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Distribution and Behavior of Dissolved Species of Nitrogen and Phosphorus in Two Coastal Red Sea Lagoons Receiving Domestic Sewage

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ABSTRACT. Two sewage treatment stations are daily dumping about 100,000 m^3 of domestic sewage into two coastal lagoons off the city of Jeddah. Field measurements and laboratory experiments were undertaken to study the behavior and impact of the effluent on the hydrochemistry of the receiving water body.

Physical and chemical characteristics of the receiving water suffered important modifications. Salinity and pH were lowered at the discharge points and increased with distance from it. Concentrations of the different species of nitrogen and phosphorus were largely in excess to those measured in Red Sea water out of the impact of land sources. Ammonium and organic nitrogen are the major constituents of total nitrogen representing more than 90% of the total nitrogen concentration at the stations in proximity of the effluents. Reactive phosphate is the major phosphorus species representing between 68 and 94% of the total phosphorus concentration.

Flux estimates showed that approximately 2000 kg of nitrogen and 800 kg of phosphorus are discharged in the area every day. Despite the laboratory evidence of the liberation of dissolved nitrogen (46%) and phosphorus (36%) from the particulate fraction within one week, and the presence of active processes of transformation between the different species, field data showed an almost conservative behavior. Deviation from this behavior was only observed when environmental conditions were highly reducing. The short residence time (~1.5 day) and the relative slowness of the biological elimination and transformation rates are the most probable reasons for the apparent conservative behavior.

KEY WORDS: Sewage, coastal water, nutrients, distribution, behavior, Red Sea.

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Introduction

Unlike the Mediterranean and Baltic seas, which are influenced by anthropogenic discharges, the landlocked Red Sea could be considered as a quasi-unperturbed marine environment (Bethoux, 1988). However, in the last two decades, some parts of the eastern coast of the Red Sea belonging to the Kingdom of Saudi Arabia has seen a vast demographic and industrial expansion.

The major nutrient transport to the world's ocean takes place through river discharge. Due to the absence of appreciable land runoff and because of its presence in a semi-arid area, the Red Sea does not receive any measurable nutrients by natural riverine transport. Under these conditions, sewage disposal may constitute a major source of nutrients to the marine coastal environment (Aminot and Guillaud, 1990). Pernetta and Milliman (1995) stated that the anthropogenic flux of dissolved nutrients from land is now equal to and in some areas in excess of the natural flux.

Large nutrient discharge to the coastal area may have dramatic ecological consequences. In the central Red sea, temperature and light are favorable for primary productivity throughout the year. A high anthropogenic input of nutrients, particularly under restricted water circulation, will support a high rate of production; organic matter may accumulate on the seafloor where it is respired until all the oxygen is depleted. At this threshold the system shifts from oxic to anoxic respiration and sulfate is used as an oxygen donor. In this process H_2S is generated, which threatens all higher life in and on top of the sediment and in bottom water.

Another threat occurs when free CO_2 is rapidly drawn from the water by photosynthesis, increasing the carbonate ion concentration and the pH. Part of the marine biota cannot tolerate such conditions and disappear while species tolerating these conditions have the opportunity to develop in massive blooms. Many biomineralizing organisms loose the ability to produce calcium carbonates at high pH, thus the disturbance of the narrow balance of the CO_2 system may have severe consequences for reefs, shell producing invertebrates and calcareous plankton. Moreover, in the arid regions where coastal water is used for several activities such as desalination and in heat exchangers, the problem of biofouling will get worse because of the presence of excess nitrogen and phosphorus.

Several studies have been undertaken on the coastal area off Jeddah (El-Rayis *et al.*, 1982; El-Rayis *et al.*, 1984; Behairy and Saad, 1984, a&b; El-Rayis, 1990; El Rayis, 1998; El Rayis and Moammar, 1998, Basaham, 1999; El Sayed and Niaz, 1999). However, studies on the fate and flux estimates of nitrogen and phosphorus components discharged with sewage effluents in areas of restricted water circulation are still lacking. This study aims at studying the behavior of nitrogen and phosphorus species in two coastal lagoons receiving urban waste disposal.

Material and Methods

The Study Area

One of the central urban agglomerations along the Red Sea eastern coast is the city of Jeddah. The city's population is approximately 2.5 millions and it possesses a wide range of heavy and light industries including food processing, refineries, petrochemicals, water desalination and other small industrial setups. Seven sewage treatment plants (STP) have been implemented in the city; they receive more than 350,000 m^3 of wastewater every day. Two STP collect used water from the city center and the old town.

A complete description of the study area is given in El-Rayis and Moammar (1998). Briefly, the area is composed of two semi-enclosed lagoons; Al-Arbaeen and Al- Shabab (Fig. 1). The effluents discharge pipes are situated at the landward extremity of the lagoons. Al-Shabab and Al-Arbaeen lagoons receive daily 35,000 m^3 and 65,000 m^3 of wastewater respectively. Both lagoons communicate with the open water through a narrow channel. Water exchange with the open sea is further limited by the presence of two artificial sills of two-meter depth crossing the communication channels. According to El-Rayis and Moammar (1998), the water column in Al-Arbaeen lagoon is composed of three layers. There is a 1-m superficial layer of mixed low-salinity water moving out to the open sea. This layer is found on a layer of the same thickness, moving in the lagoon to compensate the water lost by the outgoing movement. The characteristics of this water layer are the same as the surface Red Sea water. Below the level of the sill, water is almost stagnant, salinity is high (>50), oxygen is low and H_2S is omnipresent. This water is only renewed by rough weather conditions during winter. Another source contributing to the deterioration of the water quality is the fish market. Large quantities of fish wastes, very rich in organic matter are washed daily to the area at the entrance of Al-Arbaeen lagoon.

Sampling and Analytical Methods

Thirteen surface water samples (~30 cm depth) were manually collected, in September, 1997, using a small out-board boat. Sampling stations were selected along two transects extending roughly along the central axis of the communication channels (Fig. 1). Samples were collected in preconditioned sampling bottles (Aminot and Chaussepied, 1983). For the analysis of the different species of dissolved nitrogen and phosphorus, samples were taken in one-liter polyethy-

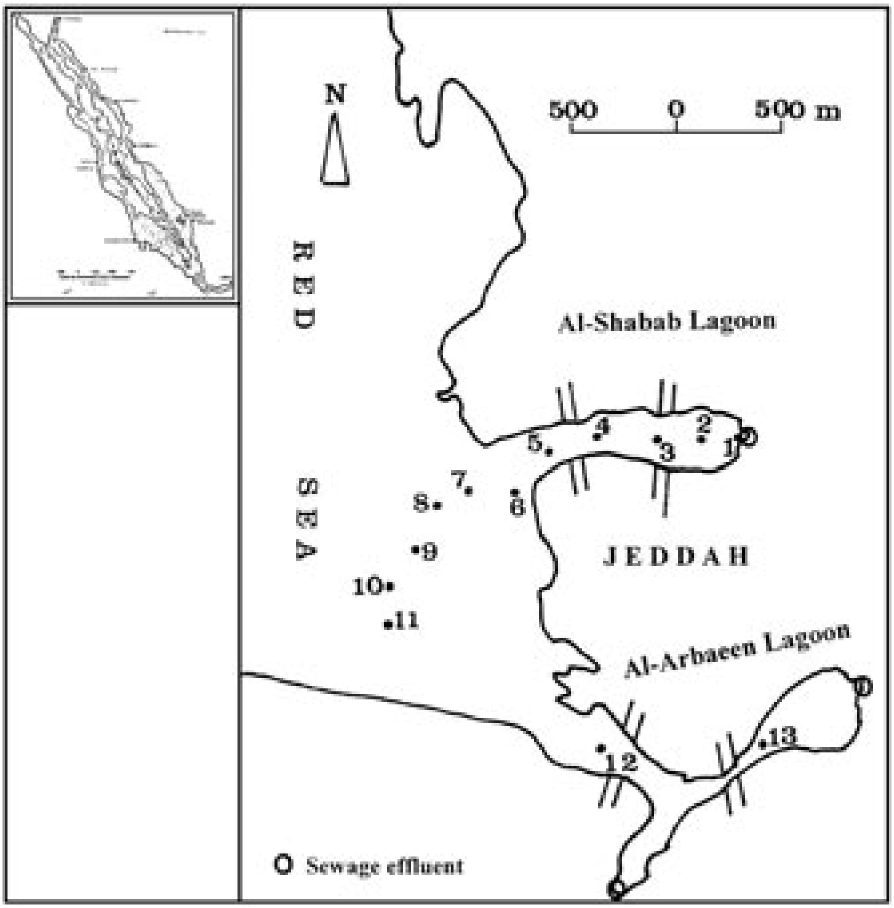

FIG. 1. Study area and location of sampling stations.

lene bottles and stored in iceboxes. In the laboratory, samples were filtered using GF/C filter membranes and kept at 4ºC until analyzed; analysis was undertaken within 24 hours. For the analysis of nitrite, nitrate, ammonium and reactive phosphate, the classical colorimetric methods were applied (Grasshoff *et al.*, 1983; Aminot and Chaussepied, 1983). Total nitrogen and total phosphorus were determined according to the method of Valderrama (1981). Total suspended matter (TSM) was measured by filtering a known volume of the sample on a dry and pre-weighed GF/C filter paper. Filters were washed with distilled water, dried at 100ºC, left to cool in a desiccator then reweighed to calculate the weight of the SPM. Natural absorbance of the filtered samples was measured at 325 nm using a Shimadzu Colorimeter (UV-160A). Natural fluorescence was measured in aliquots of the filtered samples using a Shimadzu Spectrofluorimeter (RF-5000). Excitation wavelength was fixed at 325 nm while the emission wavelength was fixed at 450 nm (Chen and Bada, 1994). Fluorescence measurements were not corrected. Salinity was determined using the volumetric method described by Strickland and Parsons (1972). Dissolved oxygen (DO) was measured using the classical Winkler method (Carpenter, 1965). pH and temperature were measured in the field using Orion pH-meter provided with combined electrode and temperature sensor.

The transformations that may take place and affect the species of nitrogen and phosphorus during the residence of the effluent water in the area were studied by conducting a series of laboratory experiments. Four portions, one liter each, of the natural, unfiltered water at station 1 were incubated in two liters dark glass bottles and kept out of light, at room temperature (around 27ºC). These conditions ensure the inhibition of the photosynthetic activity and the maintenance of aerobic conditions to sustain the aerobic degradation of the organic matter. After 8, 14, 21 and 30 days the contents of each container were filtered and analyzed for the different species of phosphorus and nitrogen.

Results and Discussion

General Hydrochemical Characteristics

The average surface salinity of the open Red Sea water is 39 (Edwards, 1987). The distribution of the surface salinity (Fig. 2) demonstrates the dilution effect introduced by the discharge of the effluent water. In the Al-Arbaeen lagoon salinity showed an increasing trend going from 27.1 to a maximum of 40.8 at the outer most station. Seawater is relatively more diluted in Al-Arbaeen lagoon than in Al-Shabab because the first is receiving a significantly greater quantity of domestic sewage. The salinity measured at station 1, the point of discharge of the effluent at Al-Shabab lagoon was 37. This indicates that water mixing is taking place deep in the discharge pipe. Degree of penetration of seawater in the pipes will depend on the flow rate of the effluent and the tidal cycle.

The measured surface salinities are generally higher than those given by El-Rayis and Moammar (1998). However, the authors stated that in the fall and winter, the bottom hypersaline water (>50), could be flushed out and replaced by Red Sea water. However, the magnitude of the process depends on the weather conditions. During its movement out of the lagoon, bottom water partly mixes with the surface layer increasing its salinity; the resulting salinity depends on the relative proportion of the two water masses. This is the most probable explanation for the unusual increase in the surface salinity.

The pH of seawater ranges between 8.1-8.2. In coastal waters and areas of restricted circulation, natural processes such as enhanced primary productivity and organic matter degradation are causes of pH fluctuation (El Sayed, 1988). Wastewater disposal and continental water may also produce pH anomalies. In the study area, despite the absence of proportionality, the lowest pH values are associated with the lowest salinities reflecting the role of the sewage effluent as a source of acidity; pH progressively increased with the increase in salinity (Fig. 2).

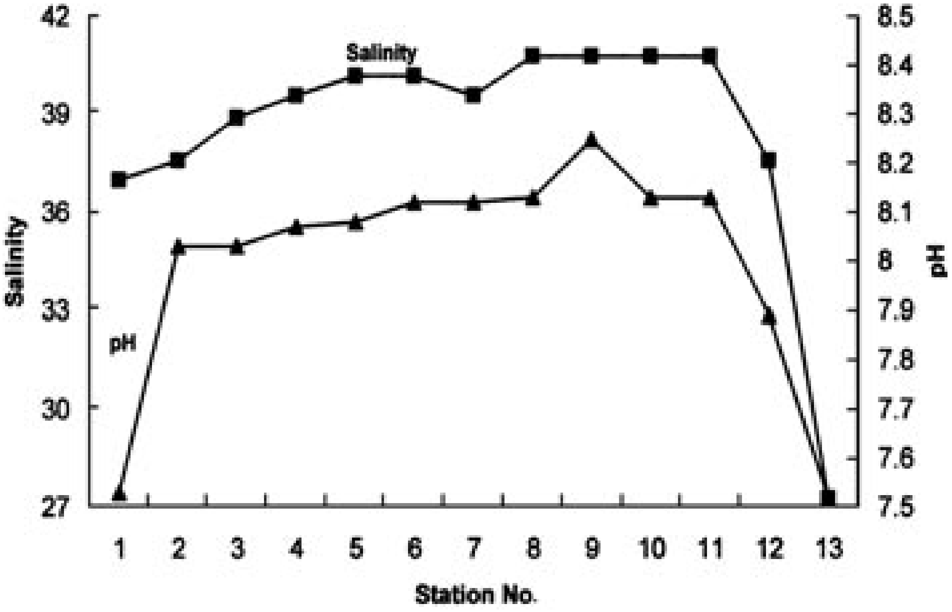

FIG. 2. Distribution of salinity and pH in the study area.

The concentration of the SPM in the open seawater hardly exceeds few hundreds of micrograms (Aminot, 1983). Concentrations become higher in the coastal areas due to natural processes such as enhanced primary productivity and sediment resuspension and anthropogenic inputs. In the study area, the concentrations of the SPM varied between 14 and 61 mgl^{-1} (Table 1). High values are generally measured near the discharge points. The relationship between SPM and salinity (Fig. 3a) indicates the presence of excess SPM relative to a simple mixing of the effluent water and seawater in the Al-Shabab lagoon. The reason behind could be a simple resuspension of bottom sediments and/or the contribution from enhanced primary productivity. Dissolved oxygen distribution supports the participation of the primary productivity. At 26-27ºC, which is the average water temperature in winter, and salinity of 40, the saturation concentration of dissolved oxygen is about 4.5 ml l^{-1}. Oxygen super saturation characterizes the DO distribution in Al-Shabab Lagoon. DO concentration is zero at station 13 and it reaches 2.26 mll^{-1} at station 12 in Al-Arbaeen lagoon (Table 1). The plot of the DO against the concentration of the SPM (Fig. 3b) clearly indicates the presence of two opposing relationships in the two lagoons and supports the role of the photosynthetic activity in contributing excess SPM in Al-Shabab lagoon.

TABLE 1. General hydrochemical properties of the surface water of Al-Shabab lagoon.

Station no.	Salinity	pH	Dissolved oxygen mill^{-1}	SPM mgl^{-1}
1	37	7.53	5.56	24.5
2	37.6	8.03	7.15	61.0
3	38.9	8.03	6.34	60.2
4	39.6	8.07	6.41	33.8
5	40.2	8.08	5.67	17.5
6	40.2	8.12	4.52	16.9
7	39.6	8.12	4.75	16.3
8	40.8	8.13	5.04	15.7
9	40.8	8.25	6.52	15.3
10	40.8	8.13	4.52	16.3
11	40.8	8.13	5.04	13.7
12	37.6	7.89	2.26	19.1
13	27.1	7.52	n.d.	33.7

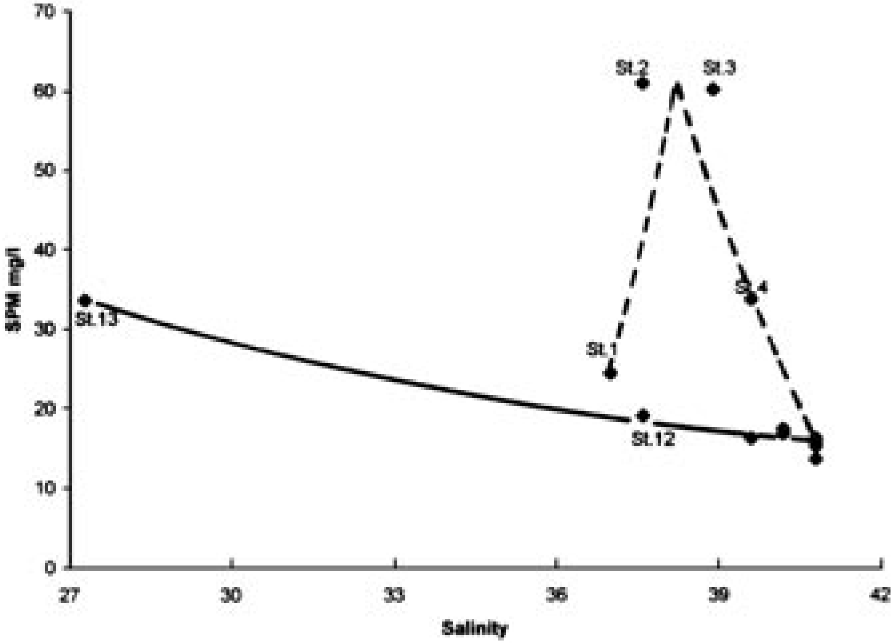

FIG. 3a. Relationship between SPM and salinity.

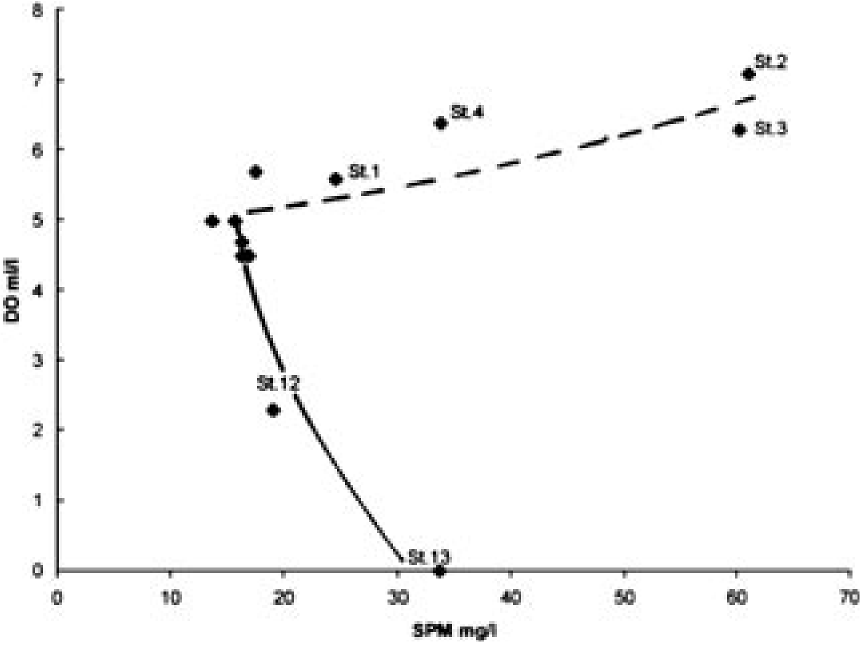

FIG. 3b. Relationship between SPM and dissolved oxygen.

It has been shown that natural fluorescence and light absorption at 325 nm correlate with dissolved organic carbon in seawater (Chen *et al.*, 1993; Chen and Bada, 1994). Natural fluorescence has also been used to trace and differentiate between river water of different origins in the coastal area (Willey and Atkinson, 1982). This physical property may therefore be used to recognize the behavior of organic matter in areas subjected to organic matter input from defined sources. Measurements of natural fluorescence and absorbance at 325 nm are generally in good agreement (Fig. 4); both parameters decrease with distance from the point source. Their relationship is described by the following equation (r = 0.964; n = 12, one doubtful measurement was omitted):

$$\text{Fluorescence} = 0.049 + 5.51^{*}\ \text{absorbance}$$

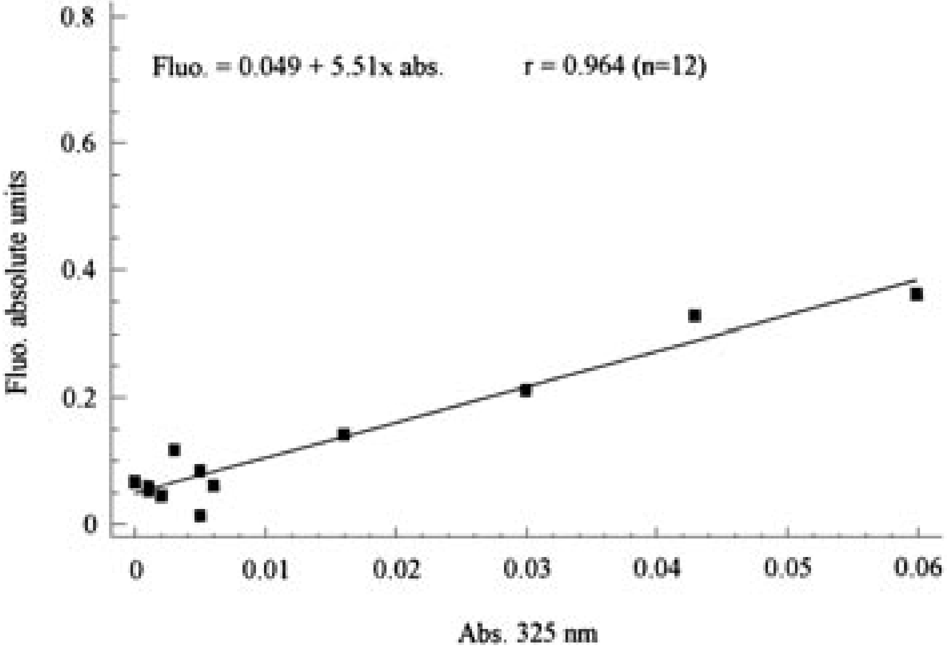

FIG. 4. Correlation between absorbance at 325 nm and fluorescence.

The presence of such a strong correlation may indicate almost uniform optical characteristics of the DOM discharged by the two effluents.

Tracing the relationship between natural fluorescence and salinity indicates that the organic matter is conservatively exported to the open coastal waters (Fig. 5). The scattering of the points may indicate some heterogeneity of the compounds containing the fluorophores. The residence time of the surface mixed water layer is approximately 1.5 days (El-Rayis and Moammar, 1998). This short residence time may explain the conservative behavior of the organic

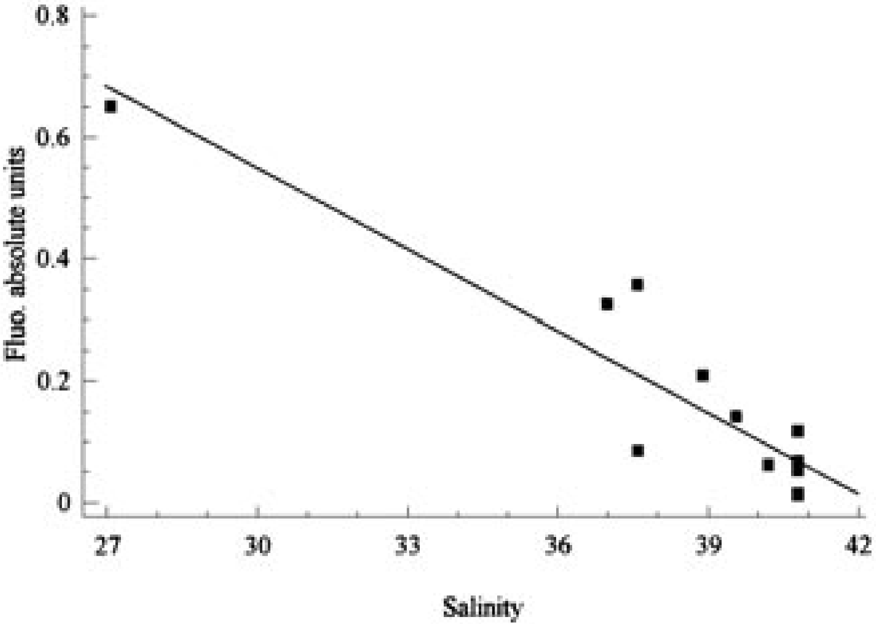

FIG. 5. Relationship between fluorescence intensity and salinity.

matter. It has been frequently shown that dissolved organic carbon behaves conservatively in estuarine environment (Mantoura and Woodward, 1983; Cauwet, 1985; El Sayed, 1988; Aminot *et al.*, 1990a). However, some studies have shown that some processes such as flocculation, precipitation and adsorption may interfere during the estuarine mixing resulting in a non-conservative behavior (Sholkovitz, 1976; Hunter, 1980).

Distribution of Nitrogen and Phosphorus

1 – Nitrogen species

The concentrations of the different components of nitrogen are presented in Table 2. Total nitrogen concentrations varied between 6 and 923 µmol l^{-1} with highest concentrations observed near the discharge points in the two lagoons. Both ammonium and organic nitrogen follow this distribution pattern. Nitrite and nitrate have a different distribution. Like ammonium and organic nitrogen, their concentrations are high at station 1 and decrease seawards, however, at station 13, where DO is zero, the concentration is very low. Undoubtedly, these nitrogen oxides are unstable in the absence of oxygen and the denitrification process is probably affecting their presence. The concentration then rises at St. 12 with the increase of oxygen concentration, which may be related to the mineralization of part of the organic nitrogen. Dilution effect then becomes dominant over any transformation process and concentration decreases with increase in salinity. Nitrate and nitrite are significantly correlated (Fig. 6) indicating a common evolution in the area. At the outer most station, concentrations of nitrate and nitrite are the lowest in the area but are still higher than concentrations measured in the open Red sea water. (Morcos, 1970).

TABLE 2. Concentrations (μmol l^{-1}) of nitrogen species in the surface water of Al-Shabab lagoon.

Station no.	Nitrite		Nitrate		Ammonium		Org. N		Total N
	Conc.	% TN	Conc.	% TN	Conc.	% TN	Conc.	% TN	
1	4.21	4.1	12.85	12.6	61.19	23.4	23.93	23.4	
2	2.98	2.1	9.31	6.4	99.72	68.1	34.34	23.4	102.19
3	2.84	2.9	8.44	8.5	75.92	76.7	11.84	11.9	146.35
4	2.77	5.0	8.57	15.6	26.63	48.5	16.91	30.8	99.04
5	1.93	4.2	6.31	13.9	20.68	45.6	16.50	36.3	54.88
6	0.44	2.2	3.76	18.6	7.71	38.1	8.28	41.0	45.42
7	0.44	2.2	3.05	15.0	3.05	15.2	3.86	67.9	20.19
8	0.33	3.9	2.18	25.5	1.98	23.2	4.03	47.3	10.41
9	0.35	4.1	2.24	26.3	2.95	36.6	2.98	35.0	8.52
10	0.44	2.1	2.37	11.4	9.8	47.1	8.20	39.4	8.52
11	0.09	1.5	0.67	11.2	0.01	–	5.23	87.2	20.82
12	1.23	0.7	3.05	1.7	140.8	79.4	31.25	17.7	5.99
13	0.28	0.03	0.54	0.06	368.3	39.9	554.7	60.6	176.3
Average	2.25		6.70		214.8		289.3		923.8
Average Red Sea	0.1-0.2* 0.02-0.2*		0.1-0.4* 1.3-0.7		2.0-3.0**		–		–

*From Weiker (1987) for open Red Sea water.
**From El Rayis (1998) for coastal water close to a sewage discharge effluent (Jeddah coast).

With a ratio higher than 80%, ammonium and organic nitrogen constitute the major constituents of nitrogen species; ammonium contributes, on average, a slightly higher percentage than organic nitrogen (Table 2). On the other hand, ammonium is the major component of inorganic nitrogen. Its contribution is higher than 97% at stations 12 and 13 and ranges between 65 and 90% at 9 stations out of 13. This pattern is caused by the reducing conditions prevailing in the inner most stations, that do not permit the oxidation of nitrogen to its higher oxidation states (Richards, 1965), and the slow oxidation kinetics coupled with short residence time in the oxygenated water. Nitrite and nitrate have relatively minor importance; their maximum contribution is about 30 % of the total nitrogen at stations 8 and 9 far from the discharge points. Surprisingly, this value decreases at the most outer stations, 10 and 11, and reached 13%; meanwhile, organic nitrogen becomes the principal component (87% at station 11). It is possible that planktonic consumption is contributing to this distribution pattern. Chugaynova *et al.* (1993) found that organic nitrogen contributed between 80 to 97% of the total nitrogen concentration in the surface waters of the white Sea Bays.

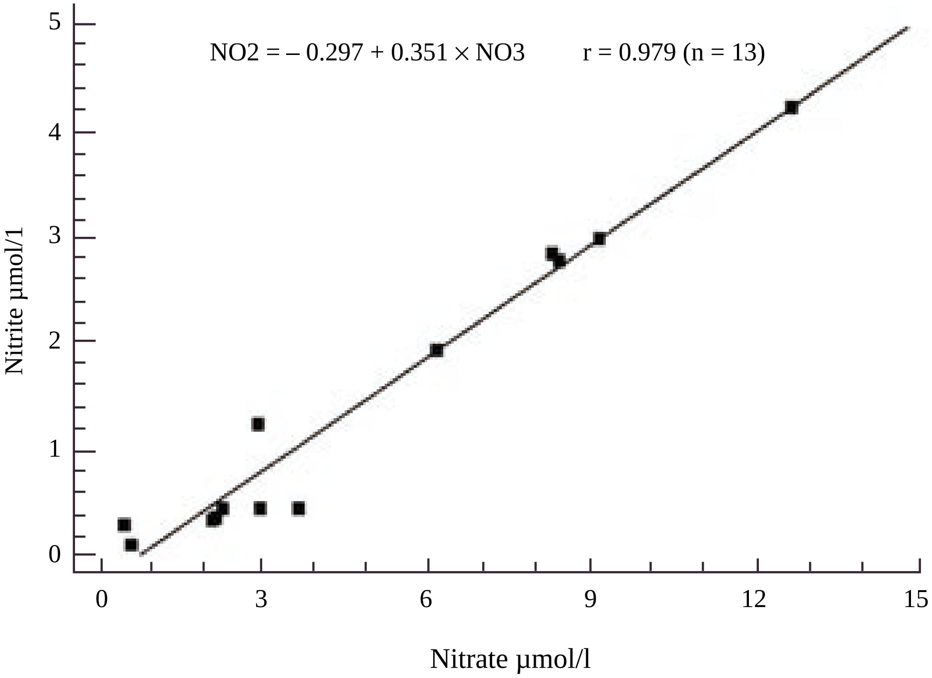

FIG. 6. Correlation between nitrate and nitrite concentrations.

Examination of the relationships between the different components of nitrogen and salinity may supply additional information on the extent of any internal processes that may have taken place during the residence of the effluent in the basin.

Nitrate and nitrite are negatively correlated with salinity. The linear relationship means the dominance of the physical dilution process over any other chemical or biological process indicating a conservative behavior. This relationship is only disturbed by the point representing station 13. Concentration at this station is far below the dilution line (Fig. 7) indicating the effectiveness of the denitrification process in anoxic environments (Santschi *et al.*, 1990; El-Rayis 1998). Ammonium does not seem to suffer any impact from the highly changing oxygen concentration, and its significant linear regression on salinity (Fig.

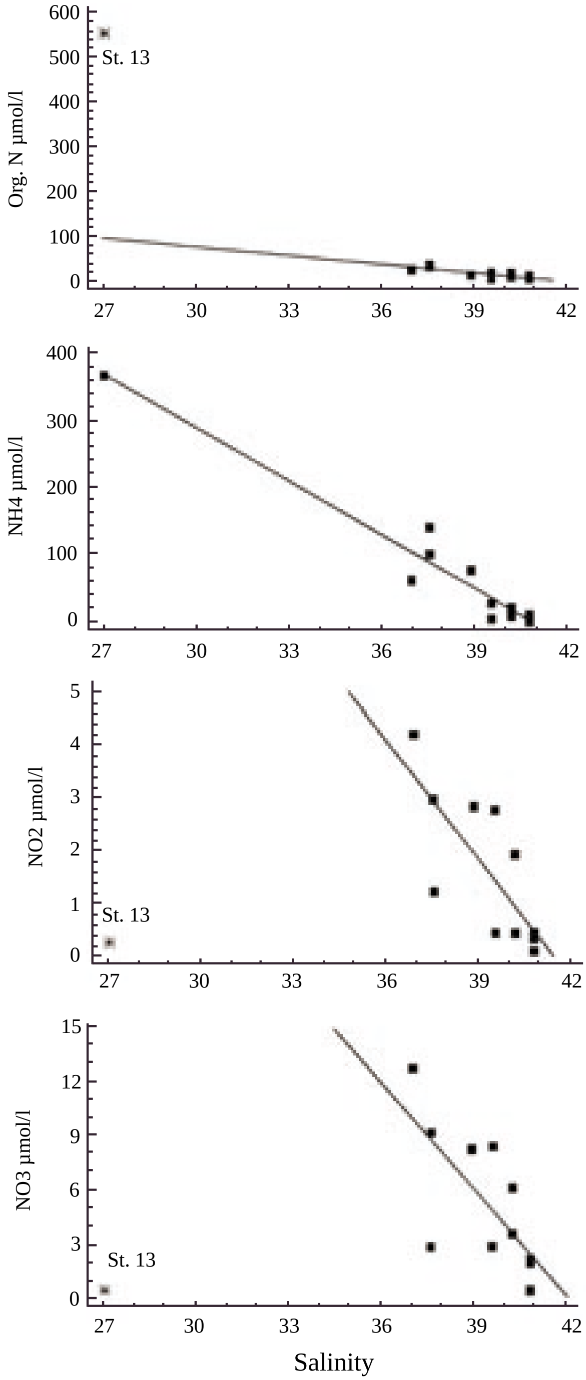

FIG. 7. Relationship between nitrogen species and salinity.

7) indicates conservative evolution during the limited residence period in the area. The increase of ammonium and organic nitrogen at station 2 may result from sediment resuspension as indicated by the SPM anomaly. This increase was not accompanied by any increase of nitrate and nitrite because these oxidized species could not be found in measurable concentrations in the reducing bottom layer. The organic nitrogen-salinity relationship contributes evidence concerning the importance of the organic matter contribution to the area from the fish market. The organic nitrogen concentration measured at station 13 is far above that given by the straight line representing the linear relationship between organic nitrogen and salinity (Fig. 7). Several tons of fish are daily processed in the market and their debris is discharged in the sea close to station 13. The main nitrogen component contributed by these proteinaceous substances is evidently organic nitrogen.

2 – Phosphorus species

Dissolved phosphorus may exist in several forms in natural waters the most dominant of which is reactive phosphate (Stumm and Morgan, 1970, Aminot *et al.*, 1990b; Valiela, 1995). There are also some indications that dissolved organic phosphorus may be found in natural waters in concentrations that may exceed that of inorganic phosphorus particularly when primary productivity is enhanced (Hutchinson, 1957; Sen Gupta, 1973; Valiela, 1995).

Results of the distribution of dissolved phosphorus species are presented in Table 3. The data shows that in this organically polluted area, reactive phosphate is the dominant component of phosphorus. At only three stations out of the thirteen, phosphate/total phosphorus ratio was below the 80% level. Organic phosphorus, however, has a higher contribution at stations 1 and 13 in the proximity of the effluent discharge points. The highest ratio and the highest concentration of organic phosphorus were recorded at station 13. In all the cases concentrations decreased with distance from the source points. The concentrations of reactive phosphate are comparable to those previously recorded in the area (El-Rayis, 1998) but are significantly higher than concentrations given for unpolluted coastal water (Kandil, 1982; Behairy and Saad 1984b; El-Rayis, 1998). The lowest concentration recorded at station 11 is still higher than concentrations given for the open Red Sea water (Weikert, 1987)

The components of phosphorus are negatively correlated with salinity (Fig. 8). Dilution appears as the major process taking place in the area. Other process that may complicate the dynamics of phosphorus such as biological consumption, uptake and release from particulate matter and formation of insoluble complexes (Valiela, 1995) may play a minor role. The reason of this conservative behavior is most probably the short residence time of the surface water layer.

TABLE 3. Concentration (µmol l^{-1}) of phosphorus species in the surface water of Al-Shabab lagoon.

Station no.	$P\text{-}PO_4$		Org. P		Total N
	Conc.	% TN	Conc.	% TN	
1	11.74	78.5	3.21	21.5	14.95
2	20.74	87.5	2.95	12.5	23.69
3	16.80	82.1	3.84	17.9	20.46
4	6.62	68.7	3.01	31.3	9.63
5	4.80	93.9	0.31	6.1	5.11
6	1.56	80.8	0.37	19.2	1.93
7	0.84	87.0	0.12	13.0	0.96
8	0.86	87.0	0.10	13.0	0.78
9	0.94	93.9	0.06	6.1	1.00
10	1.72	91.6	0.16	8.4	1.88
11	0.21	80.0	0.05	20.0	0.26
12	26.15	84.4	4.82	15.6	30.97
13	74.11	67.7	35.36	32.2	109.47
Average	42.93		19.29		62.21
Average Red Sea	0.01-0.05* 0.2-0.9**		–		–

*From Weiker (1987) for open Red Sea water.

**From El Rayis (1998) for coastal water close to a sewage discharge effluent (Jeddah coast).

Examination of the nitrogen-phosphorus atomic ratio may provide interesting information about the processes taking place in the environment. Close to the source points the ratio showed slight variability and ranged between 5 and 6.7. At the mid distance stations (stations 6-10), the ratio increased slightly and ranged between 6 and 7.7. At the outer most station 11, the ratio dropped to 3.4. These differences may be interpreted in terms of internal processes. The increase at the mid stations is most likely due to the mineralization of the organic nitrogen, which results in the production of some ammonium as will be confirmed by the results of the laboratory experiment. The decrease at the outer most station is seemingly the result of enhanced consumption due to the decrease of the SPM concentration and the increase of light transparency. This decrease is accompanied by an important increase in the percentage of organic nitrogen. These processes will not significantly influence the almost conservative behavior of both nitrogen and phosphorus.

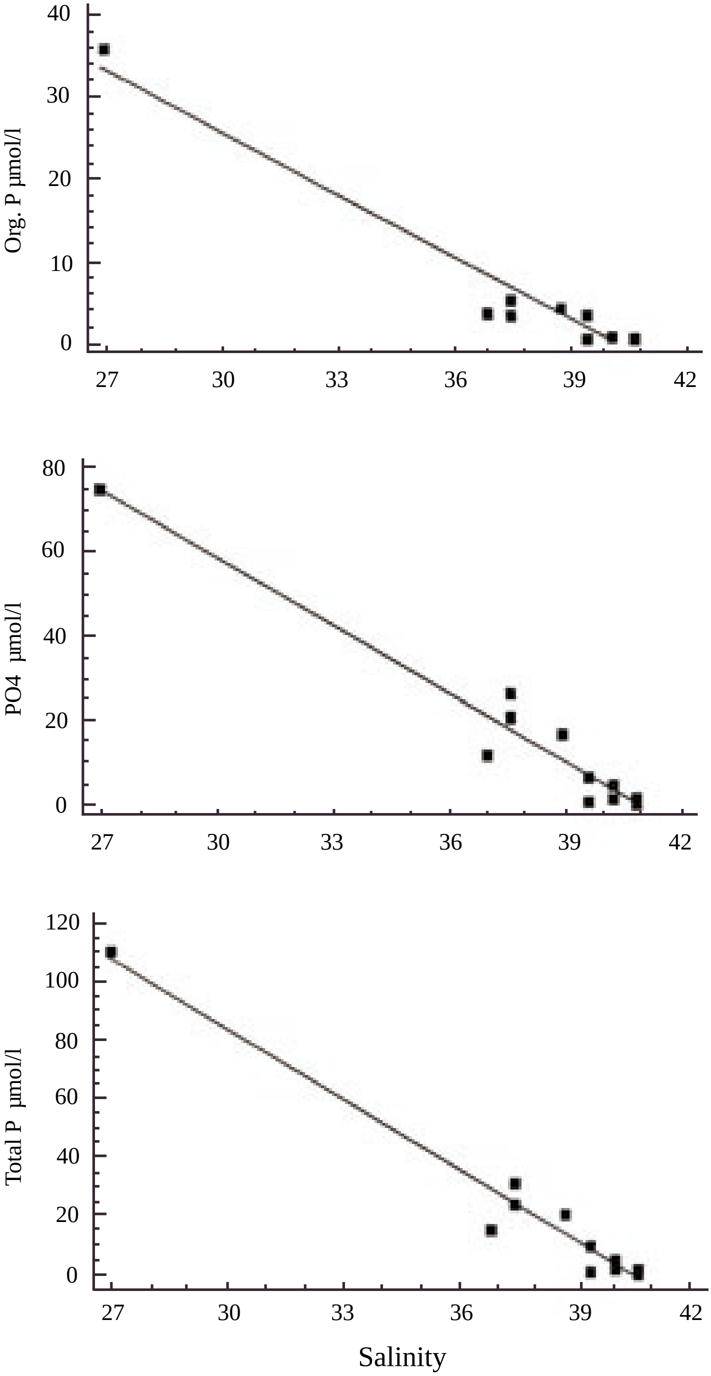

FIG. 8. Relationship between phosphorus components and salinity.

Flux Estimation

Based on the results of this study a tentative was undertaken to calculate the daily fluxes of phosphorus and nitrogen that reaches the lagoons and the organic matter that may result from their assimilation by the photosynthetic activity. The results should be taken with precaution because the real values would only be obtained by analyzing the effluent itself. The approach is based on the relationship between salinity and the measured variables. The linear relationship with salinity assumes that the two effluents have approximately the same composition. This is supported by the comparable N/P molar ratios, which averaged 5.75 in Al-Shabab lagoon (stations 1 to 5) and 5.25 in Al-Arbaeen lagoon (Sts. 12-13). The concentrations in the effluents can therefore, be determined by extrapolation to zero salinity using the linear regression equations (Table 4). The results of the extrapolation seem coherent and acceptable because they are comparable to measurements taken in the effluent of Al-Khumra STP which uses the same type of treatment (El-Sayed, 2002). It may be noticed that the concentrations of organic nitrogen and phosphorus are augmented by 1000 and 60 µmol l^{-1} respectively when concentration at station. 13 was introduced indicating the importance of the fish market as source of nitrogen and phosphorus. The daily flux from the effluent was calculated using concentrations at zero salinity (Table 4) after omitting station 13 and the daily hydraulic flow. About 2000 kg of nitrogen and 800 kg of phosphorus are delivered daily to this limited coastal area (Table 5). The global nitrogen and phosphorus budget across Bab Al Mandab Straits are strongly unbalanced (Morcos, 1970; Grasshoff, 1975; Khimista and Bibik, 1979; Naqvi *et al.*, 1986; Bethoux, 1988) Annual phosphorus and nitrogen deficiency were estimated to be 0.4×10^9 and 62×10^9 mol respectively (Bethoux, 1988). The annual contribution from these two sewage effluents would represent about 0.01 and 0.0002% of the phosphorus and nitrogen deficiency respectively.

Table 4. Linear regression equations of N and P species on salinity and comparison between concentrations at zero salinity and concentrations in Al-Khumra sewage effluent.

Regression equation	n	R-squared %	P	Concentration at zero salinity µmol l^{-1}	Concentration in the effluent in Al-Khumra WTS*
$NO_2 = 31.8 - 0.77 \times$ salinity	12	59.52	< 0.01	31.8	23
$NO_3 = 82.5 - 1.96 \times$ salinity	12	52.72	< 0.01	82.5	78
$NH_4 = 1098 - 26.9 \times$ salinity	13	94.78	< 0.01	1098	1259
Org. N = 1549 – 38.8 × salinity	13	90.44	< 0.01	1549	–
Org. N = 277 – 6.67 × salinity	12	74.27	< 0.01	227	–
Total N = 2653 – 65.6 × salinity	13	96.28	< 0.01	2653	–
$PO_4 = 218.9 - 5.37 \times$ Salinity	13	95.02	< 0.01	219	90

TABLE 4. Contd.

Regression equation	n	R-squared %	P	Concentration at zero salinity µmol l^{-1}	Concentration in the effluent in Al-Khumra WTS*
Org. P = 101 – 2.51 × Salinity	13	94.49	< 0.01	101	–
Org. P = 44.9 – 1.01 × Salinity	12	71.55	< 0.01	45	–
Total P = 321 – 9.88 × Salinity	13	96.48	< 0.01	321	–
Total P = 268 – 6.54 × Salinity	12	74.01	< 0.01	268	251

*Data from El Sayed (2001).

TABLE 5. Estimates of the approximate daily fluxes of nitrogen and phosphorus to the study area*.

Component	Daily flux µmol day^{-1}	Daily flux kg day^{-1} as N & P
Nitrite	3.2×10^9	45
Nitrate	8.3×10^9	116
Ammonium	1.1×10^{11}	1537
Org. N	2.27×10^{10}	311
Tot. N	1.44×10^{11}	2009
Phosphate	2.2×10^{10}	680
Org. P	45×10^8	140
Tot. P	2.68×10^{10}	830

*Results from St. 13 are omitted.

Inorganic nitrogen and phosphorus species are readily consumed by phytoplankton to build organic matter, given the conditions of light, temperature and residence time are favorable. If we assume that all the conditions were combined to ensure complete utilization of the available nutrients, the potential organic algal production could be calculated using the average composition, given by Redfield (1958), represented by the formula $C_{106}N_{16}P_1$, and considering organic carbon as forming 50% of the mass of the organic matter. One gram of nitrogen will be equivalent to ~11 g of organic matter and 1 g of phosphorus will produce ~82 g of organic matter. Accordingly, the estimated daily flux of inorganic nitrogen would result in a potential organic matter production of about 19 ton, while daily inorganic phosphorus delivery would produce about 56 ton of organic matter; the production will be decided by the limiting element. Due to the conservative behavior of nitrogen and phosphorus species in the two receiving lagoons, this potential organic load will be exported to the adjacent coastal area and its spreading will depend on the prevailing surface currents.

Anoxic conditions observed in the area are therefore the result of the accumulation of the dissolved and particulate organic matter discharged into the area; primary productivity does not play a significant role.

Evolution of Nitrogen and Phosphorus Species under Aerobic Conditions

Water used in this experiment was sampled from station 1. The sample had a salinity of 37, which means that it is composed of a mixture of seawater (~92.5%) and effluent water (~7.5%).

Results of the incubation experiment are presented in Tables 6&7. The common feature between nitrogen and phosphorus evolution is the appreciable increase in the concentration of the total element. In both cases the totality of the increase was almost achieved within the first week. The average increase over the thirty days experiment was about 46% for nitrogen and 36% for phosphorus with respect to the starting concentration. Since the incubated samples were not filtered, the possible source of this extra nitrogen and phosphorus is the release from the particulate organic matter present in the sample.

TABLE 6. Evolution of nitrogen species during incubation under aerobic conditions.

Incubation days	NO_2		NO_3		NH_4		Org. N		Total N μmol l^{-1}
	μmol l^{-1}	%	μmol l^{-1}	%	μmol l^{-1}	%	μmol l^{-1}	%	
0	4.21	4.1	12.85	12.60	61.2	59.9	23.9	23.4	102.2
8	1.81	1.2	0.22	0.14	92.1	61.0	57.0	37.7	151.1
14	0.71	0.47	0.80	0.50	104.0	68.1	47.2	30.9	152.7
21	1.21	0.86	1.18	0.84	105.1	75.0	32.6	23.3	140.0
30	68.57	44.9	64.05	42.00	24.1	15.8	Nd	–	152.7

Nd: not detected; % per cent of total N.

TABLE 7. Evolution of reactive phosphate, organic phosphorus and total phosphorus during incubation under aerobic conditions.

Incubation days	Reactive phosphate		Organic P		Total P μmol 1^{-1}
	μmol l^{-1}	%	μmol l^{-1}	%	
0	11.7	78.5	3.21	21.5	14.95
8	17.9	91.7	1.23	8.3	19.47
14	20.8	96.0	0.86	4.0	21.69
21	19.0	93.2	1.39	6.8	20.38
30	15.6	81.7	3.49	18.3	19.04

%: Per cent of total P.

The molar ratio of the total inorganic nitrogen to inorganic phosphorus at the beginning of the incubation (t = 0) was about 6.7:1. After 30 days of incubation, the ratio calculated for the additional inorganic nitrogen and phosphorus was found to be 12:1*. This means that the additional dissolved nitrogen and phosphorus were provided by particulate organic material having approximately the algal composition $C_{106}N_{16}P_1$ (Redfield, 1958). SPM concentration in the sample was approximately 25 mg l^{-1}. Considering that organic carbon represents 40% of the sewage solid material (Aminot and Guillaud, 1990; El Sayed, 2001), particulate organic carbon concentration in the sample would be about 10 mg l^{-1}. If the particulate material had approximately the algal composition, mineralization of only 50% of the particulate organic matter in suspension in the sample would be largely sufficient to account for the total increase of dissolved nitrogen and phosphorus. Newell *et al.* (1981) found that marine bacteria achieved 50% utilization of dissolved and particulate organic carbon of phytoplankton debris in 1.56 and 11.56 days respectively.

Total nitrogen remained almost unchanged after the first 8 days of incubation, however, internal transformations continued (Fig. 9). Nitrite and nitrate behaved almost identically. They suffered a relatively important loss during the first week. During the two succeeding weeks their concentrations remained very low but increased smoothly. By the end of the month their concentrations increased rapidly by an amount equivalent to the sum of the loss that ammonium and organic nitrogen have suffered. Transformations of nitrogen species appear to proceed according to the following order: During the first week partial transformation of particulate organic nitrogen to dissolved organic nitrogen (DON) and ammonium. During the second and third weeks DON was partially transformed to ammonium. In the fourth week mineralization of DON and ammonium to nitrite and nitrate took place. The presence of nitrite in great concentrations after 30 days suggests that the kinetics of nitrite oxidation is relatively slow and/or the presence of nitrite oxidizing bacteria in limited abundance.

Reactive phosphate increased while organic phosphorus decreased during the first two weeks (Table 7). However, dissolved organic phosphorus could not account for the entire increase. Mineralization of particulate organic phosphorus is probably the source of part of the excess inorganic phosphorus. Recycling of detritus at the sediment water interface in particular with respect to phosphate can be very rapid (Krom and Berner, 1981). Surprisingly, during the third and fourth weeks the concentration of organic phosphorus increased at the expenses of phosphate. This may only come from biological activity, however, the absence of any parallel nitrogen evolution is disconcerting. The increase of organ-

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*In order to minimize the interference from any possible phosphate adsorption on the walls of the containers, the phosphate value is represented by the average of the last three readings in Table 7.

ic phosphorus is, however, not sufficient to explain the total loss of phosphate, the difference may be attributed to adsorption on the walls of the containers.

The role played by the organic detritus in the recycling of nutrients is very effective (Bulleid, 1984). However, the rate at which regenerated nutrients are made available to the surface water will depend on the settling velocity of the particles and the stability of the water column. Since the water column in the two lagoons is characterized by prolonged periods of stability, nutrients build up particularly ammonium and phosphate, and the retention of these nutrients in the deep-water layers is highly expected.

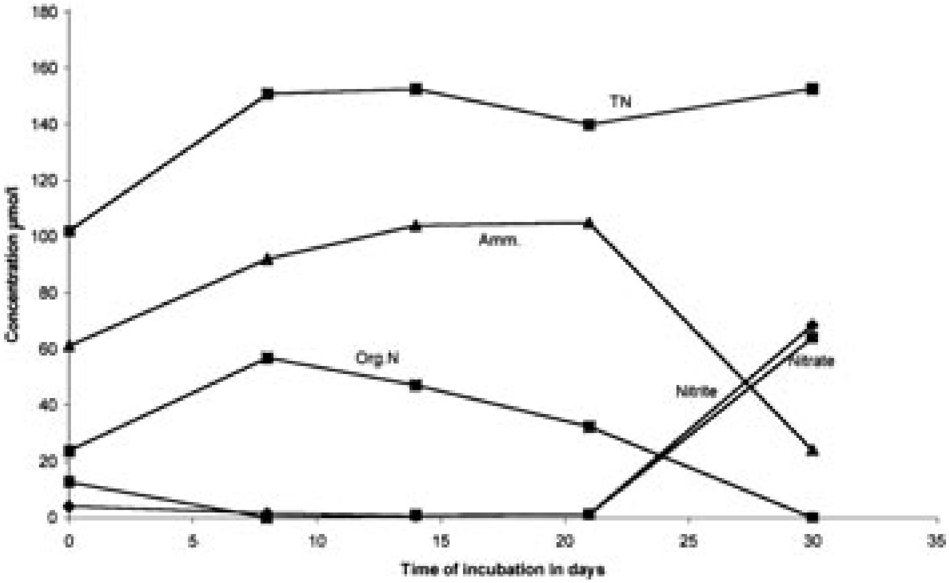

FIG. 9. Transformation of nitrogen species during laboratory incubation.

The results of this laboratory experiment, while offering interesting information on the nature and kinetics of the possible transformations that may take place in the environment; it could not be fully utilized in the interpretation of the field observations. This is due to the short residence time of the effluent water in the area relative to the time interval of the experiment. However, if we admit uniform addition/loss rate constants during the first week, it would be possible to calculate a value representing the order of magnitude of the process(s) taking place during the effluent residence in the area. Results are presented in Table 8 and are compared to the dilution rate by seawater as given by the slope of the regression equations (Table 4). It appears that the dilution effect largely dominates the magnitude of any addition or loss process during the effluent residence in the area (~1.5 day) resulting in the apparent conservative behavior of most of the components. Biological consumption might also be insignificant during this relatively short residence time.

TABLE 8. Kinetics of the addition and loss processes of the different species of nitrogen and phosphorus during the first week of incubation and comparison between the estimated addition or loss during the effluent transit in the area and the dilution rate by seawater.

Species	Rate constant µmol day^{-1}	Gain in 1.5 day µmol	Loss in 1.5 day µmol	Dilution rate µmol/unit salinity
Nitrite	– 0.3	–	0.45	0.77
Nitrate	– 1.58	–	2.20	1.96
Amm. N	+ 3.86	5.79	–	26.9
Org. N	+ 4.14	6.21	–	6.7-38.8
Total N	+ 6.98	10.47	–	65.6
Phosphate	+ 0.77	1.15	–	5.37
Org. P	+ 0.25	–	0.37	1.0-2.5
Total P	+ 0.88	1.32	–	6.54-9.88

[*]The slope in the regression equations given in Table 4.

Conclusion

About 100,000 m^3 day^{-1} of treated and untreated domestic sewage are discharged from two sewage effluents situated at the borders of two coastal lagoons in the central part of the Red Sea. The discharge water introduced important modifications on the physical and chemical characteristics of the receiving water body clearly demonstrated by the abnormal values of salinity, dissolved oxygen, pH and suspended solids.

Great quantities of dissolved phosphorus and nitrogen are discharged with the effluent. Most of the components of phosphorus and nitrogen cross the area without significant modifications. However, some field observations and separate laboratory experiments have shown the dynamic character of the nitrogen and phosphorus species. Dissolved species are liberated from particulate fraction and further transformations are taking place between the dissolved organic and inorganic forms. Denitrification is taking place in the most reducing locations. The apparent conservative character of the components of phosphorus and nitrogen is attributed to the relatively short residence time of the effluent in the area compared to the kinetics of transformation and algal consumption.

Under favorable ecological conditions, *i.e.* light intensity, temperature and residence time, the consumption of the inorganic species of nitrogen and phosphorus by the phytoplankton would result in the production of large quantities of algal organic matter in the adjacent coastal area. The accumulation of the organic matter discharged with the effluent water is responsible for the anoxic conditions observed along the water column excepting the surface layer.

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توزيع وسلوك صور النيتروجين والفوسفور الذائب في اثنتين من بحيرات البحر الأحمر الساحلية تستقبل مياه الصرف الصحي

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المستخلص. اثنتين من محطات معالجة مياه الصرف الصحي تصبان يومياً حوالي ١٠٠٠٠٠ م٣ من المياه في بحيرتي الشباب والأربعين أمام مدينة جدة. وقد أجريت هذه الدراسة للتعرف على تأثير صب هذه المخلفات على هيدروكيميائية المنطقة وسلوك الأملاح المغذية بها.

أظهرت الدراسة أن الخصائص الطبيعية والكيميائية للمياه قد تعرضت لتغيرات ملحوظة حيث انخفضت الملوحة والأس الهيدروجيني بشكل ملحوظ عند نقاط الصب مقارنة بالمياه الطبيعية للبحر الأحمر بينما ارتفعت بالابتعاد عن هذه النقاط. كما أن تركيزات الأملاح المغذية كانت أكبر بكثير من تلك المقاسة فى مياه البحر بعيدة عن المصادر الأرضية. شكل النيتروجين العضوي والأمونيوم أكثر من ٩٠٪ من النيتروجين الكلى بالقرب من موقع المصبات بينما كان الفوسفات الفعال هو المكون الرئيسي للفوسفور الكلى حيث شكل ما بين ٦٨ و٩٤٪ من الأخير فى منطقة الدراسة.

وتشير الحسابات الى أن المنطقة تستقبل يومياً حوالي ٢٠٠٠كجم من النتروجين و٨٠٠ كجم من الفوسفور غير أنه يجب اعتبار هذه النتائج تقريبية للغاية. وأظهرت التجارب المعملية علي عينة مياه أخذت عند نقطة المصب في بحيرة الشباب تحرر ٤٦٪ و٣٦٪ من قيمة النيتروجين والفوسفور غير العضوي الذائب خلال أسبوع نتيجة التحلل الهوائي للمواد العضوية العالقة وكذا وجود أدلة على عمليات تحول نشطة ما بين الصور المختلفة للفوسفور والنيتروجين الذائب وهذا يتعارض مع النتائج

الحقلية التي أظهرت السلوك المحافظ لكل المكونات. وقد عزي هذا التعارض إلى قصر زمن إقامة المياه في المنطقة وبطأ عمليات التحول.

كلمات دالة : مياه ساحلية ، أملاح مغذية ، توزيع ، سلوك ، البحر الأحمر.