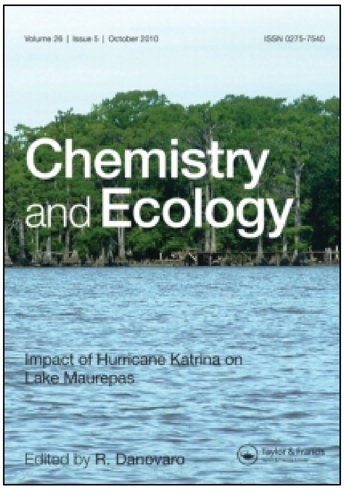

Chemistry and Ecology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713455114

Quality standard codes of reference of Jordanian coastal waters of the Gulf of Aqaba, Red Sea

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To cite this Article Badran, M. I. and Zibdah, M. K. Al(2005) 'Quality standard codes of reference of Jordanian coastal waters of the Gulf of Aqaba, Red Sea', Chemistry and Ecology, 21: 5, 337 — 350
To link to this Article: DOI: 10.1080/02757540500258831
URL: http://dx.doi.org/10.1080/02757540500258831

Chemistry and Ecology
Vol. 21, No. 5, October 2005, 337–350

Quality standard codes of reference of Jordanian coastal waters of the Gulf of Aqaba, Red Sea

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(Received 21 June 2005; accepted 13 July 2005)

Back in 1992, the Gulf of Aqaba Environmental Action Plan (GAEAP), a collaboration between the Aqaba Region Authority (ARA), Jordan and the World Bank, gave considerable emphasis to the environmental protection of the Gulf of Aqaba [The World Bank. *Gulf of Aqaba Environmental Action Plan.* Report No. 12244JO (1993).]. The document recommended the establishment of a marine reserve and the long term monitoring of the coastal habitats' environmental quality. The combination of a dedicated follow up, the collaborative efforts of ARA and the Marine Science Station (MSS), and the founding of the Aqaba Special Economic Zone Authority (ASEZA) have turned the recommendations into reality. A comprehensive monitoring program of the Jordanian coastal habitats commenced in 1999. The first three years of the program were financed by a donation from The Global Environmental Facility (GEF). In return, Jordan has committed itself to the maintenance of the monitoring program as an ongoing tool for sustainable coastal management. The monitoring program includes observations on benthic habitat, fish communities, bottom sediments and seawater quality. This paper focuses on the results of seawater-quality monitoring in the first three years. Records of weather conditions, coastal currents, seawater temperature, transparency, salinity, density, pH, alkalinity, dissolved oxygen, ammonia, nitrate, nitrite, phosphate, silicate, particulate matter, chlorophyll *a*, zooplankton biomass, total coliform, fecal coliform, hydrocarbons and sedimentation rate have been generated monthly since January 1999 at six coastal stations, and one offshore reference station, in the Jordanian waters of the Gulf of Aqaba. The coastal stations are located at sites with different benthic habitats and are occupied by different human activities. Offshore records of density (thermohaline structure), nutrients and chlorophyll *a* depicted two well-defined seasons; a nutrient-/chlorophyll *a*-rich, mixed water winter from December to April and a nutrient-/chlorophyll *a*-poor, stratified water summer from June to October. Short transition seasons appeared in May and November. The mixing and stratification seasons were also clearly depicted in the coastal waters. Statistical analysis of the three-year data collected at the offshore station revealed no significant inter-annual differences in the upper 125 m of the water column with respect to any of the measured parameters. At coastal stations, the water quality at the two northernmost stations was significantly different in comparison to the upper 125 m at the offshore station and to the other coastal stations, with respect to the two key indicator parameters: inorganic nitrogen and chlorophyll *a*. The three-year findings of the monitoring program are employed to suggest standard codes of reference for the coastal water quality.

Keywords: Nutrients; Chlorophyll *a*; Mixing; Stratification; Living resources; Fishing; Codes of reference

1. Introduction

Until the mid-1950s, the Gulf of Aqaba had been a relatively remote area with very little anthropogenic activity. During the last five decades, development along the coasts of all

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Chemistry and Ecology
ISSN 0275-7540 print/ISSN 1029-0370 online © 2005 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/02757540500258831

boundary states except Saudi Arabia has increased substantially, resulting in significant adverse effects on the natural coastal components. In response to this, the Gulf of Aqaba Environmental Action Plan (GAEAP), a collaboration between the Aqaba Region Authority (ARA), Jordan and the World Bank, has given considerable emphasis to the environmental protection of the Gulf of Aqaba and to monitoring its environmental quality [1]. The plan recommended implementation of air, marine water and ground water quality monitoring programs. The estimated cost was very high but the presence of the Marine Science Station (MSS), which has been active in fundamental scientific research and environmental monitoring since the mid-1970s, helped to reduce the cost quite substantially. The existing buildings and basic laboratory equipment saved most of the capital cost. The Global Environmental Facility (GEF 1996) provided the money required to purchase additional environmental monitoring equipment. The main objective of the GEF project was to enable Jordan to take the lead in establishing and implementing a regional collaborative framework for sustainable management of the Gulf of Aqaba and the conservation of its coastal resources. The key tool for such a framework is identification of pollution prevention, and resource conservation, measures that support the avoidance of irreversible loss of biodiversity or collapse of ecosystem functionality. Implementation of the monitoring program commenced in January 1999. In February 2000, the Aqaba Special Economic Zone Authority (ASEZA) was established and the monitoring program, under the allegiances of the Environment Commission, has gained additional weight and stronger recognition. In a parallel effort, the MSS and ARA/ASEZA won financial support in 1999 for a USAID funded research and monitoring program, the main purpose of which was to carry out resource management-oriented research and provide explanations of the monitoring programs' findings. The long-term outcome of both programs was the declared commitment of the ASEZA to finance and manage a sustainable national monitoring program of the coastal environment.

The Jordanian National Monitoring Program of the coastal environment includes observations of benthic habitats, bottom sediments, fish communities and seawater characteristics. The present paper focuses on the seawater quality. Seawater characteristics are divided into two main categories; conservative and non-conservative. Conservative characteristics are those unaffected by the biological productivity of the system, such as temperature and salinity. Non-conservative characteristics are those shaped by, and shaping, the biological productivity of the system such as nutrients, dissolved oxygen and chlorophyll *a* concentrations. Both conservative and non-conservative characteristics of a water body can serve monitoring purposes. Modifications in water temperature or salinity due to run off of cooling water or fresh water, which can be easily detected using self-recording, sensitive and reliable equipment, are extremely important because of their direct effect on biological productivity. Modifications in non-conservative characteristics can be either natural or anthropogenic. These are usually more difficult to detect, especially in oligotrophic waters, where they have low concentrations, such as is the case in the Gulf of Aqaba. They are, however, essential determinants in any monitoring program because they are direct indicators of the biological productivity of the system and, consequently, of the species density and biodiversity. The coastal waters of the Gulf of Aqaba are unique in their characteristics, and closer to oceanic waters in composition than to any coastal water elsewhere in the world. Therefore, the approach adopted herein to define modifications in conservative and non-conservative characteristics of coastal waters is based on using remote parts of the system (offshore waters) as a reference.

The aim of the monitoring program was to provide resource managers with necessary baseline data on seawater, bottom surface sediment and coastal habitat quality to help them understand the coastal ecosystem functioning and enable them to adopt suitable management schemes. The main specific objectives of the monitoring program are to: (i) generate systematic records of the seawater physical properties: transparency, colour, odour, temperature, salinity and currents; (ii) generate systematic records of the seawater chemical and biological properties: dissolved oxygen, pH, alkalinity, ammonia, nitrate, nitrite, phosphate, silicate and chlorophyll *a*; (iii) generate baseline records of the bottom sediment quality variables: sedimentation rate, colour and odour, redox potential, grain size, concentrations of calcium carbonate, organic carbon, organic nitrogen and total phosphorus; (iv) generate baseline records of the bottom habitat on live coral cover and reef health; (v) generate baseline records of fish abundance and biodiversity of coral reef and sea grass habitats; (vi) discuss the generated records and provide simple data analysis to pinpoint possible trends or abnormalities and (vii) suggest standard codes of reference for the Jordanian coastal waters of the Gulf of Aqaba.

2. Materials and methods

2.1 *Sampling stations and frequency*

Water samples were collected from six coastal stations and one offshore reference station. The coastal stations begin at the northern border and spread along the Jordanian coast as shown in figure 1. The three northernmost stations: Hotels, public cafes (Al Ghandour) and Phosphate Port represent sandy bottom habitats, while Clinker Port, MSS and the Tourist Camp (Visitor's Center) represent coral reef habitats. The last two stations, MSS and Tourist Camp, are within the Aqaba Marine Park. Samples were collected at 0.5 m depth from a water column of 10–15 m. The offshore reference station is located 3 km offshore of MSS. All stations were sampled concurrently at monthly intervals from January 1999 to December 2001.

Seawater samples were collected in Nisken Bottles using the Marine Science Station research vessel—Al Baheth—equipped with oceanographic equipment. Temperature, salinity, dissolved oxygen and pH were recorded *in situ* using a conductivity, temperature and depth

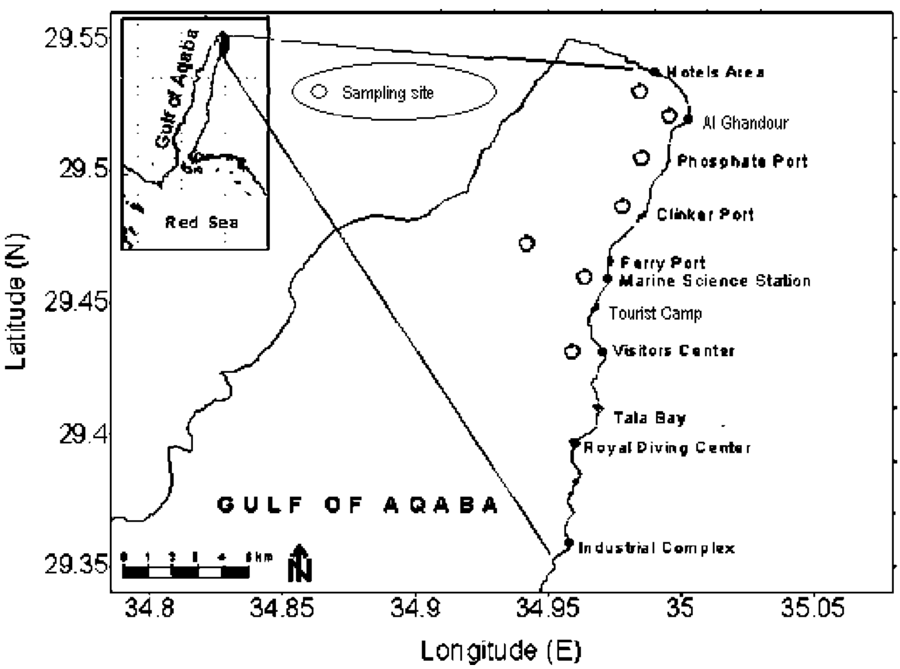

Figure 1. Gulf of Aqaba and seawater sampling sites on the Jordanian coast during the period 1999–2001.

meter (CTD) Model Ocean Sensors OS200 and OS453 and a YSI water quality monitor model 600XL. Dissolved oxygen concentration and pH values were double checked in the laboratory using bench instruments.

2.2 *Analytical techniques*

Chemical analysis was carried out according to the well-established methods at MSS, developed mainly from IOC Manuals and Guides No. 12 [2] and Strickland and Parsons [3]. These analytical methods have been used often by several authors [4–10].

Nutrient analyses were carried out on filtered seawater samples using cellulose acetate membrane filters. Reagents were of analytical grade. Solutions were prepared in distilled, deionised water (DDW). Analyses were made in duplicate. Extinctions were measured in 5 or 10 cm cells using a Pye Unicam UV/Visible spectrophotometer. Chlorophyll *a* was analysed flouremetrically following an overnight digestion of the cellulose acetate membrane filter in 90% acetone [11].

3. Results

3.1 *Physical and chemical characteristics*

Records of the three-year average values and standard deviation of the ecosystem variables water temperature (°C), salinity (PSU), sigma (t) ($kg\,m^{-3}$), dissolved oxygen ($mg\,l^{-1}$) and chlorophyll *a* ($\mu g\,l^{-1}$) concentrations down to 400 m offshore of the Marine Science Station are shown in figure 2. Records of the same variables for the surface water of the six coastal stations: Hotels, Al Ghandour, Phosphate Port, Clinker Port, MSS and the Tourist Camp, over the three years 1999–2001 are shown in figure 3.

Seawater density showed well-defined winter mixing and summer stratification. Month-to-month variations in temperature, salinity and density were similar at the coastal and offshore stations reflecting the dominance of the natural annual cycle in controlling the thermohaline structure of the coastal and offshore waters in contrast to any other anthropogenic factors.

Studying the detailed three-year picture at the coastal stations reveals that seawater was colder in January 1999 than in the two following years, reflecting earlier mixing. The minimum water temperature in the three years was recorded in March, reflecting deepest mixing during this month. March 2000 exhibited the lowest temperature of all, indicating that mixing during that year was the deepest. Salinity did not show any interesting changes. Variations were very small at all levels, station-to-station, month-to-month and year-to-year. Water density followed the temperature trend, but in an inverse relationship and so did dissolved oxygen concentrations. Chlorophyll *a* concentration was higher in winter and homogeneously distributed down to 400 m. In summer, a subsurface chlorophyll *a* concentration maximum was noticed between 50 m and 100 m.

Records of the three-year average concentration (μM) and standard deviation of the inorganic nutrients ammonia, nitrate, nitrite, phosphate and silicate down to 400 m offshore of the Marine Science Station are shown in figure 4. Records of the monthly average concentrations of the same variables for the surface water of the six coastal stations over the three years 1999–2001 are shown in figure 5.

The mixing conditions that prevailed during winter were clearly reflected on all other parameters. Nutrients exhibited homogeneous values down to the depth of the thermohaline (Pycnal) mixed layer. The spring bloom was clearly noticeable in March 2000 but not as clear

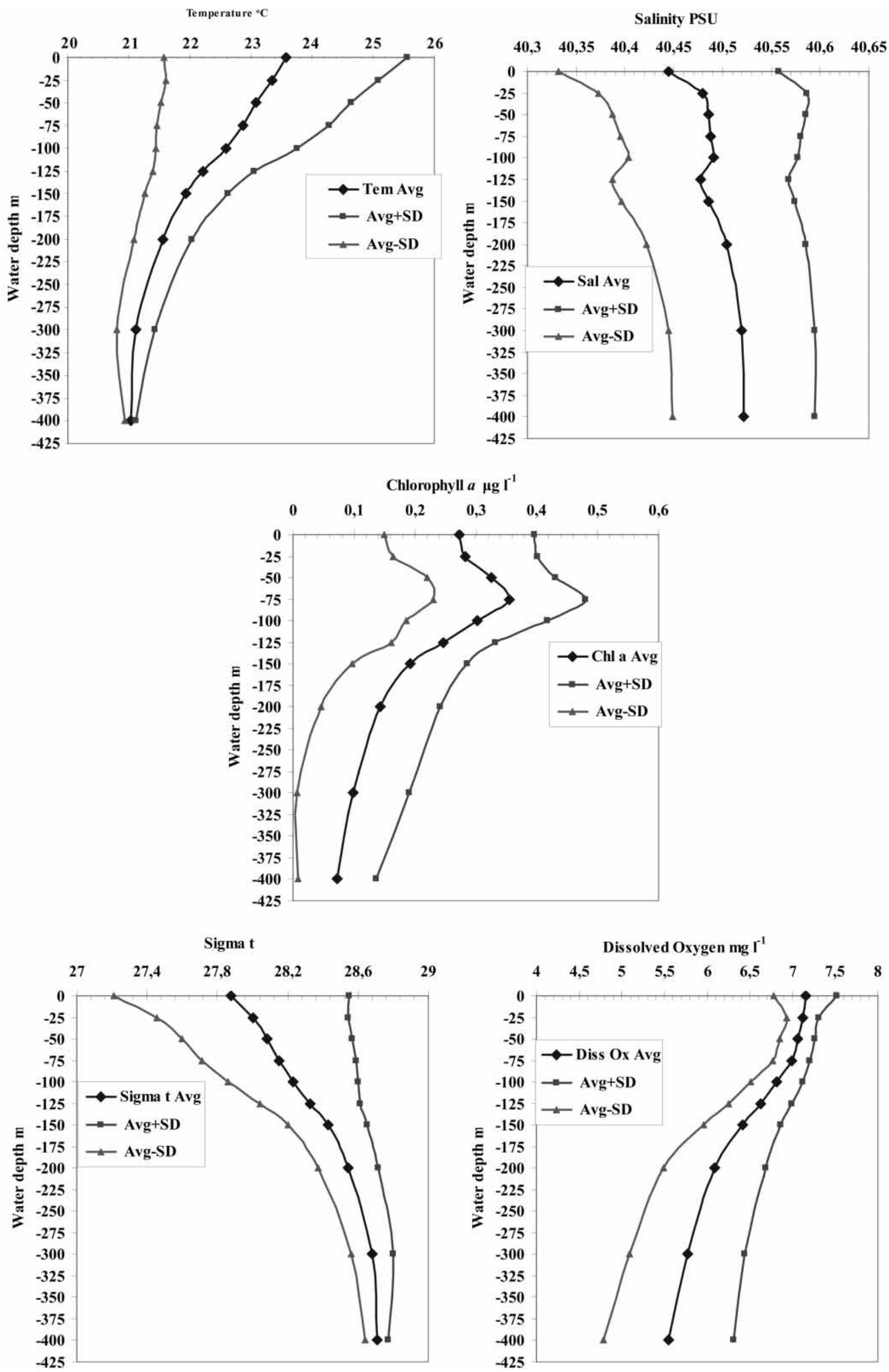

Figure 2. Records of three-years' average, (average + standard deviation) and (average − standard deviation) of water temperature (°C), salinity (PSU), density (sigma t), chlorophyll *a* ($\mu g\, l^{-1}$) and dissolved oxygen ($mg\, l^{-1}$) down to 400 m in the Jordanian offshore reference waters of the Gulf of Aqaba.

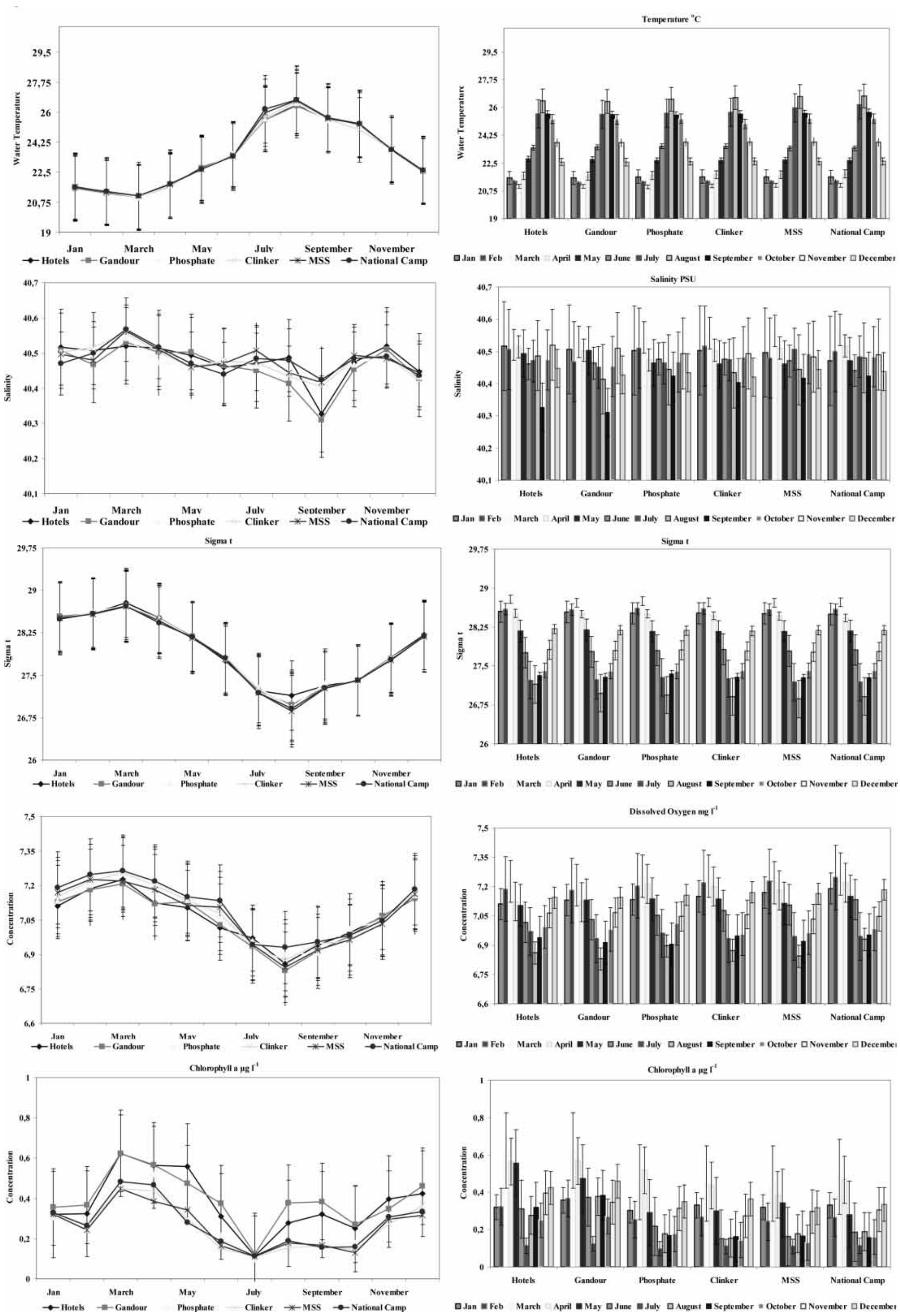

Figure 3. Three-years' monthly average and standard deviation of records of seawater temperature (°C), salinity (PSU), density (sigma t), chlorophyll *a* ($\mu g\, l^{-1}$) and dissolved oxygen ($mg\, l^{-1}$) at six stations on the Jordanian coast of the Gulf of Aqaba.

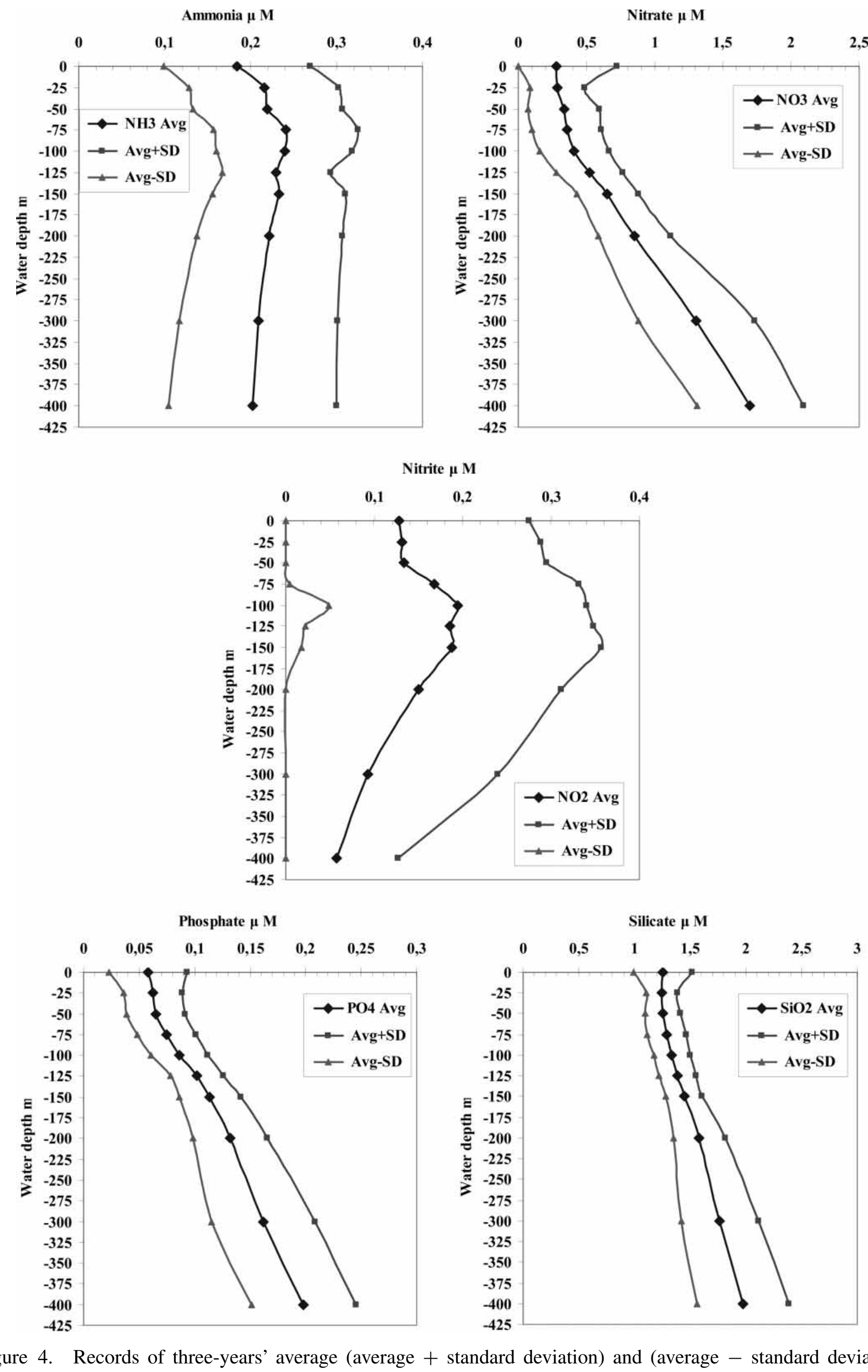

Figure 4. Records of three-years' average (average + standard deviation) and (average − standard deviation) concentrations (µM) of ammonia, nitrate, nitrite, phosphate and silicate down to 400 m in the Jordanian offshore reference waters of the Gulf of Aqaba.

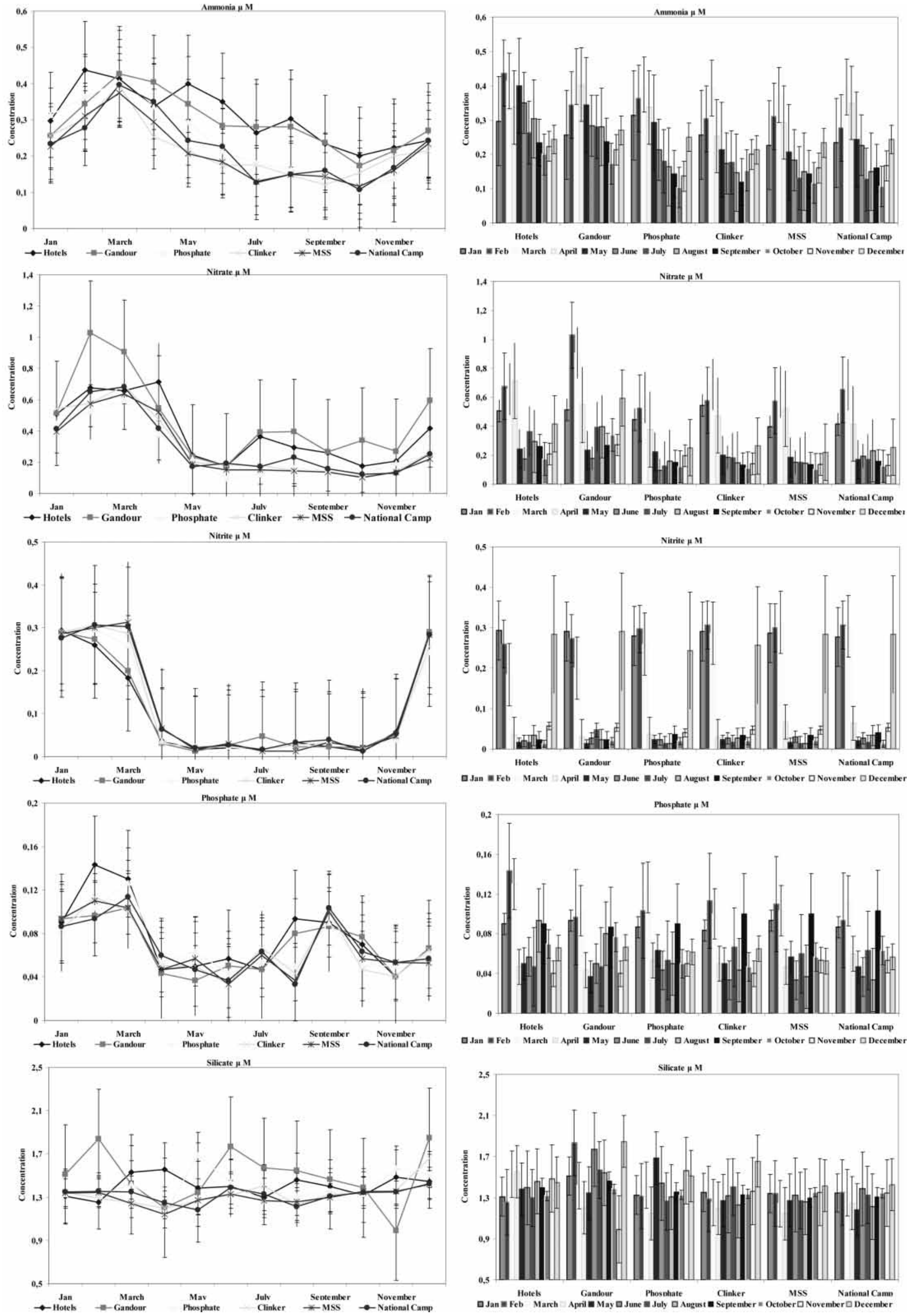

Figure 5. Three-years' monthly average concentration (μM) and standard deviation of ammonia, nitrate, nitrite, phosphate and silicate at six stations on the Jordanian coast of the Gulf of Aqaba.

in 1999 and 2001. However, lower nutrient concentrations associated with higher chlorophyll *a* concentrations, as was the case in 2001, indicate increased primary production and higher manifestation of nutrients into phytoplankton. Similar to chlorophyll *a* concentrations; nitrite concentrations during summer exhibited a clear subsurface concentration maximum. Summer also witnessed strong nutrient and chlorophyll *a* stratification characteristics, where the concentrations of the deep reservoir nutrients—nitrate and phosphate—were distinguishably low, and almost vanishing in the euphotic zone, but quite abundant in the deep water below 150 m. The water column was never depleted of silicate at any time of the year, but higher concentrations were found in the deep waters than in the upper waters during summer.

The chemical variables monitored at the coastal stations (figure 5) were generally comparable to their concurrently measured offshore reference values. Differences between stations were minor except for the two northernmost stations (Hotels and Al Ghandour) which exhibited higher inorganic nitrogen and chlorophyll *a* concentrations during most of the sampling events.

3.2 *Trend analysis*

3.2.1 Offshore waters; Jordanian seawater standard codes of reference. Trends and modifications of coastal water quality in the present work were assessed with reference to the concurrently analysed offshore water. A relative modification (RM) formula [4, 5] has been devised:

$$\mathrm{RM} = (\mathrm{Cc} - \mathrm{Cr})/\mathrm{Mr}$$

where Cc is the variable concentration at the coastal station, Cr is the concurrently measured concentration at the reference offshore station and Mr is the annual mean concentration at the reference station. RM records were tested for normality using the Anderson–Darling test in a Minitab Package. Modification was determined by ANOVA. A variable was considered significantly modified at the coastal station reference to the offshore water if its RM value was significantly different from zero, i.e., if the RM 95% confidence interval did not include zero. Two-way ANOVA was employed to test the modification at the coastal stations, compare among stations and among years.

The upper 125 m of the offshore water column was selected as the offshore reference water because these waters undergo the same seasonal cycle exhibited by the coastal waters, but still witness the summer-specific features of the subsurface chlorophyll *a* and nitrite concentrations maxima. This makes the upper 125 m offshore water column a more robust and superior reference in comparison to the surface offshore water. For the purpose of defining the Jordanian Seawater standard codes of reference, the reference offshore water (upper 125 m water column) was tested for month-to-month and year-to-year variations using two-way ANOVA at the month and year levels from 1999 to 2001. For normalisation, the values entered into the test were the difference between the individual value and the three-year annual average. All measured variables showed no significant differences between the years. Month-to-month variations in the measured variables, on the other hand, were highly significant. This implies that one standard code of reference value for the year is not suitable. Monthly standard values are more appropriate. The monthly standard code of reference is defined as the three-year monthly average of the upper 125 m of the offshore water column, surrounded by a suitable interval, based on the average standard deviation, to provide sufficient robustness and flexibility in order to be applicable. At the current time, and because insufficient data is available on the coastal system tolerance and assimilative capacity, the intervals are defined semi-objectively. These are eight two-tailed monthly average standard deviations for the conservative variables (temperature, salinity and density), and five two-tailed monthly average standard deviations for the other variables. Suggested Jordanian seawater standards code of reference derived from this approach are shown in figures 6 and 7. This novel approach to defining the seawater reference standard needs to be tested over a longer timescale and in other parts of the world. It also needs to be tested experimentally by assessment of the assimilative capacity of the ecosystem. This is one of the areas where we are investing considerable efforts at the moment.

3.3 *Coastal modifications*

Following the relative modification approach, three year records (1999, 2000, 2001) of the seawater quality at the coastal stations relative to the three-year annual average of the upper 125 m offshore water were subjected to two-way ANOVA to test the significance of modification between the individual stations and the reference offshore values as well as differences

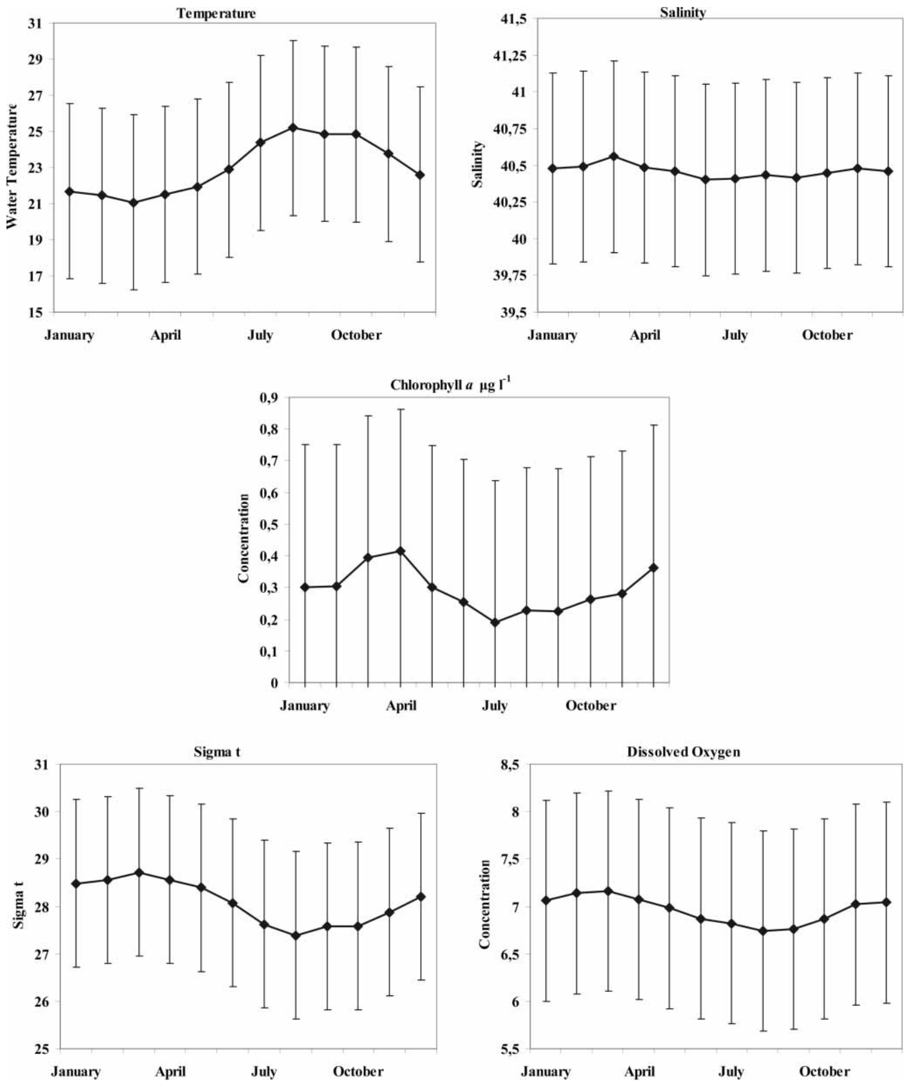

Figure 6. Suggested monthly standard codes of reference of seawater temperature, salinity, density, chlorophyll *a* concentration and dissolved oxygen concentration for the Jordanian waters of the Gulf of Aqaba, Red Sea. The allowed difference is 8 × mean standard deviation for temperature salinity and density; and 5 × mean standard deviation for other variables. The minimum value of any variable cannot be less than zero.

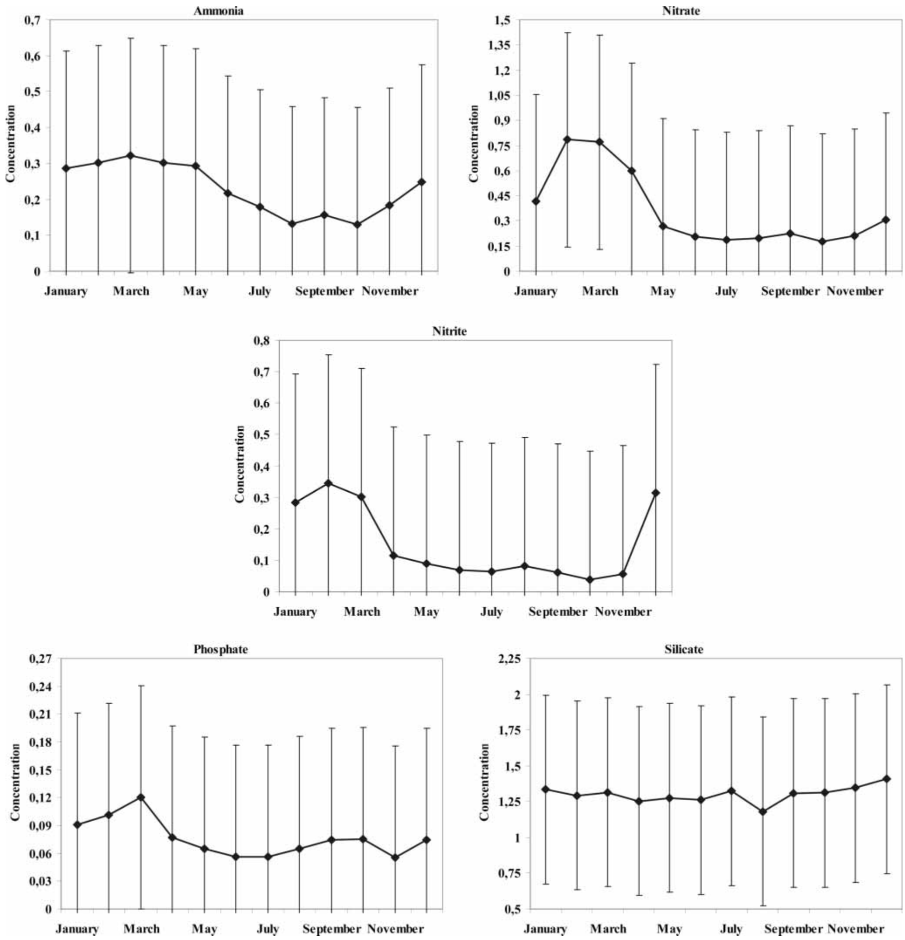

Figure 7. Suggested seawater monthly standard codes of reference of ammonia, nitrate, nitrite, phosphate and silicate concentrations (μM) of the Jordanian waters of the Gulf of Aqaba, Red Sea. The allowed difference is 5 × mean standard deviation. The minimum value of any variable cannot be less than zero.

between the coastal stations in relation to each other. Results of the two-way ANOVA on the water quality variables revealed that ammonia, nitrate and chlorophyll *a* concentrations were positively significantly modified at the northern stations (Hotels and Al Ghandour) during the three years 1999, 2000 and 2001. The other stations (Phosphate Port, Clinker Port, MSS and the Tourist Camp) showed no significant modifications with respect to any of the measured variables relative to the upper 125 m reference offshore waters, nor did any of them show any significant difference from any of the others.

4. Discussion

4.1 *Thermohaline structure of the offshore water*

The present study endeavours to analyse three years' data of Jordan's National Monitoring Program and define standard codes of reference—'baseline values' for the Jordanian coastal water quality. The offshore reference water is undoubtedly of significant importance in defining such standard values for the coastal waters. The Gulf of Aqaba is rather narrow, which makes the separation between coastal and offshore waters impractical. However, the Gulf is very deep which gives the offshore waters a strong buffering capacity and resistance to minor changes that may take place inshore. The thermohaline structure of the offshore waters of the Gulf of Aqaba has proven to be the main determinant of all other water characteristics [6, 10, 12–16]. Nutrient concentrations and biological productivity, some of the most important characteristics of a water body, are amongst the first to be driven by the thermohaline structure [17, 18]. The thermohaline structure of the Gulf of Aqaba also plays a significant role in forming the deep seawater of the Red Sea [19, 20] giving the Gulf of Aqaba significant importance in determining the environmental quality of waters in the entire Red Sea.

Similar to most other water bodies, the Gulf of Aqaba witnesses mixing during winter and stratification in summer. However, the Gulf is distinctive in two main aspects. Firstly, mixing in the Gulf of Aqaba is complete, because it receives virtually no fresh water and consequently exhibits no salinity stratification in winter [6, 19]. Secondly, the increase in nutrient concentration associated with deep mixing is accompanied by an increase in chlorophyll *a* concentration, reflecting increased primary productivity [6, 21]. The permanently high solar radiation, the comparatively mild seawater even in winter and the rapid phytoplankton turnover are the main factors behind this. In fact, the increase in chlorophyll *a* concentration is sometimes more evident than that of the nutrients. Day-to-day changes of the water column characteristics, especially during the transition period March to May, can be great. It is therefore important to emphasise that the recorded ambient conditions are more pertinent to the sampling time than to the entire month. However, with reliable three-year data available, and from a practical point of view, the Jordanian seawater standard codes of reference defined on the basis of the monthly average values can serve as acceptable reference values of the respective variables.

4.2 *Quality of the coastal water*

Results of the three years' records show that variations between the different coastal stations were, in general, minor, which reflects the dominance of the natural seasonal cycle over coastal activity in shaping the environmental variables characteristics. However, statistical analysis provides evidence that the water quality at the Hotels and Al Ghandour stations was significantly modified compared to the offshore water with respect to ammonia, nitrate and chlorophyll *a*. The exact reasons for these modifications have not yet been definitely determined. Several factors, however, can contribute to such modifications. For example, (i) the northern part of the Gulf of Aqaba is most greatly protected from the common northern winds. Consequently the water movement is lower and the residence time is higher; (ii) official sewage discharge from the towns of Aqaba and Elat to the Gulf is zero. However, uncontrolled leakage cannot be ruled out; (iii) aquaculture in Elat is a substantial source of nutrients. About 50,000 m^3 of floating cages, that produce about 3000 tons of fish $year^1$ and release at least double this amount of nutrients, extend just next to the Jordanian waters.

Dissolved oxygen, nutrients and chlorophyll *a* are collectively the most direct measure of how oligotrophic/eutrophic a system is. The lower the dissolved oxygen concentration and the higher the nutrient and chlorophyll *a* concentrations are, the more eutrophic the system is. Conditions at the Hotels and Al Ghandour stations are still in no measure or standard anywhere near eutrophication. Bell [22] considered coral reef waters to suffer eutrophication if the annual average chlorophyll *a* concentration exceeds 1 $\mu g\,l^{-1}$. Our northern beach waters (figure 3) have an annual chlorophyll *a* average concentration of much below 1 $\mu g\,l^{-1}$ and can therefore be safely considered non-eutrophic. However, the records generated at the northern stations in the framework of the present monitoring program over the three years are an early warning that these waters are undergoing significant changes in quality in comparison to other parts of the Jordanian coast. This, in terms of coastal management, should mean that water quality at the northern beach requires more thorough monitoring, especially as (i) this site is the main sandy beach site of the Jordanian coast; (ii) huge efforts are made to attract more tourists to Aqaba; and (iii) several coastal constructions that go beyond the lower water level and affect the water circulation are built there.

The Phosphate Loading Port is also in the northern section of the Gulf of Aqaba. This has been a controversial site and a subject of a long-standing debate. Studies of the 1970s and early 1980s reported elevated levels of nutrients associated with deterioration of the environmental quality there [23–25]. Recently, research [26–28] has shown that although this site still receives considerable amounts of phosphate dust, the environmental conditions have improved significantly. Nutrient concentrations reported during the 1970s and early 1980s were about five times higher than the values recorded in the present study. Until 1986 untreated sewage of the city of Aqaba used to be discharged at the same site of the Phosphate loading Port, but this was abolished in 1986. Since then, the environmental conditions appear to have reacted positively to this policy change. Additionally, the Ports Corporation installed chalk feeders for the handling of raw phosphate powder in the early 1990s, which has decreased the input of phosphate powder to the sea and ultimately contributed to the improvement of the coastal environmental quality in the region. It is worth mentioning that Jordanian phosphate powder is almost completely insoluble in Aqaba seawater [27].

Moving one step forward in defining the water quality status, serious attempts are taking place to define standard codes of reference of seawater quality worldwide. Simboura *et al.* [29] employed biological quality variables including macroinvertebrates, phytobenthos and phytoplankton in the framework of the typology classification and reference conditions defined by the European Framework Directive (WFD, 2000/60/EC) to identify water quality in the Saronikos Gulf representing the Mediterranean ecoregion. Our approach in this paper focuses more on the biogeochemical variables (nutrients and chlorophyll *a*) to define acceptable reference values of the seawater body. This work, to the best of our knowledge, is the first to touch on this issue in the Gulf of Aqaba and Red Sea region. Therefore, we have been cautious in our analysis not to suggest strictly narrow allowable intervals that cannot be tolerated by coastal users, but also not to suggest wide intervals that may lead to significant changes in the basic characteristics of the ecosystem. Three years worth of data of coastal water quality variables have shown that the Jordanian coastal waters of the Gulf of Aqaba are readily comparable to the pristine offshore waters and perfectly within the allowed range of modification suggested as standard codes of reference of Jordanian coastal waters. These codes of reference are semi-objectively defined and continuous work is in progress to evaluate them against the assimilative capacity of the coastal ecosystem. This sets the foundations for defining seawater quality directives for the Red Sea ecosystem, or in a broader sense, for all tropical and subtropical coastal ecosystems.

Acknowledgement

The work was carried out in collaboration between the Marine Science Station (University of Jordan and Yarmouk University) and the Aqaba Region Authority (ARA)/Aqaba Special Economic Zone Authority (ASEZA). Seed funds for Jordan's National Monitoring Program of the coastal environment were provided by the Global Environmental Facility (GEF). The authors would like to thank the Environment Commissioner (ASEZA), the Head of the Environment

Department (ARA; 1997–2000), Executives of the GEF project (1997–2001) and the technical and administrative staff of the Marine Science Station, Aqaba, for their dedicated efforts that made this work possible.

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