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NITROGEN AND PHOSPHORUS IN THE EFFLUENT OF A SEWAGE TREATMENT STATION ON THE EASTERN RED SEA COAST: DAILY CYCLE, FLUX AND IMPACT ON THE COASTAL AREA

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The Al Khumra Sewage Treatment Station discharges daily more than 100,000 m^3 of treated and untreated sewage into the coastal Red Sea south of Jeddah. In the effluent water, $NH_4^+ - N$ constitutes more than 90% of the total inorganic nitrogen while reactive phosphate represents about 35% of the total phosphorus. The daily input of phosphorus and nitrogen is approximately one and six tons, respectively, corresponding to a potential production of 21–22 tons of algal organic matter. The impact of the effluent on the receiving environment was felt through a net lowering of the salinity and temperature and the spectacular increase of oxygen saturation and nutrient concentrations.

In the dilution basin nitrogen and phosphorus exhibited opposed behavior. Nitrogen was reduced by more than 40%, probably due to planktonic and algal consumption. Reactive phosphate was regenerated (100% gain) and total phosphorus suffered 21% loss. Mineralization of organic phosphorus and desorption of phosphate are assumed to be the principal sources of the excess reactive phosphate. The real daily formation of organic matter in the dilution basin was estimated to be about 9 tons; 12 tons are therefore exported every day to the coastal area.

Keywords: Nutrients; Sewage deposal; Coastal water; Behavior; Budget; Red Sea

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INTRODUCTION

Recent estimates concerning the various characteristics and properties of the coastal zone demonstrate the global importance of this area for humanity and for geochemical cycles. Despite its comparatively small surface area and volume (18% of the surface of the globe, 8% of the surface of the ocean and less than 0.5% of its volume), around 60% of the human population live in the coastal domain where two thirds of the world's big cities are located. The coastal waters supply around 14% of the global ocean production and approximately 90% of the world fish catch.

The anthropogenically driven changes in the coastal areas are intense. This is due to the elevated population density and the rapid rate of population growth. 90% of the land based pollution including sewage, nutrients and toxic materials remain in the coastal areas. The anthropogenic flux of dissolved nutrients from land is now equal to and in some areas greater in excess of the natural flux [1].

In the presence of favorable conditions of light and temperature, the high anthropogenic input of nutrients to the coastal waters will provoke a high rate of production, organic matter can 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 as well. 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 biomineralising 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 due to the presence of excess nitrogen and phosphorus.

The eastern coast of the Red Sea is approximately 2000 km long. Its coral reef community is one of the most diverse in the world. The importance of the coral reef zones as suitable environment for feeding, breeding and nursery ground for marine organisms has been recognized by several ecologists [2, 3]. However, coral reefs are seriously endangered, due to intense wastewater dumping in the coastal waters. The city of Jeddah is situated at the central part of the Red Sea eastern coast. With about 2 million inhabitants it is one of the most important urban agglomerations in the area. The city's wastewater treatment is undertaken by several sewage treatment stations (STS). Al Khumra is the most important. It was constructed to receive 40000 m^3 per day of wastewater. Due to the rapidly growing population the capacity of the station has recently been doubled. However, the station still receives more than its capacity and several thousands of cubic meters are daily by-passed without any treatment. The mixture of treated and untreated sewage is dumped into a semi closed basin south of the city. Natural islets and an artificial sand barrier, south of the discharge point, limit water exchange and control the direction of water circulation.

This work aims at: 1- following the daily cycle of the different dissolved species of nitrogen and phosphorus in the effluent water and to estimate their flux; 2- studying their distribution and behaviour in the receiving coastal area and their potential impact on the environment.

SAMPLING AND ANALYTICAL METHODS

Eighteen water samples were hourly collected from the effluent in one-liter polyethylene bottles. Containers were previously prepared according to the recommendations given by Aminot and Chaussepied [4]. Sampling started at 07 o'clock and was planned to continue over twenty-four hours, however, due to some logistic problems, sample collection was stopped at midnight and only eighteen hours of the daily cycle were covered. Surface water samples were also collected from 18 selected sampling stations in the dumping site (Fig. 1). Samples were collected using Niskin bottles. Immediately, sub-samples were taken for the analysis of oxygen and salinity, and temperature was measured using an ordinary thermometer graduated from $0-100°C$. Samples for the analysis of nutrients were kept, without

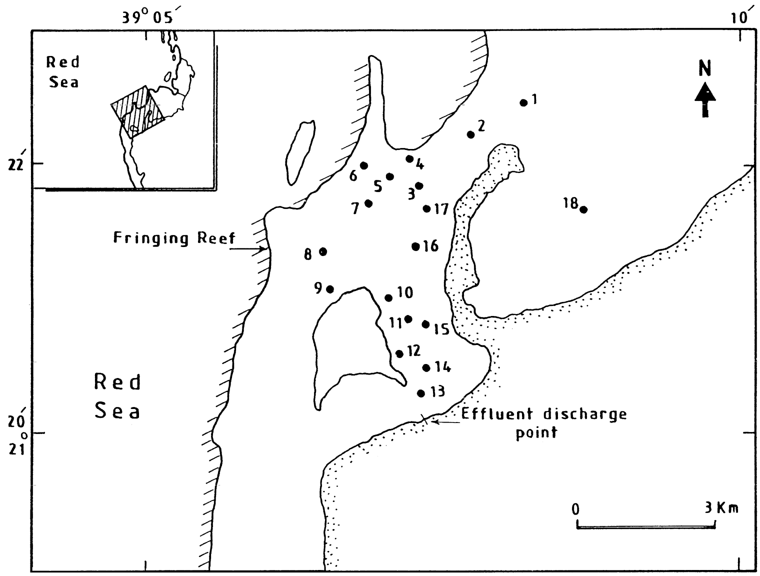

FIGURE 1 Area of the effluent discharge and sampling locations.

any particular treatment, in iceboxes until returned to the home laboratory. In the laboratory samples were immediately filtered using Whatman GF/C membranes and stored at −20°C until analysed. Analysis of reactive phosphate, ammonium nitrogen, nitrite, nitrate, dissolved oxygen and chlorinity were carried out using the classical methods [4] (Aminot and Chaussepieds, 1983). Total phosphorus (dissolved and dissolved+particulate) was determined using the persulphate method [5].

RESULTS AND DISCUSSION

The Effluent

Daily Profiles

The daily profiles of the chemical constituents of a sewage effluent are determined by the different activities connected to the network and the hydraulic flow, which determines the time of transit in the network and in the station itself. This factor is of great importance since it controls the degree of advance of some important processes such as the mineralization of the organic matter, adsorption-desorption, nitrification-denitrification and hydrolysis.

A statistical summery of the analytical results is given in Table I. Reactive phosphate showed a relatively limited variability relative to nitrogen species. Surface reactions of phosphate are known to be active and have been shown to buffer phosphate concentration in rivers [6], estuaries [7] and interstitial water of marine sediments [8]. Phosphate adsorption is a process very sensitive to pH fluctuations. The pH variation in the effluent water (Tab. I) is relatively limited, however, most of the values lies in the range where the adsorption process is effective [9]. Reactive phosphate represents about 35% of total P while polyphosphate and organic P represent about 25%. The daily profiles of nitrite and nitrate showed a reversed trend with respect to ammonium nitrogen (amm.-N) (Fig. 2). Oxidized nitrogen

TABLE I Summery statistics of the measured parameters in the effluent water

Variable	*pH*	PO_4^{3-} *μmol/l*	*P-total μmol/l*	*P/Ptot.*	*Amm. μmol/l*	NO_2^- *μmol/l*	NO_3^- *μmol/l*	N_t* *μmol/l*	*N/P atom·ratio*
Sample size	18	18	11	11	18	18	18	18	18
Average	7.28	88.2	251	2.9	1259	22.5	77.9	1359	15.98
RSD	1.5	20.86	30	0.44	31.37	114.2	148.6	22.36	30.48
Minimum	6.96	48.5	184	2.4	533	1.1	0.3	835	9.02
Maximum	7.41	114	282	3.7	1967	63.4	367.1	1981	31.69
Range	0.45	65.5	98	1.3	1434	62.3	366.8	1146	22.67

* Total inorganic N.

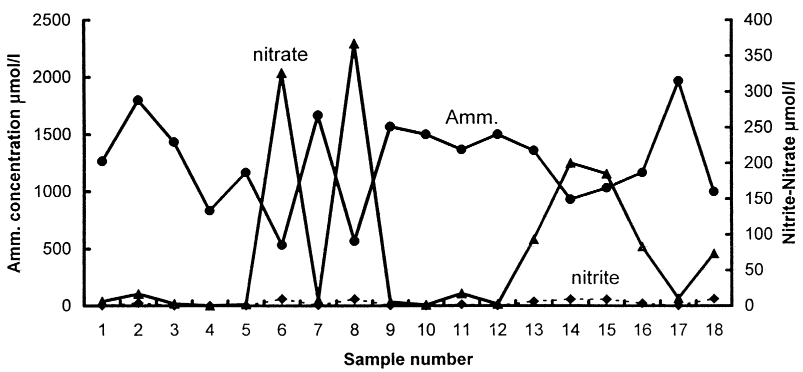

FIGURE 2 Daily cycle of nitrite, nitrate and ammonium-N in the effluent water.

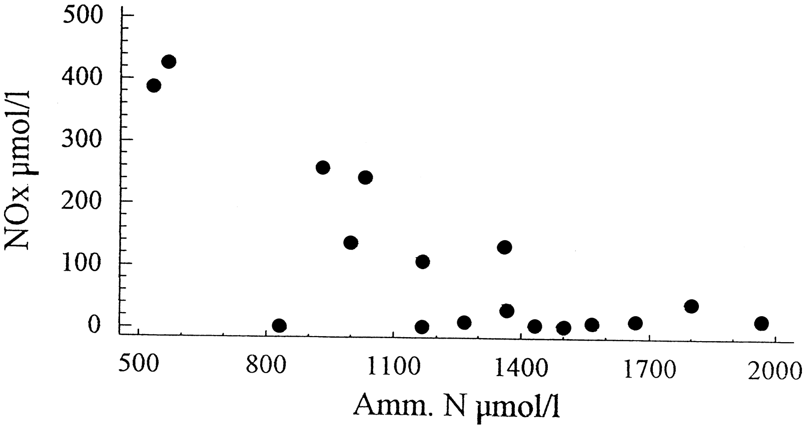

FIGURE 3 Relation ship between the sum of nitrate and nitrite and ammonium-N.

species are peaking when amm-N is the lowest, and they are maintained at very low level when amm.-N reaches about 1000 µmol l^{-1} (Fig. 3). This configuration is indicative of the interplay of reducing and oxidizing conditions and it seems that the nitrification-denitrification process is determinant in the speciation of the combined nitrogen. The presence of high amm.-N concentrations ($>90\%$ of total inorganic nitrogen) is indicative of the dominance of reducing conditions.

Nature of the Effluent

The nature of the wastewater collected by the network could be recognized using the N/P ratio. The daily profile of N/P atomic ratio seems relatively homogenous (Fig. 4), 77% of the samples have values lying between 12 and 17. The daily average of the N/P atomic ratio (16) is comparable to that of the human excretion [10]. This means that the major source of dissolved nitrogen and phosphorus is the domestic wastes and that other types of wastes are of minor importance. The absence of measurable concentrations of Pb and Cd (unpublished data) supports this assumption. This conclusion agrees with the fact that only food-processing industries (contribute about 20% of the charge) are attached to the network.

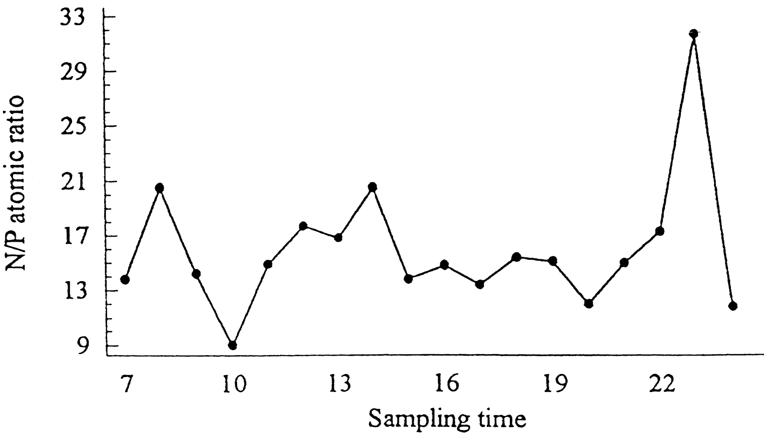

FIGURE 4 Daily cycle of the N/P atomic ratio.

The general characteristics of the effluent could be summarized in the following points:

- Domestic sewage is the major constituent of the effluent,
- Amm.-N is the major component of the inorganic nitrogen; the distribution of nitrogen species is controlled by mineralization and nitrification/denitrification processes,
- Dissolved P species constitutes about 60% of the total P; buffering processes such as adsorption/desorption seem regulating the reactive phosphate concentration.

Global and Specific Flux

The daily global flux of the different species of N and P could be calculated using the average concentrations (Tab. I) and the average official hydraulic flow. The results (Tab. II) indicate that the effluent carries daily a minimum of one tone of phosphorus and six tons of nitrogen to the coastal area. These quantities could simply be doubled if the un-official estimations of the hydraulic flux of the station (200,000 m^3) were revealed true.

The global nitrogen and phosphorus budgets across Bab Al-Mandab are strongly unbalanced [11 – 15]. The nitrogen and phosphorus flux (Tab. II) was compared to annual deficiency in the Red Sea-Gulf

TABLE II Daily flux of the different components of N and P to the coastal area*

Constituent	*Flux mmol/day*	*Flux kg/day*
P-PO_4	8.8×10^6	273
Total P**	2.6×10^7	819
NH_4-N	1.3×10^8	1763
NO_2-N	2.2×10^6	31
NO_3-N	7.8×10^6	109
N_{ing}-total	1.4×10^8	1903
Total N**	4.1×10^8	5706

* Calculated on the basis of an average daily discharge of 100,000 m^3.
** Reactive phosphate and total inorganic nitrogen constitute one third of total P and N respectively as given in Table I.

of Aden budget, and the results are presented in Table III. It is clear that addition from terrestrial sources may contribute appreciable quantities of nitrogen and phosphorus to the Red Sea budget.

Comparison between the different treatment stations is not possible due to the difference in the population densities. However, this comparison would be possible if the flux were calculated per inhabitant (Specific flux). The number of the population attached to the network was calculated assuming a daily water consumption of 300 l/inhab. [16] and a hydraulic flow of $1 \times 10^5 \, m^3 \, day^{-1}$. A Comparison between the specific flux calculated for this study and that given for two French stations (Tab. IV) shows clearly the weak purification efficiency of Al-Khumra STS, particularly for nitrogen. This is greatly because of the by-passed untreated sewage.

TABLE III Comparison of the annual deficiency of nitrogen and phosphorus across Bab Al-Mandab with the annual flux from the effluent and its contribution relative to the deficiency

	N *mol*	*P* *mol*
Annual deficiency*	62×10^9	0.4×10^9
Annual flux from the effluent	150×10^6	9.5×10^6
Contribution relative to budget deficiency	0.25%	2.25%

* From Bethoux (1988).

TABLE IV Comparison of the specific flux (g/inhab./day) of total N and P for different sewage treatment stations

Sewage treatment station	*N*	*P*
Jeddah (Al Khumra)		
This work*	19^{+}	2.73^{+}
Morlaix (1986)** #	14.5	2.70
Morlaix (1989)** #	14	2.80
Toulon (1985)** #	10–18	2.70
Usual range** ##	15	3–6
Typical values**	–	4

* Treated sewage; calculated on the basis of 300,000 inhab. Connected to the network.
** Untreated sewage.
# After Aminot and Guillaud (1990).
After Metcalf and Eddy (1979) and Degremont (1989).
$^{+}$ From Table II.

The Receiving Environment

The effect of the effluent water on the dilution basin was felt through the significant modifications of the physical and chemical characteristics of the water mass with respect to the central Red Sea water characteristics (Tab. V). The average water temperature decreased by about 3°C and average salinity was about two salinity units below the normal; fresh water represents about 4.5% of the total volume of the basin. The distribution of the two parameters (Fig. 5) is identical and shows the effluent as the principal source of the anomaly. The effluent evidently affects the whole area; in those very coastal areas, salinities higher than 40 are frequently encountered [17].

Nutrient concentrations have also suffered a substantial increase due to the effluent discharge. Concentrations of N and P are 10 to 100 folds the normal Red Sea values (Tab. V). The similarity between the distribution of the hydrographic parameters and the chemical properties (Fig. 6) indicates that the effluent is the main source of the excess nutrients. The effluent water does not appear to mix evenly with seawater in the area. The effluent water seems to be forced eastward (St. 11–17) and the basin is consequently divided into two sub-basins according to the degree of impact of the effluent (Tab. VI). This preferential circulation may result from the influence of the northwesterly prevailing wind.

TABLE V Values of some physical and chemical properties of the water in the dilution basin compared to values for average Red Sea water

	Salinity *PSS*	*Temp.* $^\circ C$	*Diss. Oxyg* $ml\ l^{-1}$	*Oxyg. satur.* %	$NO_2^- - N$ $\mu mol\ l^{-1}$	$NO_3^- - N$ $\mu mol\ l^{-1}$	$NH_4^+ - N$ $\mu mol\ l^{-1}$	Nt $\mu mol\ l^{-1}$	$PO_4^{3+} - P$ $\mu mol\ l^{-1}$	*Ptd.* $\mu mol\ l^{-1}$
N	18	18	17	17	18	18	18	18	18	18
Average	37.28	24.53	6.75	143	0.47	1.13	13.5	15.15	5.53	6.58
SD	1.15	1.53	2.15	41.4	0.61	0.91	31.6	32.88	7.31	8.12
Mini.	32.52	22.5	4.32	95	0.06	0.05	0.01	0.49	0.20	0.46
Maxi.	38.82	27.0	13.2	> 200	2.23	3.83	130	136.24	26.25	30.18
Average Red Sea Water	($\sim$39)*	(27–28)	($\sim$4.5)*	(95–115)*	$(0.1-0.2)^+$	$(0.1-0.4)^+$	(2–3)**	–	(0.01–0.05)	–

* From Edwards (1987).

** From El-Rayis (1998) for coastal waters adjacent to sewage discharge effluent.

$^+$ From Weikert (1987).

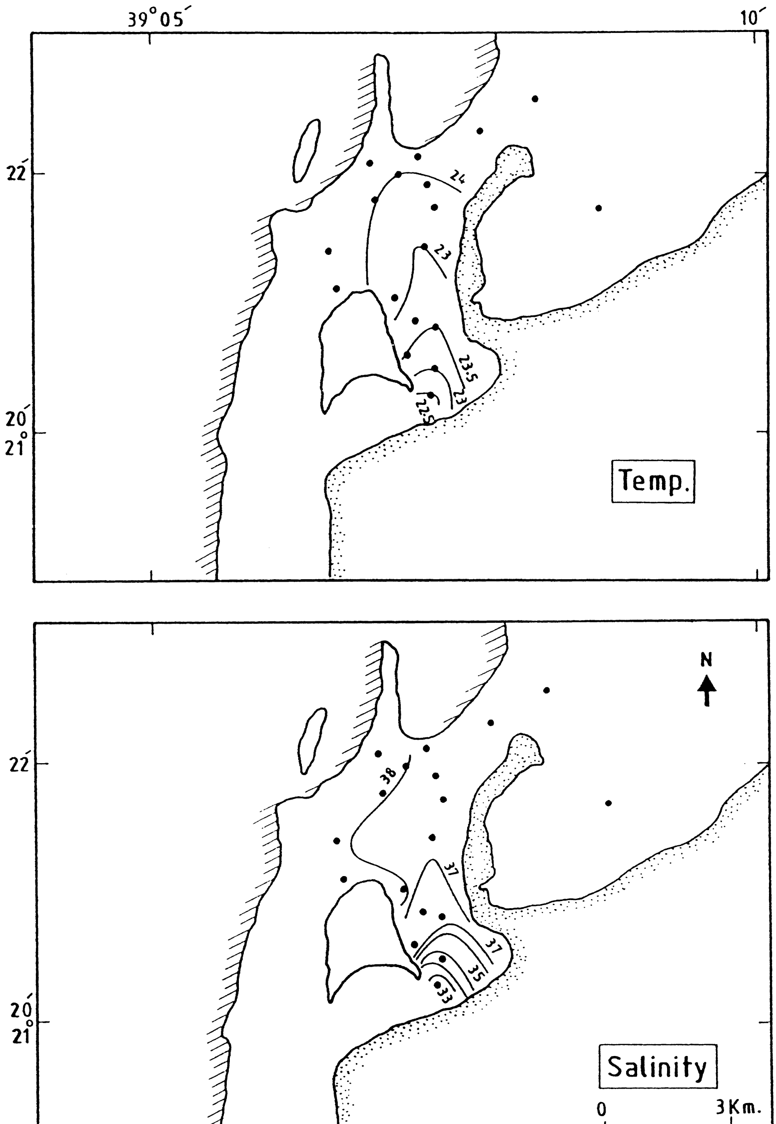

FIGURE 5 Distribution of water temperature and salinity in the dilution basin.

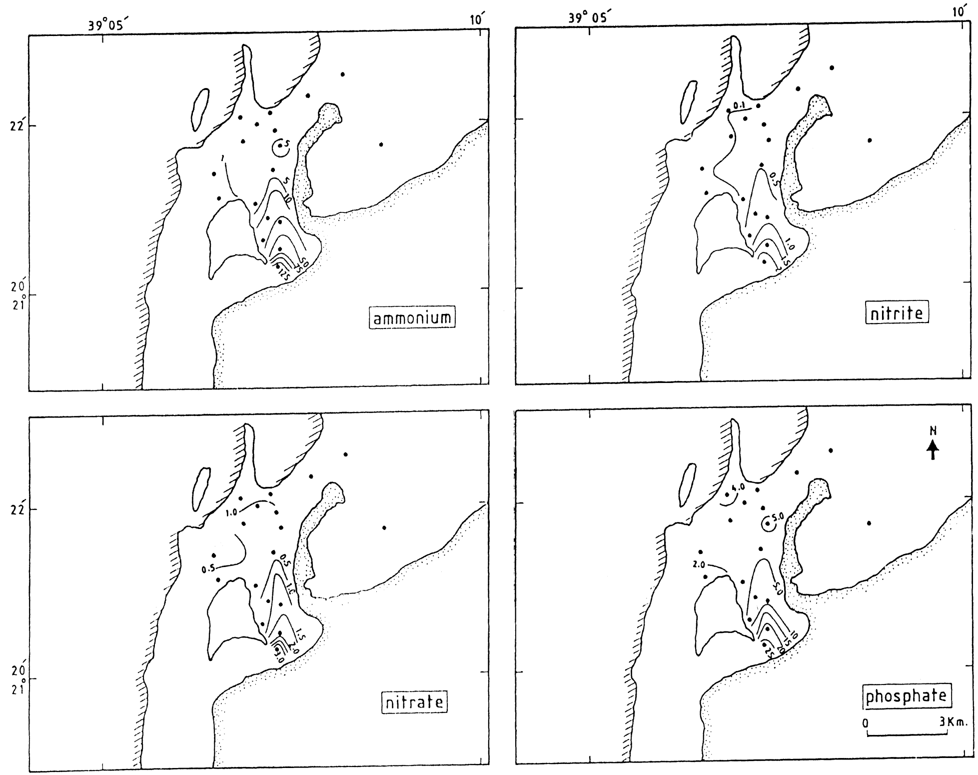

FIGURE 6 Geographic distribution of amm.-N, nitrate, nitrite and phosphate in the water of the dilution basin.

TABLE VI Average values of some physical and chemical characteristics of the slightly and heavily contaminated areas of the dilution basin

Area	*Salinity* *PSS*	*Temp.* $^\circ C$	$NO_2^- - N$ $\mu mol\ l^{-1}$	$NO_3^- - N$ $\mu mol\ l^{-1}$	$NH_4^+ - N$ $\mu mol\ l^{-1}$	Nt $\mu mol\ l^{-1}$	$PO_4^{3-} - P$ $\mu mol\ l^{-1}$	*Ptd.* $\mu mol\ l^{-1}$
Slightly contaminated	38.08	25.3	0.11	1.06	1.59	2.77	1.53	2.11
Heavily contaminated	36.02	23.3	1.05	1.24	32.31	34.61	11.83	13.6

Environmental Impact

Generally, the performance and the fulfillment of a given water treatment station to its role is based on the degree of reduction in the quantities of SPM, BOD and COD that reaches the station. This way is however far from taking in consideration the totality of the requirements of the environment. The problem should be approached on the basis of the fact that the major environmental problems associated with sewage discharge in the coastal waters are eutrophication and anoxia; both are due to organic matter accumulation. The installation of anoxic conditions will result in the disappearance of most of the living organisms and will influence the biogeochemical cycles of great number of elements.

Organic matter enrichment of the coastal marine environment due to sewage discharge could be distinguished into two components [10]: 1- a direct and measurable component represented by the organic matter discharged with the effluent; 2- an indirect and hardly measurable component corresponding to the potential algal organic matter that could build up in the receiving environment due to the nutrient supply by the effluent. The appreciation of the real magnitude of this source is hardly realizable because the consumption of the nutrients, nitrogen and phosphorus, depends on several local factors that control the algal development such as temperature, light, the limiting nutrient, and residence time. If all conditions were combined to insure a full utilization of the nutrient elements, the potential algal organic matter could be calculated using the average algal composition [18] represented by the formula $C_{106}N_{16}P_1$, and considering organic carbon as forming 50% of the mass of the organic matter. Under these conditions, the algal organic matter would be generated in the following proportions:

$$1\,\text{g dissolved inorganic nitrogen} \Rightarrow 11\,\text{g organic matter}$$

$$1\,\text{g dissolved inorganic phosphorus} \Rightarrow 82\,\text{g organic matter}$$

These ratios were used to calculate the potential organic matter flux of the effluent. It is interesting to observe that comparable quantities (21 – 22 tons) would be produced using nitrogen or phosphorus for calculation; this is because nitrogen/phosphorus ratios in the effluent are very close to the Redfield ratio.

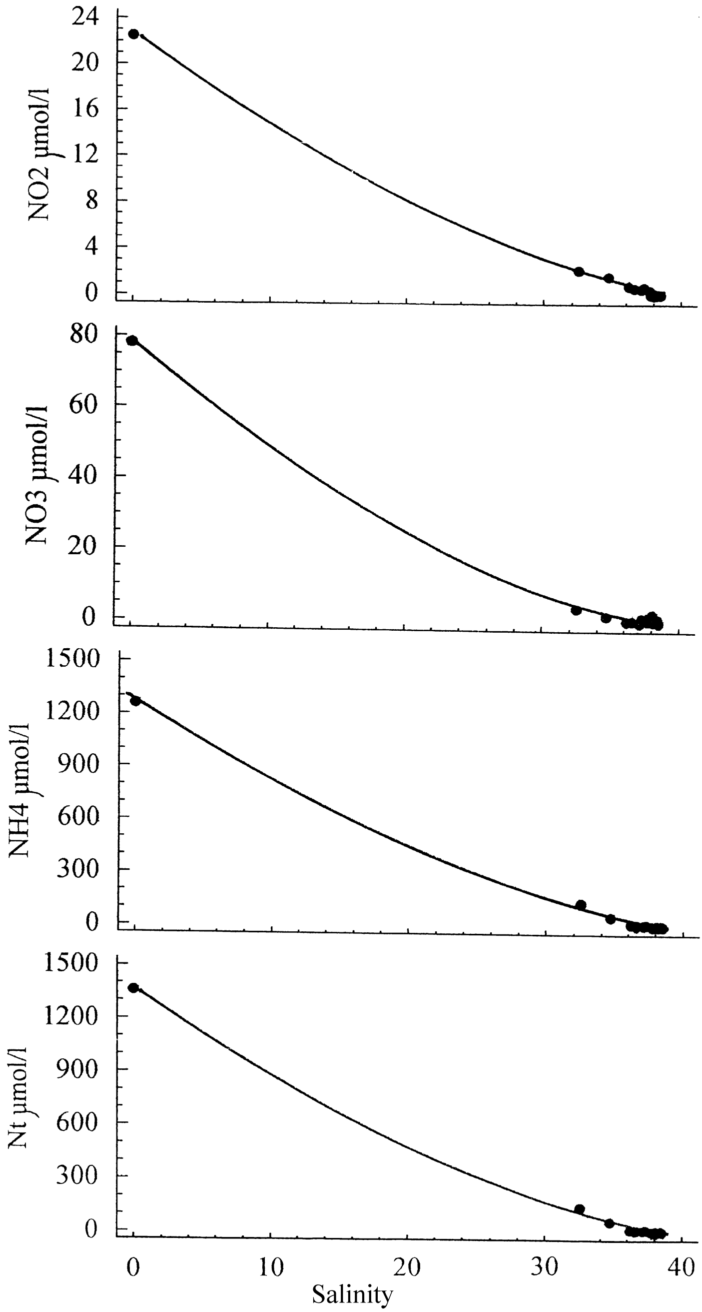

FIGURE 7 Plot of the concentration of different nitrogen species against salinity. Values at zero salinity are those measured in the effluent.

The real fate of nutrients in the dumping area could be appreciated using the salinity-nutrient relationship, the concentration at zero salinity is taken as that measured in the effluent itself. The plots of the concentration of the different nitrogen and phosphorus species against salinity (Figs. 7 and 8) indicate that all nitrogen species might suffer a significant consumption, while phosphorus is regenerated. Within the salinity range measured in the dilution basin, a significant linear correlation was found between the different components and salinity (Figs. 9 and 10). These linear regressions were used to calculate the theoretical concentrations at zero salinity (Tab. VII) and results were

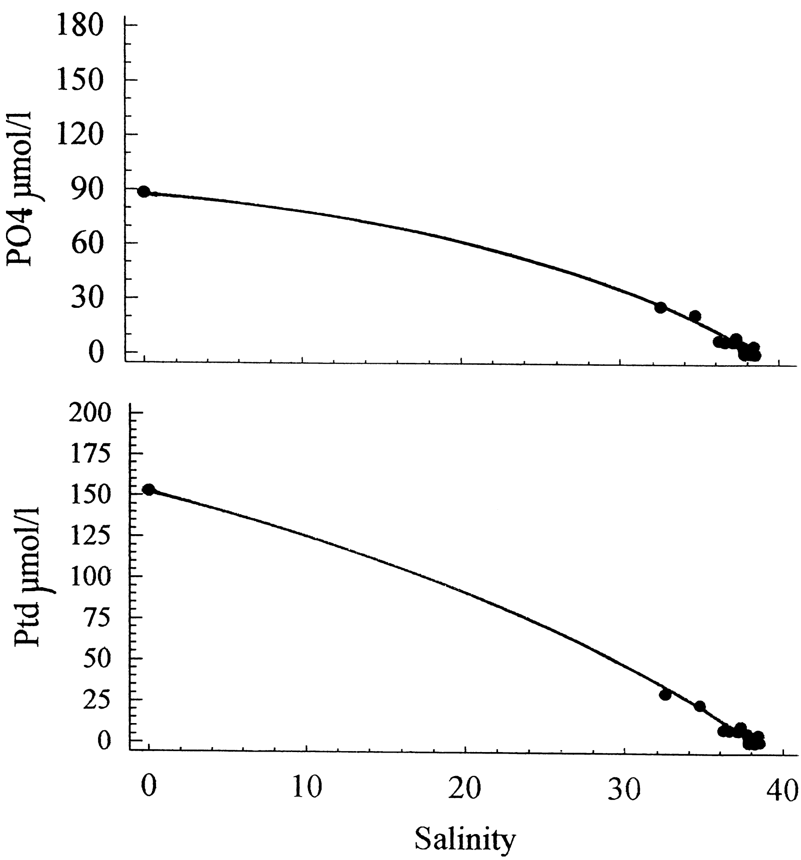

FIGURE 8 Plot of the concentration dissolved phosphate and total dissolved phosphorus against salinity. Values at zero salinity are those measured in the effluent.

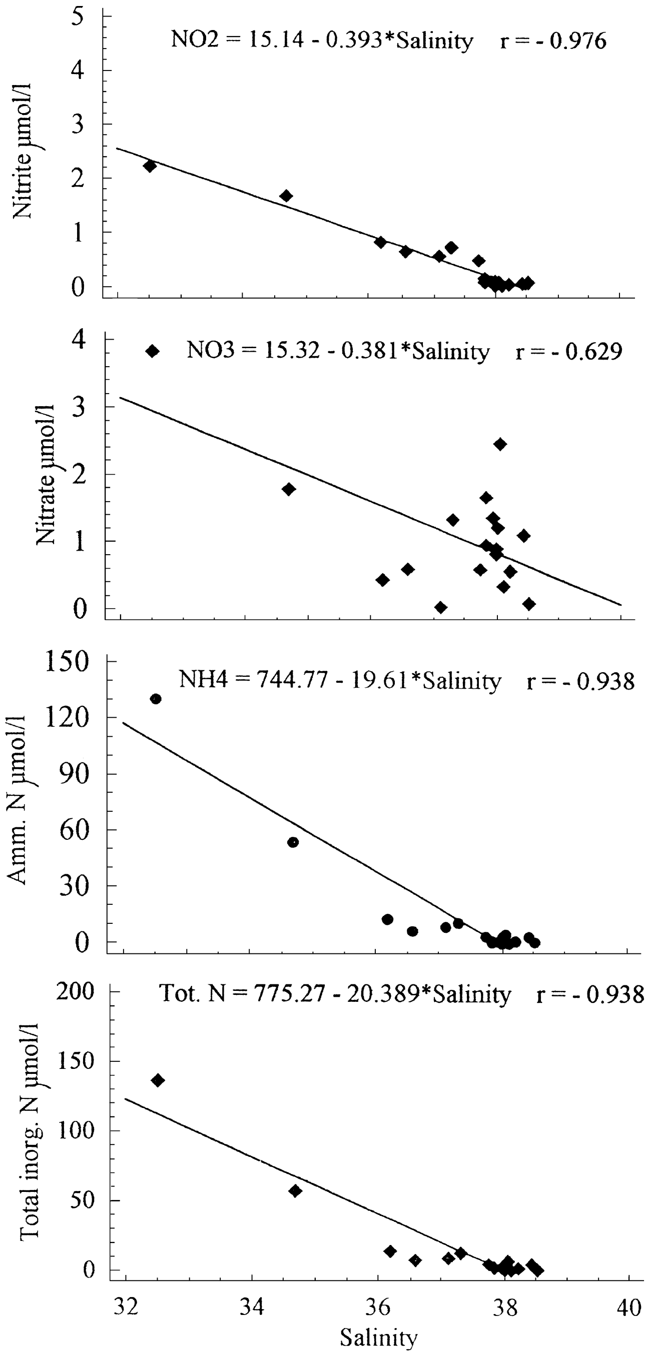

FIGURE 9 Regression of the different nitrogen species on salinity within the salinity range measured in the dilution basin.

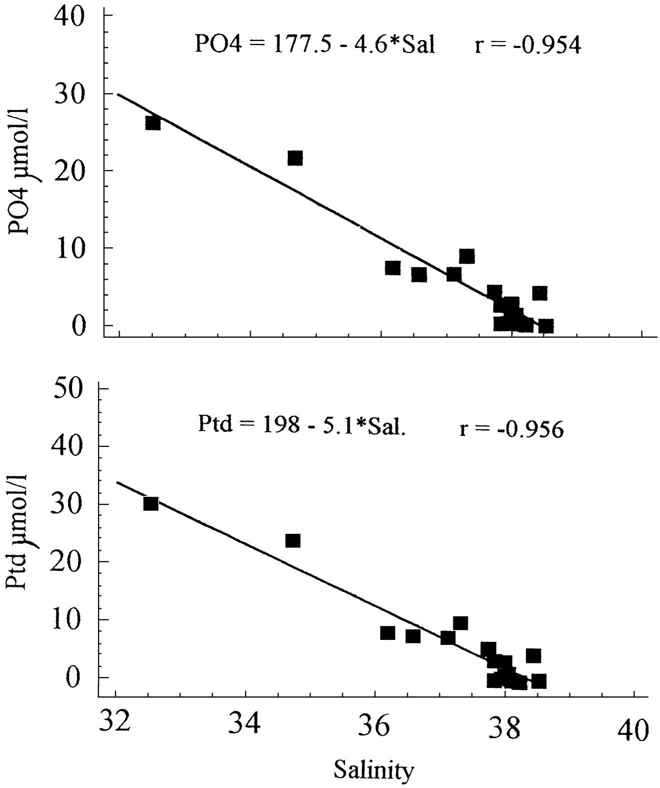

FIGURE 10 Regression of dissolved phosphate and total dissolved phosphorus on salinity within the salinity range measured in the dilution basin.

TABLE VII Linear regressions of nitrite, nitrate, ammonium-N, total inorganic nitrogen, phosphate and total dissolved phosphorus on salinity in the dilution basin

Variable	*Regression equation*	*r*	*Concentration at zero Sal. (µmol l^{-1})*
Nitrite	NO_2^- (µmol l^{-1}) = 15.14 − 0.39 × Sal.	−0.976	15.14
Nitrate	NO_3^- (µmol l^{-1}) = 15.32 − 0.38 × Sal.	−0.629	15.32
Ammonium-N	NH_4^+ (µmol l^{-1}) = 744 − 19.61 × Sal.	−0.938	744
Reactive phosphate	PO_4^{3-} (µmol l^{-1}) = 178 − 4.61 × Sal.	−0.954	178
Total dissolved P	Ptd. (µmol l^{-1}) = 198 − 5.1 × Sal.	−0.956	198

compared to the real concentrations in the effluent to calculate the nitrogen loss and the phosphorus gain. Results (Tab. VIII) show that about 44% of the total nitrogen discharged by the effluent is consumed

TABLE VIII Nitrogen consumption and phosphorus regeneration in the dilution basin

Concentration	NO_2^-N $\mu mol\ l^{-1}$	NO_3^-N $\mu mol\ l^{-1}$	NH_4^+N $\mu mol\ l^{-1}$	Nt $\mu mol\ l^{-1}$	$PO_4^{3+}-P$ $\mu mol\ l^{-1}$	$Ptd.$ $\mu mol\ l^{-1}$
Measured	23	78	1259	1359	88	153
Calculated	15	15	744	774	178	198
Regeneration	–	–	–	–	90 (101%)	45 (29)
Consumption	8 (35%)	63 (89)	515 (41%)	569 (44%)	–	–

in the dilution basin. Oxygen super saturation (≅140%) supports the assimilation of nitrogen by the photosynthetic organisms rather than loss of nitrogen through denitrification process. Nitrate-N appears as the most consumed of nitrogen compounds. On the other hand, the theoretical reactive phosphate concentration at zero salinity is the double of that measured in the effluent. This increase (90 µmol l^{-1}) is expected to be due to a combination of several processes such as the mineralization of organic phosphorus, hydrolysis of polyphosphates, desorption of particulate and sedimentary phosphorus and the mobilization of Fe-phosphorus complexes under the prevailing

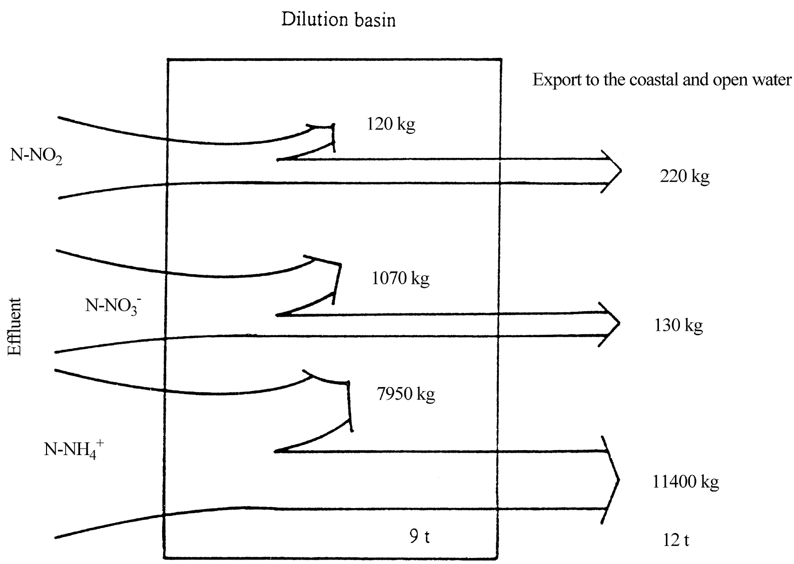

FIGURE 11 Expected organic matter production due to the fully consumption of inorganic nitrogen components.

reducing conditions. Total dissolved phosphorus was only increased by 45 $\mu mol\,l^{-1}$, which means that half of the reactive phosphate increase was provided by the particulate and sedimentary phosphorus. However, if we agree that nitrogen decrease was due to the photosynthetic activity, the regenerated phosphate (90 $\mu mol\,l^{-1}$) should be increased by 1/16 of the consumed nitrogen (37 $\mu mol\,l^{-1}$), which represents the phosphorus that might has been consumed in building the organic matter.

On the basis of the preceding calculation the budget of the potential organic matter was evaluated (Fig. 11). Nine tons of organic matter (43%) will be formed in the dilution basin, which is higher than the organic load carried by the effluent (7 tons, unpublished data). The rest of the potential organic matter ($\cong$12 t) will be exported to the coastal zone outside the dilution basin. This will take place, according to the prevailing current regime, south of the discharge point. The organic matter build up will certainly affect the water quality and will threat all the related activities and uses. It will also have an adverse effect on the coral reef community.

CONCLUSION

Wastewater discharge in the coastal area south of Jeddah is a major source of the landderived nutrients phosphorus and nitrogen. The dissolved inorganic salts of the two elements are delivered in proportions similar to that found in the algal organic matter. Ammonium nitrogen is the main nitrogen species; it is produced by the mineralization of organic nitrogen and through the denitrification process. Dissolved reactive phosphorus constitutes more than 30% of the total phosphorus and the suspended particulate matter probably buffers its concentration.

Non-conservative behaviour characterized the distribution of nitrogen and phosphorus in the receiving environment. Nitrogen loss was attributed to biological consumption while the regeneration of reactive phosphate was attributed to mineralization and desorption processes.

Organic matter directly transported by the effluent may be considerably augmented by the potential algal mass that may be locally produced, under favorable conditions, by the assimilation of the nutrient flux. This potential organic matter was estimated as 21 – 22 tons day-1, 42% of which is formed in the discharge basin and the rest is exported to the adjacent coastal area.

It is evident that the potential organic flux is much more important than the direct input of the organic matter. The ecological aspect is therefore very important, from the environmental point of view, and must be considered when deciding the strategy of water treatment. When the local environmental conditions are not favorable for the algal growth (low temperature, low light intensity, short residence time), particular treatment for the reduction of the nutrient elements my not be very necessary. If all or some of the conditions are favorable, as it is the case in our study area, it is important to determine the limiting nutrient before deciding the type of treatment whether biological (nitrogen limiting) or physico-chemical (phosphorus limiting).

Acknowledgements

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