Zooplankton**

Displacement method was utilized to determine zooplankton biomass. 300 micron filter nylon plankton net was used to filter the sample. The animals retained on the net were measured by displacement of same amounts of water. To estimate zooplankton population, the sample was washed off excess formaldehyde, sub sampled and stereo microscope was used to estimate the population qualifiedly and quantatively (Standard Methods, 1995, APHA).
4.3 Ecological Description of Ruwais Area

The study area, Ruwais coastal water, is characterized by well mixing conditions so; the stratification phenomenon is not a common feature in the region. This well mixed water column is attributed to several reasons, such as, the shallowness of the area, the wide tidal flat zone which is located at the east in addition to sinusoidal nature of the seas bed at the area which helps the mixing process to take place in an efficient way. Elshorbagy et al. (2004e) reported that over a 12-hour of the spring tide; the influx volume is equal to one third of the entire basin volume. This shows that on the average, one third of the basin volume (shifted to the west and north) is renewed each 12 hours. This refreshing allows to the northern western part of the area to mix with the Gulf water, hence to dilute the concentration of the pollutants which is emitted from the oil tankers and oil pipelines located in the area. On the other hand, the eastern and southern parts of the study area are exposed to weak water currents with average ranges from 5 to 20 cm/s. These delicate currents enhance stagnancy conditions of the eastern and southern sides, hence the flushing process is weak so that pollutant concentrations build up continuously causing adverse effects on the water quality and the marine ecology of the area.

In this part of the study, the ecological characteristics of the Ruwais marine water is discussed on the light of the environmental data obtained from a previous study done by Elshorbagy et al., 2004d. Measurements of water quality and biological parameters are averaged over the ten selected sampling stations and tabulated in Table 4.1. The measurements include the results for the four trips June 03, August 03, November 03, and January 04. These parameters include phytoplankton biomass, zooplankton biomass, particulate organic carbon (POC), dissolved organic carbon (DOC), nitrite (NO$_2$-N), nitrate (NO$_3$-N), ammonium (NH$_4$-N), phosphate (PO$_4$-P), chemical oxygen demand (COD) and dissolved oxygen (DO).

This results interpretation will be the onset for the water quality modeling interpretation in the following chapters, and it will illustrate the relation among the different water quality parameters, and how they interact with each other.
Table 4.1: Monthly average variation of measured parameters at surface layer

<table>
<thead>
<tr>
<th></th>
<th>Phytoplankton (mgC/m²)</th>
<th>Zooplankton (mgC/m²)</th>
<th>POC (mg/m²)</th>
<th>DOC (mg/m²)</th>
<th>PO₄-P (µM)</th>
<th>NO₃-N (µM)</th>
<th>NH₄-N (µM)</th>
<th>NO₂-N (µM)</th>
<th>COD (mg/l)</th>
<th>DO (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jun. 03</td>
<td>0.78</td>
<td>0.74</td>
<td>3206.9</td>
<td>1592.2</td>
<td>0.88</td>
<td>68.6</td>
<td>1.8</td>
<td>0.30</td>
<td>10.1</td>
<td>5.75</td>
</tr>
<tr>
<td>Aug. 03</td>
<td>4.42</td>
<td>0.93</td>
<td>525.1</td>
<td>2131.4</td>
<td>1.08</td>
<td>71.4</td>
<td>2.7</td>
<td>0.23</td>
<td>13.5</td>
<td>5.95</td>
</tr>
<tr>
<td>Nov. 03</td>
<td>7.25</td>
<td>1.92</td>
<td>869.7</td>
<td>3407.2</td>
<td>0.62</td>
<td>77.4</td>
<td>1.6</td>
<td>0.36</td>
<td>21.6</td>
<td>3.59</td>
</tr>
<tr>
<td>Jan. 04</td>
<td>3.83</td>
<td>0.56</td>
<td>309.5</td>
<td>2630.1</td>
<td>1.18</td>
<td>64.8</td>
<td>1.4</td>
<td>0.34</td>
<td>16.7</td>
<td>6.55</td>
</tr>
</tbody>
</table>

4.3.1 Biological Productivity

Phytoplankton

In the present study, phytoplankton term refers to micro-phytoplankton species with size larger than 20 microns.

Information regarding phytoplankton densities in the Arabian Gulf is very rare (Elshorbagy et al., 2004e). Table 4.2 lists some counts reported in the Arabian Gulf and other near water bodies.

Table 4.2: Phytoplankton counts in different coastal waters.

<table>
<thead>
<tr>
<th>Counting location</th>
<th>Phytoplankton counts per liter</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruwais coastal water</td>
<td>$15.4 \times 10^{3}$</td>
<td>Elshorbagy et al., 2004e</td>
</tr>
<tr>
<td>Dubai offshore</td>
<td>$135.8 - 245.2 \times 10^{3}$</td>
<td>Dubai Municipality, 1996</td>
</tr>
<tr>
<td>Dubai Greek Lagoon</td>
<td>$7828 - 8444.7 \times 10^{3}$</td>
<td>Dubai Municipality, 1996</td>
</tr>
<tr>
<td>Goa coastal water</td>
<td>$30.0 \times 10^{3}$</td>
<td>Qasim, 1979</td>
</tr>
</tbody>
</table>

The table shows that the phytoplankton counts in the Ruwais coastal water is very low compared with the other counts even in the UAE coast. The count in Goa is more closer to the Ruwais count, while the values in Dubai offshore is significantly greater than the Ruwais counts, whereas, Dubai Creek Lagoon undergoes a eutrophification conditions, so the counts there is extremely high.

The low values of phytoplankton counts in the Ruwais coastal waters may be due to several reasons, the most important of which is the overwhelming dosing of
chlorine at the intake of different facilities spreading along the coast. This practice has
taken place in the area for so many years to kill jelly fish and large fishes to prevent
them from entering with the influent water to avoid pump damages. Chlorine is added
in many cases in an uncontrolled manner so that a reasonable estimation of its level
becomes infeasible. Another reason of low phytoplankton biomass is the high levels
of hydrocarbon components which are produced from the oil activities in the region
such as filling tankers with oil, evacuation of ballast water from tankers in the Ruwais
basin, some oil spill accidents, in addition to the effluent discharging from the
different utilities in the Ruwais Industrial Complex. All of these activities produce
high amounts of hydrocarbon components which may have hazardous effects on the
phytoplankton biomass. Other reason is related to higher salinity concentration in the
water (45-46 ppt) in the Ruwais area. Limitation of some nutrients such as Phosphate
(to be discussed later), may be also one of the reasons.

Phytoplankton Pigments

Chlorophyll-a concentration in the coastal water is considered as an effective method
to measure the amount of phytoplankton in the marine water, whereas the existence of
photosynthetic pigments in the sea grass is sufficient indication for the primary
production. The availability of the pigments in the sea water may color it and
eventually affect its transparency. As a result, the amount of light penetrating the sea
surface may be reduced and the photosynthesis process is decreased causing a
depletion of the dissolved oxygen that can affect most of the aquatic life. The
measured values of chlorophyll-a concentration in the area ranged from 0.83 to 1.39
mg/m$^3$. The estimation of chlorophyll-a via satellite images is a primary tool to
determine the eutrophication state of the estuaries and lakes and to assess their water
quality conditions. Figure 4.2 shows a satellite image for the chlorophyll-a
concentration at the UAE coastal water. The Ruwais area marked with blue box in the
west, is characterized by low productivity due to low concentration of chlorophyll-a,
as the pigments concentration ranged between 0.5 to 1.5 mg/m$^3$. The image supports
the findings of low primary production reported by the considered measurements in
the Ruwais basin.
Phytoplankton Biomass

Phytoplankton biomass is represented by the mass of carbon which forms the phytoplankton cells. The units of phytoplankton biomass expressed as milligram carbon per cubic meter is the suitable form to use in the water quality numerical model “EUTROP”. Raymont's approach (Raymont, 1983) which depends on the average Carbon/Chlorophyll-a ratio of 15.3 (Cushing, 1958) is utilized in the current work to determine the phytoplankton carbon biomass. The average calculated values of phytoplankton biomass in the study area ranged from 0.26 to 10.9 mgC/m³, where some reported values in the Arabian Gulf measure to be > 4 gC/m³ and reach 15-18.9 gC/m³ at the northern areas of the Gulf (Al-Yamani et al., 1997a, 1997b).

Figure 4.3 shows the variation of the phytoplankton biomass over the four sampled months during the current work. It is noticeable that there is an increasing trend of phytoplankton biomass in the summer months that may refer to rising of the water temperature. Whereas, the biomass decreases in the winter season related to decrease in the temperature as the temperature is one of the main parameters affecting the growth rate of the phytoplankton.
Organic Matter

Organic matter (OM) in the present study is represented as Total Organic Carbon (TOC), Dissolved Organic Carbon (DOC), and Particulate Organic Carbon (POC). Average values for TOC, DOC and POC were found to be 3.67, 2.44, and 1.23 mg/l respectively (Elshorbagy et al. 2004e). Comparing these values with other studies in the Arabian Gulf, Emara (1998) reported that the TOC values near UAE coast ranged from 0.8 to 3.9 mg/l, which is very close to the present work. Whereas comparison with other oceanographic literatures (Starikova, 1970 and Williams, 1975) showed that TOC at the UAE coastal water is higher than those in the other parts of the world. This may refer to excessive activities of oil and petrochemical industries in the region, which produce a lot of hydrocarbon compounds due to oil spill and effluent discharging from refineries. Referring to Table 4.1, it’s noticed that POC level was much higher in June 2003 than other months, apparently caused by the turbulence in the water column caused by the prevailing strong wind conditions during the sampling time. On the other hand, DOC level was higher in November than the other months. This refers to an oil spill accident associated with a fracturing of oil line occurring toward the end of October 2003, so its effects extended up to November 2003.

Chemical oxygen demand (COD) levels in the Ruwais coastal water ranged between 8.5 to 25.2 mg/l. These values are higher than values in most of the world (Elshorbagy et al., 2004e) oceans. This may again refer to high hydrocarbon levels in the water due to oil pollution and petrochemical activities.

Carbon/Chlorophyll-a Ratio

Carbon/Chlorophyll-a ratio in the present study ranged from 0.98 to 7.55, while Cushing (1958) suggested this ratio to be in the range of 13.6 to 17.3. This wide deviation may refer to uncounted species of smaller size cells of phytoplankton such as nanoflagellates, naked dinoflagellates, and picoplankton where as mentioned earlier; the counted species covered only the phytoplankton sizes larger than 20μm. Taking the small-size species into account can potentially raise the calculated ratio of carbon/Chlorophyll-a, where several recent studies reported that the picoplankton, for example, can significantly contribute to the primary production in some coastal waters (Estrada, 1985; Kimor et al., 1987; Abdel-Moati, 1990). Due to limitation in
experimental and analytical resources in addition to restricted time for the current study, such species were not taken into account. Thus, the numerical simulation introduced later calculates the phytoplankton biomass for cells larger than 20μm only.

**Figure 4.3:** Phytoplankton biomass expressed in (mgC/m³) during the sampling work.

**Zooplankton**

Zooplankton is considered as a secondary producer and also as a primary consumer on phytoplankton species. Surveying the Ruwais coastal water gave rise to poor zooplankton biomass condition in the area. Elshorbagy *et al.* (2004e) reported that the average zooplankton biomass in the Ruwais marine water is 1.03 mgC/m³, whereas comparable studies show much higher values in different zones in the Arabian Gulf, where 104- 407 mgC/m³ was reported by Michel *et al.* (1986a). This poor productivity in the Ruwais water may be due to several reasons; one of them is the low productivity of phytoplankton as a primary producer which consequently affects the growth rate of zooplankton as the primary consumer.

Figure 4.4 shows the zooplankton biomass variation during the sampling period. The general trend is consistent with phytoplankton biomass one, where the zooplankton increases during the summer period from June to November and decreases in the winter season. This matching between zooplankton and phytoplankton biomasses gives a logical interpretation for the food web interaction in a lower tropic level.
Nutrients

Seawater usually contains low concentrations of dissolved nitrogen and phosphorous compounds. They are usually considered as limiting factors for phytoplankton population growth. Inorganic Nitrogen exists in seawater in different forms, i.e.; nitrate, nitrite and ammonium, while, the inorganic phosphorous exists as phosphate. Nutrient measurements for the sampled locations at different times are listed in Table 4.1. Inspection of these values indicates that most of nutrient measurements in the Ruwais coastal water are low to moderate, while Nitrates (NO$_3$-N) which ranges between 64 to 78 μM is considered to be extremely high when compared with Dubai and Abu Dhabi Creeks; 0.5- 23.79 μM and 0.08- 18.72 μM, respectively (Abu Hilal and Adam, 1995). This high concentration of Nitrates may refer to effluents from the fertilization plant and petrochemical industries located in the area.

The PO$_4$-P levels ranged from 0.5 to 1.4 μM. These values are less than values estimated in Dubai Creek (0.8- 28.8 μM) and in Abu Dhabi Creek (0.02- 4.53 μM), while they are close to the values in Kuwait (0.14- 0.18 μM), Saudi Arabia (0.0- 0.34 μM) and Qatar (0.2- 0.88 μM).

NOAA/EPA, 1988 reported that the nitrogen levels in healthy coastal system should range from 6.7 to 67.5 μM while the phosphorous concentration should range from 0.3 to 3.2 μM. Higher concentrations of both can lead to less diversity and/or eutrophication conditions.
In the present study, the nitrogen levels are very high whereas the phosphate levels are moderate to slightly low. As such phosphate may be a limiting nutrient constituent that prevents the phytoplankton blooms to take place. The average atomic ratio of nitrate-nitrogen to phosphate-phosphorus (N:P) is estimated at 74.1:1 that is higher than other estimations in the area, where, Shriadha and Al-Ghais (1999) estimated the N:P ratio in Abu Dhabi, Umm Al-Quwain and Ras Al-Khayma coastal water as 9.5:1, 8.9:1, and 9.8:1, respectively.

**Dissolved Oxygen**

Measured dissolved oxygen (DO) in the Ruwais marine water almost ranged from 5.2 to 6.7 mg/l for most of the samples, whereas during November sampling their average dropped to 3.4 mg/l. sudden depletion of dissolved oxygen may refer to the oil accident which occurred in October and mentioned earlier. The DO ranges in the Ruwais are comparable with other study carried out by Banat et al., 1993, where they reported that the DO levels in Abu Dhabi costal water ranged from 6.1 to 6.7 mg/l.

**4.4 Conclusion**

The introduced coverage of different measurements reveals that the study area can be classified as HNLC, i.e., high nutrients and low chlorophyll/carbon. Even though the nutrients are abundant and available, primary as well as secondary producers are extremely limited. This phenomenon is likely related to inhibitory factors such as harsh environment; in particular the high salinity and the high contents of hydrocarbons associated with oil contamination. The high chlorine dosing taking place at the intakes does indeed contribute to such phenomena especially close to the shoreline. These conditions, however indicate that the area is ecologically unstable and changes in effluent levels and qualities may give rise to blooming condition; i.e., red-tide. It is, therefore recommended to establish a monitoring program that targets observing the effluent quantities as well as the water quality of the coastal basin in general.
CHAPTER FIVE
EUTROP SIMULATION MODEL

In the current study, a water quality simulation software "EUTROP" is employed to investigate the fate transport and the effect of brine and warm water discharge from Ruwais desalination and other existing coastal facilities on the water quality of the Ruwais. EUTROP is one of the suit software CENSIS; that is a three dimensional coupled physical and biochemical model. It is used in the second stage of the modeling process after performing the hydrodynamic simulation using COSMOS model, where the COSMOS output files are used as an input files in the water quality simulation process.

This chapter presents a brief description of the numerical scheme and theoretical background of the EUTROP model. The model parameters are then tuned against the gathered field data.

5.1 EUTROP Theoretical Background

EUTROP model contains twelve state variable referred to as compartments. Four compartments are expressed as carbon stock; phytoplankton, zooplankton, detritus and dissolved organic matter. Other two intercellular nutrients of phytoplankton; nitrogen quota and phosphorus quota are also expressed. Moreover, four nutrients such as ammonium, nitrite, nitrate, and phosphate are included. Two oxygen parameters; dissolved oxygen and chemical oxygen demand. Table 5.1 shows the twelve compartments and their units. These compartments are considered as the main variables in the system that interact with each other as a basic present for the biochemical processes taking place in the real situation. Such biochemical processes among different compartments are illustrated in Figure 5.1. The description of the governing equations introduced in the current section is mostly adapted from the user guide of CENSIS Model (CENSIS user guide, Chuden CTI, 2004).
Table 5.1: Compartments of the biochemical coupled EUTROP model

<table>
<thead>
<tr>
<th>No</th>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>P</td>
<td>Phyttoplankton biomass</td>
<td>mgC/m³</td>
</tr>
<tr>
<td>2</td>
<td>SQP</td>
<td>Intracellular phosphorous quota of phyttoplankton</td>
<td>µg-atmP/l</td>
</tr>
<tr>
<td>3</td>
<td>SQN</td>
<td>Intracellular nitrogen quota of phytoplankton</td>
<td>µg-atmN/l</td>
</tr>
<tr>
<td>4</td>
<td>Z</td>
<td>Zooplankton biomass</td>
<td>mgC/m³</td>
</tr>
<tr>
<td>5</td>
<td>POC</td>
<td>Particulate (Detrital) organic matter</td>
<td>mgC/m³</td>
</tr>
<tr>
<td>6</td>
<td>DOC</td>
<td>Dissolved organic matter</td>
<td>µg-atmP/l</td>
</tr>
<tr>
<td>7</td>
<td>PO₄</td>
<td>Phosphate concentration</td>
<td>µg-atmN/l</td>
</tr>
<tr>
<td>8</td>
<td>NH₄</td>
<td>Ammonium concentration</td>
<td>µg-atmN/l</td>
</tr>
<tr>
<td>9</td>
<td>NO₂</td>
<td>Nitrite concentration</td>
<td>µg-atmN/l</td>
</tr>
<tr>
<td>10</td>
<td>N₁</td>
<td>Nitrate concentration</td>
<td>µg-atmN/l</td>
</tr>
<tr>
<td>11</td>
<td>DO</td>
<td>Dissolved oxygen concentration</td>
<td>mgO₂/l</td>
</tr>
<tr>
<td>12</td>
<td>COD</td>
<td>Chemical oxygen demand concentration</td>
<td>mg/l</td>
</tr>
</tbody>
</table>
The general equation describing the coupled physical and biological model is expressed as the following:

$$\frac{\partial B}{\partial t} + (v \cdot \nabla)B + (w + w_p) \frac{\partial B}{\partial z} = \left[ \nabla \cdot (K_h \nabla) \right] B + \frac{\partial}{\partial z} \left( K_z \frac{\partial B}{\partial z} \right) + \left( \frac{dB}{dt} \right) + q \quad (5.1)$$

Where

- $B$: the concentration of an arbitrary compartment
- $v = (u, v)$: the horizontal component of flow velocity
- $\nabla = (\partial / \partial x, \partial / \partial y)$: is the horizontal gradient operator
- $w$: the vertical velocity component
- $w_p$: is the sinking rate for a particulate organic compartment
- $K_h, K_z$: is the horizontal and the vertical component of eddy diffusivity respectively
- $\frac{dB}{dt}$: is the local change in standing stock according to the biochemical processes
- $q$: is the fluxes due to external source

The following subsections will describe briefly the major equations controlling the model biochemical processes with association with the model compartments.

### 5.1.1 Phytoplankton

Let $N_p$ be the number of phytoplankton categories and $P_j$ be biomass of each category $j$. The main equation which describes the change of the biomass of phytoplankton by biological processes can be formulated as:

$$\left( \frac{dP_j}{dt} \right) = \text{Photosynthetic growth} (B_1) - \text{Extracellular release} (B_3) - \text{Respiration} (B_5)
- \text{Grazing by zooplankton} (B_4) - \text{Natural mortality} (B_6) \quad (5.2)$$

In previous equation, each term will be interpreted separately to clear the whole processes which are related to phytoplankton biomass, as the following:
Photosynthetic Growth

\[ B_i = v_i(T) \cdot \mu_i(P, SQN, SQP) \cdot \mu_2(I, P) \cdot P \]  

(5.3)

The notations, \( v(\cdot) \), \( \mu(\cdot) \) in the equations hereinafter denote physiological rate coefficient and degree of limitation to the physiological rate, respectively.

The term \( v_i(T) \) is the maximal growth rate of the phytoplankton, it can be formulated as:

\[ v_i \equiv v_i(T) = \alpha_i \cdot \exp(\beta_i \cdot T) \]  

(5.4)

where \( \alpha_i \) is the maximal growth rate at 0 °C and \( \beta_i \) is the temperature coefficient (°C\(^{-1}\), \( \beta_i = \ln Q_{10}/10 \)).

The term \( \mu_i(P, SQN, SQP) \) represents the growth limitation by cellular pools. In the model, the cell quota works as the limiting factor for the growth rate of phytoplankton, where the growth of the phytoplankton continues due to the nutrient intracellular quota even though the ambient nutrient is went out. Nitrogen quota and phosphorous quota are considered as the main nutrients affecting the growth rate, and the most limiting nutrient is determined based on Liebig’s law of minimum. The model expression for the limiting nutrient is formulated as:

\[ \mu_i(P, SQN, SQP) = \min\left\{ \frac{SQN}{SQN + [N:C]_P \cdot P}, \frac{SQP}{SQP + [P:C]_P \cdot P} \right\} \]  

(5.5)

where \([N:C]_P\) and \([P:C]_P\) are the ratio of nitrogen and phosphorous pools to carbon stock in the cell substrate; namely, the inverses of C/N, C/P ratios, respectively.

The term \( \mu_2(I, P) \) is related to instantaneous photosynthetic growth rate which is mainly affected by light intensity \( I \). The model adopts a combination of Monod equation for enzymatic reaction and Steel (1962) equation to represent the photosynthetic light response as the following:
\[ \mu_2 = \frac{I}{I_{opt}} \cdot \exp \left( 1 - \frac{I}{I_{opt}} \right) \]  

(5.6)

where \( I_{opt} \) is the light optimum for photosynthetic process, it has a constant value.

Due to the water turbidity, an attenuation of the light intensity may occur, this prohibits the light to reach to the deep part of the estuarine, so the photosynthesis process may be affected severely or it may even stop completely. This phenomenon was described by the well known Lambert-Beer law:

\[ I_z = I_0 \cdot \exp(-k \cdot z) \]  

(5.7)

where \( I_z \) is the light intensity at the depth \( z \), \( I_0 \) is the sea-surface light intensity and \( k \) is the light extinction coefficient in the water.

The diurnal variation in sea-surface solar radiation may affect the photosynthesis process. A cubic sinusoidal light scheme was introduced by Ikushima (1967) as the following:

\[ I_0 = I_0(t) = I_{max} \cdot \sin^3 \left( \frac{\pi}{DL} t \right) \]  

(5.8)

where \( I_{max} \) is the diurnal maximum of the sea-surface light intensity at the highest solar altitude, \( DL \) is the daylight length from sunrise to sunset.

**Extracellular Release**

\[ B_3 = \mu_3(P_j) \cdot P_j \]  

(5.9)

A part of photosynthetic product in phytoplankton is released in dissolved organic form. This physiological process is called extracellular release or excretion. Almost 15% of the total carbon fixed by phytoplankton is released as excretion Watt (1966). Approved through laboratory work that there is a relation between the extracellular release and chlorophyll-a content (Chl \( a \) in mg/m\(^3\)), the empirical expression which formulate this relation can be expressed as:
\[
\ln(\% \beta) = \ln 13.5 - 0.0020 \cdot Chla
\]  

(5.10)

This equation is substituted in the model as:

\[
\mu_s(P) = \beta_0 \cdot \exp\{-\gamma \cdot [Chla : C] \cdot P \}
\]  

(5.11)

where P is the phytoplankton carbon biomass (mgC/m\(^3\)), \(\beta_0\) is the maximal fractional release rate (0.135 in the equation (5.10)), \(\gamma\) is the chlorophyll-a coefficient (0.00201 m\(^3\)/mgChla in the equation (5.10)), \([Chla : C]\) is the chlorophyll-a/carbon ratio (mg Chl a / mg C).

**Respiration**

\[
B_s = v_s(T) \cdot P_j
\]  

(5.12)

Respiration in the phytoplankton consumes a part of the photosynthesis process product. The respiration rate follows an exponential trend with temperature degree as the following:

\[
v_s(T) = \alpha_s \cdot \exp(\beta_s \cdot T)
\]  

(5.13)

where \(\alpha_s\) is the respiration rate at 0 °C day\(^{-1}\) and \(\beta_s\) is the temperature coefficient (°C \(^{-1}\)).

**Natural Mortality**

The model does not take in account the grazing of phytoplankton by higher-trophic level organisms. Decreasing of the phytoplankton cells in the model refers to two factors; grazing by zooplankton in a lower-trophic level and the natural mortality, where the phytoplankton loss turned into the detritus compartment. The natural mortality of phytoplankton is controlled by the Steele and Henderson (1992) quadratic formula which is:

\[
B_s = v_s(T) \cdot P_j^2 \quad (j=1, 2, ..., N_p)
\]  

(5.14)
where \( v_6 \), represents the temperature-dependent mortality rate. In this model, the function \( v_6 \) is formulated as:

\[
v_6(T) = \alpha_6 \cdot \exp(\beta_6 \cdot T)
\]  

(5.15)

where \( \alpha_6 \) is the mortality rate at 0 °C (in \((mgC/m^3)\cdot day^{-1}\)) and \( \beta_6 \) is the temperature coefficient (°C⁻¹).

Grazing by zooplankton (B4) term will be discussed later in section 5.1.3.

5.1.2 Phytoplankton Cell Quota

The dynamics of the intracellular quota of the phytoplankton cells can be described in the model as:

**Phosphorous Quota**

\[
\left( \frac{dSQP}{dt} \right) = \text{Phosphorous uptake} - \text{Utilization by photosynthetic growth} - \text{Grazing loss} - \text{Release due to mortality} - \text{Sinking loss}
\]

\[
= B_2^p - \left[ \frac{P \cdot C}{P} \right]_P \cdot B_1 - (B_4 + B_6) \cdot \frac{SQP}{P} - w_p \cdot \frac{\partial}{\partial z} (SQP)
\]  

(5.16)

The phosphorous uptake by the phytoplankton cells is expressed as:

\[
B_2^p = v_0^p (PO_4) \cdot \left[ \frac{P \cdot C}{P} \right]_P \cdot P
\]  

(5.17)

\[
v_0^p (PO_4) = UP_{max} \cdot \frac{PO_4}{K_p + PO_4} \cdot \mu_s (P, SQP)
\]  

(5.18)

\[
\mu_s (P, SQP) = \left\{ \frac{PQ_{P_{max}} - \left[ \frac{P \cdot C}{P} \right] \cdot P + SQP \left[ \frac{P \cdot C}{P} \right]_P \cdot P}{(PQ_{P_{max}} - 1)} \right\}
\]  

(5.19)

where \( UP_{max} \) is the maximal uptake rate for phosphate, \( PO_4 \) the phosphate concentration, \( K_p \) a half-saturation constant, \( P \) the phytoplankton carbon biomass, \( SQP \) the intracellular phosphorous quota, \( PQ_{P_{max}} \) the maximal specific phosphorous
quota (ratio of maximal quota to subsistent quota), \([P : C]_p\) is a P/C composition of cell substrate, and \(w_p\) is the sinking rate of phytoplankton living cell (in \(\text{m.day}^{-1}\)).

**Nitrogen Quota**

\[
\left(\frac{dSQN}{dt}\right) = \text{Nitrogen uptake} - \text{Utilization by photosynthetic growth} - \text{Grazing loss} - \text{Release due to mortality} - \text{Sinking loss}
\]

\[
= B_2^N - \left[\frac{N}{C}\right]_p \cdot B_1 - (B_4 + B_5) \cdot \frac{SQN}{P} - w_p \cdot \frac{\partial}{\partial z} (SQN)
\]

(5.20)

It's worth mentioning that in the existence of all nitrogen nutrients; ammonium, nitrate and nitrite, the model select even ammonium or nitrate to be uptaken by the phytoplankton neglecting the intermediate form of the nitrogen nutrient which is the nitrite. Moreover, Wrobleweski (1977) proved that when the ammonium and the nitrate are abundant in the ambient, the phytoplankton prefer to uptake the ammonium to nitrate. This phenomenon is taken also in consideration in this model so the nitrogen uptake by the phytoplankton cells is expressed as:

\[
B_2^N = v_0^N \left(\text{NH}_4, \text{NO}_3\right) \left[\frac{N}{C}\right]_p \cdot P
\]

(5.21)

\[
v_0^N \left(\text{NH}_4, \text{NO}_3\right) = UN_{\text{max}} \cdot \left\{ \frac{\text{NH}_4}{K_{\text{NH}_4} + \text{NH}_4} + \frac{\text{NO}_3}{K_{\text{NO}_3} + \text{NO}_3} \cdot e^{-\psi \cdot \text{NH}_4} \right\} \cdot \mu_6(P, SQN)
\]

(5.22)

\[
\mu_6(P, SQN) = \left(PQN_{\text{max}} - \left[\frac{N}{C}\right]_p \cdot P + SQN \right) \left[\frac{\frac{N}{C}_p \cdot P}{PQN_{\text{max}} - 1}\right]
\]

(5.23)

where \(UN_{\text{max}}\) is the maximal uptake rate for nitrogen, \(K_{\text{NH}_4}\) and \(K_{\text{NO}_3}\) are half-saturation constants for ammonium (\(\text{NH}_4\)) and nitrate (\(\text{NO}_3\)), respectively, \(SQN\) is the nitrogen quota, \(PQN_{\text{max}}\) the maximal specific nitrogen quota, \([N : C]_p\) is a tissue N/C composition, and \(\psi\) is the ammonium inhabitation factor for nitrate uptake (in \(l. \mu M^{-1}\)).
5.1.3 Zooplankton

Let $N_z$ be the number of zooplankton categories and $Z_j$ be biomass of each category $j$. The main equation which describes the change of the biomass of zooplankton by biological processes can be formulated as the following:

$$\left(\frac{dZ}{dt}\right) = \text{Grazing (B$_4$)} + \text{Detritus feeding (B$_7$)} - \text{Egestion (B$_8$)} - \text{Respiration (B$_9$)} - \text{Natural mortality (B$_{10}$)} \pm \text{Diel vertical migration (B$_{11}$)} \quad (5.24)$$

In previous equation, each term will be discussed separately to clear the whole processes which are related to zooplankton biomass, as the following:

**Feeding (Grazing)**

$$B_4 = \mu_1(P, POC) \cdot v(T; P, POC) \cdot Z_j \quad (5.25)$$

Several studies approved that there is a lower threshold for food density, below which the feeding process no longer takes place (Parsons et al., 1967). Ivlev (1945) proposed an equation to describe the grazing process of the zooplankton as the following:

$$R = R_{\text{max}} \cdot \left[1 - \exp\left\{-\lambda \cdot (\Pi - \Pi^*)\right\}\right] \cdot Z \quad (5.26)$$

where $R$ denotes feeding amount (ration) of zooplankton at the food density $\Pi$, $Z$ the zooplankton biomass, $R_{\text{max}}$ the maximal feeding rate, $\lambda$ is a constant and $\Pi^*$ stands for lower threshold for feeding activity and it is expressed in the model as a constant value.

The maximum feeding rate ($R_{\text{max}}$) follows an exponential temperature response and expressed as:

$$R_{\text{max}} = \alpha_4 \cdot \exp(\beta_4 \cdot T) \quad (5.27)$$
where $\alpha_4$ is the maximal feeding rate at $0^\circ$C and $\beta_4$ is the temperature coefficient.

In the model, it is considered that there are two forms of particulate organic matters which can be grazed by zooplankton: phytoplankton and detritus. These foods can be expressed numerically as:

Phytoplankton category $j$; 
\[
\mu_j^i(P, POC) = \frac{P_j}{\left(\frac{\sum_{n=1}^{N_p} P_n}{N_p}\right) + POC}
\]  
\tag{5.28}

Total phytoplankton; 
\[
\mu_j(P, POC) = \sum_{j=1}^{N_p} \mu_j^i(P, POC)
\]  
\tag{5.29}

Detritus; 
\[
1 - \mu_j(P, POC) = \frac{POC}{\left(\frac{\sum_{n=1}^{N_p} P_n}{N_p}\right) + POC}
\]  
\tag{5.30}

\[
\Pi = \sum_{j=1}^{N_p} P_j + POC \quad ; (j = 1, 2, \ldots, N_p)
\]  
\tag{5.31}

The final formula of the feeding rate of zooplankton (in day$^{-1}$) can be expressed by substitution of the equations (5.27) and (5.31) into equation (5.26) to become:

\[
v_4(T; P, POC) = \alpha_4 \cdot \exp(\beta_4 \cdot T) \cdot \left[1 - \exp\left(-\lambda \cdot \left(\frac{\sum_{j=1}^{N_p} P_j + POC - \Pi^*}{\Pi}\right)\right)\right]
\]  
\tag{5.32}

Detritus feeding by zooplankton is expressed as:

\[
B_\gamma = \left[1 - \mu_j(P, POC)\right] \cdot v_4^j(T; P, POC) \cdot Z_j
\]  
\tag{5.33}

**Egestion**

The excretion process from zooplankton is called egestion. It is calculated in the model as:

\[
B_\delta = (1 - e) \cdot v_4(T; P, POC) \cdot Z
\]  
\tag{5.34}

where $(e)$ is the assimilation efficiency in the zooplankton.
Respiration

\[ B_s = v_s(T; P, POC) \cdot Z_j \]  \hspace{1cm} (5.35)

The respiration process in the zooplankton is divided into two types; stationary respiration which is produced of the basic metabolism and active respiration which is produced due to the energy expenditure during the feeding activities. The stationary respiration is expressed as:

\[ v_s = \alpha_3 \cdot \exp(\beta_3 \cdot T) \]  \hspace{1cm} (5.36)

where \( \alpha_3 \) is the basic metabolic rate at 0 °C and \( \beta_3 \) is the temperature coefficient.

Whereas, the active respiration is expressed as:

\[ v_a = \eta \cdot v_4(T; P, POC) \]  \hspace{1cm} (5.37)

where \( \eta \) is a proportional constant (0<\( \eta \)<1) and \( v_4 \) is the feeding rate described by equation (5.32). So, the total respiration loss is considered as the sum of stationary and active respiration and it can be described as:

\[ v_s(T; P, POC) = v_s + v_a = \alpha_3 \cdot \exp(\beta_3 \cdot T) + \eta \cdot v_4(T; P, POC) \]  \hspace{1cm} (5.38)

Natural Mortality

The loss of zooplankton biomass is referred to natural mortality and feeding by carnivorous animals. As mentioned before, the model is taking in consideration the lower trophic level, so all the losses of zooplankton will be considered as related to the mortality and it is expressed in a quadratic form as the following:

\[ B_{10} = v_{10}(T) \cdot Z^2 \]  \hspace{1cm} (5.39)

where \( v_{10} \) represents the temperature-dependent mortality rate, which is formulated as:

\[ v_{10}(T) = \alpha_{10} \cdot \exp(\beta_{10} \cdot T) \]  \hspace{1cm} (5.40)
where $\alpha_{10}$ is the mortality rate at 0 °C (in (mgC/m³)⁻¹·day⁻¹) and $\beta_{10}$ is the temperature coefficient.

**Diel Migration**

\[
B_{1j} = w_z(t) \cdot \frac{\partial Z_j}{\partial z}; \quad (j=1,2, \ldots, N_z)
\]  
(5.41)

Diel vertical migration phenomenon is referred to ascending of zooplankton community to upper layer in the night time and descending to the lower layers in the daytime. This can be described in the model as a sinusoidal function with time and the day length.

Ascending rate is expressed as:

\[
w_z(t) = w_{up} \cdot \sin \left( \frac{\pi}{1 - DL} (t - DL) \right); \quad (DL \leq t \leq 1)
\]  
(5.42)

where $w_{up}$ represents the maximal nocturnal ascending rate (in m/s), and DL id the functional daytime length.

Descending rate is expressed as:

\[
w_z(t) = -w_{down} \cdot \sin \left( \frac{\pi}{DL} t \right); \quad (0 \leq t \leq DL)
\]  
(5.43)

where $w_{down}$ is the maximal diurnal descending rate (in m/s) here $w_{down}$ is the maximal diurnal descending rate (in m/s).

**5.1.4 Detritus**

The particulate organic matter in the model represents dead phytoplankton and zooplankton in addition to non-biological components. Other particulate organic carbon is excluded from the detritus term. Biological change in the standing sock is given as:

"
\[
\left( \frac{dPOC}{dt} \right) = \text{Phytoplankton mortality} \ (B_6) + \text{Zooplankton mortality} \ (B_{10})
\]
\[
\quad + \text{Egestion by zooplankton} \ (B_8) - \text{Feeding by zooplankton} \ (B_7)
\]
\[
\quad - \text{Mineralization} \ (B_{12}) - \text{Biodegradation} \ (B_{13})
\]
\[
= \sum_{j=1}^{N_z} B_6' + \sum_{j=1}^{N_z} \left( B_{10}' + B_8' - B_7' \right) - B_{12} - B_{13} \quad (5.44)
\]

where \( B_6, B_{10}, B_8 \) and \( B_7 \) terms are discussed in earlier sections in the current chapter, and can be reformattting as the following:

\[
B_6' = v_6'(T) \cdot P_j^2 \quad (j=1,2, \ldots, N_p) \quad (5.45)
\]

\[
B_{10}' = v_{10}'(T) \cdot Z_j^2 \quad (j=1,2, \ldots, N_2) \quad (5.46)
\]

\[
B_8' = (1-e) \cdot v_8'(T; P, POC) \cdot Z_j \quad (j=1,2, \ldots, z) \quad (5.47)
\]

\[
B_7' = \frac{POC}{\sum P_j + POC} \cdot v_7'(T; P, POC) \cdot Z_j \quad (j=1,2, \ldots, N_2) \quad (5.48)
\]

The other two terms \( B_{12} \) and \( B_{13} \) are related to bacterial decomposition, where the bacteria decomposes the most of organic parts of detritus and transfers them to dissolved inorganic matter in a process called mineralization. The infrangibly fraction of detritus remains in organic form for long time. According to the notations in the model, the part of detritus which is subjected to bacterial decomposition (mineralization) can be expressed as the following:

\[
B_{12} = (1-\kappa) \cdot v_{12}(T, DO) \cdot POC \quad (5.49)
\]

where \( \kappa \) represents the infrangibly fraction, \( \kappa \ (0<\kappa<1) \) The mineralization of the detritus responses to Monod equation, where:

\[
v_{12}(T, DO) = \alpha_{12} \cdot \exp \left( \beta_{12} \cdot T \right) \cdot \frac{DO}{DO_l + DO} \quad (5.50)
\]
where \( \alpha_{12} \) is the apparent decomposition rate at \( 0 \degree C \), \( \beta_{12} \) the temperature coefficient, and \( DO_i \) the half-saturated oxygen concentration that reflects limitation of dissolved oxygen to bacterial decomposition.

The infrangibly fraction of detritus is expressed in the model as:

\[
B_{13} = \kappa \cdot v_{12}(T; DO) \cdot POC
\]  

(5.51)

### 5.1.5 Dissolved Organic Matter (DOC)

As mentioned in the previous section (5.1.4), the particulate organic matter (detritus) is referred to died phytoplankton and zooplankton in addition to non-biological components. The reminder part of organic matter is considered as dissolved organic matter and it is expressed as carbon stock. The biological change in the dissolved organic matter is expressed in the model as the following:

\[
\left( \frac{dDOC}{dt} \right) = \text{Extracellular release by phytoplankton (B3)} + \text{Biodegradation of detritus (B13)} - \text{Bacterial decomposition (B14)}
\]

\[
= \sum_{j=1}^{N_p} B_j^i + B_{13} - B_{14}
\]  

(5.52)

where the first two terms (B3) and (B13) are discussed in previous section and they can be reformating:

\[
B_j^i = \left[ 1 - \mu_3(P_j) \right] \cdot B_j^i \quad (j=1,2, \ldots, N_p)
\]  

(5.53)

\[
B_j^i = v_j^i(T) \cdot \mu_1(P_j, SQN_j, SQP_j) \cdot \mu_2(I, P_j) \cdot P_j
\]  

(5.54)

whereas the bacterial decomposition term can be expressed as the following:

\[
B_{14} = v_{14}(T, DO) \cdot DOC
\]  

(5.55)

where the dissolved organic matter has an exponential temperature response along with a hyperbolic oxygen response as the following:
\[ v_{14}(T, DO) = \alpha_{14} \cdot \exp(\beta_{14} \cdot T) \cdot \frac{DO}{DO_2 + DO} \]  

where \( \alpha_{14} \) is the decomposition (mineralization) rate at 0 °C \((\text{day}^{-1})\), \( \beta_{14} \) is the temperature coefficient \((\text{°C}^{-1})\), \( DO_2 \) is the half-saturated oxygen concentration \((\text{mgO}_2/l)\) standing for limitation by dissolved oxygen.

### 5.1.6 Phosphate

The nutrient part of the model comprises of four main nutrients which are, Phosphate, ammonium, nitrite and nitrate. The biochemical change in phosphate concentration is given as follows:

\[
\left( \frac{dP_4}{dt} \right) = - \text{Uptake by phytoplankton (B2)} + \text{Excretion by zooplankton (B9)} + \text{Mineralization of detritus (B12)} + \text{Mineralization of dissolved organic matter (B14)} + \text{Benthic regeneration (B19)}
\]

\[
= -\sum_{j=1}^{N_p} B_{2p}^j \cdot \sum_{j=1}^{N_p} [P : C]_j^P \cdot P_j + [P : C]_{POM} \cdot B_{12} + [P : C]_{DOM} \cdot B_{14} + B_{19} \quad (5.57)
\]

where the first four terms \((B2), (B9), (B12)\) and \((B14)\) are discussed earlier in the previous sections, and they can be reformating as the following:

\[
B^j_{2p} = v_{2p}^j (PO_4) \cdot [P : C]^P_j \cdot P_j \quad (j=1,2, ..., N_p) \quad (5.58)
\]

\[
B^j_{14} = v_{14}^j (T; P, POC) \cdot Z_j \quad (j=1,2, ..., N_2) \quad (5.59)
\]

The last term of equation (5.57) is represents the benthic regeneration of phosphorus which is regulated by physical diffusion and metabolic processes of the benthic community, and it is expressed as:

\[
B_{19} = v_{19}(T, DO) \quad (5.60)
\]

Where

\[
v_{19}(T, DO) = \alpha_{19} \cdot \exp(\beta_{19} \cdot T - \gamma_p \cdot DO) \quad (5.61)
\]
In the equation, $T$ represents the water temperature ($^\circ C$) and $DO$ represents dissolved oxygen concentration ($mgO_2/l$) just above the seabed. $\alpha_{ij}$ is the phosphorous regeneration rate at $0$ $^\circ C$ ($mgP/m^2.day^{-1}$), $\beta_{ij}$ is the temperature coefficient ($^\circ C^{-1}$) and $\gamma_p$ is a parameter ($l/mgO_2$) that represents inhibition of phosphorous regeneration by dissolved oxygen.

5.1.7 Ammonium, Nitrite and Nitrate

In the model, the dissolved inorganic nitrogen is distinguished into three forms: ammonium, nitrite and nitrate. Biochemical changes in concentration of these constituents are described as follows:

**Ammonium**

\[
\left(\frac{dNH_4}{dt}\right) = - \text{Uptake by phytoplankton} (B_2) + \text{Excretion by zooplankton} (B_9)
\]

\[+ \text{Mineralization of detritus} (B_{12}) + \text{Mineralization of dissolved organic matter} (B_{14}) - \text{Nitrification} (B_{15}) + \text{Deoxidization of nitrate} (B_{17})
\]

\[+ \text{Benthic regeneration} (B_{20})
\]

\[= -\sum_{j=1}^{Np} B_{2,j,NH_4} + \sum_{j=1}^{Np} \left[ N : C \right]_j \cdot B_9 + \left[ N : C \right]_{POM} \cdot B_{12} + \left[ N : C \right]_{DOM} \cdot B_{14} - B_{15} + B_{17} + B_{20}
\]

(5.62)

Where

\[B_{2,j,NH_4} = v_{2,NH_4} (NH_4, P, SQN) \cdot \left[ N : C \right]_p \cdot P_j \quad (j=1, 2, \ldots, N_p)
\]

(5.63)

\[v_{2,NH_4} (NH_4, P, SQN) = UN_{max} \cdot \frac{NH_4}{K_{NH_4} + NH_4} \cdot \mu_6 (P, SQN)
\]

(5.64)

\[\mu_6 (P, SQN) = \left( \frac{PQN_{max}}{ \left[ N : C \right]_p \cdot P + SQN} \right) \left( PQN_{max} - 1 \right)
\]

(5.65)

\[B_9 = v_9 (T, P, POC) \cdot Z_{ij} \quad (j=1, 2, \ldots, N_2)
\]

(5.66)

\[B_{15} = v_{15} (T, DO) \cdot NH_4
\]

(5.67)

\[B_{17} = v_{17} (T, DO) \cdot NO_3
\]

(5.68)

\[B_{20} = v_{20} (T, DO)
\]

(5.69)
Nitrite

\[
\left( \frac{d\text{NO}_2}{dt} \right) = \text{Oxidization of ammonium (1st Nitrification; B}_{15} \right) - \text{Oxidization of nitrite}
\]

\[
\text{Nitrification (2nd Nitrification; B}_{16} \right) = B_{15} - B_{16}
\]

Where

\[
B_{15} = v_{15} (T, DO) \cdot NH_4
\]

\[
B_{16} = v_{16} (T, DO) \cdot NO_2
\]

Note that the nitrification corresponds to ammonium transfer to NO\textsubscript{2} while the 2\textsuperscript{nd} nitrification corresponds to NO\textsubscript{2} transfer to NO\textsubscript{3}.

Nitrate

\[
\left( \frac{d\text{NO}_3}{dt} \right) = - \text{Uptake by phytoplankton (B}_{2} \right) + \text{Nitrification (B}_{16} \right) - \text{Deoxidization (B}_{17} \right) - \text{Denitrification (B}_{18} \right)
\]

\[
= - \sum_{j=1}^{N_p} B_{2,NO_3}^f \cdot +B_{16} - B_{17} - B_{18}
\]

Where

\[
B_{2,NO_3}^f = v_{2,NO_3} (NH_4, NO_3, P, SQN) \cdot \left[ \frac{N : C}{P} \cdot P_j \right] (j=1,2, ..., N_P)
\]

\[
v_2^{\text{NH}} (NH_4, NO_3) = UN_{\text{max}} \cdot \frac{NO_3}{K_{NO_3} + NO_3} \cdot e^{-\psi_{NH_4}} \cdot \mu_6 (P, SQN)
\]

\[
\mu_6 (P, SQN) = \left\{ \frac{PQN_{\text{max}} - \left[ \left( N : C \right)_P \cdot P + SQN \right]}{\left[ N : C \right]_P \cdot P} \right\} \left( PQN_{\text{max}} - 1 \right)
\]

\[
B_{16} = v_{16} (T, DO) \cdot NO_2
\]

\[
B_{18} = v_{18} (T) \cdot NO_3
\]

Nitrification

The oxidation process of nitrogen is called nitrification. In model the rate of
nitrification process depends on the nitrifying bacteria activity as follows:

\[
\begin{align*}
\frac{dNH_4}{dt} &= -k_{NH_4} \cdot NH_4 \quad (5.79) \\
\frac{dNO_2}{dt} &= +k_{NH_4} \cdot NH_4 - k_{NO_2} \cdot NO_2 \quad (5.80)
\end{align*}
\]

where \( k_{NH_4} \) and \( k_{NO_2} \) denote the nitrification rates of ammonium and nitrite, respectively.

The nitrifying rates are expressed in the model as the following:

\[
\begin{align*}
k_{NH_4} &= v_{15}(T, DO) = \alpha_{15} \cdot \exp(\beta_{15} \cdot T) \cdot \frac{DO}{DO_{NH_4} + DO} \quad (5.81) \\
k_{NO_2} &= v_{16}(T, DO) = \alpha_{16} \cdot \exp(\beta_{16} \cdot T) \cdot \frac{DO}{DO_{NO_2} + DO} \quad (5.82)
\end{align*}
\]

where \( \alpha_{15} \) and \( \alpha_{16} \) are the nitrification rates (in \( \text{day}^{-1} \)) of ammonium and nitrite, respectively, at 0 °C and without oxygen limitation, \( \beta_{15}, \beta_{16} \) are the corresponding temperature coefficients (\( ^{°}C^{-1}, \ln Q_{10}/10 \)), and \( DO_{NH_4}, DO_{NO_2} \) are the half-saturated oxygen concentration (\( \text{mgO}_2/l \)) standing for limitation by dissolved oxygen.

**Deoxidization and Denitrification**

In the model it is assumed that the deoxidizing reaction of nitrate-nitrogen toward ammonium-nitrogen takes place under the anaerobic condition and follows the exponential temperature response. The expression is given as:

\[
\begin{align*}
v_{17}(T, DO) &= \alpha_{17} \cdot \exp(\beta_{17} \cdot T) \cdot \mu_{17}(DO) \quad (5.83) \\
\mu_{17}(DO) &= \begin{cases} 
0 & (DO \geq DO_{NO_3}) \\
1 & (DO \leq DO_{NO_3})
\end{cases} \quad (5.84)
\end{align*}
\]
where $\alpha_{17}$ is the deoxidization rate (in day$^{-1}$) of nitrate at 0 °C and $\beta_{17}$ is the temperature coefficient (°C$^{-1}$). The function $\mu_{17}$ reflects the upper threshold of dissolved oxygen, $DO_{NO3}$ (in mgO$_2$/l), above which the deoxidizing reaction no longer proceeds.

Denitrification process is the inverse of the nitrification one. It is expressed in the model as:

$$B_{18} = v_{18}(T) \cdot NO_3, v_{18}(T) = \alpha_{18} \cdot \exp(\beta_{18} \cdot T)$$  \hspace{1cm} (5.85)

where $\alpha_{18}$ is the overall denitrification rate day$^{-1}$ at 0 °C and $\beta_{18}$ is the temperature coefficient (°C$^{-1}$).

**Benthic Nitrogen Regeneration**

Benthic nitrogen regeneration is related only to the ammonium compartment. It is expressed in the model as:

$$v_{20}(T, DO) = \alpha_{20} \cdot \exp(\beta_{20} \cdot T - \gamma_N \cdot DO)$$ \hspace{1cm} (5.86)

where $\alpha_{20}$ represents the nitrogen regeneration flux at 0°C and zero oxygen concentration (mgN·m$^{-2}$·day$^{-1}$), $\beta_{20}$ is the temperature coefficient (°C$^{-1}$) and $\gamma_N$ is an oxygen inhibition parameter (l/mgO$_2$).

**5.1.8 Dissolved Oxygen (DO)**

Dissolved oxygen is one of the most important parameters in the biochemical model, where it plays the main role in oxidizing and nitrifying of the other compartments. The biochemical change in dissolved oxygen concentration is given as follows:

$$\left(\frac{dDO}{dt}\right) = \text{Photosynthetic supply (D$_1$)} - \text{Respiratory loss by phytoplankton (D$_2$)}$$

$$- \text{Respiratory loss by zooplankton (D$_3$)} - \text{Loss due to bacterial}$$
decomposition of detritus (D4) – Loss due to mineralization of DOM (D5)
- Oxidation of ammonium (D6) – Oxidation of nitrite (D7) – Consumption by
sediment (D8) ± aeration (D9)
\[
= \sum_{j=1}^{N_p} [\text{TOD} : C]_p \cdot (B'_j - B'_i) - \sum_{j=1}^{N_p} [\text{TOD} : C]_z \cdot B'_i - [\text{TOD} : C]_{\text{DOM}} \cdot B_{12} - [\text{TOD} : C]_{\text{DOM}} \cdot B_{14} - 0.048 \cdot B_{15} - 0.016 \cdot B_{16} - F_{DO} (T) + k_a \cdot (DO_2 - DO)
\] (5.87)

Where

\[B'_1 = v'_1(T) \cdot \mu_1(P_j, SQN_j, SQP_j) \cdot \mu_2(I, P_j) \cdot P_j \quad (j=1, 2, \ldots, N_p)
\] (5.88)
\[B'_2 = v'_2(T) \cdot P_j \quad (j=1, 2, \ldots, N_p)
\] (5.89)
\[B'_3 = v'_3(T; P, POC) \cdot Z_j \quad (j=1, 2, \ldots, N_z)
\] (5.90)
\[B_{12} = (1 - \kappa) \cdot v_{12} (T; DO) \cdot POC
\] (5.91)
\[B_{14} = v_{14} (T, DO) \cdot DOC
\] (5.92)
\[B_{15} = v_{15} (T, DO) \cdot NH_4
\] (5.93)
\[B_{16} = v_{16} (T, DO) \cdot NO_2
\] (5.94)

It is clear that all biochemical processes which are related to dissolved oxygen are converted from carbon fluxes to oxygen fluxes are expressed in oxygen/ carbon ratio [TOD: C] as shown in equation (5.87). The main oxidation and deoxidation processes in the model will be discussed below in a brief manner.

Photosynthetic Supply

Referring to section 5.1.1, the carbon flux photosynthetically assimilated by each phytoplankton category is given as:

\[B'_1 = v'_1(T) \cdot \mu_1(P_j, SQN_j, SQP_j) \cdot \mu_2(I, P_j) \cdot P_j \cdot (mg\text{C}\cdot m^{-3} \cdot \text{day}^{-1}; j=1, 2, \ldots, N_p)
\] (5.95)

By converting to oxygen flux by specific [TOD: C] ratio, the photosynthetic oxygen supply can be expressed as follows:

\[D_1 = \sum_{j=1}^{N_p} [\text{TOD} : C]_p \cdot B'_1 \cdot (mgO_2 \cdot l^{-1} \cdot \text{day}^{-1})
\] (5.96)
Respiratory Losses by Plankton

The respiratory oxygen losses by phytoplankton and by zooplankton, they can be calculated as follows:

\[ D_2 = \sum_{j=1}^{N_D}[TOD:C]_{[\rho]} \cdot B_{9} \cdot (mgO_2 \cdot l^{-1} \cdot day^{-1}) \quad (5.97) \]

\[ D_3 = \sum_{j=1}^{N_D}[TOD:C]_{[\rho]} \cdot B_{9} \cdot (mgO_2 \cdot l^{-1} \cdot day^{-1}) \quad (5.98) \]

Consumption through Bacterial Decomposition

A part of dissolved oxygen is consumed by respiration activities which take place by bacteria during decomposing of particular organic matter. This part of dissolved oxygen is expressed in the model as:

\[ D_4 + D_5 = [TOD:C]_{DOM} \cdot B_{12} + [TOD:C]_{DOM} \cdot B_{14} \cdot (mgO_2 \cdot l^{-1} \cdot day^{-1}) \quad (5.99) \]

Oxygen Consumption through Nitrification

The nitrification process of ammonium-nitrogen to nitrite-nitrogen and nitrite-nitrogen into nitrate-nitrogen by nitrification bacteria consumes a part of dissolved oxygen. It is expressed respectively in the model as:

\[ D_6 = 0.048 \cdot B_{15} = 0.048 \cdot v_{15} (T, DO) \cdot NH_4 \cdot (mgO_2 \cdot l^{-1} \cdot day^{-1}) \quad (5.100) \]

\[ D_7 = 0.016 \cdot B_{16} = 0.016 \cdot v_{16} (T, DO) \cdot NO_2 \cdot (mgO_2 \cdot l^{-1} \cdot day^{-1}) \quad (5.101) \]

Consumption by Sediment

Consumption of dissolved oxygen due to benthic sediments is related to physicochemical and biological processes which take place in the sediment, such as, bacterial decomposition, respiration by benthic organisms, nitrification in the surface mud, etc. All these types of consumptions are expressed in the model as:
\[ D_s = \alpha_{DO} \cdot \exp(\beta_{DO} \cdot T^*) \cdot h_b \cdot DO, T^* = \max\{0, T - T_b\} \] (5.102)

where \( T \) and \( DO \) denote water temperature \((^\circ C)\) and dissolved oxygen concentration \((mgO_2/l)\) just above the seabed, respectively, \( T_b \) is the lower temperature threshold \((^\circ C)\) above which the oxygen consumption takes place, \( \alpha_{DO} \) gives the consumption rate \((day^{-1})\) at \( T = T_b \), \( \beta_{DO} \) the temperature coefficient \((^\circ C^{-1})\), and \( h_b \) the height of the benthic water column (length from the seabed to the center of bottom level).

**Aeration**

The sea-surface aeration is expressed in the model as:

\[ D_s = k_a \cdot (DO_s - DO) \] (5.103)

where \( DO \) and \( DO_s \) are respectively the dissolved oxygen concentration and the saturated oxygen concentration in the surface layer (both in \( mgO_2/l \)), \( k_a \) is the aeration rate \((day^{-1})\).

The aeration rate is a function of the wind velocity \((m/s)\) and it is formulated in the model as:

\[ k_a = \frac{1}{\zeta + 0.5 \cdot h_1} \begin{cases} 0.13 \times W & (W \leq 3.6) \\ 2.2 \times (W - 3.39) & (3.6 \leq W \leq 13) \\ 4.3 \times (W - 8.36) & (13 \leq W) \end{cases} \] (5.104)

where \( \zeta \) is the tide level and \( h_1 \) is the thickness of the top level (both in \( m \)).

**5.1.9 Chemical Oxygen Demand (COD)**

Chemical oxygen demand \((COD)\) in the model is a parameter associated with the fragile fraction of organic matter, which includes phytoplankton, zooplankton, detritus and dissolved organic matter. COD is expressed in the mode as follows:
\[ COD = \sum_{j=1}^{N_r} \lambda_{P,j} \cdot P_j + \sum_{j=1}^{N_c} \lambda_{Z,j} \cdot Z_j + \lambda_{POC} \cdot POC + \lambda_{DOM} \cdot DOC \]  

(5.105)

Where, \( \lambda \) stands for the COD/C ratio of each organic compartment, which is closely related to the tissue composition of total oxygen demand (TOD) vs. carbon.

### 5.2 Calibration of Model Parameters

Marine ecological models have a large numbers of water quality parameters which control the behavior of the model compartments as well as the biochemical processes among them. Some of these parameters may differ greatly from one region to another around the world due to the peculiar physical, biological, chemical and physiological characteristics of each environment especially in the lower-trophic level where, biochemical processes are imbricate and complicated. Most of the biological parameters need laboratory experiments to determine their values.

An important step of any water quality modeling process is to stabilize the model results via adjusting these parameters. In other words, to validate the model to be used for predictive process, some parameters have to be justified to adapt the ambient conditions for the study area, hence to get reasonable results. The stabilization process involves tuning a selected number of the model parameters and the model is run until the computed values match the field-observed values with an acceptable level of accuracy. In the current study, due to resources and time limitation, many of these parameters are determining according different related literatures, while other parameters are tuned many times to get the best results as described earlier.

It should be noted that EUTROP water quality model is run using the same grid regime employed in the flow model, so that the simulated temperature, salinity, tides, current velocities, and vertical eddy diffusivity are readily accommodated in the ecological simulation.

In the present work, there are four sets of data. Due to the large variation of the summer and winter climate conditions in the gulf area, these sets are classified into two major groups, one is for the summer condition (June 2003 and August 2003) and the other is for winter condition (November 2003 and January 2004). As
mentioned earlier (chapter 4), each set of data comprised 30 field measurements from 10 stations taken at three different levels, surface, middle and bottom.

Here, the main considered component which will be investigated is the desalination plant located in the RIC. It is worth mentioning that the desalination plant is not the only component which may deteriorate the coastal water quality of the Ruwais. That is because several other facilities are located in the same area as mentioned in chapter 4. Most of these facilities dispose their effluents in the Ruwais coastal water. But the desalination plant can be distinguished as a higher concentration brine disposal and one of the major sources of the temperature increment in the Ruwais waters. Whereas, the effluents of the other facilities have ambient physical and nutrient conditions with the exception of fertile factory (Table 5.2).

Summer parameter stabilization is performed over two month period between the two observed summer sets; June 2003 and August 2003. The field measurements of June 2003 are considered as initial conditions and the calculated values at the end of two-month period are compared with the field observed values of August 2003. An extensive effort was done to stabilize the compartment parameters, where the model was run several times, in each run, one of these parameters was tuned until reasonable match between the observed and the calculated values is achieved. Figure 5.2 shows a comparison between the observed and the calculated values for the summer condition.

The stabilization process is repeated for winter condition where the initial conditions are taken as the data set of November 2003 and the model calculated results are compared with the field-observed data at January 2004. Figure 5.3 shows the calculated values of various compartments versus the field observed data for the winter condition. The calculated and measured compartment values are distributed almost symmetrically indicating fair agreement similar to the summer results with a better match obtained in case of NO₂ results.

It is worth mentioning for both Figures 5.2 and 5.3, the model calculated values in summer and winter seasons are distributed in a horizontal fashion with a narrow range of variation, whereas, the field-observed values distribute over a wider range and scattered randomly around the ideal trend line. This shows clearly that the output results of the water quality model are more homogenous than the field-observed data. This may refer to several reasons. One of them is the high influence of the model boundary results. As the most of the observed compartments close to the
boundary showed less variation, the variation in the output results over the entire area became small. Other local reason may also arise, which is related to the uncounted petrochemical and oil amounts which pollute the marine water in the Ruwais area due to the continuous movement of the tankers and in accidental oil spill at the existing SPMs (Single Point Mooring). This can potentially contribute to the erratic and non-homogeneity nature of the field-observed data especially DOC and COD.

The stabilized parameters of the model compartments for summer and winter seasons are listed in Table 5.3. Many of the physiological parameters of the model plankton are employed from another study (Taguchi and Nakata, 1998).

Brief comments are presented below about selected compartments in light of the conducted stabilization process parameter values (Table 5.3) and their relevant theoretical aspects.
<table>
<thead>
<tr>
<th>Utility</th>
<th>Q (m³.day⁻¹)</th>
<th>NO₂ (kg.day⁻¹)</th>
<th>NO₃ (kg.day⁻¹)</th>
<th>NH₄ (kg.day⁻¹)</th>
<th>PO₄ (kg.day⁻¹)</th>
<th>COD (kg.day⁻¹)</th>
<th>DOC (kg.day⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outfall 1 Oil Refinery (TAKREER)</td>
<td>243600</td>
<td>194.88</td>
<td>316.70</td>
<td>0.00</td>
<td>19.49</td>
<td>19488.00</td>
<td>974.40</td>
</tr>
<tr>
<td>Gas Production Plant (GAZCO)</td>
<td>600000</td>
<td>300.00</td>
<td>600.00</td>
<td>10.00</td>
<td>1.40</td>
<td>36000.00</td>
<td>2400.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>843600</strong></td>
<td><strong>494.90</strong></td>
<td><strong>916.70</strong></td>
<td><strong>10.00</strong></td>
<td><strong>20.90</strong></td>
<td><strong>5548.00</strong></td>
<td><strong>3374.40</strong></td>
</tr>
<tr>
<td>Outfall 2 Desalination and Power Plant</td>
<td>192000</td>
<td>19.20</td>
<td>192.00</td>
<td>0.00</td>
<td>15.36</td>
<td>9600.00</td>
<td>768.00</td>
</tr>
<tr>
<td>Fertilization Factory</td>
<td>120000</td>
<td>12.00</td>
<td>120.00</td>
<td>60.00</td>
<td>9.60</td>
<td>6000.00</td>
<td>480.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>312000</strong></td>
<td><strong>31.20</strong></td>
<td><strong>312.00</strong></td>
<td><strong>60.00</strong></td>
<td><strong>24.96</strong></td>
<td><strong>15600.00</strong></td>
<td><strong>1248.00</strong></td>
</tr>
<tr>
<td>Outfall 3 Petrochemical Factory (Borooj)</td>
<td>840000</td>
<td>420.00</td>
<td>480.00</td>
<td>100.00</td>
<td>84.00</td>
<td>33600.00</td>
<td>12600.00</td>
</tr>
</tbody>
</table>
Figure 5.2: Parameter-stabilization results based on the summer data at three different levels; surface, middle and bottom (● Surface, ■ Middle, ▲ Bottom), and are representing both upper and lower hourly fluctuation respectively of different compartments.
Figure 5.3: Parameter-stabilization results based on the winter data at three different levels; surface, middle and bottom (Surface, Middle, Bottom), and are representing both upper and lower hourly fluctuation respectively of different compartments.
Table 5.3: Final stabilized values for the summer and winter conditions at the Ruwais coastal water.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nomenclature</th>
<th>Unit</th>
<th>Arabian Gulf values</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Phytoplankton</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum growth rate</td>
<td>$G_{\text{max}}$, $\beta_{G_{\text{max}}}$</td>
<td>day$^{-1}$, $^\circ$C$^{-1}$</td>
<td>0.50 . exp(0.0633T)</td>
<td>Stabilized, Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td>Maximum nutrient uptake rates</td>
<td>$U_{\text{P_{max}}}$, $U_{N_{\text{max}}}$</td>
<td>day$^{-1}$</td>
<td>Phosphorus 36, nitrogen 12</td>
<td></td>
</tr>
<tr>
<td>Half saturation constants for nutrient uptake</td>
<td>$K_{p_{\text{sat}}}$, $K_{n_{\text{sat}}}$, $K_{NO_{3}}$</td>
<td>$\mu$M.l$^{-1}$</td>
<td>Phosphate 1.0, Ammonium 1, nitrate 2</td>
<td>Stabilized</td>
</tr>
<tr>
<td>Ammonium inhibition factor for nitrate uptake</td>
<td>$\psi$</td>
<td>$\mu$M.l$^{-1}$</td>
<td>1.462</td>
<td></td>
</tr>
<tr>
<td>Maximum capacity of cell quota</td>
<td>$P_{Q_{\text{P_{max}}}}$, $P_{Q_{N_{\text{max}}}}$</td>
<td>-</td>
<td>Phosphorus 16, nitrogen 8</td>
<td>Stabilized, Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td>Maximum surface radiation</td>
<td>$I_{\text{max}}$</td>
<td>cal.cm$^{-2}$. day$^{-1}$</td>
<td>Summer = 2000, Winter = 800</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td>Daytime length</td>
<td>$D_{L}$</td>
<td>Day</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photosynthetic light optimum</td>
<td>$I_{OPT}$</td>
<td>cal.cm$^{-2}$. day$^{-1}$</td>
<td>150</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td>Light extinction coefficient</td>
<td>$k$</td>
<td>m$^{-1}$</td>
<td>0.21 + 0.0088 . Chl-a</td>
<td>Stabilized</td>
</tr>
<tr>
<td>Fraction of extracellular release</td>
<td>$E_{\text{ext}}$, $b_{\text{ext}}$</td>
<td>-</td>
<td>0.135 .exp(-0.002.Chl-a)</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td>Respiration rate</td>
<td>$P_{\text{resp}}$, $b_{\text{resp}}$</td>
<td>day$^{-1}$, $^\circ$C$^{-1}$</td>
<td>0.03 . exp(0.0524T)</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td>Sinking rate of living cells</td>
<td>$w_{p}$</td>
<td>m.day$^{-1}$</td>
<td>0.2</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td>Rate of natural mortality</td>
<td>$P_{\text{mot}}$, $b_{\text{mot}}$</td>
<td>m$^{-3}$.mg C$^{-1}$.day$^{-1}$, $^\circ$C$^{-1}$</td>
<td>2.0 X 10$^{-2}$ . exp(0.0693T)</td>
<td>Stabilized</td>
</tr>
<tr>
<td>C/Chl-a ratio</td>
<td>[Chl-a.C]</td>
<td>by weight</td>
<td>15.3</td>
<td>Calculated</td>
</tr>
<tr>
<td>C / P, C / N ratios (except for cell quota)</td>
<td>$[C/P]$, $[C/N]$</td>
<td>by weight</td>
<td>C / P 161.3, C / N 15.9</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td>O / C ratio</td>
<td>$\lambda_{p}$</td>
<td>mg O$_2$.mg C$^{-1}$</td>
<td>3.41</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td>COD / C ratio</td>
<td>$I_{p}$</td>
<td>Mg COD.mg C$^{-1}$</td>
<td>1.38</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td><strong>Zooplankton</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum ration</td>
<td>$R_{\text{max}}$, $b_{R_{\text{max}}}$</td>
<td>day$^{-1}$, $^\circ$C$^{-1}$</td>
<td>0.18 . exp(0.0693 T)</td>
<td>Stabilized</td>
</tr>
<tr>
<td>Ivlev's constant</td>
<td>$\lambda$</td>
<td>m$^{-3}$.mg C$^{-1}$</td>
<td>0.01</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td>Feeding threshold</td>
<td>$\Pi$</td>
<td>mg C. m$^{-3}$</td>
<td>0.0</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td>Rate of basic metabolism</td>
<td>$Z_{\text{resp}}$, $b_{Z_{\text{resp}}}$</td>
<td>day$^{-1}$, $^\circ$C$^{-1}$</td>
<td>0.0214 . exp(0.0637T)</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td>Energy expenditure in grazing activity</td>
<td>$\eta$</td>
<td>-</td>
<td>30% of the daily carbon ration</td>
<td></td>
</tr>
<tr>
<td>Assimilation efficiency</td>
<td>$e$</td>
<td>%</td>
<td>70.0</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td>Rate of natural mortality</td>
<td>$z_{\text{mot}}$, $b_{Z_{\text{mot}}}$</td>
<td>m$^{-3}$.mgC$^{-1}$.day$^{-1}$, $^\circ$C$^{-1}$</td>
<td>5.0 X 10$^{-2}$ . exp(0.0693T)</td>
<td>Stabilized</td>
</tr>
</tbody>
</table>

5-29
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Formula/Definition</th>
<th>Unit</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>C/P, C/N ratios</strong></td>
<td>[C:P], [C:N] by weight</td>
<td>C/P</td>
<td>50.0, C/N 6.0</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td><strong>O/C ratio</strong></td>
<td></td>
<td>O/C</td>
<td>3.31</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td><strong>COD/C ratio</strong></td>
<td></td>
<td>COD/C</td>
<td>1.46</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td><strong>Detrital carbon</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mineralization rate</td>
<td>$V_{POM}, \beta_{POM}$</td>
<td>day$^{-1}$, C$^{-1}$</td>
<td>0.0015, exp(0.0693T)</td>
<td>Stabilized</td>
</tr>
<tr>
<td>Oxygen limitation</td>
<td>$DO_{POM}$</td>
<td>mg O$_2$.l$^{-1}$</td>
<td>0.5</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td>Fraction of biodegradation</td>
<td>$k$</td>
<td>-</td>
<td>25% of mineralization</td>
<td>Assumed</td>
</tr>
<tr>
<td><strong>C/P, C/N ratios</strong></td>
<td>[C:P], [C:N] by weight</td>
<td>C/P</td>
<td>63.9, C/N 7.2</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td><strong>O/C ratio</strong></td>
<td></td>
<td>O/C</td>
<td>3.31</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td><strong>COD/C ratio</strong></td>
<td></td>
<td>COD/C</td>
<td>1.46</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td>Sinking rate</td>
<td>$\gamma_{POM}$</td>
<td>m.day$^{-1}$</td>
<td>0.5</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td><strong>Dissolved organic carbon</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mineralization rate</td>
<td>$V_{DOC}, \beta_{DOC}$</td>
<td>day$^{-1}$, C$^{-1}$</td>
<td>0.001, exp(0.0693T)</td>
<td>Stabilized</td>
</tr>
<tr>
<td>Oxygen limitation</td>
<td>$DO_{DOC}$</td>
<td>mg O$_2$.l$^{-1}$</td>
<td>0.5</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td><strong>C/P, C/N ratios</strong></td>
<td>[C:P], [C:N] by weight</td>
<td>C/P</td>
<td>124.98, C/N 10</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td><strong>O/C ratio</strong></td>
<td></td>
<td>O/C</td>
<td>2.82</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td><strong>COD/C ratio</strong></td>
<td></td>
<td>COD/C</td>
<td>1.38</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td><strong>Others</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrification rate of ammonium</td>
<td>$k_{NH4}, \beta_{NH4}$</td>
<td>day$^{-1}$, C$^{-1}$</td>
<td>0.01, exp(0.0693T)</td>
<td>Stabilized</td>
</tr>
<tr>
<td>Oxygen limitation</td>
<td>$DO_{NH4}$</td>
<td>mg O$_2$.l$^{-1}$</td>
<td>0.5</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td>Nitrification rate of nitrite</td>
<td>$k_{NO2}, \beta_{NO2}$</td>
<td>day$^{-1}$, C$^{-1}$</td>
<td>0.1, exp(0.0693T)</td>
<td>Stabilized</td>
</tr>
<tr>
<td>Oxygen limitation</td>
<td>$DO_{NO2}$</td>
<td>mg O$_2$.l$^{-1}$</td>
<td>0.5</td>
<td>Taguchi &amp; Nakata, 1998</td>
</tr>
<tr>
<td>Aeration rate</td>
<td>$k_a$</td>
<td>day$^{-1}$</td>
<td>0.5</td>
<td>Stabilized</td>
</tr>
</tbody>
</table>
5.2.1 Phytoplankton

Phytoplankton is considered as the most important compartment in the model, where it affects and is affected by many other model compartments. As some parameters have a distinct effect on the phytoplankton, other parameters have a slight or even null effect as follows:

Maximum growth rates of phytoplankton $G_{\text{max}}$ are the most effective parameters on its biomass. Increasing $G_{\text{max}}$ by 40% tends to increase the phytoplankton biomass by 59%, whereas there is a slight increase (5%) of the particular organic matter (POC). Referring to equation (5.44), this slight increase of (POC) may be due to the increased mortality of phytoplankton associated with the high growth rate. It is worth mentioning that even with high growth rate of phytoplankton biomass, the zooplankton biomass was not affected, this may refer to scarcity of zooplankton species in the Ruwais coastal water as the amounts of phytoplankton do not contribute to their grazing. So excess amount of phytoplankton may not be grazed, and is may cause red tides and push toward the eutrophication conditions.

Rate of natural mortality $P_{\text{mot}}$ has an essential effect on the phytoplankton biomass, where increasing $P_{\text{mot}}$ by 90% tends to decrease the phytoplankton biomass to 76% without any change on the other compartments.

Some other parameters are used to make fine tuning of the phytoplankton compartment, where changing their values have a slight effect on the phytoplankton results. These parameters are; half saturation constants for nutrient uptake (KP04, KNH4, KNO3), ammonium inhibition factor for nitrate uptake ($\psi$), and light extinction coefficient ($k$).

5.2.2 Zooplankton

Zooplankton has complex relations with the other model compartments through different parameters as follows:

Maximum ration $R_{\text{max}}$ has a crucial role in controlling the zooplankton biomass, where increasing $R_{\text{max}}$ by 90% tends to increase the zooplankton biomass by 370%. This result has many effects on most of the model compartments, where phytoplankton biomass decreases by 9.2%. This indicates that even with the tremendous increase of zooplankton, phytoplankton is not severely affected. This refers to the very few number of zooplankton species which originally exist.
Moreover, "R_{max}" increasing causes (POC) to decrease by 7.8%. Referring to equation (5.44), this may be occurred due to high feeding rate of zooplankton on the detritus. Also, increasing "R_{max}" by 90% tends to increase (PO_{4}) by 6.2% due to the excretion of zooplankton; according to equation (5.57). This similarly increases (NH_{4}) by 15.6% due to the same reason; equation (5.62).

Rate of natural mortality "Z_{mot}" is the second parameter that affects the zooplankton biomass, where increasing "Z_{mot}" by 90% causes a decrease of zooplankton biomass by 5.5% as reflected by equation (5.24).

5.2.3 Detritus

As mentioned in the previous section (5.1.4), detritus is related to dead phytoplankton, zooplankton and non-biological components. In the model, detritus is affected by several factors. Mineralization rate of detritus ($\alpha_{I2}$) was used to stabilize the (POC) compartment. It was found that increasing ($\alpha_{I2}$) by 90%, POC compartment increases by 3.9%, NH_{4} increases by 5% which causes an increase in the nitrification processes rate so, NO_{2} increases by 3.6% as can be seen from equations (5.44), (5.62), and (5.70) respectively.

5.2.4 Dissolved Organic Matter

Increasing the mineralization rate of bacterial decomposition ($\alpha_{I4}$) by 100% yields an increase of (NH_{4}), (NO_{2}), and (PO_{4}) compartments by 7.1%, 5%, and 1.68% as reflected in equations (5.62), (5.70), and (5.57), respectively. Whereas, a decreasing by 2% and 0.63% occurs for (DOC) and (DO) compartments corresponding to equations (5.52) and (5.87) respectively.

5.2.5 Ammonium and Nitrite

To stabilize the nitrogen-related nutrients, nitrification rate of ammonium ($K_{NH4}$) and nitrification rate of nitrite ($K_{NO2}$) were tuned to get the desirable trend of results. It was found that increasing ($K_{NH4}$) by 100% tend to decrease (NH_{4}) by 9.1% and increase (NO_{2}) by 1.7%. These are corresponding to equation (5.62) and 5.70) respectively. Whereas, increasing ($K_{NO2}$) by 100% produces an increase of 10.6% for (NO_{2}) compartment.
The remaining compartments such as (PO₄), (DO), and (COD) are stabilized implicitly during tuning of other compartments as shown in equations (5.57), (5.87), and (5.105).

5.3 Aerial Distribution of Simulated Results

This section presents the simulated results and describes their aerial distribution.

Figures from 5.4 to 5.13 show the surface spatial distribution of different compartments in summer season. Due to homogeneity of the water column in the area as mentioned before, the compartments have slight difference in their values in the three depths; surface, middle and bottom. Hence, the surface layer is used herein to explain the general trend for the different compartments in the Ruwais coastal area.

Figure 5.4 shows the phytoplankton distribution in the area. It is noted that its value fluctuates almost from 2 to 5 mg/m³. The value of phytoplankton biomass is higher in the south due to high nutrient rates corresponding to the RIC effluents which dump high quantities of the nutrients in the coastal water, whereas its values decreases southward and westward.

Figure 5.5 shows that the zooplankton biomass varies from 0.6 to 1.3 mg/m³. It is clear that the distribution of the zooplankton have a trend contrasting with phytoplankton distribution, where the zooplankton biomass is lower in south and higher in the north in spite of the abundance of the phytoplankton in south. This may be attributed to high pollution due to the effluents from the RIC in addition to the petrochemical contaminants due to oil activates in the port of Ruwais which may threaten the zooplankton biomass and diminish its growth.

Figure 5.6 shows that the particulate organic matter (POC) is varying from 300 to 700 mg/m³. The values decreases eastward and northward and increases southward and westward.

The dissolved organic matter (Fig. 5.7) is high in the south due to the RIC effluents which contribute to raise the DOC concentration in the southern area up to 2400 mgC/m³, and it reduces toward the east to around 1200 mgC/m³ due to mixing with the eastern boundary with the Gulf water that causes a dilution for the DOC concentration.

Figure 5.8 shows the phosphate (PO₄) spatial distribution that varies from 0.3 to 1.0 μmol/L, and it increases eastward. At the effluent area, it is noticeable that the
phosphate concentration increases due to the nutrient discharges from the industrial complex.

The distribution of ammonia (NH₄) which is shown in Figure 5.9 indicates high concentrations near the open boundary and vicinity to the effluent area reach up to 2.66 μmol/L, whereas values in the middle area fluctuate around 2.3 μmol/L.

Figure 5.10 illustrates the nitrite (NO₂) distribution as its values increase toward the shoreline and decrease offshore. Its value varies from 0.3 to 2 μmol/L with the high concentration around the effluent area due to the industrial complex discharging.

The nitrate NO₃ (Fig. 5.11) has a general increasing trend eastward, and its values vary from 59 to 87 μmol/L.

Figure 5.12 shows the dissolved oxygen (DO) distribution. DO varies between 5 to 10 mg/L, and it decreases toward the shoreline. This decrease may refer to high petrochemical pollutants that lead to more oxygen consumption by the bacteria for their decomposition.

Figure 5.13 shows the surface distribution of the chemical oxygen demand (COD). It is clear that the COD decreases eastward and it varies from 5 to 13 mg/L. At the effluent points, DOC has high levels in association with high the bacterial decomposing activities.
Figure 5.4: Surface spatial distribution of phytoplankton in summer season

Figure 5.5: Surface spatial distribution of zooplankton in summer season
Figure 5.6: Surface spatial distribution of POC in summer season

Figure 5.7: Surface spatial distribution of DOC in summer season
Figure 5.8: Surface spatial distribution of PO$_4$ in summer season

Figure 5.9: Surface spatial distribution of NH$_4$ in summer season
Figure 5.10: Surface spatial distribution of NO$_2$ in summer season

Figure 5.11: Surface spatial distribution of NO$_3$ in summer season
Figure 5.12: Surface spatial distribution of DO in summer season

Figure 5.13: Surface spatial distribution of DOC in summer season
Figures from 5.14 to 5.23 show the surface spatial distribution of the different water quality model compartments in the winter season.

Figure 5.14 shows that the phytoplankton biomass varies from 2 to 5 mgC/m³. The RIC effluent zone has the lowest phytoplankton biomass concentration (2.5 mgC/m³), whereas values increase toward the open boundaries in the north and the east up to 5 mgC/m³.

Figure 5.15 shows the zooplankton biomass distribution in the modeled area. It varies from 0.8 to 1.3 mgC/m³. The zooplankton has a similar phytoplankton trend in winter; i.e., the concentration decreases toward the shoreline and increases toward the boundaries.

Figure 5.16 shows the POC distribution. It ranges from 350 to 730 mgC/m³. It is clear that the POC concentration increases eastward in the winter while it tends to increase westward in summer. In general, the POC values in summer are higher than its values in winter. This may refer to the higher growth rate of phytoplankton and zooplankton in summer than in winter, which produces higher mortality rates. It may be also attributed to increased levels of oil contamination as the tanker activities increase significantly in the summer.

Figure 5.17 shows the spatial distribution of the DOC. It ranges from 2500 to 3400 mgC/m³. Generally, higher concentrations are toward the middle of the modeled area (3000 mgC/m³), while the highest spot is located in the south near the effluent discharging area where it reaches up to 3400 mgC/m³. These extreme values at the middle and near the discharging area may be caused by the effluent loads from the RIC.

Figure 5.18 shows the PO$_4$ spatial distribution that ranges from 0.5 to 2.0 µmol/L. It is noticeable that the PO$_4$ concentrations in winter are higher than the summer. This may be related to the low concentration of phytoplankton in the winter, indicating that the phosphate is highly affected with the phytoplankton biomass in the coastal water area of Ruwais, and supports the speculation that the phosphate is a limiting nutrient.

Figure 5.19 shows that NH$_4$ concentration ranges from 1.5 to 2.5 µmol/L in the area. It increases toward the shoreline and reach its maximum values at the discharging area.
Figure 5.24 shows the NO₂ spatial distribution that ranges from 0.5 to 1.8 μmol/L and increases toward the shoreline. It is clear that there is no large difference in the summer and winter values of NO₂.

Figure 5.25 shows that NO₃ concentration varies from 63 to 76 μmol/L as it increases south-western ward in contrast with the summer trend.

Figure 5.22 shows that the DO varies from 5.5 to 10 mg/L. It increases toward the south-east. This may be attributed to high rate of aeration of the water due to the tanker and ships movement in that area where the port is located.

Figure 5.23 shows that COD ranges from 13 to 22 mg/L. The higher concentration values are located in the middle of the modeled area. This may relate to high DOC values in that area. Generally, COD in winter is higher than in summer due to higher values of DOC in winter than in summer.
Figure 5.14: Surface spatial distribution of Phytoplankton for winter season

Figure 5.15: Surface spatial distribution of Zooplankton for winter season
Figure 5.16: Surface spatial distribution of POC for winter season

Figure 5.17: Surface spatial distribution of DOC for winter season
Figure 5.18: Surface spatial distribution of PO₄ for winter season

Figure 5.19: Surface spatial distribution of NH₄ for winter season
Figure 5.20: Surface spatial distribution of NO$_2$ for winter season

Figure 5.21: Surface spatial distribution of NO$_3$ for winter season
Figure 5.22: Surface spatial distribution of DO for winter season

Figure 5.23: Surface spatial distribution of COD for winter season
CHAPTER SIX

FUTURE PREDICTION FOR PHYSICAL AND
ECOLOGICAL CONDITIONS

In this chapter, the numerical approach used in the water quality modeling for long
term prediction is explained, and then the considered scenarios used in the impact
assessment investigation are presented. Results of the hydrodynamic modeling to
investigate the future salinity and temperature are discussed on the light of the results
obtained from the water quality modeling.

6.1 Numerical Approach

In order to investigate the effect of temperature and salinity on the marine ecosystem,
the 1 km coarse grid model developed earlier for the Ruwais coastal area is nested
with the regional model of the entire Arabian Gulf basin. The local nested model is
employed in the simulation of both hydrodynamic and biological features of the
Ruwais coastal environment. In the present study, the simulated periods by the water
quality model are dictated by the water quality data collected from site of application.
As mentioned in chapter 4, there are four sets of water quality data. Three of them
were at the beginning of spring, summer and autumn seasons (June, August and
November, respectively), and the last one at the end of winter (January). In the
numerical simulation for both hydrodynamic and water quality, only two seasons are
taken in consideration; i.e. summer and winter.

The time domain considered in long term simulation is divided into years; each
year is divided into 4 periods as follows in Table (6.1).

<table>
<thead>
<tr>
<th>Period Number</th>
<th>Number of months</th>
<th>Time</th>
<th>Season condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period 1</td>
<td>2</td>
<td>June, 1st to July, 31st</td>
<td>Summer</td>
</tr>
<tr>
<td>Period 2</td>
<td>2</td>
<td>Aug., 1st to Sep. 30th</td>
<td>Summer</td>
</tr>
<tr>
<td>Period 3</td>
<td>4</td>
<td>Oct., 1st to Jan., 31st</td>
<td>Winter</td>
</tr>
<tr>
<td>Period 4</td>
<td>4</td>
<td>Feb., 1st to May, 31st</td>
<td>Summer</td>
</tr>
</tbody>
</table>
To accommodate the proposed periods with the available data set in the first year, an approximation is made in which the needed data for October is considered equivalent to the available November data, while the needed data for February is considered equivalent to the available January data set.

6.1.1 Hydrodynamic Modeling Numerical Approach

Due to the lack of data for regional boundary conditions at Strait of Hormuz for future years, the hydrodynamic model is run for one full year in four separate runs considering the four proposed periods in Table 6.1. Thus, the successive iterations for the water quality future simulation are modeled over the same regime of hydrodynamic conditions that take into account the differences between both summer and winter seasons but repeated in typical annual cycles.

The four separate runs of hydrodynamic modeling conducted to cover one full year are described here. First, the boundary condition files of the four simulation periods for different model parameters are prepared using auxiliary software as mentioned in chapter 4. The data used for such files are the field measured data. In the first run for the period 1, the field measured values on June 1st are employed as initial conditions along with summer set of model parameters listed in Table 3.3. The output files of the previous simulation process are used as initial condition files for the second simulation period 2, again along with summer set of model parameters. Then, the output file produced from the second period is used as initial condition file for the third simulation period 3 with winter set of model parameters listed in Table 3.3. Finally, the output of the third simulation period is considered as initial condition for the last simulation period 4 with summer set of model parameters.

6.1.2 Water Quality Numerical Modeling Approach

Water quality data available for ecological modeling is also limited to one year similar to the hydrodynamic data. The difference here is that the water quality model “EUTROP” is run for several future years utilizing one-year data set only; where the open boundary conditions for the successive years are recreated from the previous years.

The simulation process of the first year starts from the first of June and extend to 31st of May of the next year. Initial and boundary conditions of the water quality
model for the first year are illustrated in Figure 6.1. It is shown that the initial condition used in the first year is the observed data of June 2003. These data and August 2003 observed data are both used to create the boundary condition for the first period. This is accomplished by extrapolating each data set to approximate the boundary data in June and August. The two extrapolated sets are then utilized to produce linear time-dependent boundary condition over the period in question. The model is run considering summer condition, and the results for different compartments are obtained for August 2003. For each compartment, the average of the obtained result and the observed data is considered as initial conditions for the second simulation period. Moreover, this averaged file is used with October observed data set to create the boundary condition for the second simulation period. The process of creating such initial and boundary conditions continues similarly for the whole first year taking into consideration the proper set of model parameters, i.e. summer and winter.

In order to proceed with the simulation for the second and further extended years, the process of creating the boundary condition is different due to the absence of data for the next years. So, two different approaches are used to achieve this task.

**Approach 1: Boundary conditions based on the previous year results**

This approach is illustrated in Figure 6.2. For the simulation of the first period in the second year starting at the first of June 2004, the result files obtained from the last simulation of the first year (June 2004 results) are used as initial conditions and it is also used with the average results of August 2003 to create the boundary conditions for the first simulation period (June, 1st to July, 31st). For the second simulation period, the result file of the previous simulation is used as an initial condition and it is also used with results of October 2003 to create the boundary condition of the second period, and so on. In Figure 6.2, the boxes which have the same color indicate that they have the same data sets.

The reason for using such technique for creating boundary conditions for the second year periods is referring to the speculation that the effect of the first year condition vanishes gradually in the second year and almost disappears with extended periods. This approach is consistent with the initial condition assumption where its effect normally disappears after certain period of time. The disadvantage of such
technique is the new simulations are always restrained by the previous year results. The second approach is used to overcome this limitation.

**Approach 2: Constant Boundary Conditions**

This approach is simpler and straightforward as it tends to avoid the influence of the previous year conditions on the future simulations. Figure 6.3 illustrates the procedure of dealing with boundary conditions for further year simulations. As shown in the figure, the starting point is similar to the previous approach (Result June, 2004). This result set is used as an initial condition for the first period of simulation in the second year (June, 1st to July, 31st). Moreover, the same set is used to generate the boundary condition for that period, so the boundary conditions are considered constant over the simulation period. Then, the results of previous simulation is used as an initial condition for the next period and also used to create the boundary condition of the same period (Aug., 1st to Sep., 30th), and the process goes on for other periods of following years. In Figure 6.3, the boxes which have the same color indicate that they have the same data sets. The results of using such approaches are discussed in detail later in the current chapter.
Figure 6.1: Schematic diagram of initial and boundary conditions (I.C. and B.C respectively) utilized in the first year of the water quality modeling.
Figure 6.2: Schematic diagram of initial and boundary conditions (I.C, and B.C respectively) utilized in the second and further extended years of the water quality modeling based on the previous year results (Approach 1).

Figure 6.3: Schematic diagram of initial and boundary conditions (I.C, and B.C respectively) utilized in the second and further extended years of the water quality modeling based on constant B.C’s, (Approach 2).
6.2 Considered Modeling Scenarios

In order to model environmental and/or ecological component for long term changes, the future development of such component has to be taken into account. Assessment process for future prediction has to investigate the component situation in the current conditions and to study how it may respond to such conditions over long time period.

As such three scenarios are considered to investigate the temperature and salinity effects on Ruwais water quality in general and on Sir Bani Yas Island in particular. The first scenario (Q-Base) examines the long term effects of the current discharging situations from the RIC on the water quality state of the Ruwais coast. This scenario takes into account the amount of discharges from all the RIC facilities which dispose their effluent at the coastal water of Ruwais given as before in Table 5.2. The second scenario (20Q-Desal.) investigates the expansion of the desalination plant alone with all the other facilities remain unchanged. And the third scenario (20Q-All) explores the expansion of both the desalination plant as well as the other facilities together in order to investigate their long term effects on the ecology of the area.

Due to rapid accelerated development rate of the UAE coast as well as the oil related activities, a large expansion factor is considered for the desalination plant and the other facilities located in the Ruwais area. For both hydrodynamic and water quality modeling, an enhancement by a factor of 20 is taken for all the effluent amounts of different facilities including the desalination plant. Table 6.2 lists the effluents loads for the three considered sections.
6.3 Temperature-Salinity Simulation

In order to investigate the long term effects of salinity and temperature for the present and future expansion of the RIC facilities on the Ruwais ecosystem; hydrodynamic modeling for the Ruwais coastal water is run for a full year over the four successive time periods proposed earlier. The simulation is conducted for the three different scenarios discussed in the previous section (Q-Base, 20Q-Desal., and 20Q-All).

Effluent flows, temperature, and salinity values for both summer and winter conditions for the three different scenarios are shown in Table 6.2. The salinity and the temperature values for each outfall are calculated using a weighted average method as follows:

\[
T = \frac{\sum_{i=1}^{n} (Q_i \cdot T_i)}{\sum_{i=1}^{n} Q_i}, \quad (i = 1, 2, 3, \ldots, n) \quad (6.1)
\]

\[
S = \frac{\sum_{i=1}^{n} (Q_i \cdot S_i)}{\sum_{i=1}^{n} Q_i}, \quad (i = 1, 2, 3, \ldots, n) \quad (6.2)
\]

Where \(Q_i\) (m\(^3\)/day) is the flow rate of the effluent source and \(T_i\) (°C), \(S_i\) (ppt) are the temperature and salinity values for the effluent source, respectively.

In the current section, the salinity and temperature for both summer and winter seasons are spatially and temporally investigated in the modeled area for different scenarios. The same selected observation points; S1, S2, and S3 used in chapter 3 (Figure 3.8) are used here too.

The figures hereinafter show the temperature and salinity for the surface layer. As mentioned before the water column in the modeled area is homogeneous, so the other layers have the same spatial and temporal distributions of as surface layer.
Table 6.2: Discharge loads scenarios and some of their physical properties in summer and winter seasons

<table>
<thead>
<tr>
<th>Utility</th>
<th>Q (m³·day⁻¹)</th>
<th>$T_{\text{Summer}}$ (°C)</th>
<th>$T_{\text{Winter}}$ (°C)</th>
<th>Salinity (ppt)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scenario 1 (Q-Base): Base conditions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outfall 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil Refinery (TAKREER)</td>
<td>243600</td>
<td>30.0</td>
<td>23.0</td>
<td>46.0</td>
</tr>
<tr>
<td>Gas Production Plant (GAZCO)</td>
<td>600000</td>
<td>45.0</td>
<td>35.0</td>
<td>46.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>843600</td>
<td>40.7</td>
<td>31.5</td>
<td>46.0</td>
</tr>
<tr>
<td>Outfall 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Desalination and Power Plant</td>
<td>192000</td>
<td>45.0</td>
<td>40.0</td>
<td>70.0</td>
</tr>
<tr>
<td>Fertilization Factory</td>
<td>120000</td>
<td>40.0</td>
<td>35.0</td>
<td>46.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>312000</td>
<td>43.1</td>
<td>38.1</td>
<td>60.8</td>
</tr>
<tr>
<td>Outfall 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petrochemical Factory (Borooj)</td>
<td>840000</td>
<td>45.0</td>
<td>35.0</td>
<td>50.0</td>
</tr>
</tbody>
</table>

**Scenario 2 (20Q-Desal.): Expansion for desalination plant only**

<table>
<thead>
<tr>
<th>Utility</th>
<th>Q (m³·day⁻¹)</th>
<th>$T_{\text{Summer}}$ (°C)</th>
<th>$T_{\text{Winter}}$ (°C)</th>
<th>Salinity (ppt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outfall 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil Refinery (TAKREER)</td>
<td>243600</td>
<td>30.0</td>
<td>23.0</td>
<td>46.0</td>
</tr>
<tr>
<td>Gas Production Plant (GAZCO)</td>
<td>600000</td>
<td>45.0</td>
<td>35.0</td>
<td>46.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>843600</td>
<td>40.7</td>
<td>31.5</td>
<td>46.0</td>
</tr>
<tr>
<td>Outfall 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Desalination and Power Plant</td>
<td>3840000</td>
<td>45.0</td>
<td>40.0</td>
<td>70.0</td>
</tr>
<tr>
<td>Fertilization Factory</td>
<td>120000</td>
<td>40.0</td>
<td>35.0</td>
<td>46.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3960000</td>
<td>44.8</td>
<td>39.8</td>
<td>69.3</td>
</tr>
</tbody>
</table>

**Scenario 3 (20Q-All): Expansion for all facilities including the desalination plant**

<table>
<thead>
<tr>
<th>Utility</th>
<th>Q (m³·day⁻¹)</th>
<th>$T_{\text{Summer}}$ (°C)</th>
<th>$T_{\text{Winter}}$ (°C)</th>
<th>Salinity (ppt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outfall 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil Refinery (TAKREER)</td>
<td>4872000</td>
<td>30.0</td>
<td>23.0</td>
<td>46.0</td>
</tr>
<tr>
<td>Gas Production Plant (GAZCO)</td>
<td>1200000</td>
<td>45.0</td>
<td>35.0</td>
<td>46.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>16872000</td>
<td>40.7</td>
<td>31.5</td>
<td>46.0</td>
</tr>
<tr>
<td>Outfall 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Desalination and Power Plant</td>
<td>3840000</td>
<td>45.0</td>
<td>40.0</td>
<td>70.0</td>
</tr>
<tr>
<td>Fertilization Factory</td>
<td>2400000</td>
<td>40.0</td>
<td>35.0</td>
<td>46.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>6240000</td>
<td>43.1</td>
<td>38.1</td>
<td>60.8</td>
</tr>
<tr>
<td>Outfall 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petrochemical Factory (Borooj)</td>
<td>16800000</td>
<td>45.0</td>
<td>35.0</td>
<td>50.0</td>
</tr>
</tbody>
</table>

6.3.1 Temperature Simulation

Figure 6.4 shows a comparison of the temperature temporal variation at the three observation points (St.1, St.2, and St.3) for the three different scenarios. The two-months period (June, 1st to July, 31st) is selected to display the summer results, and the two-months (Oct., 1st to Nov., 30th) is selected for winter results.

It is quite noticeable that a tangible effect of the disposed warm water from the desalination plant and other facilities is taking place in the vicinity of the discharging
zone. These discharges increase the water temperature in the discharging area represented by Station 1. The temperature at that station are 33.78 °C, 34.16 °C and 36.07 °C for the Q-Base, 20Q-Desal., and 20Q-ALL scenarios, respectively (Table 6.3). This indicates that there is around 0.38 °C average temperature increment in case of expanding the desalination plant only (20Q-Desal.) and is around 2.29 °C average temperature increment in case of expanding all facilities twenty times (20Q-All) in summer, and about 0.46 °C, 3.18 °C temperature increase in winter, respectively. This indicates that the desalination expansion by itself (20Q-Desal.) does not greatly affect the coastal temperature, whereas the expansion of all facilities (20Q-All) causes a pronounced increase in the coastal temperature due to the high temperature effluent released from the other facilities especially from Borooj outfall; where the quantity of the disposed effluents from that outfall is about 4 times higher than the effluents of the desalination plant itself. Moreover, the water temperature of this effluent is higher than the desalination plant effluent by around 1.9 °C (Table 3.2), which mainly causes high jump of the coastal water temperature in scenario 3.

Station 2 is located in the middle of the modeling area, around 10 km away from the discharging zone. As shown in Figure 6.4, there is a light temperature increase due to expansion of the desalination plant (20Q-Desal.) and the other facilities (20Q-All) relative to the base condition (Q-Base) as shown in Table 6.3. This is around 0.02 °C, 0.31 °C in summer and 0.07 °C, 0.71 °C in winter, respectively. This temperature variation is considered low with respect to the daily or seasonally temperature variation, so such expansions have limited influences on the coastal water temperature and their influences constrained to some kilometers around the outfalls (< 10 km).

At station 3, near Sir Bani Yas Island, it is clear from Figure 6.4 that there are no temperature effects due to discharging from the RIC facilities on the coastal water of the island in all scenarios. As mentioned earlier, this is due to the large distance separating the island from the discharging zone (around 20 km). Over that distance, currents, tides, and water exchanging through the model boundaries contribute effectively to vanish the thermal effects of such effluents over long distances like the Bani Yas Island.

Incremental increases of temperature for the three scenarios at the three stations are little higher than the case of summer with a maximum of 3.18 °C for the 20Q-All scenario at station 1.
Spatial distribution of the temperature due to the different scenarios in both summer and winter are shown in the Figures from 6.5 to 6.10. Generally, the temperature increases toward the shoreline and decreases toward the model boundaries. The general trend of temperature increment in south is referred to the shoal of such areas which is influenced directly by the land temperature. On the other hand, the zone near the RIC outfalls is highly influenced by the warm discharges from the different facilities. The effect of such discharges decreases toward the model boundaries (Gulf ward) and disappears after several kilometers (<10 km) as discussed above.

Table 6.3: Average temperature at the observation stations in mid of summer and winter

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Q-Base Value</th>
<th>20Q- Desal Value</th>
<th>20Q- All Value</th>
<th>Summer Average Temperature (°C) Δ</th>
<th>Winter Average Temperature (°C) Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station 1</td>
<td>33.78</td>
<td>34.16</td>
<td>36.07</td>
<td>2.29</td>
<td>22.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>21.66</td>
</tr>
<tr>
<td>Station 2</td>
<td>33.42</td>
<td>33.44</td>
<td>33.73</td>
<td>0.31</td>
<td>21.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2) - (1)</td>
<td>(3) - (1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Station 3</td>
<td>33.25</td>
<td>33.25</td>
<td>33.30</td>
<td>0.05</td>
<td>21.56</td>
</tr>
</tbody>
</table>

Table 6.3: Average temperature at the observation stations in mid of summer and winter
Figure 6.4: Temperature time series at the three selected observation stations (St.1, St.2, and St.3) in summer and winter seasons.
Figure 6.5: Surface temperature spatial distribution at summer (July 31st) for base condition (Q).

Figure 6.6: Surface temperature spatial distribution at winter (Nov. 30th) for base condition (Q).
Figure 6.7: Surface temperature spatial distribution at summer (July 31st) for expansion of desalination plant only (20Q-Desal.).

Figure 6.8: Surface temperature spatial distribution at winter (Nov., 30th) for expansion of desalination plant only (20Q-Desal.).
Figure 6.9: Surface temperature spatial distribution at summer (July 31st) for expansion of all facilities (20Q-All).

Figure 6.10: Surface temperature spatial distribution at winter (Nov. 30th) for expansion of all facilities (20Q-All).
6.3.2 Salinity Simulation

In the present study, it is remarkable that with the desalination plant effluent has the highest salinity concentration of the outfalls; it has almost the smallest volume of flow discharge. This note will be beneficial hereafter to interpret some phenomena taking place in the different scenarios.

Salinity temporal variations for the different scenarios are shown in Figure 6.11. It is clearly observed that the salinity concentration at station 1 is higher than station 2 and 3 in both summer and winter for all scenarios. Moreover, the incremental increase of average salinity at station 1 over the Q-Base scenario for 20Q-Desal. and 20Q-All scenarios are 1.53 ppt and 2.19 ppt in summer and 1.21 ppt and 2.56 ppt in winter, respectively (Table 6.4), which means that the salinity increase due to expansion of all facilities is tangible and is more tangible and referred to two reasons; the locations of the three stations that play the main rule to the generally increased levels of the southern part of the modeled area, where, as mentioned before that the high temperate of the southern part causes more evaporation that leads to higher salinity. The other reason is referred to as the influence of brine disposal from the different outfalls located at the south that contributes to increasing the salinity concentration.

At station 2, Figure 6.11 shows that the effect of brine disposal is insignificant in all scenarios, where the salinity difference between scenario 1 and scenario 2 does not exceed 1 ppt (Table 6.4) which is relatively small. The lower salinity concentration Gulf-ward is referring to the exposed mixing processes due to currents, tides and boundary exchanges that tend to reduce the brine disposal concentration.

At station 3 near Sir Bani Yas Island, the influence of the brine discharged from the different facilities of the RIC for all scenarios completely disappears due to the large separation (about 20 km).

It can be concluded that the effect of brine disposal from the desalination plant and other facilities as well has a tangible effect in case of expanding all the facilities (20Q-All) only at station 1 nearby the discharge area.
Figure 6.11: Salinity time series at the three selected observation stations of summer and winter seasons.
Table 6.4: Average salinity at the observation stations in mid of summer and winter

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Q-Base</th>
<th>20Q- Desal.</th>
<th>20Q- All</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1) Value</td>
<td>(2) Value</td>
<td>(2) – (1)</td>
</tr>
<tr>
<td>Station 1</td>
<td>45.83</td>
<td>47.36</td>
<td>1.53</td>
</tr>
<tr>
<td>Station 2</td>
<td>45.07</td>
<td>45.26</td>
<td>0.19</td>
</tr>
<tr>
<td>Station 3</td>
<td>44.73</td>
<td>44.76</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Summar Average Salinity (ppt)</td>
<td></td>
</tr>
<tr>
<td>Station 1</td>
<td>44.86</td>
<td>46.07</td>
<td>1.21</td>
</tr>
<tr>
<td>Station 2</td>
<td>44.69</td>
<td>45.09</td>
<td>0.4</td>
</tr>
<tr>
<td>Station 3</td>
<td>44.52</td>
<td>44.57</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Spatial distribution of salinity in both summer and winter for all scenarios are shown in the Figures 6.12 to 6.17. Generally, the distribution trend for salinity is similar to the temperature one, where the salinity concentration is higher in the south near the discharging zone and reduces toward the model boundaries due to reasons mentioned earlier.
Figure 6.12: Surface salinity spatial distribution at summer (July.31st) for base condition (Q).

Figure 6.13: Surface salinity spatial distribution at winter (Nov..30th) for base condition (Q).
Figure 6.14: Surface salinity spatial distribution at summer (July 31st) for expansion of desalination plant only (20Q-Desal.).

Figure 6.15: Surface salinity spatial distribution at winter (Nov 30th) for expansion of desalination plant only (20Q-Desal.).
Figure 6.16: Surface salinity spatial distribution at summer (July 31\textsuperscript{st}) for expansion of all facilities (20Q-All).

Figure 6.17: Surface salinity spatial distribution at summer (July 31\textsuperscript{st}) for expansion of all facilities (20Q-All).
6.4 Ecological Long-Term Simulation

Based on the biochemical processes of the ecological model, most of the biological processes have an exponential response to temperature values, and no response for the salinity concentration. Moreover, the limited thermal influence of expanding the desalination plant only (Scenario 2, 20Q-Desal.) on the coastal water temperature does not qualify to test this scenario in the ecological assessment. In addition to that, the expansion of the desalination plant is directly proportional to the expansion of other facilities, as the Ruwais plant mostly cater to the RIC industrial demands, so its expansion will be a natural result of the expansion of the other facilities. Hence, the second scenario (20Q-Desal.) is discarded in the water quality simulations in the next section, and the analysis of ecological impacts is limited to the first and third scenarios (Q-Base, 20Q-All) only.

Two different cases are examined under the aforementioned two scenarios; zero plankton in the effluent loads and non-zero plankton in the effluent loads to represent the uncontrolled chlorination practical at the intakes yield erratic plankton loads ranging from zero to ambient levels from time to another.

6.4.1 Zero Plankton in Effluent Loads

Two sets of results are obtained using approach 1 and approach 2 boundary conditions of the further years. This situation resembles the case of complete death of planktons due to intense chlorination practiced at all intakes.

Q-Base Scenario Using Approach 1

Time series of the major ten compartments are obtained over three years at the same three stations considered before (Figure 6.18). For each year, 4 values are plotted representing the average compartment value in the last day of the simulation period. Whereas the first value for all the compartments represents the field observation measurement. It should be noticed that the origin (0) of these plots represents June 2003 and 12 represents June 2004 and so on. The long term variation of each compartment is further discussed separately and in more details below.
Phytoplankton Biomass

As shown in Figure 6.18, phytoplankton biomass concentration fluctuates temporally through the years in a cyclic manner keeping identical values over the corresponding periods of each year for all the observation stations. It attains maximum values in August, after which it decreases slightly in October then it dramatically decreases to the lowest concentration value in February. The main reason for such behavior is the temperature variation through the years as shown in Figure 6.19. It is clearly noticed that the phytoplankton trend in all stations follow the temperature variation trend that is considered as the dominant factor of phytoplankton fluctuation.

Other factor may have an influence in such trend is the light intensity which varies from one season to another. Light intensity value is much higher in the summer than the winter due to the clear sky and larger radiation on the water. This increases the photosynthesis process hence increases the phytoplankton biomass.

Spatially, phytoplankton varies in a tangible way, where its concentration at station 1 is higher than the other stations, whereas the concentration at station 3 is higher than station 2. Due to slight difference in the temperature among the three stations all over the year, temperature effect can be discarded as a variation factor. According to Figure 6.18, the nutrients (PO$_4$, NH$_4$, NO$_2$, and NO$_3$) are seen to dominate in such spatial distribution of the phytoplankton. In this scenario, the effect of NO$_2$ can be neglected due to its low concentration (less than 0.8 μmol/L) while the inhabitation factor ($\Psi$) for the nitrogen nutrients is taken as 1.462 μmol/L, (Table 5.3). NH$_4$ and NO$_3$ trends follow the phytoplankton trends, increase in summer and decrease in winter, so it is clear that there are abundant of such these nutrients in the coastal water, hence PO$_4$ can be considered as a limiting nutrient in the modeled region. This can be noticed by the inverse relation between the phytoplankton growth and PO$_4$ concentration.
Figure 6.18: Compartment values for the base scenario (Q-Base) using approach 1 to create the boundary conditions and zero plankton in effluent loads. The results are at the three observation stations (St.1, St.2, and St.3).
Temperature Vs. Time

Figure 6.19: The simulated temperature variation through the year for the Q-Base scenario at the three observation stations

Zooplankton Biomass

Figure 6.18 shows that zooplankton biomass concentration oscillates according to temperature variation as same as phytoplankton. It is noticeable that there is a declining trend for the zooplankton over the years, but the value reaches ultimately to about 0.6 mgC/m³ after which the fluctuation is minimal. It is worth mentioning that the peaks of phytoplankton and zooplankton over the years are consistent. This may be ecologically abnormal; but since we do not have any information regarding the zooplankton grazing efficiency, we may attribute such result to either erratic measurements or it could be a specific phenomenon that may need a special biological survey.

Particulate Organic Matter (POC)

POC has a decreasing trend over the years (Fig. 6.18). This may associate with the decreasing trend of zooplankton. The dramatic increase during June may relate to the field measurements which show higher POC concentrations in June 2003. That was as mentioned earlier due to the strong winds which occurred during the sampling time causing turbulence for the water column.
**Dissolved Organic Carbon (DOC)**

As shown in Figure 6.18, DOC fluctuates periodically yearly. The lowest concentrations of DOC occur in summer season at June and August, whereas it reaches its maximum value around 3500 mgC/m³ in October, then it continues decreasing up to June through the winter season. As explained in chapter 4, the maximum value of DOC in October is related to the rapture of oil pipeline that took place during the sampling period, which caused unreal peak for the DOC concentration.

**Phosphate (PO₄)**

As shown in Figure 6.18, PO₄ has a sinusoidal trend with constant amplitude over the years. It fluctuates between 0.5 to 3 μmol P/L. It has an inverse relation with the phytoplankton biomass concentration, where it drops to the lowest values in the summer when the phytoplankton reaches its maximum and rises to its maximum values at February when phytoplankton reaches its minimum concentration. This indicates that the phosphate may be controlling the phytoplankton biomass.

**Ammonium (NH₄)**

Ammonium variation is constant over the years (Fig. 6.18); that is almost similar to the phytoplankton trend. This indicates that the ammonium is not affected by the phytoplankton biomass concentration, and can’t be regarded as a limiting nutrient for the phytoplankton growth.

**Nitrite (NO₂)**

As shown in Figure 6.18, nitrite has a constant trend over the years. Moreover, it fluctuates in a narrow range (i.e. less than 0.1 μmol /L). Its amounts in the Ruwais coastal water are very limited, so in the current scenario, it can not be classified as a limiting nutrient for the phytoplankton growth, because their values in all stations are less than the inhibition factor for the nitrogen nutrient uptake discussed earlier (considered as 1.462 μmol /L).
Nitrate (NO₃)
Nitrate has a constant trend over the years as shown in Figure 6.18 where it fluctuates between 65 to 75 µmol/L.

Dissolved Oxygen (DO)
Dissolved oxygen concentration has a typical cyclic trend over the simulated years (Fig. 6.18). It decreases in summer and increases in winter. The increase in winter is mostly due to the high currents taking place that increase the mixing process in the water column and hence increase the aeration. The other reason is related to higher saturation capacity of oxygen in the water during the winter of low temperature.

Chemical Oxygen Demand (COD)
As shown in Figure 6.18, COD has a symmetric trend over the years at all stations. In the current study, this trend is mostly corresponding to DOC concentrations. The high level of COD due to the oil spill incident increased the consumption of dissolved oxygen, hence the DO levels declined in October severely and COD increased dramatically.

20Q-All Scenario Using Approach 1
This scenario considers expansions of all the RIC facilities by 20 times. Figure 6.20 shows the results of simulation based on approach 1 considered to handle the boundary conditions of the expansion condition is addressed.

Phytoplankton Biomass
As shown in Figure 6.20, the phytoplankton trend does not change from the Q-Base scenario. The main difference is limited to the drop of phytoplankton biomass concentration at station 1 by 1 mgC/m³. The reason for such drop refers to the excessive effluents from the RIC facilities having zero plankton loads (phytoplankton and zooplankton) that tends to dilute the ambient phytoplankton concentration originally exists in the coastal water.
Zooplankton Biomass

As shown in Figure 6.20, the zooplankton trend at the expansion scenario does not change. The only change is limited again to drop of the zooplankton biomass concentration at station 1. This decreasing refers to the same reason mentioned with the phytoplankton case.

Particulate Organic Matter (POC)

POC does not suffer major changes due to expansion either in trend or values.

Dissolved Organic Carbon (DOC)

DOC has the same trend over the years, whereas, its value at station 1 is almost doubled due to extensive discharging effluents to reach up to 6000 mgC/m³. It is clear that there is no any effect due to these discharging at either station 2 or station 3. This indicates that the effects of these effluents are limited to the discharging area.

Phosphate (PO₄)

The results show that PO₄ trend is not affected by the expansion of the facilities. In both stations 2 and 3, the PO₄ values are around their original values. Whereas, PO₄ values in summer periods rise to about 0.5 μmol/L. This increase is apparently due to the drop of phytoplankton biomass in these periods, so the consumption of PO₄ is reduced and its concentration is increased.

Ammonium (NH₄)

Ammonium trend remains unchanged over the years due to expansion. As the other compartments, its concentration at station 2 and station 3 does not suffer any change in the concentration values in either the summer or winter. At station 1, its concentration value is almost doubled to reach up to 5 μmol/L. This may be due to the increase of the nutrients loads because of the expansion.
Figure 6.20: Compartment values for the expansion scenario (20Q-All) using approach 1 to create the boundary conditions and zero plankton in effluent loads. The results are at the three observation stations (St.1, St.2, and St.3).
**Nitrite (NO$_2$)**

Nitrite trend does not change over the years too. However, station 1 experiences dramatic increase, where the concentration value increases up to 10 times to reach 7 μmol /L. This is related to extensive loads of nutrients from the different effluents that enrich the discharging area with nitrogen compounds, so NO$_2$ is largely influenced by such loads.

**Nitrate (NO$_3$)**

Nitrate concentration has a slight increase trend over the modeled years. Its concentration at station 1 increases to almost 5 μmol /L.

**Dissolved Oxygen (DO)**

DO trend remains the same as the base scenario over the modeled years. Moreover, the concentration values at station 2 and station 3 do not change but drops to 1.5 mg/L at station 1. This reduction is attributed to the large increasing of DOC that tends to more consumption of DO values associated with the bacterial decomposition activities.

**Chemical Oxygen Demand (COD)**

COD trend does not change. Also, at station 2 and 3 its concentration values remain unchange. Whereas at station 1 its value is increased to 13 mg/L. This large increment and other fluctuations are synchronized with the DOC temporal change explained earlier.
Figure 6.21: Compartment values for the base scenario (Q-Base) using approach 2 to create the boundary conditions and zero plankton in effluent loads. The results are at the three observation stations (St.1, St.2, and St.3).
O-Base Scenario Using Approach 2

The above time series results show repetitive trends for all the compartments over the modeled years. These trends can be attributed to use approach 1 that the previous year results to create the boundary conditions for the second and the third year as discussed in section 6.1.2. This process may give a misleading trend of the different compartment concentration values. So, approach that considers constant boundary conditions over the simulated period is investigated with the same previous simulations. The result values of the last simulated period are now used as initial and boundary condition of the next period. This allows avoiding the effect of the previous-year results on the next years’ results, so the difference will start to appear after the first year simulation, whereas the results for the first year in both approaches 1 and 2 are identical. The results in this case are illustrated in Figure 6.21.

Comparison between approach 1 results (Fig. 6.18) and approach 2 results (Fig. 6.21) reveals that most of the nutrients have a declining trends and flattening-out for most of the compartments after the first year. This is with the exception of phytoplankton and dissolved oxygen that are both influenced by the temperature variation and keep displaying cyclic trends. Generally, these flatten-out trends are corresponding to constant boundary conditions used in the present case.

20Q-All Scenario Using Approach 2

Figure 6.22 shows the produced model values for the different compartments over 4-year simulation period, using approach 2 with an expansion scenario.

Comparing Figure 6.22 and 6.20 shows that phytoplankton, zooplankton, NO₂, and DO do not experience any change either in trend or values. Whereas, the rest of compartments are flattening-out after the second year.
Figure 6.22: Compartment values for the expansion scenario (20-All) using approach 2 to create the boundary conditions and zero plankton in effluent loads. The results are at the three observation stations (St.1, St.2, and St.3).
6.4.2 Non-Zero Plankton in Effluent Loads

The results are obtained using both approach 1 and 2 in handling the boundary conditions of further years. This situation resembles the partial or null effect of chlorination on plankton in effluents. This has been resolved by utilizing a feature in the EUTROP model that allows mirroring the plankton as well as other nutrients of the nearby ambient water into the introduced effluent.

Q-Base Scenario Using Approach 1

In order to investigate the new setup, the model is run over a period of three years. Figure 6.23 shows the model results. Figure 6.23 and Figure 6.18 are compared. It is noticed that there is no difference between the two figures for all the compartments including the plankton ones. This can be attributed to the low plankton biomass reported in the ambient water in association with small effluent discharges that have overall small impact on the water quality.

20Q-All Scenario Using Approach 1

The model is also run over the period of 3 years and the results are plotted in Figure 6.24. Comparison between Figure 6.24 and Figure 6.20 shows that all the compartments have the same trends and values except phytoplankton and zooplankton, as they more increase to levels close to their original values corresponding to the Q-Base scenario. This indicates that the preserved levels of biological loads in the effluent loads does the dilution action repeated in case of zero plankton and therefore the drop of phytoplankton and zooplankton reported before does no longer happen in this case.

Q-Base Scenario Using Approach 2

In the base scenario, all the compartments remain at their trends and levels for all the years, as shown in Figure 6.25. They are exactly similar to Figure 6.21. Phytoplankton and zooplankton do not change, because the concentration of the effluent is equivalent to the concentration of the discharging area, so the final concentration of the area does not change.
20Q-All Scenario Using Approach 2

Figure 6.26 shows the results of the compartments for the expansion conditions. Comparing Figure 6.26 and Figure 6.22 shows that all the compartments have similar trends and values except the phytoplankton and zooplankton at station 1. Where, their values in Figure 6.22 are lower than their values in Figure 6.26. The phytoplankton and zooplankton concentrations in the current approach resumes to their concentrations in the base condition. Again the non zero levels of phytoplankton and zooplankton in the effluent loads explain that as before.
Figure 6.23: Compartment values for the base scenario (Q-Base) using approach 1 to create the boundary conditions and non-zero plankton in effluent loads. The results are at the three observation stations (St.1, St.2, and St.3).
Figure 6.23: Compartment values for the base scenario (Q-Base) using approach 1 to create the boundary conditions and non-zero plankton in effluent loads. The results are at the three observation stations (St.1, St.2, and St.3).
Figure 6.24: Compartment values for the expansion scenario (20Q-All) using approach 1 to create the boundary conditions and non-zero plankton in effluent loads. The results are at the three observation stations (St.1, St.2, and St.3).
Figure 6.25: Compartment values for the base scenario (Q-Base) using approach 2 to create the boundary conditions and non-zero plankton in effluent loads. The results are at the three observation stations (St.1, St.2, and St.3).
Figure 6.26: Compartment values for the expansion scenario (20-All) using approach 2 to create the boundary conditions and non-zero plankton in effluent loads. The results are at the three observation stations (St.1, St.2, and St.3).
Expanding and developing of communities in the UAE increased the pressure on the coastal marine environment due to major industrial zones constructed along the coastal line. The Ruwais Industrial Complex (RIC) is one of these industrial zones. It has the largest refinery plant in the country. It also includes many facilities attached with the refinery plant, among which a desalination plant that caters to domestic, industrial, and agricultural fresh water demands. Other coastal industrial facilities present in the complex include a gas production plant, a power plant, a fertilizer factory and a petrochemical factory. All of these facilities discharge their effluent in the coastal water after a reasonable level of treatment. One effluent, however, has a high level of nitrogenous compounds which increase the nutrient budget of the coastal waters, and may potentially affect the water quality of the coast in a negative way. Moreover, the desalination plant discharges large quantities of highly saline and warm water that can also increase the salinity and temperature of the coastal waters.

In order to assess the impacts of such effluents on the coastal waters, a coupled physical-biochemical model is employed to simulate the Ruwais coastal water. The hydrodynamic model is first run for the entire basin of the Arabian Gulf as a regional model that has an open boundary at the Strait of Hormuz. The regional model is developed based on 5 km grid interval, with 6 layers in the vertical dimension. Four main rivers are taken in consideration, and various other model parameters are gathered from available literature. The model simulations are made for summer and winter conditions. Results have been verified against the field measurements of the water level in the southern part. The water temperature in that part is found to fluctuate from 31 °C to 32.5 °C in the summer and from 20 °C to 23 °C in the winter; the salinity from 39 ppt to 46 ppt in the summer and from 41 ppt to 46 ppt in the winter.

The hydrodynamic conditions at the boundary of the target area are then nested from the simulated regional model. The local model of the RIC is run for the whole year taking into consideration the effluents discharging from different facilities existing in the area. It is found that the water dynamics near the shore line are close to stagnant conditions as the mean currents rarely exceed 3 cm/s. The salinity in the
summer varies from 44.5 to 46.3 ppt and decreases offshore, whereas in winter it varies from 43.0 to 45.3 ppt and also decreases offshore. On the other hand, it is found that the water temperature has a wide variation between the summer and winter, varying in the summer from 31.5 °C to 33.4 °C, and in the winter from 21 to 22 °C. The basin thus has about 12 °C difference between the summer and winter water temperature and about 1.25 ppt difference in the salinity.

In terms of ecological characterization, the Ruwais marine water has been classified as HNLC (high nutrients and low chlorophyll/carbon) due to availability of nutrients and lack of biological production in the lower trophic level. That has been attributed to harsh environment conditions such as high temperature and salinity, in addition to the possible damaging effect of major chlorine spiking practiced at all facilities' intakes that potentially kill the marine biota to prevent them from entering the desalination plant and other facilities. The high potential for pollution in the area due to the oil related activities and accidental spills may also affect the zooplankton biomass in an adverse way.

The water quality model parameters have been reasonably calibrated for summer and winter conditions based on the field observed date.

Three scenarios (Q-Base, 20Q-Desal., and 20Q-All) are considered to represent the present and future loading conditions and to investigate their effects on the temperature and salinity of the Ruwais water. It is concluded that the expansion of the desalination plant only has no tangible effect upon the temperature of the whole area while the salinity is found to moderately increase (about 1.2 ppt) within a distance of about 4 km from the desalination plant. Expanding all the facilities (20Q-All scenario) produced larger effects on the temperature and salinity as the influence extends up to 10 km offshore. The temperature in the vicinity of the outfall increases of about 2.29 °C in summer and 3.18 °C in winter from the base scenario condition, while the salinity increases with 2.19 ppt in summer and 2.56 ppt in winter.

Since the scenario of future expansion in the desalination plant (20Q-Desal.) reflects tangible effects of salinity only while the salinity effects is not considered by the EUTROP model in different biochemical reactions, this scenario has been excluded from the long term water quality analysis. Hence, the long term simulation is conducted only for two scenarios; Q-Base and 20Q-All. Two approaches are conducted under each scenario. These approaches handle the boundary conditions for future years other than the first year, in different methods. The first method utilizes
the previous years observed data and therefore produce linearly interpolated B.C. over the simulated period. The second approach eliminates the effect of the previous records by considering constant B.C. over the simulated period.

Long term simulation is done over 3 to 4 years. It is noticed that the phytoplankton and zooplankton biomass decreases during the expansion scenario at station 1 by about 25% and 43%, respectively. This has been attributed to dilution effect that takes place in connection with disposing zero biological loads from the different facilities in the area. Zero loads of plankton represent the extreme condition of complete death of plankton due to the practice of disinfection at the influent waters. Taking these biological loads into consideration, it is noticed that the previous drop of phytoplankton and zooplankton biomasses is no longer reproduced in this case. Increasing trends are noticed for DOC, PO₄, NH₄, NO₂, NO₃, and COD due to expanding conditions; whereas, the other compartments (POC, DO) almost remain the same as in the original ranges.

In summary, extreme amplification of effluents discharged from other coastal facilities in the RIC only causes a moderate increase in the modeled temperature and salinity in the discharging area within a distance of 10 km from the shoreline. The water quality of the entire area and in particular near Sir Bani Yas Island does not experience major changes for the investigated expansion scenarios.
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ملخص الأطروحة

يعتبر الماء أساس الحياة على كوكب الأرض حيث قال الله تعالى "وجعلنا من الماء كل شيء" في آياته "يثوبون" (الأبيات - آية 30). لذلك يعد الحفاظ على موارد المياه من الأولويات التي لا بد للإنسان أن يوليها جل اهتمامه. وحذرت النيروجينية أن منطقة الخليج العربي تعد من المناطق الجافة التي يندر وجود الأمطار بها، كما أن معظم بلدان الخليج تعتبر قارة من حيث موارد المياه الطبيعية العذبة.

تعتبر دولة الإمارات العربية المتحدة من الدول التي تتعالى من شح الموارد المائية، حيث أنها تمتلك قدرًا ضعيفًا من المياه الجوفية التي لا تكفي لتغطية الطلب على المياه العربية، لذا فإن ضرورة المحافظة على موارد المياه الطبيعية العذبة تمثل في هذه الدولة أولوية كبيرة. لذلك، مهمات التحليل لدلت على جودة المياه العذبة التي تحتاجها في شتى مراقبة الحياة، فنجد أن مراكز التحليل تنتشر على طول الساحل المحلي على الخليج العربي للدولة.

تعني هذه الأطروحة بدراسة تأثير مخلفات محطة التحلية المقدمة على شاطئ منطقة الروض - غربي العاصمة أبو ظبي - على جودة ونوعية المياه البحرية في تلك المنطقة، حيث تميز مياه المنصرفة من محطة التحلية بارتفاع في درجة الحرارة وكذلك نسبة الملوحة. وحذرت بالذكر أن هناك عدة مشاكل أخرى مقدمة أيضًا في منطقة الروض ملحية ببعضها تكرر البتولا هناك. حيث ينتج عن هذه المشكلات بعض المشكلات التي تصرف أيضا إلى الخليج، وتتميز بوجود مركبات نتاجية وفوسفورية والتي تجعل العناصر الغذائية الأولية للكائنات البحرية النقيفة.

وقد تمت دراسة الأثر المترتبة على تصرف المياه العادمة من محطة التحلية والمناطق الأخرى، تم الاستعانة ببيانات متعلقة بنوعية المياه في منطقة الروض الساحلية لاستخدام مدلين اثنين لدراسة حركة الأمواج والرياح والجزر بالملاحة بالإضافة إلى تغطية درجات الحرارة والملوحة الناتجة عن المخلفات المنصرفة، والدورة الثانية EUTROP على جودة المياه في المنطقة. أيضاً جمع البتولا عدة متغيرات كيميائية وبيولوجية. وقد تم استخدام كلا البرامجين لدراسة عدة مصادر من مختلفهما في الوضع الحالي لهذه المخلفات المنصرفة وذلك بعد المسافة المستقلة في حال توضيع مثل هذه المشكلات وبالتالي زيادة كمية المياه المنصرفة إلى الخليج.

وقد تمت من خلال استخدام النمذجة الحسابية أن المخلفات المنصرفة من محطة التحلية والمياه الأخرى ليس لها أي تأثير جانبي واضحة للمعالج في الوقت الراهن سوى ارتفاع طفيف في ملوحة ودرجة حرارة المياه بالقرب من نقاط التصرف حيث تتشكل هذه الظاهرة تحتوي ويشمل هذه التحذيرات على بعد 4 كم من منطقة التصرف، بينما قد تأثير الارتفاع في ملوحة وحرارة مياه الخليج نتيجة التصرف هذه المياه في حال توضيع النفسات الممتازة في المستقبل قد ينتج إلى حوالي 10 كم وبالتالي فإنه لن يشكل ضرراً حقيقياً على الحياة البحرية في المنطقة.
تقييم تأثير مخلفات عمليات التحلية على نوعية المياه البحرية بمنطقة الرويس- تطبيق نمذجة حسابية

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أطروحة مقدمة من الطالب
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بكالوريوس هندسة مدنية
جامعة بيروت (2001)

استكمالاً لمتطلبات الحصول على درجة الماجستير في علوم موارد المياه

يناير 2005