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Abstract: Al Khumra Sewage Treatment Station is the most important of all the wastewater treatment plants in Jeddah, eastern Red Sea. Prior the year 2000, the semi treated sewage was disposed at the Southern Corniche area, south of the city. The sewage outlet was situated at about 1 meter above the sea surface and sewage was dumped into a semi closed lagoon to limit its dispersion southwards by the prevailing northwesterly wind. During the year 2000, the effluent was transferred about 3 km south of the old one. The new effluent is placed just on the edge of the fringing reef, ~500 m from the shore line, at about 20 m below the surface. In order to measure the impact of the new disposal conditions on the Southern Corniche area, the physical and chemical properties of the surface water (salinity, dissolved oxygen, dissolved nutrients, SPM, Chl-α, DOC and POC) were measured during April 2003 and January 2004 and compared to the results of a previous study carried out in 1999. The results of the present study indicate that the area has suffered a measurable modification. While concentrations of nutrients did not suffer great modifications, the relative distribution of inorganic nitrogen constituents and the phosphorus /nitrogen ratio have suffered dramatic modifications. The distribution of all the parameters indicated that the new effluent is a point source for all the analyzed parameters. The transfer of the effluent to the open coastal area, while facilitating the dilution of the discharged sewage, is suspected to enhance the spread of the different contaminants over larger areas and may represent a potential threat to the marine life and the health of the humans.

Key words: Nutrients, DOC, POC, SPM, Red Sea, Jeddah, Sewage, pollution, coastal waters

INTRODUCTION

Globally 2.2 billion people or 39% of the world population live within 100 km from the coast. These estimates were based on 1995 population figures (http://earthtrends.wri.org). However, recent estimates indicate that the actual (end of year 2008), the world population exceeds 6.7 billion people, with 3.4 billion of inhabitants (~50%) living in coastal areas (www.worldbank.org). Coastal waters are subjected to a significantly increasing stress. The anthropogenically driven changes in the coastal area are intense essentially due to elevated population density and rapid rate of population growth. These water bodies receive different hazardous wastes which reach the environment with industrial, agricultural and municipal wastewater.

The eastern coast of the Red Sea is about 1930 km long; 90 % of which belongs to the Kingdom of Saudi Arabia (Couper, 1983, Edwards and Head, 1987). Since the beginning of the seventies, the Kingdom is seeing an unprecedented economic expansion that lead to a massive expansion of the urban areas of the Kingdom. The city of Jeddah is one of the biggest Red Sea coastal agglomerations. Jeddah has grown from a small seaport town of 30,000 inhabitants and occupying just over one square kilometer in 1947; its population in the beginning of the seventies reached about 300,000 inhabitants. At present, the area of the city is more than 1200 square kilometers and its population is about 3.4 millions, and is continuously expanding (www.jeddah.gov.sa).

The economic expansion of the city was accompanied by growing industrial activities. More than 450 factories are implemented in the industrial area lying at the southern part of the city. These factories cover a wide variety of industrial activities, the most important of which are refineries, petrochemicals, food processing, paper mill, canning, car repair and painting, tanning, chemical and pharmaceutical, soap and cleaning products.
As a trade centre, the city is connected to the other parts of the world through a highly developed maritime transport network and its Islamic port is one of the greatest ports on the Red Sea. The water balance in the Jeddah area that is the supply, use and removal of water has changed rapidly with the growth of the city. Over the last three decades, significant infrastructures have been established to provide residents throughout the city with dependable water supply. Today, however, the increased volume and mixed contents of the wastewater that must be disposed is greater than the environment’s natural ability to assimilate, whether treated or not (MEPA, 1995).

Sewage dumping into the coastal water is producing one of the major marine environmental problems. The City of Jeddah has a network (750 km long according to Mandoura, 1996) to collect municipal wastewater. It covers between 10 to 20 percent of the city area. The network receives daily between 200 to 280 thousand cubic meter of municipal and industrial wastewater. These waters are treated in seven sewage treatment stations of varying importance, and one industrial waste treatment unit. However, due to rapid expansion of the city and its population the treatment capacity of the sewage treatment stations is largely insufficient and great part of the raw sewage is dumped into the coastal area creating dramatic environmental situations as has been shown in the Southern Corniche area (El Sayed and Niaz, 1999), Al- Arbaeen Lagoon (El-Rayis, 1990; Basaham, 1998) and Reayat Al-Shabab Lagoon (El Sayed, 2002a; Turki et al, 2002).

Municipal and industrial wastes carry a wide variety of chemicals, organic matter, nutrients, trace elements, petroleum hydrocarbons, polyaromatic hydrocarbons (PAH), chlorinated hydrocarbons. This list is continuously growing due to the introduction of new chemicals. An equivalent volume (~200,000 m3) of entirely raw sewage is transported and dumped in a huge sewage lake at the east of the city. This sewage, after contaminating the underground water, finds its way, by gravitation, to the coastal water.

Al Khumra Sewage Treatment Station is the most important amongst the wastewater treatment network in Jeddah. Its nominal treatment capacity is approximately 100,000 m3 day⁻¹. However, it is believed that the wastewater, that the station receives daily, is largely greater than the nominal capacity and is estimated to be 200,000-300,000 m³. It is evident that the effluent of the station dumps semi treated sewage that does not meet the environmental requirements. This has been revealed in a previous study (El Sayed and Niaz, 1999).

Prior the year 2000, the semi treated sewage was dump into the coastal water south of Jeddah, in the area known as Southern Corniche. The waste water outlet was placed on the shore about 1 m above sea surface. Sewage was dumped into a semi closed lagoon of about 2.3 km², artificially constituted by the addition of a sand barrier to prevent sewage dispersion southwards forced by the prevailing wind induced surface water current. Practically, this configuration created an additional decantation tank for the almost untreated sewage dumped into the area and could be considered as part of the treatment operation. Measurements undertaken in the lagoon and along the coastal area up to10 km south of the dumping site (El Sayed and Niaz, 1999, El Sayed, 2002b, El Sayed, 2002c) revealed that most of the solid charge of the effluent with its associated organic and metallic pollutants was retained in the lagoon; about half of the nutrients load was assimilated by the primary productivity. However, the dispersion of sewage out of the lagoon and up to the most southern limits of the area was detected by the presence of coprostanol, a fecal sterol indicator of sewage pollution. The study of El Sayed and Niaz, 1999 generated important information about the composition of the effluent, the behavior of its constituents in the receiving environment and their fate as well as the flux of phosphorus, nitrogen, organic matter and trace elements.

By the year 2000, a decision has been taken and the effluent was transferred about 3 km further south. The new effluent is about 500 m from the shore just on the edge of the fringing reef at about 10 m below the surface. The effluent is no more visible; the threat has however been increased for both the environment and the public health for the following reasons: 1) Direct dumping in seawater enhances a wider dispersion of the effluent and increases its impact on the environment; 2) Dumping in the vicinity of the fringing reef represents a real and great threat to the reef ecosystem; 3) Increasing threat for all the coastal habitats such as mangrove and benthic communities; 4) Fishermen are regularly fishing in the area; some preliminary analysis revealed the presence of some heavy metals in fishes caught in the area in relatively high concentrations which may represent a real threat to the public health. A recent visit to the area has shown that the threat is real and the area is experiencing a real modification evidenced by the following visual indications: 1) Increasing algal development in the area between the edge of the reef and the coast particularly south of the new effluent; 2) Sediments became sludgy and dark colored indicating more reducing conditions; 3) Dramatic degradation of the mangrove stands.

The foreign substances that are introduced to the environment may harm directly or after a series of transformations and digenesis the entire ecosystem and finally affect the human being. Pollution behavior is multivariate. The pathways pollutants follow are complex; transformations into more or less hazardous substances can be critical and the presence of other pollutants is often significant, e.g. cumulative, additive and synergistic effects are becoming increasingly evident (UNEP, 1980).
The main objective of the present work is to answer the question: do physical and chemical properties of water have changed since the transfer of the effluent? The strategy fixed to achieve this goal was to sample at approximately the same locations that have been sampled by El Syed and Niaz, 1999 in the inner coastal area (Fig. 1); to analyze the same hydrochemical variables (salinity, dissolved oxygen, dissolved nutrients, SPM, Chl a, DOC and POC), and to compare the results. Additionally, sampling was undertaken in the outer coastal area, seaward from the fringing reef, in order to complete the picture of the impact of sewage dumping on the environmental condition of the receiving water body.

Fig. 1: Map showing the geographical distribution of the stations in Southern Corniche during April 2003 and January 2004. (A) Red Sea; (B) the coastal waters of Jeddah including the study area; (C) the study area with the stations denoted with A letter (outer coastal area) and C letter (Inner coastal area); (D) the new sewage discharge area with the station denoted with B letter (outer coastal area).

MATERIALS AND METHODS

Study Area:

The central part of the Red Sea is characterized by a tropical to subtropical climate. The wind is mostly north to north-northwest all the year round (Patzert, 1974). Waves are generated by winds and tidal action. Water temperature ranges between 25.5-31.0°C, but higher temperatures could be reached in the very shallow and isolated coastal areas (Edwards and Head, 1987). The same fact applies to salinity which has an average of 39.2 but may exceed 40. Water horizontal transport is the result of the combination of the wind and tidal stream action. It has a general north-south direction but in the coastal area, local conditions like bottom topography may largely influence surface water movement.

The near shore zone, extending between the shore line and the fringing reef, is a shallow water area of small but variable depth and width. The bottom is rocky and is composed of hard reefal limestone structures covered by a more or less thin layer of unconsolidated reefal sediments. Some land-derived material could also be detected. In accordance with the northerly surface current, the long shore sediment transport takes place from north to south (Durgaprasada and Behairy, 1982).

The area of study (Fig. 1) lies about 25 km south of Jeddah. It extends for about 12 km between 21.3207° N and 21.3483° N. The area is composed of two parts: The first extends between the shoreline and the fringing reef. The area is shallow; depths are less than 2 meter at high water. The bottom is hard reef rocks covered with a thin cover of soft sediments. The width of the area is relatively regular and ranges between 500 and 700 m (this part will be named Inner coastal area). The second part extends seaward to the west of the fringing reef for about 2 km. Depths vary widely from less than 20 m to more than 200 m (this part will be named Outer coastal area).
Sampling and Analytical Methods:
Field Visits and Sample Collection and Preservation:

Surface water samples were collected twice from the study area. The first sampling was done in April, 2003 and the second in January, 2004. Sampling was undertaken separately from the inner and outer areas. Samples from the inner shallow area were manually collected, directly in the corresponding sampling bottles, from 10 sampling stations distributed at almost equal intervals (Fig. 1). Oxygen bottles were also manually filled using a home-made filling system to prevent bubbling during filling, and dissolved oxygen was fixed immediately after sampling. Samples from the outer deeper area were collected using a 5 l Niskin bottle manually lowered from an 8-meters outboard. Samples were collected from 18 surface stations (Fig. 1). Extra samples (8 samples) were taken at 100 m intervals around the effluent to emphasize the dispersion process (Fig. 1). Samples for nutrients, suspended particulate materials (SPM), chlorophyll-α (Chl-α) were then transferred to the preconditioned appropriate bottles (Aminot and Chaussepied, 1983). Water samples were preserved in ice boxes until transported to the laboratory for further treatment (filtration with GF/C filter, 0.45 μm pore size) and analysis. Two set of filtration was carried out for the analysis of SPM and Chl-α. The particles on the filters of the first set was used for determination of SPM and whereas the second set was used for determination of Chl-α. The filtered water was used for determination of dissolved nutrients. Samples for DOC were collected in pre-combusted glass bottles. In the laboratory, the samples were filtered with pre-combusted glass fiber filter (Whatman GF/F 0.7 μm pore size), and subsequently stored in pre-combusted glass bottles.

Analytical Methods:

Dissolved oxygen was determined using the classical Winkler method optimized by Carpenter (1965) and Carrit and Carpenter (1966). The method is described in detail in Aminot and Chaussepied (1983). Salinity was measured by the volumetric method based on the precipitation of the halides using silver nitrate (Strickland and Parsons, 1972). Temperature and pH were measured in the field using an ordinary thermometer 0-100 °C and a pH-meter with combined electrode. Nutrients, nitrogen and phosphorus, were analyzed according to methods described in Grasshoff et al. (1999). Chlorophyll (Chl) a, b and c were measured by extracting the suspended matter retained on a GF/C filter with 90% acetone in water according to Lorenzen, (1967). The absorbance of the extract was spectrophotometrically measured at 663, 645 and 630 nm. The equations recommended by the UNESCO (1966) are used to calculate the concentrations of Chl a, b and c. Only data on Chl-α are presented. Dissolved organic carbon (DOC) was measured using the high-temperature catalytic oxidation technique (HTCO). A Shimadzu total organic carbon analyzer (TOC-5000) was used for the analysis. The principal of the method is based on acidification of filtered water sample with phosphoric acid, then purging with zero air to get form of inorganic carbon (IC). The sample is submitted to the combustion tube at 680 °C. Carbon dioxide obtained from this step is related to DOC that is detected by non-dispersive infrared (NDIR). The blanks were estimated from the analysis of high purity Milli-Q water (18.2 M Ω). Particulate organic carbon (POC) was measured using the sulfo-chromic method (Le Core, 1983).

RESULTS AND DISCUSSION

The Situation Before the Transfer of the Effluent (Prior the Year 2000):

In January 1999, El Sayed and Niaz studied the environmental conditions of the area. The study was restricted to a small lagoon, that received the direct sewage discharge, and to a shallow coastal strip extending about 10 km south of the lagoon. The results obtained during the study have shown that despite the input of important quantities of phosphorus, nitrogen, organic matter and solid material, the impact of the effluent was only restricted to the lagoon where sewage was discharged (Fig. 1, old sewage discharge basin). Inside the discharge basin, higher concentrations of nutrient salts were measured near the discharge outlet and concentrations decreased with distance from the effluent. The behavior of nitrogen species appeared non conservative; net nitrogen consumption was observed in the dilution area and was attributed to nitrogen assimilation by phytoplankton. Meanwhile, the non conservative behavior of phosphorus was attributed to its emission by desorption from bottom sediments and the mineralization of organic matter. Mass balance calculations permitted the evaluation of the quantity of phosphorus and nitrogen that was exported out of the dilution basin (El Sayed, 2002b). The impact on the shallow coastal area south of the old effluent while mainly limited to the area just beside the effluent resulted in a little increase of phosphorus and nitrogen concentrations compared to concentrations measured in open and coastal waters.
Water of the shallow coastal area was either saturated with dissolved oxygen or even over saturated as a result of the enhancement of the primary productivity due to elevated nutrient concentrations. Average salinity was 39.6 but variations were important and were attributed to enhanced water evaporation in the closed areas. Unfortunately, no data are available for the outer coastal area where the new effluent is implemented.

**Present Situation after the Transfer of the Effluent (After the Year 2000):**

**The Inner Coastal Area; Consequences of the Transfer:**

Results of the analysis of the samples from the inner coastal area are given in Tables 1 and 2. Seasonal differences are apparent and significant. During spring (April 2003), the average salinity is two salinity units higher than in winter (January 2004). This is the result of higher evaporation rate and the shallowness of the area. The highest salinity (≥ 45) is measured at the most northerly station where water exchange and flushing is limited due to the particularly isolated nature of the area. The salinity values during winter are in good agreement with the values reported by Mudarris et al., (2000).

Most of the parameters that are directly or indirectly related to the biological activity showed significant seasonal differences. Dissolved oxygen (DO) concentrations are slightly higher during spring probably due to enhanced primary productivity. To calculate the saturation percentage of DO during spring, an average water temperature of 28.6°C was used (Mudarris et al., 2000) in combination with the average salinity (41.24) obtained from the present study (Table 1). For winter, calculations are based on average value of temperature (27.4°C) measured from the outer coastal waters during this study (Table 5), in combination with average salinity value (39.21) in winter (Table 2). The DO during spring was close to saturation (average of 97%) whereas it was relatively below saturation (average of 89%) in winter. Although the photosynthesis and respiration processes have great impact on the concentrations of DO in surface water, the concentration of DO in the surface water of the study area is likely to be controlled by the atmosphere water exchange with measurable contribution from photosynthesis and respiration processes as indicated by the good agreement between Chl-a and DO concentration in January (Fig. 3E). Station C4 has shown a unique feature with respect to DO concentration and percentage of saturation; the concentration of DO was low (123 μM) coinciding with low percentage of saturation (63%). This could be attributed to the mineralization of organic materials in both water and organic rich bottom sediments.

Chl-a is remarkably higher in spring and on an average basis (2.05 μg l⁻¹) is more than three times higher than that measured during winter (0.63 μg l⁻¹). This observation is also valid for DOC which has an average value of 291 μM C in spring and 127 μM C in winter. Surprisingly, DOC is weakly associated with chlorophyll in spring (Fig. 2A) while it is strongly correlated with it in winter (Fig. 3A). Association between the two parameters could be affected by several factors of which we can mention the time difference between the onset of the algal production and the consequent increase of DOC, external DOC source(s) and the complex morphological nature of the area. Little is known about the distribution pattern and concentrations of DOC in the coastal and open waters of the Red Sea. Karbe and Lange, 1981 described the vertical profile of the total organic carbon (TOC) in the open waters of the Red Sea. For most of the water column, the concentration was almost less than 83 μM C, which reflects the oligotrophic nature of the Red Sea (Edward and Head, 1987). The concentrations of DOC in the surface waters of Southern Ocean were in the range between 43 and 48 μM C (Ogawa et al., 1999) whereas its concentration ranged between 8 and 22 μM C in the equatorial waters of the Pacific Ocean (Clark et al., 1998). Concentrations of DOC in the inner shallow coastal waters of the South Corniche fluctuated between 83 and 392 μM C; these values are several times higher than values measured in the outer deeper area. Therefore, the inner coastal area is a potential source of organic carbon to the open waters of the Red Sea.

The contribution of the primary productivity to the organic matter burden in the area can be approximately estimated based on the difference of the concentration of DOC measured in spring and winter. According to several authors (Duursma, 1963; Menzel, 1974; Williams, 1975) dissolved organic matter is partly composed of biologically active and easily degradable molecules (sugars, amino acids, short chain fatty acids); these molecules do not contribute significantly to the DOC (Billen et al., 1980; Wolter, 1982) The principal components of DOC are inactive molecules that are hardly degradable such as polyphenols and biopolymers (Manitoura and Woodward, 1983).

The annual degradation rate of organic matter can be calculated from the difference between the DOC concentration in the fall and its concentration in winter where its production is supposed to be at lowest rate. If we consider that DOC concentration during spring was the same as during the fall (meteorological conditions are almost the same), the rate of degradation will be equal to the difference between the average concentration during spring and that of winter (Tables 1 and 2) divided by the number of months from October to January. This degradation rate was estimated at about 55 μmol l⁻¹ month⁻¹. The total production attributed to the primary productivity during the period from April to October will be equal to the measurable increase 164 μmol l⁻¹.
augmented by 385 μmol l⁻¹ (55 μmol l⁻¹ x 7 months) which gives about 6,59 mg l⁻¹. If we suppose a uniform primary production from April to October over the whole water column (average 1 m depth) and that production is negligible the rest of the year, we obtain 6,59 g m⁻² y⁻¹ C. According to Duursma (1963), DOC production is one tenth the actual primary production which gives an annual primary productivity of 69,5 g m⁻² y⁻¹ C. The area of the shallow inner coastal part is about 8,960,000 m² and its average depth is approximately 1 m which gives a water volume 8,960,000 m³. Since organic carbon represents about 50 % of the organic matter, the corresponding organic matter production in the area is approximately 1245 ton y⁻¹.

These estimates give approximate and minimum values that should be verified using other direct methods. We have to precise that given the fact that light and temperature do not limit the productivity in the area and that only the availability of nutrients is the limiting factor, part of the DOC is contributed by the winter primary productivity. The positive correlations between DOC vs Chl-a, SPM vs POC, POC vs Chl-a, and DOC vs POC (Fig. 3A, 3B, 3C, 3D) strongly support this assumption. Marine algae may contribute DOC to the marine environment through several processes like cell leakage (Bjørnsen, 1988) and release during cell lysis (Wilhelm and Suttle, 1999).

Nutrients distribution in the area shows a more apparent geographical order rather than a seasonal one. Generally, concentrations are high in the northern part of the area near the old effluent. NO₃⁻ and PO₄³⁻ concentrations did not show any significant difference between spring and winter. This was not the case with NH₄⁺; its winter average concentration was two times that of spring. NH₄⁺ is the first nitrogen species that results from the degradation of organic nitrogenous compounds; it can accumulate if consumption was slowed which may happen in winter (Wada and Hattori, 1991). NH₄⁺ can also accumulate under reducing conditions as in interstitial water and then it diffuses back to the bottom water (Wada and Hattori, 1991). NO₃⁻ also showed a marked seasonal variability. The average concentration in winter was almost two times that in spring. Mineralization of organic nitrogenous compounds associated with decreasing nitrogen consumption may explain this increase.

Average concentrations of nutrients measured by El Sayed and Niaz (1999) are compared to the results of this study (Table 3). Comparing the individual nutrients shows that only NH₄⁺ and PO₄³⁻ were higher before the effluent transfer. The most striking change concerned NO₃⁻ which has shown a spectacular jump after the transfer. These new conditions resulted in the modification of the relative proportions of the components of the total inorganic nitrogen (TIN) and the phosphorus/nitrogen atomic ratio. While NH₄⁺ was the principal component of the TIN in 1999 samples (83%), it became a minor constituent and NO₃⁻ the dominant one (>60%) after the transfer, meanwhile, TIN concentration showed slightly increased in winter. The dissolved inorganic nitrogen contributed by the sewage effluent is largely composed of NH₄⁺ (~ 93%) and only 6% as NO₃⁻ (El Sayed, 2002b). Three probable reasons could be advanced to explain the redistribution of the inorganic nitrogen constituents: 1) decrease of the direct input from the sewage effluent due to its significant dilution after its transfer; 2) preferential consumption of NH₄⁺ as can be indicated by the low NH₄⁺ concentrations in spring; 3) active nitrification process as depicted from the saturation levels of DO; NH₄⁺ is rapidly oxidized by DO to NO₂⁻ as - intermediate species, and finally to NO₃⁻. However, the linear correlation between DO and NO₃⁻ was insignificant when the whole data set was used; but the correlation was positive at concentrations of DO higher than 190 μM (Fig. 2B). Therefore, the process of nitrification could have a significant impact on the NO₃⁻ concentrations at DO concentrations higher than 190 μM. The correlation of DO with DOC and NH₄⁺ was linear and negative (Fig. 2C and 2D), indicating the importance of mineralization process in the production of DOC and NH₄⁺. Another significant difference between the two sampling periods is the increase of the nitrogen/phosphorus ratio in the inner coastal area after the transfer of effluent (Table 3). This increase was measured in samples of April 2003 and January 2004 which indicates that a real modification has been produced. Table 3 shows that the average TIN concentrations are almost the same as before the transfer. This increase is therefore the result of the remarkable decrease of PO₄³⁻ concentration. Values of N/P ratio are still far below the Redfield ratio indicating a disturbed environment.

POC averaged 175 and 112 μM C in spring and winter respectively. Average organic carbon concentrations in the SPM were 6.18 and 14.6 % for the two respective periods. Surprisingly, SPM appear as being richer in organic carbon in winter rather than in spring. It is believed that this is an artifact resulting from the resuspension of bottom sediments due to rough weather during sampling in spring. This resulted in an abnormal increase of SPM which averaged 42 mg l⁻¹ in spring compared to an average of 8.2 mg l⁻¹ in winter. This process, while resulting in a net increase of the concentration of POC expressed in μM C, caused the lowering of organic carbon in the SPM due to the resuspension of low organic carbon sediment particles. However, Chl-a and DOC are still correlate positively with POC (Fig. 3C, 3D).
Table 1: Physico-chemical characteristics of the inner coastal surface waters (April-2003)

<table>
<thead>
<tr>
<th>Station No</th>
<th>Salinity (μM)</th>
<th>O₂ Sat. (%)</th>
<th>O₂ (mg l⁻¹)</th>
<th>Chl a (μg l⁻¹)</th>
<th>DOC (μM C)</th>
<th>POC (μM C)</th>
<th>POC (%)</th>
<th>NO₂ (μM)</th>
<th>NO₃ (μM)</th>
<th>NH₄ (μM)</th>
<th>PO₄ (μM)</th>
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<tr>
<td>C1</td>
<td>45.22</td>
<td>198</td>
<td>105</td>
<td>18.5</td>
<td>4.21</td>
<td>323</td>
<td>106</td>
<td>6.86</td>
<td>0.06</td>
<td>3.05</td>
<td>0.55</td>
</tr>
<tr>
<td>C2</td>
<td>41.75</td>
<td>173</td>
<td>90</td>
<td>29.5</td>
<td>0.78</td>
<td>301</td>
<td>183</td>
<td>7.42</td>
<td>0.29</td>
<td>1.03</td>
<td>1.45</td>
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<tr>
<td>C3</td>
<td>41.75</td>
<td>183</td>
<td>95</td>
<td>38.9</td>
<td>2.27</td>
<td>343</td>
<td>149</td>
<td>4.60</td>
<td>0.04</td>
<td>0.67</td>
<td>0.55</td>
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<tr>
<td>C4</td>
<td>40.40</td>
<td>123</td>
<td>63</td>
<td>26.5</td>
<td>1.70</td>
<td>316</td>
<td>180</td>
<td>8.15</td>
<td>0.10</td>
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<tr>
<td>C5</td>
<td>41.42</td>
<td>218</td>
<td>113</td>
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<td>3.84</td>
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<td>300</td>
<td>3.76</td>
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<td>205</td>
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<td>18.3</td>
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<td>269</td>
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<td>260</td>
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<td>0.01</td>
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<td>Avg.</td>
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<td>188</td>
<td>97</td>
<td>42</td>
<td>2.05</td>
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<td>175</td>
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<td>27.6</td>
<td>1.22</td>
<td>61</td>
<td>52</td>
<td>2.57</td>
<td>0.16</td>
<td>0.32</td>
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SD= not available

Table 2: Physico-chemical characteristics of the inner coastal surface waters (January 2004)

<table>
<thead>
<tr>
<th>Station No</th>
<th>Salinity (μM)</th>
<th>O₂ Sat. (%)</th>
<th>O₂ (mg l⁻¹)</th>
<th>Chl a (μg l⁻¹)</th>
<th>DOC (μM C)</th>
<th>POC (μM C)</th>
<th>POC (%)</th>
<th>NO₂ (μM)</th>
<th>NO₃ (μM)</th>
<th>NH₄ (μM)</th>
<th>PO₄ (μM)</th>
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<tr>
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<td>0.49</td>
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<td>0.40</td>
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SD= not available

Table 3: Comparison between the average concentrations of nutrients given by El Sayed and Niaz (1999) and values obtained during this study.

<table>
<thead>
<tr>
<th>Study/variable</th>
<th>NH₄ (μM)</th>
<th>NO₂ (μM)</th>
<th>NO₃ (μM)</th>
<th>TIN (μM)</th>
<th>NH₄ +/TIN</th>
<th>PO₄ (μM)</th>
<th>PO₄/²/TIN</th>
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</thead>
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<tr>
<td>El Sayed &amp; Niaz (1999)</td>
<td>1.85</td>
<td>0.125</td>
<td>0.14</td>
<td>2.12</td>
<td>0.87</td>
<td>0.83</td>
<td>2.55</td>
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<tr>
<td>This work</td>
<td>0.58-1.11</td>
<td>0.14-0.13</td>
<td>1.07-1.85</td>
<td>2.05-3.09</td>
<td>0.28-0.36</td>
<td>0.36-0.38</td>
<td>5.47-8.58</td>
</tr>
</tbody>
</table>

Fig. 2: Correlations between selected parameters for the inner coastal area in April 2003. Points in square were omitted.
The results of the analysis of the chemical and physical characteristics of the water of the study area are presented in Tables 4 and 5. The surface distribution pattern was also presented in Figs. 4 and 5.

The average Red Sea surface salinity at its central part is 39 (Edward and Head, 1987). Departure from this value is expected in shallow and isolated areas particularly in summer. The average water salinity during the period of the study did not show a significant difference. Average salinity during spring (39.4) was slightly lower than during winter (39.95) but the difference could easily be attributed to the dilution effect of the effluent. This appears clearly when comparing the geographic distribution of salinity during the two seasons. Apart from the dilution effect which seems more pronounced during spring, the dispersion pattern of the effluent seems comparable during the two periods (Figs. 4 and 5). The geographic expansion of the dilution effect of the effluent indicates the limited effect of the expected impact of the effluent on the area. The effluent seems rapidly diluted and in order to have a measurable effect, concentrations of its constituents should be very high (i.e. untreated sewage). The surface water temperature measured in winter was fairly constant and varied between 27.36–27.38°C. This temperature corresponds to the usual Red Sea surface temperature at this time of the year (Edwards and Head, 1987; Mudarris et al., 2000).

The saturation concentration of DO decreases with the increase of temperature and salinity. For this reason DO concentration in the Red Sea water is inevitably lower than in cooler and less saline water. In spring, DO concentrations varied between 123 and 213 μM with an average of 188 μM. Saturation values vary between 65 and 90% with an average of 84%. DO concentrations and saturation values in winter are almost the same. These values are quite comparable to the average Red Sea surface concentrations (Morcos, 1970; Edwards and Head, 1987).

The distribution pattern of DO during the two sampling periods is characterized by relatively lower values in the vicinity of the effluent (Figs. 4 and 5) that could be attributed to DO consumption during the mineralization of the organic matter discharged with the effluent and the depletion of the effluent water in DO. A slight difference is, however, remarkable between the two periods; water with lower DO concentrations extends further southward during spring which probably correlates with an extended southward dispersion of the effluent.

The pH was only measured during the second cruise of January 2004. The pH varied in a very narrow range and ranged between 8.19 and 8.24 with an average of 8.22. Despite the absence of a significant difference with the average seawater pH (8.2 ± 0.1), which can easily be explained by the buffering capacity of seawater and the important dilution of the effluent, it is worth noting the relatively lower pH values around the effluent discharge point and the positive correlation between salinity and pH (Fig. 6A). The average pH of the effluent pH is 7.4 ±0.45 (El Sayed and Niaz, 1999). pH distribution agrees with the distribution of DO (Fig. 5); and adds evidences on the impact of the sewage effluent on the ecosystem.
DOC concentrations showed a significant seasonal variability. In spring concentrations were high and varied between 128 and 277 μM C with an average of 194 μM. In winter, concentrations were significantly lower and the average value for the whole area was 86 μM. This seasonal difference was first observed by El-Sayed (1985) who measured DOC along the Red Sea coast of Saudi Arabia. The author gave an average concentration of 132 and 95 μM for November and February respectively. These concentrations are lower than our measurements probably because they represent water far from the coast and out of any direct sources of contamination. Most of DOC measured in winter during this study is lower than or comparable to concentrations generally found in coastal seawater (Aminot et al., 1990). The distribution of DOC is characterized by the presence of an area of relatively elevated concentrations in the vicinity of the discharge point (Figs. 4 and 5). The plot of salinity versus DOC confirms the importance of the effluent as a source of DOC in the study area (Fig. 6B). However, the geographic distribution during the two seasons showed a significant difference.

During spring, patches of high DOC dispersed north and south of the effluent and separated by areas of low concentrations are recorded. This scattered distribution is attributed to the appearance of zones of preferential algal development according to the local environmental conditions. It is worth to mention that during sampling, a water mass of about 3000 m² with very high algal production was encountered. This water had 683 μM C DOC, 35.46 mg l⁻¹ Chl-α, 13.1 μM PO₄³⁻ and 25.8 μM NH₄⁺. The situation seems different in winter; primary productivity is retarded, but not stopped, while the contribution from the sewage discharge appears to influence the DOC distribution. The distribution of DOC appears as being mainly the product of the continuous mixing of the effluent water and seawater.

Chl-α, POC and SPM showed the same seasonal trend. Concentrations of the three variables were distinctly higher in spring than in winter (Tables 4 and 5). The distribution of Chl-α showed the same characteristics of the DOC distribution. In April, the distribution is patchy with zones of high concentrations scattered irregularly in the whole area (Fig. 4). Chl-α correlates positively but weakly with SPM and POC. In winter, the distribution is regular; productivity is much more active in the northern part of the area and decreases westward (Fig. 5). This appears to coincide with the distribution of nutrients particularly NH₄⁺ and NO₂⁻ (Fig. 5). Chl-α is positively correlated with the nutrients, which explains the co-variation of these variables.

Table 4: Physico-chemical characteristics of outer surface coastal waters (April, 2003).

<table>
<thead>
<tr>
<th>Station No.</th>
<th>Salinity (μM)</th>
<th>O₂ (mg l⁻¹)</th>
<th>Sat. O₂ (%)</th>
<th>SPM (μg l⁻¹)</th>
<th>Chl-α (μg l⁻¹)</th>
<th>DOC (μM C)</th>
<th>POC (%)</th>
<th>NO₂ (μM)</th>
<th>NO₃ (μM)</th>
<th>NH₄ (μM)</th>
<th>PO₄ (μM)</th>
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</thead>
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<td>160</td>
<td>82</td>
<td>19.80</td>
<td>0.93</td>
<td>229</td>
<td>212</td>
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NA= not available
Excepting of NO₃⁻, all the nutrients showed distinctly higher concentrations in winter (Tables 4 and 5). This is logically attributed to the mineralization of the organic matter that was built during spring, summer and fall. The decrease of DOC concentration is a direct indication of the mineralization process that resulted in lowering the pH of seawater. This is proved by the inverse relationship of pH with both DOC and NH₄⁺ (Fig. 6C and 6D) and the positive correlation of DOC with NH₄⁺ (Fig. 6E and 6F). The concentration of NH₄⁺ and PO₄³⁻ are almost tripled in winter. NO₂⁻ has increased by a small amount. Generally NO₂⁻ is found at very low concentrations which make its analysis very delicate in seawater. In spring the distribution of NH₄⁺ and PO₄³⁻ is regular and characterized by a zone of high concentration around the discharge point, and then concentration decreases gradually with distance from the effluent (Fig. 4). NO₂⁻ while showing an area of relatively high concentrations around the effluent, its distribution is less regular (Fig. 4). We believe that this is due to its presence at the limit of detection of the analytical method.

In winter, this ordered distribution pattern is replaced by a relatively patchy distribution for PO₄³⁻ and NO₂⁻; and a more regular one for NH₄⁺ and NO₃⁻ (Fig. 5). In all the situations, the impact of the effluent as a source of nutrients appears clearly through the presence of an area of high concentration around the discharge point; NH₄⁺ and PO₄³⁻ are negatively correlated to salinity (Fig. 6G and 6H). In addition, NH₄⁺ and PO₄³⁻ co-vary indicating a probable common source (Fig. 6I). The non conformity of NH₄⁺ with the patchy distribution may result from the discharge of high NH₄⁺ water from the sewage effluent that spreads out and makes the distribution appear as regular.

The following scenario is suggested to represent the relationship between phytoplankton growth and nutrient distribution. During winter, phytoplankton growth, however slow, is regular and everywhere due to the availability of nutrients that have accumulated after the fall peak. In spring, when productivity reaches its maximum intensity, it will be limited by the availability of nutrients which will depend on the balance between consumption and regeneration. This balance will certainly be affected by some physical features such as coastal morphology, bathymetry and local currents and water circulation; localized external sources may certainly have their own impact also. This may explain the patchy nature of the distribution of Chl-α and DOC during spring and the agreement between the distribution of POC and Chl-α.

**Conclusion:**

Comparison of the average concentrations of the different nutrients gives a first indication that since the transfer of the effluent, no marked changes have occurred in the inner coastal area. Results are comparable excepting for PO₄³⁻ which was significantly higher in 1999. However, while concentrations of TIN are almost comparable, the relative distribution of the TIN components has completely changed after the transfer of the effluent. NO₂⁻ took the place of NH₄⁺ and became the dominant constituent constituting more than 60% of the TIN. Comparing the average concentrations hides the new trend that has resulted since the effluent transfer.
The general trend in the distribution of nutrients in 1999 was characterized by a north-south concentration decrease, i.e., with increasing distance from the source point. In 2004, most of the nutrients did not maintain this distribution pattern but showed a significant increase south of the new effluent before decreasing away from it. In the outer coastal area, the impact of the new effluent could be viewed through the detectable decrease of salinity, pH and DO, and the measurable increase of all the nutrients as well as DOC, POC, SPM. It is safely can be predict that all other chemical and microbiological contaminants are also dispersed with the effluent water. In both the inner and outer coastal area, DOC, Chl-a and nutrients showed a pronounced seasonal variability. Nutrients were depleted in spring and this depletion was accompanied by the increase of DOC and Chl-a.

![Fig. 4: Surface distribution of physico-chemical parameters in the outer coastal area in April 2003.](image-url)
Fig. 5: Surface distribution of physico-chemical parameters in the outer coastal area in January 2004.

Surface distribution of physico-chemical parameters in the outer coastal area in January 2004.
Fig. 6: Correlations between selected parameters for the outer coastal area in January 2004.

REFERENCES


