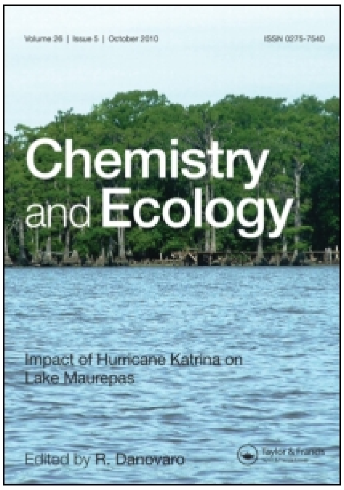

Chemistry and Ecology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713455114

Water quality in the Red Sea coastal waters (Egypt): Analysis of spatial and temporal variability

Mamdouh Fahmy[a]
[a] National Institute of Oceanography and Fisheries, Alexandria, Egygt

To cite this Article Fahmy, Mamdouh(2003) 'Water quality in the Red Sea coastal waters (Egypt): Analysis of spatial and temporal variability', Chemistry and Ecology, 19: 1, 67 — 77
To link to this Article: DOI: 10.1080/0275754031000087074
URL: http://dx.doi.org/10.1080/0275754031000087074

Chemistry and Ecology, 2003, Vol. 19(1), pp. 67–77

WATER QUALITY IN THE RED SEA COASTAL WATERS (EGYPT): ANALYSIS OF SPATIAL AND TEMPORAL VARIABILITY

MAMDOUH A. FAHMY*

National Institute of Oceanography and Fisheries, Anfoushi, Alexandria, Egygt

(In final form 13 January 2003)

In order to provide a background picture of the water quality of the Egyptian Red Sea a number of hydrological and chemical parameters have been measured bimonthly in 2000. Few data are available on this area, which is apparently subjected to an increasing human impact due to recreational (swimming and diving), industrial (mainly phosphate shipping and industry) and fishing/harbor activities. The results of the present study indicate that changes in the salinity and pH were not significant with highly oxygenated seawaters. The levels of suspended solids (as total suspended matter, TSM) and chlorophyll-a (Chl-a) were generally low and showed an homogeneous distribution in the study region. The ratio of chlorophyll-a to total suspended matter concentrations increased between November and March and decreased from May to September. Chlorophyll-a was significantly correlated with transparency and total suspended matter concentrations in July, September and November. Nitrogen, phosphorus and reactive silicate concentrations were generally low, and allowed classifying the Egyptian Red Sea coastal water as oligotrophic to mesotrophic. The middle region of the study area, which was located between Safaga and Qusair displayed relatively high phosphate contents when compared with other coastal areas. The high values of N:P ratios indicate that PO_4—P is the limiting factor for phytoplankton growth in the Red Sea coastal waters, with the possible exception of the middle region. Significant relationships were found between chlorophyll-a concentrations and nutrient levels in different sampling periods. Spatial distribution patterns of the studied variables revealed that productivity of the Red Sea coastal waters is mostly controlled by phosphate concentrations, salinity, temperature and dissolved oxygen.

Keywords: Physicochemical; Nutrients; Red Sea; Coastal waters; Trophic levels

1 INTRODUCTION

The Red Sea, with a length of about 1930 km and average width of 280 km, lies between 12–30 °N and 32–44 °E. In the southern part, the Red Sea joins Gulf of Aden through the strait of Bab El Mandab. In the northern sector, the Sinai peninsula divides the Red sea into the shallow Gulf of Suez (55–73 m, average depth) and the deep Gulf of Aqaba (average depth *ca*. 650 m). The Red Sea, due to the low population density along the coast, is a considered relatively pristine area. Previous works carried out in this region have performed by the Russian R/V *Ichthyology* in winter 1964–1965 (Beltagi, 1984) and within the frame of the Intensive Data collecting Program (DCPE) by RV Arnon during 1974–1975 (Hottinger, 1984). The Red Sea is experiencing a rapid increase of coastal utilization for recreational

---

* E-mail: mamfahmy@netscape.net

ISSN 0275-7540 print; ISSN 1029-0370 online
DOI: 10.1080/0275754031000087074

purposes. Therefore, a proper environmental management is highly desired. However, very little information is available on the present state of the water quality of this region. Due to the importance of the Red Sea for tourism and the consequent important national income, the Environmental Information and Monitoring program (EIMP) promoted the initiation of a consistent monitoring aim at the construction of a database system for the Red Sea coastal water quality, as the basis for the proper management of this coastal region. The EIMP programme was coordinated by a steering committee with representatives from the Danish International Development Assistance (Danida) and Egyptian Environmental Affair Agency (EEAA). The present study is part of this program and aims at investigating the spatial and temporal patterns of the water quality along the Egyptian coasts of the Red Sea. The area under investigation is the most directly affected in Egypt by recreational resorts, urban agglomeration, fishing ports, shipping and industrial activities causing phosphate release as well as very limited fresh water sources.

2 MATERIALS AND METHODS

Within the EIMP program, six field surveys have been performed in January, March, May, July, September and November, 2000. A total of 15 coastal stations were selected to represent all different environmental conditions in terms of human activities, public resort beaches and some reference sites (Fig. 1). Water temperature, salinity, dissolved oxygen (DO) and pH were measured *in situ* at each station using a CTD (YSI-6000). Duplicate water samples

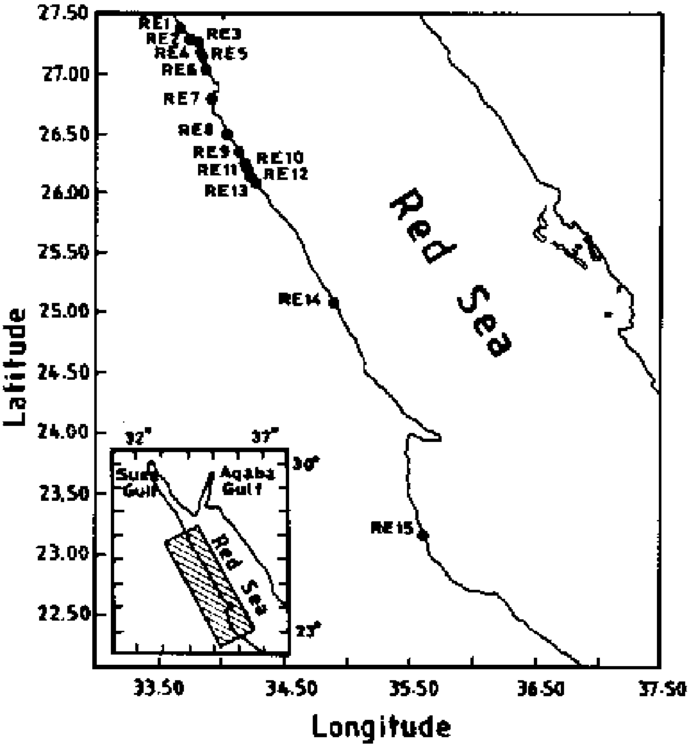

FIGURE 1 The Red Sea: study area and location of sampling locations.

for water quality variables were collected at 2-m depth (below surface water), using a PVC Niskin bottle. NH_4—N concentrations were determined according to IOC (1983). NO_2—N, NO_3—N, PO_4—P and SiO_4—S_i concentrations were determined on pre-filtered seawater samples, (Whatman GF/C) following the techniques described by IOC (1993) and Strickland and Parsons (1972). Total-P and total-N were estimated in unfiltered water samples following the procedure described by Valderrama (1981). The concentration of Dissolved Inorganic Nitrogen (DIN as the sum of NH_4—N + NO_2—N + NO_3—N) was calculated. Total suspended matter (TSM) was collected from 3 L seawater samples by filtration through washed, dried and pre-weighed 0.45 μm membrane filter. The filters with the retained particles, were washed then air dried in the oven at 60 °C for 24–48 hours until constant weight. The difference between the dry weight of membrane filters before and after filtration was expressed in $mg\,L^{-1}$. For chlorophyll-a (Chl-a) determination, additional water samples were collected and filtered on 0.45 μm filters. Chl-a was extracted by using 90% acetone and measured spectrophotometrically according to Strickland and Parsons (1972). Water transparency was measured using a Secchi disk.

3 RESULTS AND DISCUSSION

3.1 Hydrographic Conditions

Water temperature, salinity, pH and dissolved oxygen (DO) values reported in the present study are shown in Table I. Their bimonthly average values are illustrated in Figure 2. Distribution of water temperature was accompanied with their geographic and temporal variations *i.e.* they followed seasonal changes in air temperature at different regions of the present study. Temperature varied from 16.84 to 33.24 °C (at Sts Re1 and Re15 in January and July, respectively). Their seasonal variations ranged from 20.62 °C in January to 30.02 °C in July. A slight increase in water temperature was observed moving southward. The spatial distribution of salinity, pH and DO did not display clear changes. The general distribution of DO indicated high values and the presence of well oxygenated waters. Patterns, in terms of punctual (the average values of all field surveys at each station) and bimonthly (the average values of all stations at each field survey) averages, ranged from 7.42 to 7.80 $mg\,l^{-1}$ (equivalent to 112–116%) at Sts Re7 and Re2 and from 7.20 to 7.91 $mg\,l^{-1}$ (equivalent to 103–115%) in November and March respectively, with an annual mean 7.62 $mg\,l^{-1}$ (equivalent to 103%). Salinity fluctuated from 39.63 to 40.22 at Sts Re13 and Re1, and from 38.99 to 40.09 in September and January (average values) with an annual mean 39.80. Punctual and bimonthly values of pH varied from 8.13 at St Re2 to 8.22 at Sts Re9 and Re10 and 8.06–8.34 in November and January respectively, with an annual mean 8.19. Minor changes of these variables reveal that the effect of human impact on the distribution pattern of different hydrographical conditions in the Red sea coastal waters are still limited. This was expected due to the low population there, the absence of freshwater sources and the limitation of land based sources (*i.e.* sewage, agriculture and/or industrial effluents). Accordingly, these conditions could be principally controlled by the circulation pattern of seawater in the Red Sea Regions. Beltagi (1984) reported that during the N-NW winds of summer, surface water and a layer of highly saline bottom water flow from the Red Sea to the Gulf of Aden, and between these layers a counter current of Indian Ocean water sets into the Red Sea. In winter, surface water enters the Red Sea from the Gulf of Aden, but Red Sea water continues to discharge at depth. Outside and inside Foul Bay of the Red Sea, Beltagi (1984) reported a range 19–32 °C for surface water temperature and 39.38–39.97‰ for salinity. Also our result dealing with DO distribution fit well with data reported by Beltagi (1984) and Hottinger (1984).

TABLE I Range and Annual Averages of the Different Physicochemical Variables in the Red Sea Surface Coastal Waters during 2000. Reported are: Temperature, Salinity, Dissolved Oxygen (DO), Chlorophyll-a (Chl-a) and Total Suspended Matter (TSM) Concentrations, Transparency (as Secchi disk depth, DS) and the ratio of Chlorophyll-a to Total Suspended Matter Concentration. Average Values are in Parenthesis.

Station	*Temp.* °*C*	*Salinity*	*pH*	*DO* $mg\,l^{-1}$	*DO %*	*Chl–a* $\mu g\,l^{-1}$	*TSM* $mg\,l^{-1}$	*DS m*	*Chla/TSM* $\times 10^{-3}$
Re1	16.8–27.6	39.6–40.7 (40.2)	8.05–8.20 (8.14)	7.20–8.10 (7.65)	103–120 (111)	0.07–0.17 (0.13)	5.64–9.91 (7.23)	3.0–5.0 (3.80)	0.018
Re2	17.9–29.4	39.3–40.3 (39.9)	8.04–8.20 (8.13)	7.61–8.01 (7.80)	108–125 (116)	0.05–0.22 (0.12)	4.75–6.93 (5.87)	1.25–12.5 (7.38)	0.020
Re3	18.6–29.1	39.0–40.2 (39.7)	8.09–8.24 (8.16)	7.35–8.01 (7.61)	106–123 (113)	0.03–0.14 (0.09)	3.63–7.37 (5.14)	2.0–14.0 (9.25)	0.018
Re4	21.4–29.2	38.8–40.2 (39.7)	8.06–8.39 (8.18)	7.01–8.01 (7.56)	101–131 (114)	0.07–0.13 (0.11)	3.94–7.01 (5.45)	5.5–11.5 7.12	0.020
Re5	19.6–28.3	39.1–40.1 (39.8)	8.06–8.34 (8.19)	7.10–8.37 (7.60)	101–135 (113)	0.08–0.17 (0.12)	4.11–6.98 (5.45)	6.0–9.0 (7.2)	0.022
Re6	21.2–30.4	38.7–40.2 (39.8)	8.08–8.33 (8.18)	7.01–8.33 (7.70)	101–132 (116)	0.04–0.21 (0.11)	3.78–6.85 (5.38)	6.0–7.0 (6.29)	0.025
Re7	20.7–30.7	38.7–40.1 (39.8)	8.12–8.37 (8.20)	6.93–8.05 (7.42)	100–121 (112)	0.04–0.48 (0.18)	4.06–6.55 (5.38)	6.0–11.0 (9.17)	0.034
Re8	20.3–29.9	39.1–40.1 (39.8)	8.04–8.39 (8.21)	7.02–8.09 (7.50)	100–120 (112)	0.09–0.21 (0.14)	4.65–7.39 (5.82)	3.0–8.0 (5.68)	0.024
Re9	20.8–29.5	39.0–40.3 (39.9)	8.04–8.42 (8.22)	7.18–8.23 (7.51)	102–122 (114)	0.09–0.15 (0.13)	3.80–6.74 (5.27)	6.0–12.50 (8.62)	0.025
Re10	22.0–30.5	38.9–40.3 (39.8)	8.02–8.43 (8.22)	7.10–8.46 (7.68)	102–127 (118)	0.05–0.17 (0.11)	4.19–10.14 (6.09)	4.80–9.0 (6.13)	0.018
Re11	22.0–30.9	38.7–40.0 (39.6)	8.01–8.40 (8.21)	7.22–8.15 (7.50)	106–122 (115)	0.04–0.22 (0.12)	4.07–10.65 (6.88)	4.50–23.0 (14.63)	0.017
Re12	21.9–31.4	38.8–40.1 (39.7)	8.00–8.42 (8.21)	7.35–7.92 (7.67)	106–128 (117)	0.05–0.19 (0.11)	4.68–7.79 (6.22)	6.5–13.0 (9.0)	0.018
Re13	21.9–31.1	38.7–40.0 (39.6)	8.08–8.42 (8.21)	7.32–8.01 (7.61)	107–134 (116)	0.05–0.16 (0.12)	2.60–7.22 (5.26)	6.5–13.0 (9.33)	0.023
Re14	21.4–29.0	38.7–40.2 (39.7)	8.02–8.37 (8.20)	6.67–8.73 (7.70)	96–142 (117)	0.09–0.17 (0.14)	3.87–8.57 (5.43)	7.0–9.20 (8.12)	0.026
Re15	19.5–33.2	39.7–40.2 (40.0)	8.00–8.33 (8.18)	7.20–8.25 (7.78)	107–131 (121)	0.10–0.27 (0.18)	4.98–8.91 (6.86)	3.5–4.5 (4.0)	0.026
Bimonthly and annual average	20.6–30.0	39.0–40.1 (39.8)	8.08–8.34 (8.19)	7.20–7.91 (7.62)	103–126 (11.5)	0.07–0.16 (0.13)	4.47–7.58 (5.85)	5.70–8.93 (7.71)	0.012–0.036 (0.022)

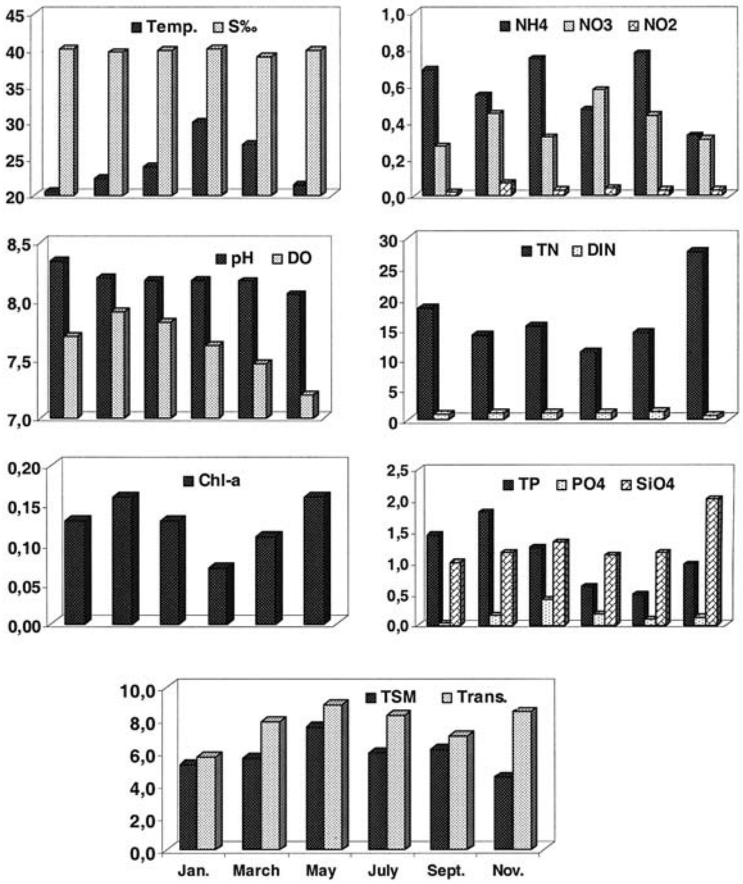

FIGURE 2 Bimonthly averages of different studied parameters in the Red Sea coastal waters during 2000.

These authors also reported that the water above the thermocline was, in mot cases, saturated. These conditions are comparable to that of the present study and confirms the limited effect of human impact on this region.

3.2 Variables of Trophic State

Chlorophyll-a, Total Suspended Matter and Secchi Disk Depth

Ranges and average values of Chl-a, TSM and Secchi disk (as transparency measure) are reported in Table I. The relationship between their bimonthly average values are illustrated in Figure 2. Low Chl-a and TSM concentrations and high transparency were generally encountered at most stations. This can be highlighted by punctual and bimonthly average values, in which Chlorophyll-a ranged from 0.09 to 0.18 $\mu g\,l^{-1}$ at St. Re3 and Sts Re5-Re7, respectively and from 0.07 to 0.16 $\mu g\,l^{-1}$ in July and March–November, with an annual average of 0.13 $\mu g\,l^{-1}$. Total suspended matter ranged from 5.14 to 7.23 $mg\,l^{-1}$ at Sts Re3 and Re1 and from 4.47 to 7.58 $mg\,l^{-1}$ in November and May respectively, with an annual mean 5.85 $mg\,l^{-1}$. Finally, Secchi disk transparency ranged from 3.75 to 14.63 m at Sts Re1 and Re11 from 5.73 to 8.93 m in January and May respectively, with an annual average of 7.71 m. Transparency reached bottom depth at most stations. TSM and Chl-a concentrations showed an homogeneous distribution at several locations. The ratio of Chl-a/TSM was calculated on both punctual and bimonthly average basis, and ranged from 0.017 to 0.034×10^{-3} at Sts Re11 and Re7 and from 0.012 to 0.036×10^{-3} in July and November, respectively, with an annual average of 0.022×10^{-3}. This ratio displayed a slight increase during November–March and a decrease in May–September (Tab. I). Chlorophyll-a values were significantly correlated with transparency and TSM concentrations in July, September and November (Fig. 3). Low levels of Chl-a and TSM coupled with high values of the Secchi disk transparency clearly indicate that the effect of human impact in the investigated Red sea coastal waters is still negligible. This result if further confirmed by the comparison with average Chlorophyll-a concentrations reported for Red sea coastal waters by

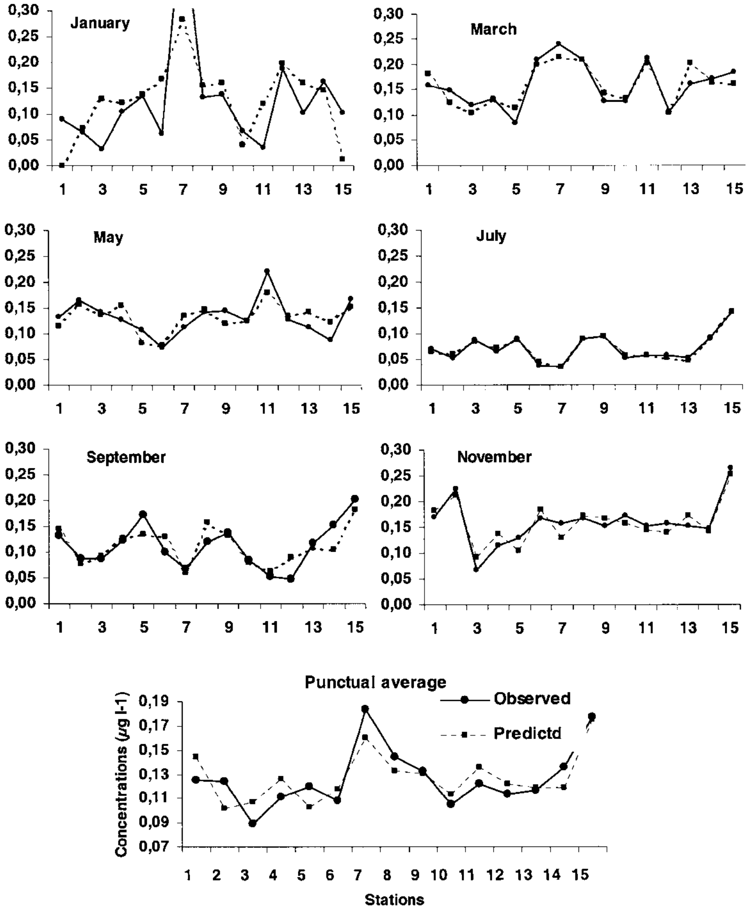

FIGURE 3 Relationship between Chl-a and other environmental variables obtained from the Red Sea coastal waters during different field surveys of year 2000. Reported are observed values and predicted levels according to the relationship: Chl-a $= 1.314 - 0.170$ DO $+ 0.1387$ TP $- 0.27956$ NO3 ($r = 0.667$, $P < 0.80$) in January, Chl-a $= 0.850 - 0.0176$ TN $+ 0.0537$ NH_4 $- 0.001405$ DO% $- 0.00363$ Trans ($r = 0.88$, $P < 0.00198$) in March; Chl-a $= -0.33377 - 0.04$ SiO_4 $+ 0.00458$ Trans $+ 0.0655$ DO $- 0.00218$TN ($r = 0.769$, $P < 0.04467$) in May; Chl-a $= 0.111 + 0.0035$ TN $+ 0.0927$ NO_2 $+ 0.095219$ TP $- 0.0223$ TSM $- 0.0212$ NH_4 $+ 0.01289$ DO $- 0.00355$ Temp $+ 0.0011$Trans ($r = 0.988$, $P < 0.00024$) in July; Chl-a $= -0.2056 - 0.008$ Trans $+ 0.030$ TSM $+ 0.0237$ Temp $- 0.067$ TP $- 0.055$ DO ($r = 0.826$, $P < 0.037$) in September; Chl-a $= -11.7 + 0.223$S‰ $+ 0.047$ Temp $- 0.02$ SiO_4 $+ 0.275$ pH $- 0.00288$ Trans $- 0.00425$ TN $- 0.021$ TSM ($r = 0.91$, $P < 0.024$) in November and on the basis of the annual punctual average: Chl-a $= 5.012 + 0.1327$S‰ $+ 0.0378$ Temp $- 0.00917$ DO% $- 0.0427$ PO4 ($r = 0.810$, $P < 0.02$).

Halim (1969) in which the average value was 0.15 $\mu g\,l^{-1}$ *vs.* 0.13 $\mu g\,l^{-1}$ reported in the present study.

Nutrient Salts

The hydrochemical characteristics of the Red Sea depend on the dynamics of its water as well as on the geographical location. Beltagi (1984) suggested that, in the Red Sea, due to the exceptionally high water temperature, all the biochemical processes proceed all year round at high rates. However, the Red Sea does not receive any significant nutrient supply from river out flow. Therefore, the replenishment of these elements in the Red Sea depends upon the inflow of Indian Ocean water through Bab El Mandab, ($12.5 \times 10^3\,k^3\,y^{-1}$) and the mixing of surface with deeper waters.

Ranges as well as mean values of different nutrients are listed in Table II. Their bimonthly average values are illustrated in Figure 2. Our data indicate that dissolved inorganic nitrogen concentrations are quite low. This is evident from both punctual and bimonthly average values of NH_4-N, which ranged from 0.33 to 1.26 µM at Sts Re9 and Re8 and from 0.33 to 0.76 µM in November and September respectively, with an annual average of 0.59 µM. Nitrite concentrations were always less than 0.1 µM, with an annual average 0.04 µM. Nitrate concentrations ranged from 0.18 to 0.72 µM at Sts Re6 and Re8 and from 0.27 to 0.56 µM in January and July respectively with an annual average of 0.39 µM.

Based on the mean annual values, the concentrations of dissolved inorganic nitrogen forms followed the order $NH_4 > NO_3 \geq NO_2$, accounting from 57.8, 38.2 and 3.9% of DIN, respectively. The increase of NH_4 concentration, which is the preferred N form for phytoplankton uptake is unclear. These concentrations, based on the classification reported by Skrivanic and Strin (1982) and Franco (1983), allow classifying the Red sea coastal waters as oligotrophic to mesotrophic. These authors indicated as oligotrophic, seawater displaying concentrations of 0.5 µM for both NH_4 and NO_3. Whereas, in eutrophic waters the concentration of these nutrients are usually in the order of 2.0 µM for NH_4 and 4 µM for NO_3. The levels of total nitrogen (TN) displayed remarkable variations and ranging from 12.2 to 25.6 µM at Sts Re7 and Re15, respectively and from 11.3 to 27.9 µM in July and November, respectively with an annual average of 17.0 µM for the whole Red sea coastal waters. Based on the annual mean values, DIN accounted for 6% of TN. The large difference between TN and DIN concentrations suggest that nitrogen is found in the Red sea coastal waters mostly in organic forms. This result is in agreement with the general view of microbial food web and phytoplankton dynamics, in which NH_4, NO_2 and NO_3 are rapidly processed by phytoplankton and other microbial components. Meanwhile, the organic nitrogen is assimilated by aquatic organisms in a much slower rate (Riley and Chester, 1971). Faganeli (1983) pointed out that, in the eutrophic Bay of Koper (North Adriatic), the relative composition of total nitrogen are 11.3% for particulate, 68.8% for dissolved organic and 20.1% for the inorganic forms. DIN levels obtained during the present investigation are remarkably lower than those mentioned above, and suggest the limited effect of land based sources on the Red sea coastal waters.

A remarkable increase of PO_4 concentrations was observed in the middle Red Sea (Sts. Re8–Re10) as compared to the southern and northern sides of the Red sea coastal waters. The punctual average levels of PO_4 concentrations reached 0.54, 0.53 and 0.55 µM at Sts Re8, Re9 and Re10, respectively. This area represents the main shipping and industry of phosphate release in Egypt, since the Red Sea Phosphate Company (Re8), Abo Tartour Phosphate Company (Re9) and El Hamraween main phosphate shipping Harbour (Re10) are located here. An increase of PO_4 concentrations was also observed at Sts Re5, Re11 and Re13 (0.10, 0.17 and 0.12 µM, respectively). In other stations PO_4 concentrations

TABLE II Ranges and Annual Average Values for the Different Nutrients (expressed as µM) and DIN/P Ratios in the Red Sea Surface Coastal Waters during 2000. ND = not detected. Average Values are in Parenthesis.

	N-forms					*P-forms*		*Silicates*	
Station	*NH_4—N*	*NO_2—N*	*NO_3—N*	*DIN*	*TN*	*PO_4—P*	*TP*	*SiO_4—Si*	*DIN/P*
Re1	0.13–1.75	ND–0.07	0.20–1.32	0.56–2.13	8.8–24.9	0.02–0.13	0.40–1.08	0.68–2.41	5–94
	(0.72)	(0.03)	(0.58)	(1.33)	(14.9)	(0.06)	(0.71)	(1.44)	(35)
Re2	0.36–0.87	ND–0.06	0.14–0.74	0.50–1.60	7.7–56.8	ND–0.16	0.40–1.35	0.77–1.06	4–154
	(0.59)	(0.03)	(0.45)	(1.08)	(22.6)	(0.08)	(0.87)	(0.94)	(42)
Re3	0.07–1.04	ND–0.12	0.12–0.75	0.25–1.50	5.1–46.2	ND–0.12	0.18–1.67	0.57–4.21	11–90
	(0.60)	(0.05)	(0.39)	(1.04)	(21.2)	(0.06)	0.75	(1.49)	(30)
Re4	ND–1.44	ND–0.04	0.15–0.33	0.16–1.63	5.4–27.4	0.02–0.32	0.26–1.16	0.87–2.78	2–23
	(0.47)	(0.02)	(0.22)	(0.71)	(12.2)	(0.09)	(0.59)	(1.42)	(12)
Re5	ND–1.19	ND–0.03	0.10–0.38	0.16–1.32	6.5–27.2	ND–0.33	0.18–1.21	0.91–4.06	4–54
	(0.46)	(0.02)	(0.20)	(0.68)	(14.8)	(0.10)	(0.79)	(1.67)	(17)
Re6	ND–0.84	ND–0.03	0.10–0.28	0.12–0.96	10.0–24.4	ND–0.09	0.26–1.41	0.62–2.20	4–69
	(0.39)	(0.01)	(0.18)	(0.58)	(14.8)	(0.02)	(0.62)	(1.36)	(13)
Re7	0.13–0.67	ND–0.03	0.14–0.28	0.32–0.92	4.4–26.2	ND–0.10	0.46–1.67	0.67–3.00	3–57
	(0.38)	(0.01)	(0.20)	(0.60)	(12.2)	(0.04)	(0.85)	(1.35)	(26)
Re8	0.12–3.08	0.01–0.11	0.34–2.34	0.50–5.02	7.1–29.1	0.04–2.23	0.51–3.64	0.72–1.76	1–79
	(1.26)	(0.05)	(0.72)	(2.02)	(15.3)	(0.54)	(1.92)	(1.18)	(22)
Re9	0.11–0.79	ND–0.12	0.17–0.74	0.30–1.10	11.0–31.6	ND–2.80	0.36–4.78	1.01–2.07	<1–110
	(0.33)	(0.04)	(0.30)	(0.67)	(17.0)	(0.53)	(2.13)	(1.56)	(27)
Re10	0.09–0.74	ND–0.14	0.36–0.76	0.52–1.52	5.0–34.9	0.04–1.26	0.57–3.10	0.65–1.52	<1–29
	(0.54)	(0.05)	(0.59)	(1.18)	(14.2)	(0.55)	(1.49)	(1.08)	(7)
Re11	0.16–1.17	ND–0.18	0.12–0.73	0.38–1.53	5.4–27.7	0.04–0.63	0.33–4.98	0.55–1.31	2–29
	(0.58)	(0.04)	(0.37)	(0.99)	(14.1)	(0.17)	(1.50)	1.00	(13)
Re12	0.39–1.12	ND–0.18	0.22–0.57	0.62–1.45	9.0–57.5	ND–0.28	0.52–2.05	0.65–1.29	3–123
	(0.64)	(0.04)	(0.32)	(1.00)	(22.7)	(0.09)	(1.11)	(1.05)	(43)
Re13	0.35–1.06	ND–0.16	0.16–0.75	0.75–1.43	3.4–27.6	0.02–0.37	0.43–1.75	0.74–1.57	3–65
	(0.67)	(0.04)	(0.39)	(1.10)	(14.4)	(0.12)	(0.88)	(1.14)	(27)
Re14	0.22–1.08	0.03–0.15	0.35–0.88	0.90–1.61	11.2–28.6	ND–0.08	0.33–4.08	0.25–2.76	19–123
	(0.58)	(0.08)	(0.53)	(1.19)	(18.7)	(0.04)	(1.43)	(1.39)	(45)
Re15	ND–1.58	ND–0.11	0.18–1.06	0.25–2.75	8.5–52.2	ND–0.12	0.46–1.54	0.23–2.98	2–156
	(0.69)	(0.04)	(0.45)	(1.18)	(25.6)	(0.06)	(0.87)	(1.48)	(52)
Annual average	0.33–0.76	0.02–0.07	0.27–0.56	0.68–1.23	11.3–27.9	0.04–0.41	0.49–1.81	1.01–2.03	12–57
	(0.59)	(0.04)	(0.39)	(1.02)	(17.0)	(0.17)	(1.10)	(1.30)	(29)

were very low consequently N:P ratios were high, reaching an annual average of 29:1. The high N:P ratios suggest that phosphate could be the limiting nutrient for phytoplankton growth. Seasonal variations in PO_4 concentrations was associated with the level of impact on the middle region of the Red Sea coastal waters. Low PO_4 contents could be related mostly to their sorption and deposition on iron born dust conveyed to the basin from the surrounding deserts. Suzumura *et al.*, (2000) reported the effect of composition and physicochemical characteristics of natural particles on phosphate adsorption-desorption processes under various aquatic environment. Marchetti (1984) pointed out that, generally, the concentrations of PO_4 in the Mediterranean surface waters are extremely low (expressed as values for orthophosphate 0.03 µM or less), whereas typical concentrations for eutrophic coastal waters are above 0.15 µM and for highly eutrophic system will be beyond 0.30 µM.

These results are consistent with the oligotrophic characteristics of the Red Sea coastal waters. In the Red Sea surface waters, Beltagi (1984) reported phosphate concentrations of 4–4.5 $\mathrm{mg\,P\,m^{-3}}$ (equivalent to 0.12–0.14 µM PO_4—P) or less. These values are slightly higher than those reported in the present study, except in the middle region. The geographic and temporal distribution pattern of TP displayed a large variability during the investigation period. TP ranged from 0.59 to 2.13 µM at Sts Re4 and Re9, respectively, and from 0.49 to 1.81 µM in September and March respectively, with an annual mean of 1.10 µM for the whole investigated region. Based on the mean annual values, PO_4 constituted 15.4% of TP, implying that phosphate, in Egyptian Red Sea waters principally is mostly accounted by particulate and organic forms. These data also suggest that the coastal waters of the Red Sea are moderately polluted. Such conclusion is consistent with indications provided by Nalewajko and Lean (1980) who pointed out that in moderately polluted coastal waters, the relative importance of phosphorus forms is: 28.5–98% for particulate, 1.2–4% for colloidal, 0.1–22% for reactive phosphate and 0.1–6% for dissolved organic P. Giovanardi and Tromellini (1992) stated that the levels of TP and TN in oligotrophic waters are 0.27 and 47.2 µM, whereas in mesotrophic waters reach 0.89 and 53.8 µM and in eutrophic seawaters 2.81 and 133.9 µM. These levels when compared with those reported in the present study indicate that the Egyptian Red Sea coastal waters are "located" within the oligo to mesotrophic conditions.

Farah (1991) reported that the hydrological and chemical characteristics of the Dongonab Bay coastal waters (Sudanese Red Sea), with a pH 8.65 ± 0.05, were found to fluctuated between 20 and 32.5 °C for water temperature, from 8.01 to 9.01 $\mathrm{mg\,l^{-1}}$ for DO, from 0.35 to 0.51 µM for NO_3-N and from 0.01 to 0.05 µM for PO_4—P. These values when compared with those of the present study reveal notably higher pH values and slightly lower PO_4—P values, whereas the other parameters were more or less comparable. Such differences should be further investigated, but apparently suggest that, in the last 10 year, significant changes might have occurred in terms of primary production.

The distribution pattern of SiO_4 concentrations displayed small spatial and seasonal variations. Punctual and bimonthly average values ranged from 0.94 to 1.67 at Sts Re2 and Re5 and from 1.01 to 2.03 µM in January and November respectively, with an annual average of 1.30 µM. A slight increase in SiO_4 concentrations was observed in the northern side of Red Sea coastal waters, except at St. Re2. (Tab. II). Beltagi (1984), pointed out that primary producers of the northern Red Sea are mainly composed of blue green algae (*Trichodesmium erythrium*) and to a lesser extent by diatoms, the main consumer of SiO_4. This means that diatoms constitute a minor component in the northern Red Sea. The main factors controlling SiO_4 distribution in the Egyptian Red Sea coastal waters are: i) the supply of SiO_4, which flows in the Red sea through the straight of Bab El Mandab, ii) biological consumption, iii) organic matter decomposition and iv) the partial dissolution of quartz and clay particles transported to the sea from the surrounding deserts during sand storms. A stepwise regression analysis technique was applied by using Chlorophyll-a as dependent and other studied parameters as independent variable. They showed significant relationship between Chl-a and NO_3—N and TP in January, between NH_4—N, TN and S_iO_4—S_i in May NH_4—N, between NO_2—N, TN and TP in July, and TP in September, and between TN and S_iO_4—S_i in November. Spatial distribution patterns of these variables revealed highly significant relationships between Chlorophyll-a, from one side, and salinity, water temperature, DO% and PO_4—P. Although correlation analysis does not allow inferring on cause-effect relationships, these results suggest that the productivity of the Red Sea coastal waters is related to salinity, water temperature and DO% (among physical and chemical variables) and to PO_4—P (among trophic state variables; Fig. 3).

4 CONCLUSIONS

Productivity of the Red Sea coastal waters is mostly controlled by phosphate concentrations, salinity, water temperature and dissolved oxygen. It is reasonable to conclude that the effect of human coastal zone utilization of different locations of the Red Sea coastal waters is still limited and not detectable on the basis of the parameters utilized in the present study, except for the middle region, which is located between Safaga and Qusair. This area is subjected to the most intense shipping activity and industrial discharge of phosphate in Egypt. This coastal area displayed relatively high phosphate concentrations as compared with other coastal locations.

Acknowledgements

The support of the Danish International Development Assistance (Danida) and Egyptian Environmental Affair Agency (EEAA) is acknowledged.

References

Beltagi, A. I. (1984). *Oceanographic and Fisheries Investigations in the Egyptian Red Sea.* Special publication, Academy of Scientific Research and Technology, NIOF Egypt, p. 98.

Faganeli, J. (1983). Organic nitrogen and phosphorus in the Gulf of Trieste (N. Adriatic). *Archives Oceanography and Limnology*, **20**, 153–177.

Farah, O. M. (1991). Water characteristic of Dongonab Bay, Sudanese Red Sea. *Symposium on marine chemistry in the Arab Region*, Suez, Egypt, April 1991, pp. 21–23.

Franco, P. (1983). Fattori influenti sulla produttività primaria dell'Adriatico settentrionale. *Proceedings International Conference: Problems of the Adriatic Sea Trieste*, Vol. 155, p. A4.

Halim, Y. (1969). Plankton of the Red Sea. *Oceanography and Marine Biology, Annual Review*, **7**, 231–275.

Intergovernmental Oceanographic Commission (1983). Chemical methods for use in marine environmental monitoring. *Manuals and Guides.* UNESCO, p. 53.

Intergovernmental Oceanographic Commission (1993). Nutrient analysis in tropical marine waters. *Manuals and Guides*, Vol. 28, UNESCO, pp. 1–24.

Giovanardi and Tromellini, E. (1992). Statistical assessment of tropic conditions. *Marine Eutrophication Proceedings of an International Conference Bologna*, Italy, 21–24 March 1990, pp. 211–233.

Hottinger, L. Z. R. (1984). *The Gulf of Aqaba Ecological Micropaleontology.* Springer–Verlag Berlin Heidelberg, New York, Tokyo, p. 354.

Marchetti, R. (1984). Quadro analitico complessivo del risultati delle indagini condotte negli anni 1977–1980. II problema dell'eutrofizzazione nelle acque costiere dell'Emilia -Romagna: Situazione ipotesi di intervento, Bologna, Regione Emilia Romagna, p. 308.

Nalewajko, C. and Lean, D. R. (1980). Phosphorus. In: Morris (Ed.), *The Physiological, Ecology of Phytoplankton*, Blackwell Science Publisher, Oxford, pp. 235–258.

Riley, J. P. and Chester, R. (1971). *Introduction to Marine Chemistry*, Academic Press, p. 757.

Skrivanic, V. A. and Strin, J. (1982). *Basic Physical Chemical and Biological Data Reports R. V. A Mohorov ICIC Adriatic Cruises 1974–76.* Hydrograhic Institute of Yugoslav Navy split, p. 175.

Strickland, J. D. H. and Parsons, T. R. (1972). *A Practical Hand Book of Sea Water Analysis. Fisheries Research Board of Canada Bulletin 167*, 2nd ed., p. 310.

Suzumura, M., Ueda, S. and Suni, E. (2000). Control of phosphate concentration through adsorption and desorption process in ground water and seawater mixing at sand beaches in Tokyo Bay. *Japan Journal of Oceanographic Society of Japan*, **56**, 667–673.

Valderrama, J. C. (1981). The simultaneous analysis of total nitrogen and total phosphorus in natural waters. *Marine Chemistry*, **10**, 109–122.