Journal of Coastal Research	30	2	283–290	Coconut Creek, Florida	March 2014

Environmental Assessment of the Gulf of Aqaba Coastal Surface Waters, Saudi Arabia

Awni Batayneh[†]*, Eslam Elawadi[†], Haider Zaman[‡], Ahmed A. Al-Taani[§], Yousef Nazzal[†], and Habes Ghrefat[†]

[†]Department of Geology and Geophysics
King Saud University
Riyadh 11451, Saudi Arabia

[‡]Department of Geology
Taibah University
Madinah 41477, Saudi Arabia

[§]UNESCO Chair for
Desert Studies and
Desertification Control
Yarmouk University
Irbid 21163, Jordan

ABSTRACT

Batayneh, A.; Elawade, E.; Zaman, H.; Al-Taani, A.A.; Nazzal, Y., and Ghrefat, H., 2014. Environmental assessment of the Gulf of Aqaba coastal surface waters, Saudi Arabia. *Journal of Coastal Research,* 30(2), 283–290. Coconut Creek (Florida), ISSN 0749-0208.

A research project on the Saudi Gulf of Aqaba was initiated in January 2012 to evaluate, protect, and develop a proper management plan for sustainable use of water resources in the coastal region. Within the framework of this project, a total of 85 surface water samples was collected and investigated to document the surface distribution of the hydrographical parameters (including water temperature, salinity, density, hydrogen ion concentration, and dissolved oxygen) as well as concentration of the nutrient salts (ammonium, nitrite, nitrate, phosphate, and silicate). The results show no thermocline or thermal pollution in the studied water and that they are mostly well oxygenated. In addition, no significant variations in the pH and salinity values have been observed. Relatively low levels of nitrogen, phosphorus (in the dissolved and total forms), and reactive silicate are observed. Inorganic nitrogen is found in the order of NO_3-N > NO_2-N > NH_4-N. On the basis of the relatively low level of nutrient salts, the Gulf of Aqaba coastal water is classified as oligotrophic to mesotrophic in nature, and the study area is not yet seriously affected by contamination in spite of rapid population growth and fast infrastructural/recreational development during the past decade.

ADDITIONAL INDEX WORDS: *Hydrographical conditions, nutrient salts, oligotrophic–mesotrophic state.*

INTRODUCTION

The Gulf of Aqaba (GOA) is one of the two waterways that originate from the northern margin of the Red Sea. It is located between 34°20′ and 35°00′ E longitude and 27°54′ to 29°35′ N latitude (Figure 1). The GOA, which is about 180 km long, has an average width of 20 km and a mean depth of 800 m. This structure is a part of the Syrian–African rift valley, which is flanked by a mixture of mountains and deserts both to the east and west. The southern end of this important waterway is separated from the Red Sea by a shallow sill at the Straits of Tiran (Berman, Paldor, and Brenner, 2000).

The GOA is of growing interest because it hosts an ecological system that includes coral reefs and other tropical biota that are unique at such latitudinal positions (Biton and Gildor, 2011). Climate of this region is arid with an average evaporation of 5–10 mm/d. The GOA water is the most saline gulf water in the world, with salinity value of 40–41 practical salinity units (PSU). The model view of the general circulation in the Gulf, as first reported by Klinker *et al*. (1976) and cited in numerous studies thereafter (*e.g*., Al-Rousan *et al.,* 2002; Badran, 2001; Badran *et al.,* 2005; Ben-Sasson, Brenner, and Paldor, 2009; Manasrah *et al.,* 2004; Manasrah, Rasheed, and Badran, 2006; Silverman and Gildor, 2008), is that the net buoyancy loss due to large evaporation and heat loss drives an inverse estuarine circulation, causing a northward flow of warm and low-salinity surface water from the Red Sea into the GOA. As the surface water moves northward, it becomes denser by cooling and evaporation. As a result water sinks down at the northern end of the Gulf and returns to the Red Sea as a lower-level denser layer through the Straits of Tiran.

Observations of tidal variations in currents and elevation taken in the GOA, Red Sea were discussed by many authors (*e.g*., Berman, Paldor, and Brenner, 2000; Monismith and Genin, 2004; Sofianos and Johns, 2001). The authors show that both currents and elevations appear to be strongly affected by conditions in the main body of the Red Sea. Tidal currents, which vary considerably in strength throughout the year, appear to be associated with internal waves generated at the Strait of Tiran where density-driven exchanges between the GOA and the Red Sea take place. Water level also has significant annual and interannual variations and appears to be associated with corresponding variations in winds acting on the entire Red Sea. Also, the authors attribute the annual variation in tidal currents to the changes in stratification strength throughout the year and show that the tidal currents are strong in summer season (*i.e*. stratification is strong) and when stratification is weak, tidal currents are weak.

The GOA and surrounding areas have been studied to understand and describe the dynamics, hydrochemistry, and thermodynamics of the water masses (*e.g*., Al-Taani *et al.,* 2013; Batayneh *et al.,* 2013; Berman, Paldor, and Brenner,

DOI: 10.2112/JCOASTRES-D-13-00112.1 received 20 May 2013; accepted in revision 2 July 2013.
Published Pre-print online 19 September 2013.
*Corresponding author: awni@ksu.edu.sa

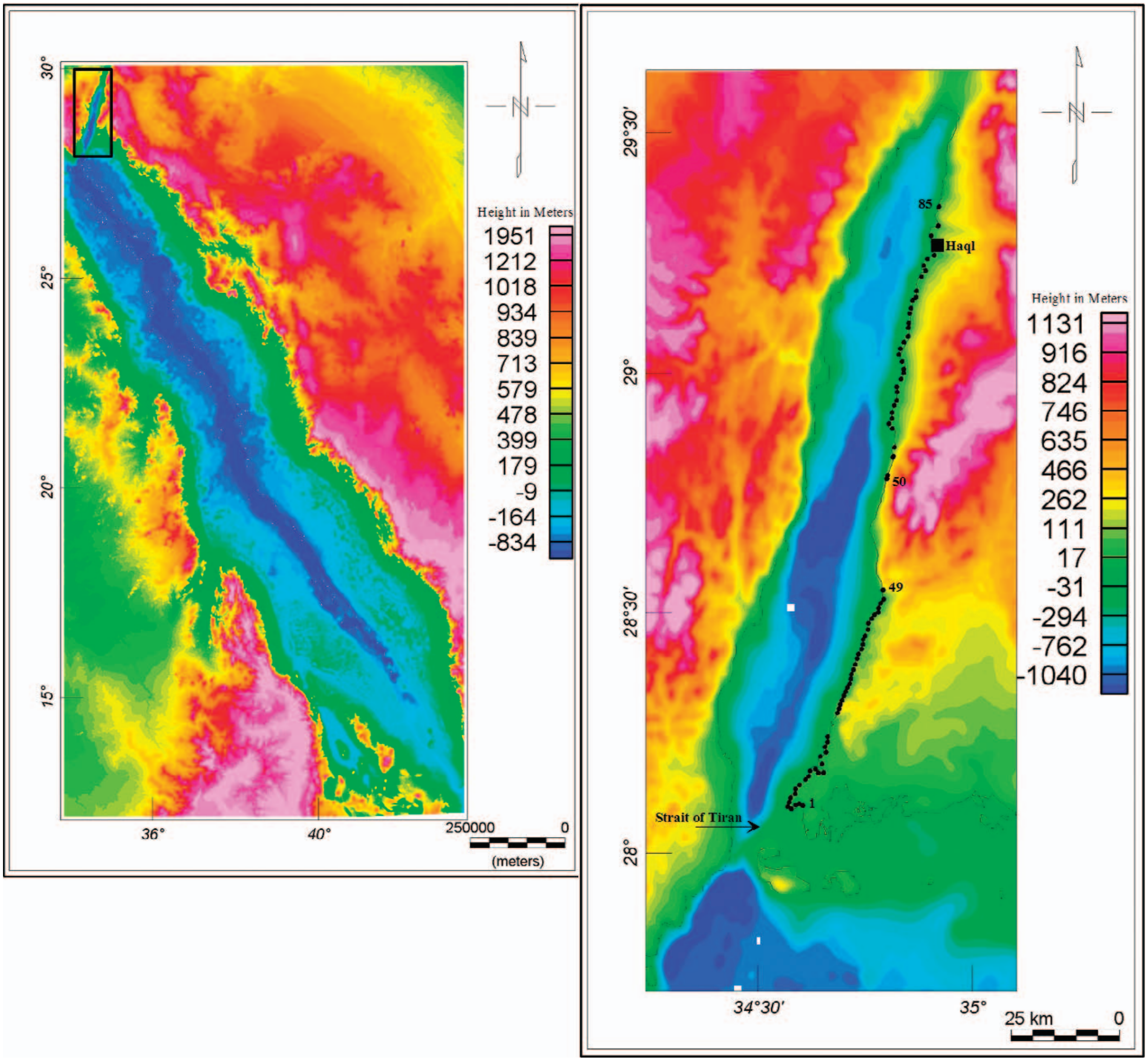

Figure 1. Location and bathymetry map for the entire Red Sea (left panel) and the Gulf of Aqaba (right panel). Bathymetric data is extracted from the global data set of the world ocean (GEBCO-08).

2000). Because of the importance of the GOA as a tourist spot and its contribution to the region's economy, a research project No. 11-WAT1731-02 (financially supported by the National Plan for Science, Technology and Innovation "NPST" program, King Saud University, Saudi Arabia) was initiated to establish a database for the water quality and help in developing a proper management plan for the coastal area protection and use. This national project is coordinated by a steering committee with most members from the Department of Geology and Geophysics, King Saud University, Saudi Arabia. The present study is a part of this project that aims to investigate a pattern of spatial changes in the water quality along the GOA coast in northwestern Saudi Arabia. In particular, it intends to assess the relations between different hydrographical parameters (*i.e*. water temperature, salinity, density, hydrogen ion concentration, and dissolved oxygen [DO]) and determine the concentration of the dissolved inorganic nutrients (*i.e*. ammonium, nitrite, nitrate, phosphate, and silicate) of the surface water by investigating 85 surface water samples collected from the area.

METHODS

A total of 85 surface water samples was collected from the GOA coastline in January 2012. Locations of the sampling sites (Figure 1) were determined in the field using Garmin navigation system (Garmin Ltd., Southampton, U.K.). Two teams worked to accomplish the survey coast in one working day. The first was cover from sample nos. 1 to 49, whereas the other from sample nos. 50 to 85.

Samples were collected in polyethylene bottles of 1-L capacity. Before their filling with sampled water, these bottles were rinsed to minimize the chance of any contamination. The sample preservation and the used analytical techniques were in accordance with the standard methods from American Public Health Association (APHA, 1998). Three replicas were taken from each sampling location.

In situ measurements were made at each site for water temperature, hydrogen ion concentration (pH), salinity, and DO using Orion 5 Star conductivity meter (Thermo Scientific, Beverly, Massachusetts, U.S.A.). Dissolved inorganic nutrients (such as ammonium, nitrite, nitrate, phosphate, and silicate) were determined calorimetrically in the filtered water samples according to the methods described by Strickland and Parsons (1972).

Ammonium (NH_4-N) concentration was measured using the indophenol blue technique. Accordingly, ammonium was allowed to react with hypochlorite in slightly alkaline medium to form monochloramine, which in the presence of phenol, nitroprusside ion, and excess hypochlorite gave indophenol blue. After 24 hours, the developed blue color was measured at 640 nm wavelength. Nitrite (NO_2-N) was determined on the basis of the Griess reaction, in which 50 mL of the filtered water reacted with sulfanilamide for 2–8 minutes to produce diazonium salt coupled with N-(1-naphthyl)-ethylenediamine dihydrochloride solution. After 10 minutes, the pink azo dye color extinction was measured at 543 nm. Nitrate (NO_3-N) was determined by the cadmium reduction method, where 100 mL of slightly acidified filtered water was passed through a cadmium-filled glass column (loosely coated with metallic copper). In this procedure, all nitrate content was reduced to nitrite, but after a proper correction that subtracted nitrite if any was present initially in the water sample.

The dissolved inorganic phosphorus (PO_4-P) was also determined by forming a phosphor-molybdate complex through the reaction of 50 mL of filtered water with a 5-mL composite reagent (a mixture of molybdic acid, ascorbic acid, and trivalent antimony). The extinction of the reduced blue color was measured spectrophotometrically at 885 nm. In contrast to the above analyses, unfiltered water samples were used to estimate the total phosphorus (TP) and total nitrogen (TN) using the procedure of Valderrama (1981). Spectrophotometric measurements of the nutrient salts were made using the Milton Roy 601 spectrophotometer. Concentrations of the dissolved inorganic nitrogen (DIN) as a sum of $NH_4\text{-N} + NO_2\text{-N} + NO_3\text{-N}$ were also calculated.

Silicate (SiO_4-Si) was determined by inductively coupled plasma-optical emission spectrometry, Thermo Scientific Model iCAP 6000 Series, Fisher Scientific UK Ltd, Loughborough, U.K.

RESULTS AND DISCUSSION

Hydrographical Parameters

Results obtained from the investigated water samples for this study are listed in Table 1 and graphically displayed in Figure 2, where the ranges and mean values of water temperature, salinity, density, pH, and DO are also presented. As shown in Figure 2a, the distribution of seawater temperature is highly dependent on the sampling locations, where they follow a variation in air temperature in different areas along the GOA coast, which is in the range of 19.8 and 23.2°C (Table 1). A slight decrease in water temperature is observed when moving northward along the GOA. The main factors controlling seawater temperature in the gulf area are the warm-water inflow from the Red Sea and the air–sea heat flux (Genin, Lazar, and Brenner, 1995; Manasrah *et al.,* 2004). Water temperature at the entry point between the Red Sea and the GOA (as evident from samples 1–8 in Figures 1 and 2a) is about 2°C higher than the waters already in there. Direct air–sea heat flux has much greater effect on temperature increase than the warm-water inflow from the Red Sea. During the winter season, which normally starts in October, variation in the concentrations of nutrients (including nitrate, phosphate, and silicate) initially begins in the upper parts of the Gulf (Al-Qutob *et al.,* 2002; Badran, 2001; Klinker *et al.,* 1976). This is explained by a drop in the nighttime air temperature to below 18°C. A progressive decrease in air temperature leads to a permanent loss of buoyancy, causing the density of the surface water to pass through a critical threshold.

However, the salinity values between 39.9 and 40.9 PSU show no significant variation, suggesting that salinity is not likely a major factor affecting changes in the surface seawater density. The spatial distribution of salinity between samples 60 and 80 (Fig. 2b) displays a slight increase in the northern part (near the Haql City), which may be due to human activities in the nearby city, particularly from the Haql desalination station. Seawater density varies from 1.01 to 1.02 g/mL (Figure 2c, Table 1), indicating an obvious increase when moving northward. Seawater temperature is the major factor controlling its density, and plays a major role in winter mixing and summer stratification that in turn drive the biogeochemical cycle in the GOA (as suggested by Labiosa *et al.,* 2003).

Variation in other hydrographical parameters (like pH and DO) is not clearly observed during the period of this study (Figures 2d and e). As shown in Table 1, the pH values vary from 8.09 to 8.17, whereas the DO values remain in the range of 5.8 mg/L (equivalent to 72% DO saturation) and 6.91 mg/L (equivalent to 85.3% saturation). The oxygen saturation concentration depends on temperature and salinity (Weiss, 1970). In addition to these conservative parameters, DO concentration depends on the photosynthetic rate and subsequently on nutrient concentrations. High temperature and salinity cause the oxygen to be relatively low (Badran, 2001; Rasheed, Badran, and Huettel, 2003); the higher the temperature, the lower the solubility of oxygen in seawater.

Only minor changes in water temperature, salinity, density, pH, and DO in the surface seawater column along the Saudi GOA coast reveal no significant impact of human activities on the distribution pattern of different hydrographical parameters. This was expected because of low population density in the

Table 1. *Mean ± standard deviation (range) of studied physiochemical parameters for samples 1–85 (see Figure 1, right panel) from Gulf of Aqaba surface coastal water during January 2012.*

Temperature (°C)	Salinity (PSU)	Density (g/mL)	pH	DO (mg/L)
20.98 ± 0.98 (19.8–23.2)	40.2 ± 0.22 (39.9–40.9)	1.02 ± 0.003 (1.01–1.02)	8.12 ± 0.017 (8.09–8.17)	6.31 ± 0.29 (5.8–6.91)

PSU = practical salinity units; DO = dissolved oxygen.

area. The absence of freshwater resources and low population size in the area could explain the negligible contamination from sewage, agriculture, and industrial effluents. Accordingly, these conditions could be principally controlled by the circulation pattern of seawater in the study area. Cross-correlations among the hydrographical characteristics and nutrient salts for the studied water samples are shown in Table 2. A significant negative correlation between the water temperature and density ($r = -0.86$) is noticed, whereas weak correlations were observed between water temperature and DO ($r = 0.17$) as well as between salinity and density ($r = 0.24$). In addition, a weak negative correlation is observed between density and DO ($r = -0.18$). All these characteristics also confirm the limited impacts of human activities on the seawater in the GOA region.

Nutrient Salts

Seawater characteristics are either conservative or nonconservative. Conservative characteristics such as temperature and salinity are not affected by the primary productivity of the system, but nonconservative characteristics such as DO and nutrient concentrations are influenced directly or indirectly. The most important nutrients are nitrogen and phosphorus. Silicon can also be important for some organisms that have siliceous frustules. Nutrient salts input to the sea may occur anthropogenically or naturally through physical, chemical, and biological processes. Anthropogenic sources include desalination, groundwater, river input, sewage discharge, and industrial runoff (both terrestrial and sea-based), whereas natural sources include nitrogen-fixing processes when organic matter decomposition occurs in the sediments (Badran and Foster, 1998; D'Elia, Webb, and Porter, 1981; Rasheed *et al.,* 2004; Wild *et al.,* 2004). In addition, the nutrient salts can be produced naturally in the coral reef framework (Richter *et al.,* 2001) and in the water column itself (Rasheed *et al.,* 2002). The current action as a physical process also plays an important role in nutrient redistribution (Niemann *et al.,* 2004).

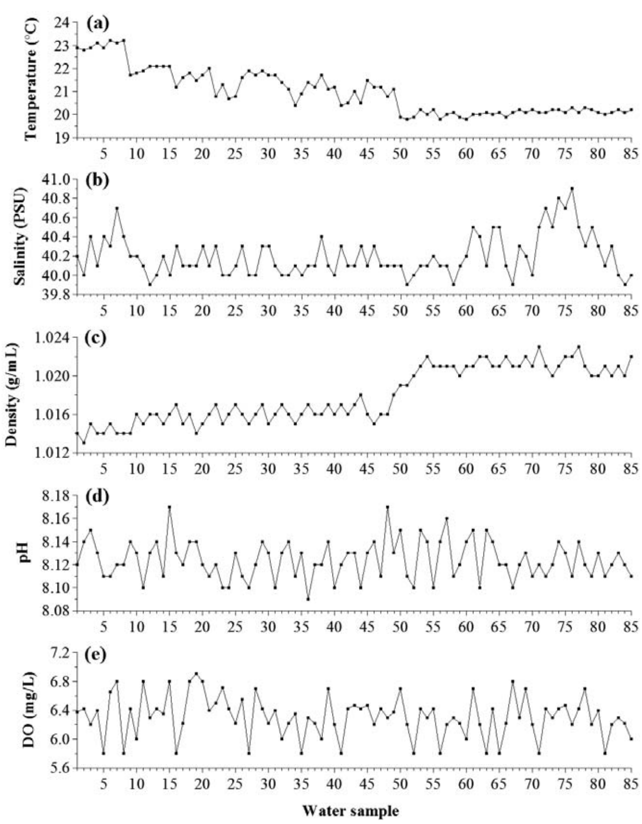

Figure 2. Variations in the values of some physicochemical parameters in the surface water along the Saudi Gulf of Aqaba coast during January 2012.

Hernandez-Ayon *et al*. (1993), Gianesella, Saldana-Correa, and Teixeira (2000), and Montani *et al*. (1998) studied the effect of a tidal cycle on the dynamics of nutrients and concluded that the nutrient balance was rapidly influenced by the tidal cycle. They showed that the effect of the tidal amplitude was stronger between the lower low tide and the higher high tide. Main sources of nutrients came either from the freshwater runoff (silicate, and partially nitrate + nitrite and phosphate) or the intertidal flat (ammonium, and partially nitrate + nitrite and phosphate).

Water mixing in the GOA during winter season is a well-known phenomenon for transferring nutrients from deep water to the upper layers (Badran, 2001; Rasheed, Badran, and Huettel, 2003). Heat-flux variations in arid areas that neither receive considerable rain nor have any source of freshwater runoff are the main factors controlling the water-column density structure. This directly affects the water movement both vertically and horizontally (Straneo and Kawase, 1999) and subsequently determines the redistribution of all soluble and free-drifting material. Such movement of soluble and particulate nutrients plays a milestone role in shaping the trophic characteristics of the water column.

The ranges and mean values of different nutrient salts (NH_4-N, NO_2-N, and NO_3-N) in the studied samples are listed in Table 3 and represented in Figure 3. The respective ranges for NH_4-N, NO_2-N, and NO_3-N are 0.43–1.01 μM, 2.14–14.29 μM, and 29.29–51.4 μM, whereas their mean values are 0.72 μM, 8.95 μM, and 38.42 μM. As evident from these values, variations of the DIN in the studied samples are relatively low.

On the basis of the mean values, the concentrations of DIN have been found in the order of NO_3 (38.42 μM) > NO_2 (8.95 μM) > NH_4 (0.72 μM). As evident from the range of the values, no significant variation in the distribution of NH_4-N contents of the water along the GOA coast is observed (Figure 3a).

Table 2. *Cross-correlation among hydrographical characteristics and nutrient salts in Gulf of Aqaba surface water samples. Large correlation values (>0.50) are marked in bold.*

	Temperature	Salinity	Density	pH	DO	NH_4-N	NO_2-N	NO_3-N	TN	PO_4-P	TP	SiO_4-Si
Temperature (°C)	1											
Salinity (PSU)	−0.05	1										
Density (g/mL)	**−0.86**	0.24	1									
pH	0.00	0.02	0.02	1								
DO (mg/L)	0.17	−0.01	−0.18	0.10	1							
NH_4-N (μM)	0.05	−0.05	−0.08	0.05	−0.09	1						
NO_2-N (μM)	−0.20	0.05	0.18	0.12	−0.24	0.36	1					
NO_3-N (μM)	**−0.71**	0.19	**0.87**	0.02	−0.10	−0.06	0.15	1				
TN (μM)	**−0.52**	0.23	**0.71**	0.02	−0.03	−0.03	0.16	**0.79**	1			
PO_4-P (μM)	**0.81**	−0.04	**−0.70**	0.04	0.13	0.10	−0.05	**-0.55**	−0.37	1		
TP (μM)	**0.85**	−0.06	**−0.77**	0.08	0.09	0.09	−0.10	**-0.64**	−0.41	**0.91**	1	
SiO_4-Si (μM)	**0.80**	−0.01	**−0.63**	0.06	0.11	0.08	−0.09	−0.45	−0.24	**0.81**	**0.88**	1

PSU = practical salinity units; DO = dissolved oxygen; TN = total nitrogen; TP = total phosphorus.

Generally, the NO_2-N contents show a slight increase northward (Figure 3b), whereas a clear increase in the NO_3-N concentrations is noticed from sample number 50 toward the north (Figure 3c). The increase in NO_3-N is likely attributed to increased human activities in the northern part of the Saudi GOA coast, particularly in the Jordanian part of the coast. As listed in Table 2, a significant negative correlation ($r = -0.71$) is observed between water temperature and NO_3-N contents, which becomes weak ($r = -0.20$) between water temperature and NO_2-N contents.

TN levels show a remarkable variation and ranged from 166.4 to 314.3 μM (Table 3 and Figure 3d). On the basis of the average values, the DIN accounts for about 20% of the TN (15.50–25.96%). A large difference between the TN and DIN concentrations suggests that nitrogen found in the GOA coastal surface waters is probably inorganic in nature. This is in agreement with the general view of microbial food and phytoplankton dynamics, in which NH_4, NO_2, and NO_3 are rapidly processed by phytoplankton and other microbial components (Abdel-Halim *et al.,* 2007), whereas the organic nitrogen is assimilated by aquatic organisms in a much slower rate (Riley and Chester, 1971). Faganeli (1983) has pointed out that in the Gulf of Trieste (North Adriatic), the relative composition of TN is 11.3% for particulate, 68.8% for dissolved organic, and 20% for inorganic. The DIN levels obtained by the present study are close to those values reported for inorganic form.

The ranges and mean values of PO_4, TP, and SiO_4 concentrations are listed in Table 3 and presented in Figure 4. A remarkable decrease in the PO_4 contents is observed northward (Figure 4a). The concentration of PO_4 in the water samples ranges from 0.03 to 0.10 μM, which is very low compared with TN concentrations (Table 3). A very high value (680:1) of N : P ratio is observed (where mean TN and TP values are 244.8 μM and 0.36 μM, respectively) (Table 3), suggesting that PO_4 could be the limiting nutrient for phytoplankton growth. The low PO_4 contents could be mostly due to their sorption and deposition on iron-borne dust conveyed to the Gulf from the surrounding mountains and deserts. Suzumura, Ueda, and Suni (2000) reported the effect of composition and physicochemical characteristics of natural particles on PO_4 adsorption–desorption processes under various aquatic environments and concluded that the concentration of PO_4 in the surface water is generally low. Okbah, Mahmoud, and El-Deek (1999) reported very low levels of inorganic phosphorus concentrations in the GOA, particularly in the euphotic zone (∼200 m depth), and higher concentrations of PO_4 in the northern parts of Red Sea. In this study, a high negative correlation ($r = -0.52$) is obtained between the PO_4 and DIN.

As shown in Table 3, the TP concentrations display a slight variation during the investigation period (from 0.16 to 0.90 μM). As indicated in the case of PO_4, a remarkable decrease in TP content is observed as one moves from south to north along the GOA (Figure 4b). On the basis of the mean values calculated by this study (Table 3), PO_4 constitutes 14% of the TP (where mean PO_4 and TP values are 0.05 μM and 0.36 μM, respectively), suggesting that PO_4 is mostly in the forms of particulate and organic. Similar to the conclusions obtained from other parameters, the levels of PO_4 and TP also suggest that the surface water along the Saudi GOA coast is likely unpolluted. According to Giovanardi and Tromellini (1992), the level of TP in oligotrophic water is 0.27 μM, in mesotrophic water it reaches up to 0.89 μM, and in eutrophic seawater it increases further up to 2.81 μM. Comparison of these levels with those obtained from the present study indicates oligotrophic to mesotrophic conditions to the surface water in the Saudi GOA coast.

Table 3. *Mean ± standard deviation (range) of studied nutrient salts for samples 1–85 (see Figure 1, right panel) from Gulf of Aqaba surface coastal water during January 2012.*

NH_4-N (μM)	NO_2-N (μM)	NO_3-N (μM)	TN (μM)	PO_4-P (μM)	TP (μM)	SiO_4-Si (μM)
0.72 ± 0.15 (0.43–1.01)	8.94 ± 2.23 (2.14–14.29)	38.42 ± 7.43 (29.29–51.4)	244.8 ± 38.73 (166.4–314.3)	0.05 ± 0.02 (0.03–0.10)	0.36 ± 0.17 (0.16–-0.90)	5.26 ± 2.93 (3.3–20.6)

TN = total nitrogen; TP = total phosphorus.

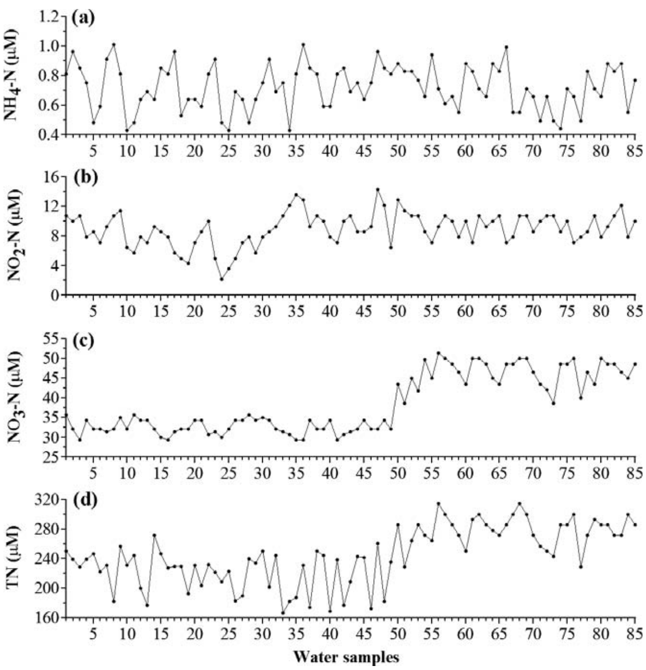

Figure 3. Observed variations of nitrogen in the Saudi Gulf of Aqaba surface water during January 2012.

The concentration of silicate (SiO_4) shows a relatively high variation from 3.3 to 20.6 μM (Table 3). Similarly, a remarkable decrease in SiO_4 contents is observed northward along the GOA (Fig. 4c). Okbah, Mahmoud, and El-Deek (1999) have pointed out that concentration of silicate in the GOA area is lower than that in the northern Red Sea water. Fahmy (2003)

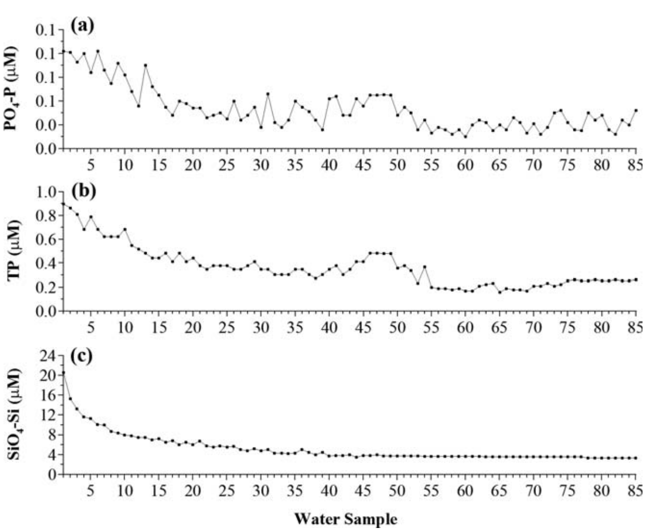

Figure 4. Variations of phosphate and reactive silicate in the surface water along the Saudi Gulf of Aqaba coast.

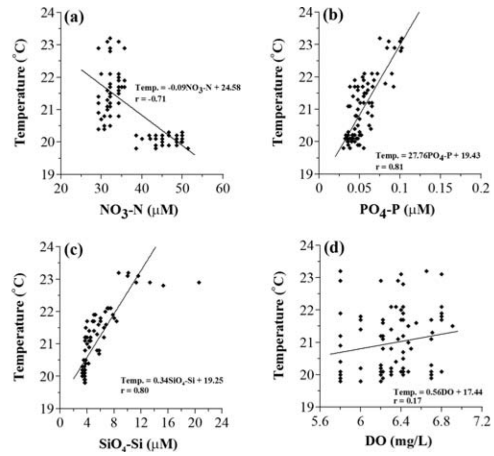

Figure 5. Relationship of the nutrients (μM) and dissolved oxygen (mg/L) with water temperature (°C) in the surface water along the Saudi Gulf of Aqaba coast.

indicated that the main factors controlling SiO_4 distribution in the Egyptian Red Sea coastal water are: (1) the supply of SiO_4 to the Red Sea through the Straits of Bab El-Mandab, (2) biological composition, (3) organic matter decomposition, and (4) partial dissolution of quartz and clay particles transported to the sea from the surrounding deserts during sandstorms.

The results also show that the SiO_4 concentration is positively correlated with water temperature and PO_4 ($r = 0.80$ and 0.81, Table 2, respectively) and negatively correlated with density, NO_3-N, TN, and DIN ($r = -0.63$, –0.45, –0.24, and –0.44, Table 2, respectively).

The concentrations of nitrate, phosphate, silicate, and DO were plotted against water temperature (Figure 5). The inverse relationship between water temperature and nitrate (Figure 5a) is categorized in two ways. In one part, when the level of temperature remains <20.5°C in the upper water column, the nitrate concentrations become higher. However, when the temperature rises above the 20.5°C level, the concentrations of nitrate are reduced in the surface waters. The concentrations of phosphate and silicate (Figures 5b and c) follow a similar trend to that of the DO (Figure 5d) but with different relationships. This is more likely due to the reason that primary productivity is not limited by silicate, which enters the GOA ecosystem from the surrounding desert as well as from the deepwater basin.

The DO exhibits weak correlation ($r = 0.17$, Table 2) with water temperature (Figure 5d), which could be attributed to higher photosynthetic rate associated with higher light intensity in the upper water. However, in the uppermost water, where the temperature rises above the 25°C level, oxygen concentration decreases as a result of its lower solubility in warmer seawater (Weiss, 1970).

CONCLUSIONS

As part of this study, different hydrographical and nutrient salts variables in the surface water along the Saudi GOA coast were continuously monitored during the month of January

2012. According to these investigations, no significant change was observed in the salinity and pH levels. Well-oxygenated seawater and low levels of some parameters (including nitrogen, phosphorus, and reactive silicates) suggest that the water is oligotrophic to mesotrophic. The results also suggest that the majority of the Saudi GOA coast is not polluted or seriously affected by human activities in spite of rapid recreational and residential developments in the area during the past 10 years.

ACKNOWLEDGMENTS

This work is financially supported by the National Plan of Science, Technology and Innovation (NPST) program, King Saud University, Saudi Arabia (Project No. 11-WAT1731-02). We are also thankful to staff members from General Directorate of Water in Al-Bad City (Ministry of Water & Electricity, Saudi Arabia) for their help and valuable information during the course of the fieldwork.

LITERATURE CITED

Abdel-Halim, A.M.; Aboel-Khair, E.M.; Fahmy, M.A., and Shridah, M.A., 2007. Environmental assessment on the Aqaba Gulf coastal waters; Egypt. *Egyptian Journal of Aquatic Research*, 33(1), 1–14.

Al-Qutob, M.; Haese, C.; Tilzer, M.M., and Lazar, B., 2002. Phytoplankton drives nitrite dynamics in the Gulf of Aqaba, Red Sea. *Marine Ecology Progress Series*, 239, 233–239.

Al-Rousan S.; Al-Moghrabi, S.; Patzold, J., and Wefer, G., 2002. Environmental and biological effects on the stable oxygen isotope records of corals in the Gulf of Aqaba, Red Sea. *Marine Ecology Progress Series* 239: 301–310.

Al-Taani, A.; Batayneh, A.; Nazzal, Y.; Ghrefat, H.; Zaman, H.; Zumlot, T.; Mogren, S.; Elawadi, E., and Qaisy, S., 2013. Groundwater quality of coastal aquifer systems in the eastern coast of the Gulf of Aqaba, Saudi Arabia. *Earth Science Research Journal*. In press.

APHA (American Public Health Association), 1998. Standard Methods for the Examination of Water and Wastewater, 20th edition. Washington, D.C, 1325p.

Badran, M. I., 2001. Dissolved oxygen, chlorophyll a and nutrients: seasonal cycles in waters of the Gulf Aqaba, Red Sea. *Aquatic Ecosystem & Health Management*, 4(1), 139–150.

Badran, M.I. and Foster, P., 1998. Environmental quality of the Jordanian coastal waters of the Gulf of Aqaba, Red Sea. *Aquatic Ecosystem & Health Management*, 1(1), 75–90.

Badran, M.I.; Rasheed, M.; Manasrah, M., and Al-Najjar, T., 2005. Nutrient flux fuels summer primary productivity in the oligotrophic waters of the Gulf of Aqaba, Red Sea. *Oceanologia*, 47(1), 47–60.

Batayneh, A.; Zaman, H.; Zumlot, T.; Ghrefat, H.; Mogren, S.; Nazzal, Y.; Elawadi, E.; Qaisy, S.; Bahkaly, I., and Al-Taani, A., 2013. Hydrochemical facies and ionic ratios of the coastal groundwater aquifer of Saudi Gulf of Aqaba: implication for seawater intrusion. *Journal of Coastal Research*. In press.

Ben-Sasson, M.; Brenner, M.S., and Paldor, N., 2009. Estimating air–sea heat fluxes in semienclosed basins: the case of the Gulf of Elat (Aqaba). *Journal of Physical Oceanography*, 39(1), 185–202.

Berman, T.; Paldor, N., and Brenner, S., 2000. Simulation of wind-driven circulation in the Gulf of Elat (Aqaba). *Journal of Marine Systems*, 26(3–4), 349–365.

Biton, E. and Gildor, H., 2011. The general circulation of the Gulf Aqaba (Gulf of Eilat) revisited: the interplay between the exchange flow through the Straits of Tiran and surface fluxes. *Journal of Geophysical Research*, 116(C08020), 1–15.

D'Elia, C.F.; Webb, K.L., and Porter, J.W., 1981. Nitrate-rich groundwater input to Discovery Bay, Jamaica: a significant source of N to local coral reefs. *Bulletin of Marine Science*, 31(4), 903–910.

Faganeli, J., 1983. Organic nitrogen and phosphorus in Gulf of Trieste (N. Adriatic). *Archives Oceanography and Limnology*, 20, 153–117.

Fahmy, M.A., 2003. Water quality in the Red Sea coastal waters (Egypt): analysis of spatial and temporal variability. *Chemistry and Ecology*, 19(1), 67–77.

Genin, A.; Lazar, B., and Brenner, S., 1995. Vertical mixing and coral death in the Red Sea following the eruption of Mt. Pinatubo. *Nature*, 377, 507–510.

Gianesella, S.M.F.; Saldanha-Correa, F.M.P., and Teixeira, C., 2000. Tidal effects on nutrients and phytoplankton distribution in Bertioga Channel, Sao Paulo, Brazil. *Aquatic Ecosystem Health & Management*, 3(4), 533–544.

Giovanardi, F. and Tromellini, E., 1992. Statistical assessment of trophic conditions. Application of the OECD methodology to the marine environment. *In:* Vollenweider, R.A.; Marchetti, R., and Viviani, R. (eds.), 1990. *Proceedings of Marine Coastal Eutrophication Conference*.. London: Elsevier, pp. 211–233.

Hernandez-Ayon, J.M.; Galindo-Bect, M.S.; Flores-Baez, B.P., and Alvarez-Borrego, S., 1993. Nutrient concentrations are high in the turbid waters of the Colorado River Delta. *Estuarine, Coastal and Shelf Science*, 3, 593–602.

Klinker, J.; Reiss, Z.; Kropach, C.; Levanon, I.; Harpaz, H.; Halicz, E., and Assaf, G., 1976. Observation on the circulation pattern in the Gulf of Aqaba, Red Sea. *Israel Journal of Earth Sciences* 25, 85–103.

Labiosa, R.G.; Arrigo, K.R.; Genin, A.; Monismith, S.G., and Dijken, G., 2003. The interplay between upwelling and deep convective mixing in determining the seasonal phytoplankton dynamics in the Gulf of Aqaba: Evidence from SeaWiFS and MODIS. *Limnology and Oceanography*, 48(6), 2355–2368.

Manasrah, R.; Badran, M.; Lass, H.U., and Fennel, W., 2004. Circulation and winter deep-water formation in the northern Red Sea. *Oceanologia*, 46(1), 5–23.

Manasrah, R.; Rasheed, M., and Badran, M.I., 2006. Relationships between water temperature, nutrients and dissolved oxygen in the northern Gulf of Aqaba, Red Sea. *Oceanologia*, 48(2), 237–253.

Monismith, S.G. and Genin, A., 2004. Tides and sea level in the Gulf of Aqaba (Eilat). *Journal of Geophysical Research*, 109, C0415, doi:10.1029/2003JC002069.

Montani, S.; Magni, P.; Shimamoto, M.; Abe, N., and Okutani, K., 1998. The effect of a tidal cycle on the dynamics of nutrients in a tidal estuary in the Seto Inland Sea, Japan. *Journal of Oceanography*, 54, 65–76.

Niemann, H.; Claudio, R.; Jonkers, H., and Badran, M., 2004. Red Sea gravity currents cascade near-reef phytoplankton to the twilight zone. *Marine Ecology Progress Series*, 269, 91–99.

Okbah, M.A.; Mahmoud, Th.H., and El-Deek, M.S., 1999. Nutrient salts concentrations in the Gulf of Aqaba and Northern Red Sea. *Bulletin of the National Institute of Oceanography and Fisheries*, 25, 103–116.

Rasheed, M .; Badran, M., and Huettel, M., 2003. Particulate matter filtration and seasonal nutrient dynamics in permeable carbonate and silicate sands of the Gulf of Aqaba, Red Sea. *Coral Reefs*, 22(2), 167–177.

Rasheed, M.; Badran, M.; Richter, C., and Huettel, M., 2002. Effect of reef framework and bottom sediment on nutrient enrichment in coral reef of the Gulf of Aqaba, Red Sea. *Marine Ecology Progress Series*, 239, 277–285.

Rasheed, M.; Wild, C.; Franke, U., and Huettel, M., 2004. Benthic photosynthesis and oxygen consumption in permeable carbonate sediments at Heron Island, Great Barrier Reef, Australia. *Estuarine, Coastal and Shelf Science*, 59(1), 139–150.

Richter, C.; Wunsch, M.; Rasheed, M .; Kotter, I., and Badran, M., 2001. Endoscopic exploration of Red Sea coral reefs reveals dense populations of cavity-dwelling (coelobite) sponges. *Nature*, 413, 726–730.

Riley, J.P. and Chester, R., 1971. *Introduction to Marine Chemistry*. Waltham, Massachusetts: Academic, 757p.

Silverman, J. and Gildor, H., 2008. The residence time of an active versus a passive tracer in the Gulf of Aqaba: a Box model approach. *Journal of Marine Systems*, 71(1–2), 159–170.

Sofianos, S.S. and Johns, W.E., 2001. Wind induced sea level variability in the Red Sea. *Geophysical Research Letters*, 28, 3175–3178.

Straneo, F. and Kawase, M., 1999. Comparisons of localized convection due to localized forcing and to preconditioning. *Journal of Physical Oceanography*, 29, 55–68.

Strickland, J.D.H. and Parsons, T.R., 1972. *A Practical Handbook of Seawater Analysis*, 2nd edition.. Ottawa, Canada: Fisheries Research Board of Canada Bulletin 167, 310p.

Suzumura, M.; Ueda, S., and Suni, E., 2000. Control of phosphate concentration through adsorption and desorption process in groundwater and seawater mixing at sand beaches in Tokyo Bay. *Journal of the Oceanographical Society of Japan*, 56(6), 667–673.

Valderrama, J.C., 1981. The simultaneous analysis of total nitrogen and total phosphorus in natural waters. *Marine Chemistry*, 10(2), 109–122.

Weiss, R.F., 1970. The solubility of nitrogen, oxygen and argon in water and seawater. *Deep Sea Research*, 17(4), 721–735.

Wild, C.; Huettel, M.; Kremb, S.; Rasheed, M.; Woyt, H.; Gonelli, S., and Klueter A., 2004. Coral mucus functions as energy shuttle and nutrient trap in the reef. *Nature*, 428, 66–70.