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Research Article

Assessment of the Trophic Status of the South Lagoon of Tunis (Tunisia, Mediterranean Sea): Geochemical and Statistical Approaches

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The trophic status assessment of the South Lagoon of Tunis, a shallow Mediterranean coastal area after its restoration, is addressed herein with respect to its various environmental settings which are taken as indicators of water quality. The lagoon had, in the past, witnessed severe environmental quality issues. To resolve these problems, a large restoration project of the lagoon was undertaken which consisted of dredging the bottom sediments removing areas of water stagnation and improving water circulation. After this restoration work, the lagoon morphology has radically changed. In this paper, we attempt to evaluate the lagoon water's trophic state to analyze the eutrophication risk after almost 16 years. In order to achieve these purposes, two water quality monitoring campaigns were conducted (July 2013 and February 2014). Natural and anthropogenic factors controlling the nutrient content of the lagoon water have been assessed through both geochemical methods and multivariate statistical tools. The results show that the nutrients are from external sources due to the discharge of municipal and industrial wastewater from the surrounding city of the catchment in the lagoon's south side. According to the TRIX index, the lagoon remains eutrophic presenting a "poor" water quality, notwithstanding the engineering project due to the high level of nutrients.

1. Introduction

Coastal lagoons are very important for the ecological preservation of biodiversity [1]. However, they are fast turning into threatened ecosystems around the world [2]. The intense anthropogenic development around this area also has negative effects. Recently, the water quality of coastal lagoons in many areas of the world has deteriorated due to massive discharge of nitrogen and phosphorous from domestic and industrial wastewater as well as urban drainage [3–5]. Consequently, there has been a growing interest in eutrophication as one of the most pertinent disturbance processes on aquatic ecosystems caused by humans [6]. Due to increasing human pressure including fisheries, tourism, demographic expansion, and global climate change, the preservation of biodiversity and natural processes in coastal lagoons has become a challenge in recent decades [7].

The Tunisian coastline on the Mediterranean Sea is about 1300 km long. Because of the development of its industrial, touristic, and agricultural activities, Tunisian marine resources began to get contaminated. These activities, together with the expansion of its population had affected the quality of the aquatic environment in the long term.

The present study is integrated in this framework. The Lagoon of Tunis, one of the four major lagoons in Tunisia, is located near the capital and close to the most populated region. This Mediterranean lagoon is characterized by an anthropogenic catchment. Its geographical location had made it, over many decades, as a site of domestic and industrial discharge, causing a massive introduction of nutrients and organic matter. The combination of hydrodynamic and anthropogenic factors (poor circulation, shallow depth (average of 1 meter)) and very high nutrient pollution have led the ecosystem to the state of eutrophication. It has been

considered as the most eutrophicated lagoon on the Tunisian coast [8–10].

In order to resolve the pollution problem and to improve the water quality of the South Lagoon of Tunis (the south basin of the lagoon of Tunis being the subject of our studies) for ecological and economical purposes, an environmental restoration project was conducted from April 1998 to July 2001 [11, 12]. The overall aim of the project was to achieve a good ecological status in the lagoon and to realize substantial land reclamation all around. After this restoration work, the lagoon morphology has radically changed.

The general aspect of the project was to increase the flushing power of the lagoon water with marine water from the Gulf of Tunis and to reduce the water residence time. These purposes were reached by setting two groups of locks in order to allow water exchange between the Gulf of Tunis and the lagoon. In order to avoid water stagnation, different areas located in both the Southeast and the southwest side of the lagoon were removed (reducing the lagoon area from 13 km^2 to 7 km^2), and the shoreline was rectified to be straightened. Moreover, polluted sediments were dredged and removed from the north area of the lagoon. To improve water circulation, fishery was removed, and the Canal of Rades and the Canal of Tunis were restored [13, 14].

Understanding the ecosystem response to this restoration project is essential to assess its rehabilitation. The time elapsed after restoration is a critical indicator of the real restoration success [15]. Indeed, this coastal ecosystem recovery requires a continuous survey through an ecological trophic state evaluation.

The assessment of the status of the lagoon after 16 years of the installation of the restoration works is much needed in order to project further solutions for the decision makers. In this study, this assessment targets mainly the nutrient elements and the trophic index to see if the eutrophication of the lagoon has been improved or otherwise. To our knowledge, this is the unique study which is addressing such problematic related to nutrient elements in relation to eutrophication within the Lagoon of Tunis as previous investigations were conducted from a biological and hydrodynamic point of view only (algae, mussels, etc.). However, the trophic status has received little attention, and this research aims to overcome this gap.

In this paper, these investigations were conducted throughout the lagoon to assess the restoration level and improvement of water quality. Furthermore, we attempt to evaluate the trophic state of lagoon water for eutrophication's risk analysis after almost 16 years.

Surface water samples were collected in wet and dry seasons (July/February) and then were analyzed. Distribution maps and plots of chemical parameters were used to determine the geochemical characteristics of the lagoon water and to identify major natural and anthropogenic processes governing water geochemistry.

In addition, multivariate statistical analysis, such as principal component analysis (PCA) and hierarchical cluster analysis (HCA) were used, in order to help interpreting the complex data matrices for better understanding of the water quality and to allow the identification of possible factors that influence the water system [16–18].

It is widely recognized that the water quality assessment in coastal ecosystems is complicated since a great number of variables, including cause (nutrients) and response (chlorophyll a) variables are interrelated [19, 20]. Several methods are thus used to characterize water quality and to assess eutrophication. In this study, the TRIX developed by Vollenweider et al. [21] is used to estimate the trophic status of the lagoon water.

2. Materials and Methods

2.1. Study Area. The lagoon of Tunis is located in the northeast of Tunisia. Cutting across the lagoon and connecting the Mediterranean with the old port of Tunis, the Canal of Tunis divides the lagoon into two basins, commonly known as the South Lake and the North Lake of Tunis.

The South Lagoon of Tunis coordinates extend from 12′ to 10°16′E longitudes and from 36°46′ to 36°48′N latitudes (Figure 1). This area was used to be heavily polluted [8, 22], but it has recently been rehabilitated [23]. After the restoration program, the lagoon appears shaped as an eclipse stretching in a SW-NE direction with about 10 km long and 3.5 km wide (Figure 1). It extends over an area of 720 ha with a regular depth of about 2.1 m, except in some restricted areas, on the east side, where it reaches a maximum of 5 m. Its shores are rectilinear and protected by large rockery stones.

The lagoon is characterized by a semiarid Mediterranean climate. The annual temperature ranges between 7 and 30°C. The mean annual rainfall is 528 mm with interannual variations. The luminosity is about 6 h per day, with 155 h in December and 359 h in July. Evaporation ranges between 62 and 201 mm, respectively, in January and July [24].

Coastal lagoons maintain a connection to the sea through a restricted inlet. At the South Lagoon, the water flow between the lagoon and the Gulf of Tunis is impeded by two inlets (or outlets): seawater generally flows into the lagoon from the east side through the Canal of Rades (2 km length and 4 m deep) and goes out from the western side through the Canal of Tunis (10 km length and 4.5 m deep).

The hydrodynamic of the lagoon is mainly controlled by wind and tide which is semidiurnal [23, 25]. The locks at Rades and Tunis are opened and closed in an alternative way, imposing a one-way water flow going from the east to the west. The average water residence time in the lagoon varies from 6.6 to 8.2 days [25]. The total exchange of water volume with the sea via the Canal of Rades is about 2.57 million·m^3/day. The water speed of the lagoon is not homogenous. It varies from 65 cm/s, to no more than 5 cm/s, going from the Canal of Rades to the canal of Navigation, leading to the appearance of little stagnation zones in the northwestern part of the lagoon [26] (Figure 2).

The South Lagoon of Tunis has a drainage watershed of 4000 ha where more than 1500 ha are industrial areas (food industries, wholesale, etc.) [23]. Rapid urbanization around the lagoon during the past decade has resulted in a substantial increase in the volume and pollutant load of the storm-water and wastewater flowing into the lagoon. The lagoon receives water from draining the urban area of

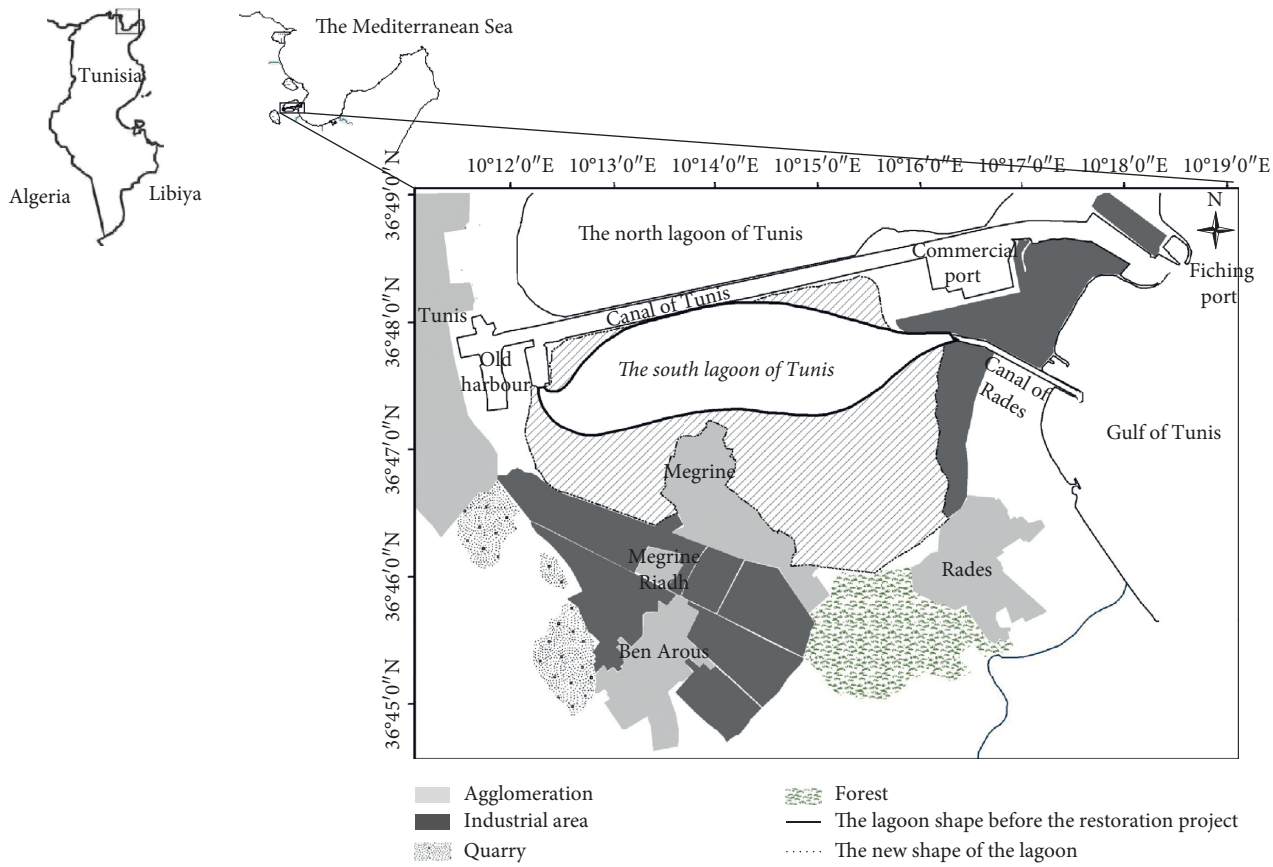

Figure 1: Map showing the study area.

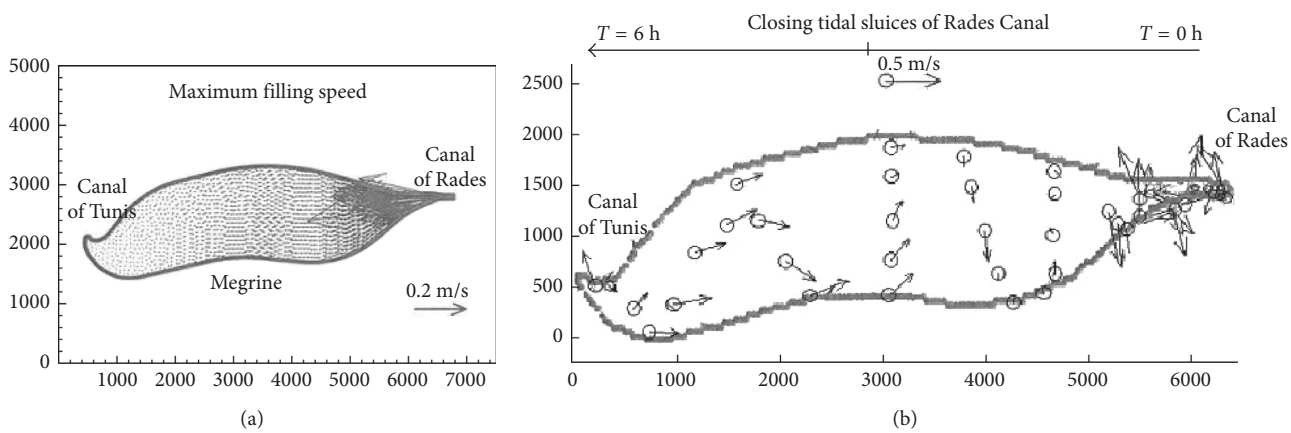

Figure 2: Water circulation in the South Lagoon of Tunis: (a) filling speed of the lagoon [25] and (b) the direction of water circulation on the lagoon [26].

Megrine, runoff of newly developed areas after their planning, as well as a channel called the belt channel, which protects the city of Megrine from flooding [27]. Whereas, the industrial and domestic water of Jbel Jloud, Ben Arous, and Megrine, located in the west side of the lagoon, are discharged to the catchment area of the oueds (Oued Essalaas and canal of Ben Arous) and transported to the lagoon. During the rainy season, they are mixed by runoff [27]. It received about 5500 m^3/day of untreated industrial wastewater, enriched with nutrients and heavy metals [23].

2.1.1. Sampling and Analysis. A spatiotemporal monitoring of nutriments concentrations was carried out in July 2013 and in February 2014. Samples were taken from 14 sites, which cover most of the surface area (Figure 3). In order to estimate the anthropogenic nutrient intake of the lagoon water, samples collected from manholes dumped into the lagoon, presented in the map (Figure 3) as point and nonpoint sources, are also taken. On the other hand, other samples were taken from the Canal of Rades in order to see the water quality coming from the Gulf.

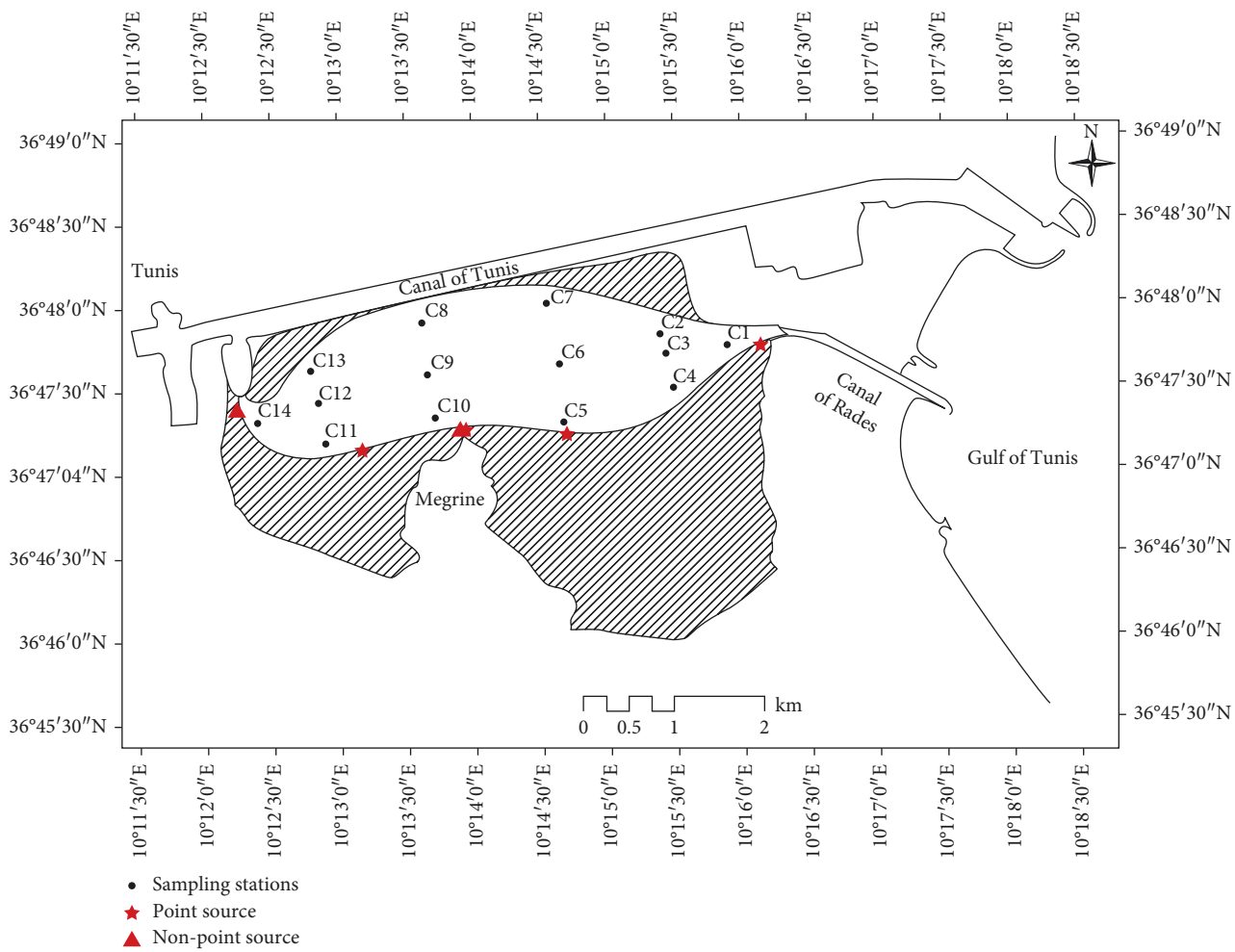

Figure 3: Map showing the location of sampling stations.

Temperature, pH, dissolved oxygen content, salinity, and transparency were measured in the field using calibrated portable digital meters. All water samples were filtered through a 45 μm millipore cellulose member and were stored at 4°C in the laboratory until their subsequent analysis. Those membranes are dried and weighed before and after filtration. The difference in weight allows knowing the total dry mass of suspended particulate matter (SPM) [28].

Dissolved inorganic nutrients (nitrate, nitrite, ammonium, and orthophosphate) were measured by standard Rodier [29] colorimetric method using UV–Vis spectrophotometer. Nitrate (NO_3^-) was measured colorimetry on 420 nm. Sulfosalicylic acid forms with nitrate in anhydrous environment and releases in basic environment a nitrosalicylate complex which is yellow. A colorimetric determination of this ion allows to determine the concentration of nitrate ions in a solution [29]. The nitrite (NO_2^-) was determined by complexation with the diazotization of sulfanilamide in and with N (1-naphthyl) ethylene diamine in acidic pH, which gave a purple-colored complex. Nitrite was measured colorimetry on 540 nm [29]. The ammonium ions (NH_4^+) are treated, in an alkaline pH, with sodium hypochlorite and phenol giving indophenol blue coloration. This reaction is catalyzed by nitroprusside. Ammonium was measured colorimetry on 640 nm [29]. Orthophosphates react in the presence of antimony molybdate to give phosphomolybdic acid compounds that were reduced by ascorbic acid, giving a blue coloration. Ortho-P was measured colorimetry on 720 nm [29].

Turbidity measurements (expressed in Nephelometric Turbidity Unit, NTU) were performed using a HACH 2100P turbidimeter.

The chlorophyll a (chl a) contents were determined using the spectrophotometric method of Lorenzen [30] and following the procedure given by Parsons et al. [31] after 24 h extractions in 90% acetone at −5°C in the dark.

Spatial distribution maps of these water quality parameters were carried out through GIS 9.3.

2.2. Statistical Analysis. Multivariate statistical analysis of the experimental data has been performed using the Xlstat. Two multivariate statistical techniques were used: the hierarchical cluster analysis (HCA) and the principal component analysis (PCA). In addition, Pearson's correlation analysis was, also, performed. These methods are considered as good tools to classify water samples according to their geochemical characteristics [32].

2.3. Trophic State Assessment

2.3.1. Trophic Index (TRIX). The TRIX proposed by Vollenweider et al. [21], which can be considered as an adaptation of Carlson's TSI to transitional waters, is used in order to assess the trophic state of the lagoon. The TRIX is frequently used to characterize the ecosystem trophic status. The TRIX has been applied to many ecosystems of coastal marine waters, such as the Tyrrhenian [33] and the Caspian Seas [34], Bizerte Lagoon in Tunisia [35], and the Greek coastal lagoon [36] are among others.

It is a mathematical tool derived from the combination of dissolved inorganic nitrogen, inorganic phosphorus, dissolved oxygen, and chlorophyll a. The TRIX analytical expression is given as follows:

$$\mathrm{TRIX} = \frac{\left[\log_{10}\left(\mathrm{DIN} * \mathrm{DIP} * |\mathrm{D\%DO}| * \mathrm{chl}(a)\right) + a\right]}{b}, \quad (1)$$

where $\mathrm{chl}(a)$ represents the chlorophyll a concentration (in μg/L), while |D%DO| represents the absolute value percentage deviation of the oxygen concentration from saturation conditions (in %). DIN and DIP represent dissolved inorganic nitrogen (in μg/L) and dissolved inorganic phosphorus (in μg/L), respectively. The parameters $a = 1.5$ and $b = 1.2$ are scale coefficients used to fix the index lower limit and the scale ranges from 0 to 10 [33].

According to Vollenweider et al. [21], the scores are as follows:

(i) TRIX < 4 indicates high state of water quality with low eutrophication.

(ii) 4 < TRIX < 5 indicates good state of water quality with medium eutrophication.

(iii) 5 < TRIX < 6 indicates bad state of water quality with high eutrophication.

(iv) 6 < TRIX indicates poor state of water quality with high eutrophication levels.

3. Results and Discussion

Descriptive statistics for the minimum, maximum, and average concentrations for each variable at each sampling period are reported in Table 1.

3.1. Physicochemical Parameters. The collected water from the Southern lagoon of Tunis were characterized by a temperature ranging between 28.8 and 30°C and between 15.1 and 17.5°C, respectively, in July 2013 and February 2014, with salinity values that range between 48.3 to 49.1‰ and 47.5 to 48.5‰, respectively, in summer and in hibernal seasons (Table 1). These parameters undergo wide seasonal variations.

pH values vary from 8.48 to 8.95 in July and from 8.5 to 8.94 in February.

These parameters show a progressive increase in the water flow direction, going from the east to the west (Figure 4). This variation is supported by evaporation and by the hydrodynamic regime of the lagoon driven by seawater circulation from the inlet gates to the outlet ones from the east to the west.

Dissolved oxygen values in the lagoon, varied between 2.9 and 4.4 mg/L (51.4 and 75.6% of saturation) in July and between 6.5 and 11 mg/L (86.5 and 148.3% saturation) in February. Dissolved oxygen in aquatic ecosystems is the function of many physicochemical parameters, which govern their solubility. Obviously, oxygen solubility increases as salinity and temperature decrease, which could be the reason of the low DO concentration in summer.

The important biological processes associated with oxygen distribution are photosynthesis, respiration, and decomposition [37]. In the South Lagoon of Tunis, the lowest values of DO are measured in July mainly due to the high rate of bacterial degradation of organic matter and the highest values of the algae population presented during this season. In contrast, the lagoon water is well oxygenated and even oversaturated in February due to wind agitation especially in low depth as well as the decrease of biomass production.

The compilation of the distribution maps of dissolved oxygen contents (Figure 5) with the algal distribution of the lagoon (Figure 6) shows that the most oxygenated water is in the west side of the lagoon, where the water depth is low and rich in algae.

SPM ranges from 0.025 to 0.043 mg/L and from 0.018 to 0.032 mg/L, respectively, in July 2013 and February 2014. The highest values could be attributed to the low depth of the water where the particle resuspension is much easier and to the decomposition/release of organic particles from the macrophytes in summer. The turbidity varies between 8 and 20 (100 NTU) in July, due to the high rate of chlorophyll a. In the other hand, the lagoon is almost transparent, and the turbidity ranges between 1 and 9 (100 NTU) in February. The Secchi disk transparency values vary between 1.3 and 2 m in July and between 1.5 and 1.8 m in February which indicating a generally moderate water visibility. The lowest values of transparency were recorded in July due to the growth of chlorophyll a.

3.2. Nutrients. For the lagoon water samples, the nitrogen inorganic compounds are mainly composed by nitrates (90%).

Nitrite contents range between 0.08 and 0.09 mg/L in July and between 0.53 and 0.76 mg/L in February. Ammonium varies between 0.071 and 0.117 mg/L in July and from 0.042 to 0.052 mg/Lin February. Nitrate contents vary between 8.06 and 13 mg/L in July, and from 2.08 to 15.58 mg/L in February (Table 1). These values are close to those found by Saccon et al. in the Marano lagoon (Italy) [39]. As shown in Table 1, the lagoon water is richer in nutrient compared to seawater.

Rapid mobilization resulted in low values of ammonium and nitrite. In fact, these elements are transitory and unstable in water, having very weak dissolved oxygen concentrations [40]. Ammonium may differ from steady-state conditions reflecting the balance between production through mineralization of organic matter [41], nitrification/denitrification,

Table 1: Statistical summary of physicochemical parameters and nutrients in South Lagoon of Tunis.

		Depth (m)	T (°C)	pH	DO (mg/L)	Salinity (‰)	Conductivity (S/cm)	SPM (mg/L)	NH_4^+ (mg/L)	NO_2^- (mg/L)	NO_3^- (mg/L)	Ortho-P (mg/L)	Chl-a (μg/L)	Pheo (μg/L)	Turbidity (100 NTU)	Transparency (m)
July campaign	Minimum	2	28.8	8.48	3	48.3	56.8	0.025	0.071	0.079	9.295	2.129	1.108	4.424	8	1.3
	Maximum	5.4	30	8.95	4.4	49.1	57.7	0.043	0.117	0.095	14.429	2.409	3.324	8.759	24	2
	Average	2.9	29.5	8.72	3.5	48.6	57.1	0.034	0.088	0.087	11.593	2.275	2.137	6.230	15.7	1.5
February campaign	Minimum	1.8	15.1	8.5	6.2	47.5	55.9	0.019	0.043	0.550	3.070	1.601	0.997	0.598	1	1.5
	Maximum	4.2	17.5	8.94	11	48.4	56.9	0.032	0.052	0.901	15.580	2.958	2.659	2.726	9	1.8
	Average	2.7	15.9	8.73	8	48.1	56.6	0.027	0.046	0.643	9.423	1.790	1.994	1.612	4	1.6
Gulf of Tunis (July)		—	22.7	7.57	6.9	43.5	51.1		0.244	0.11	1.375	0.465				
Nonpoint source		—	24.7	7.55	3.9	6.1	7.12		0.291	0.399	11.063	1.283				
Point sources		—	24.7	7.63	3.9	51.8	51.8		0.018	0.063	11.265	1.243				

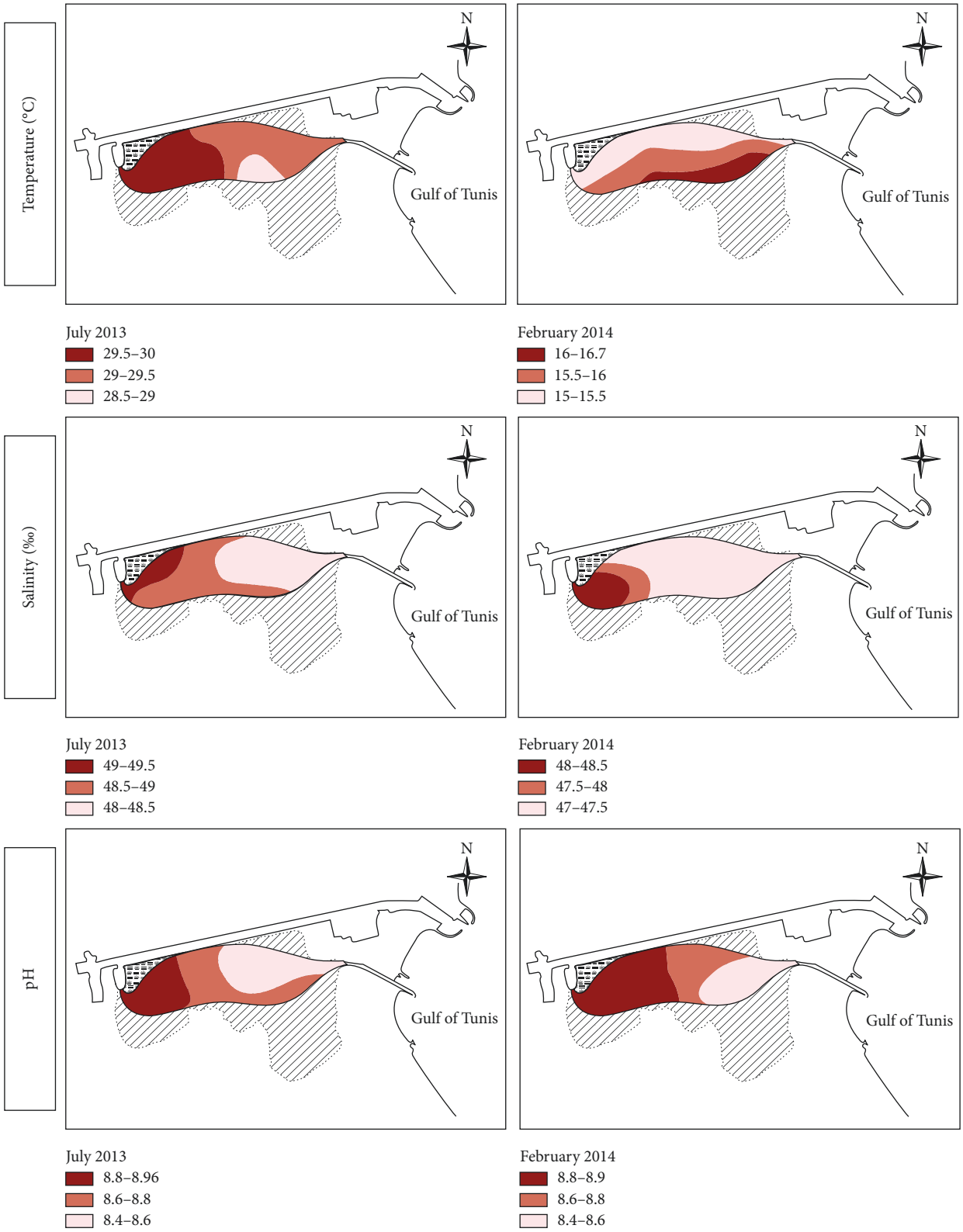

Figure 4: Physicochemical distribution maps of the South Lagoon of Tunis.

and consumption by the abundant primary producers living near the sediment-water interface [42].

As for nitrate, the characterization of its origins in the lagoon is much more difficult to achieve because of complex mixing processes among different water types like seawater, rainwater, and wastewater charges from the catchment area [39]. Generally, nitrate can be originated from airborne (atmospheric), nitrification process, or agricultural (leaching of agricultural land).

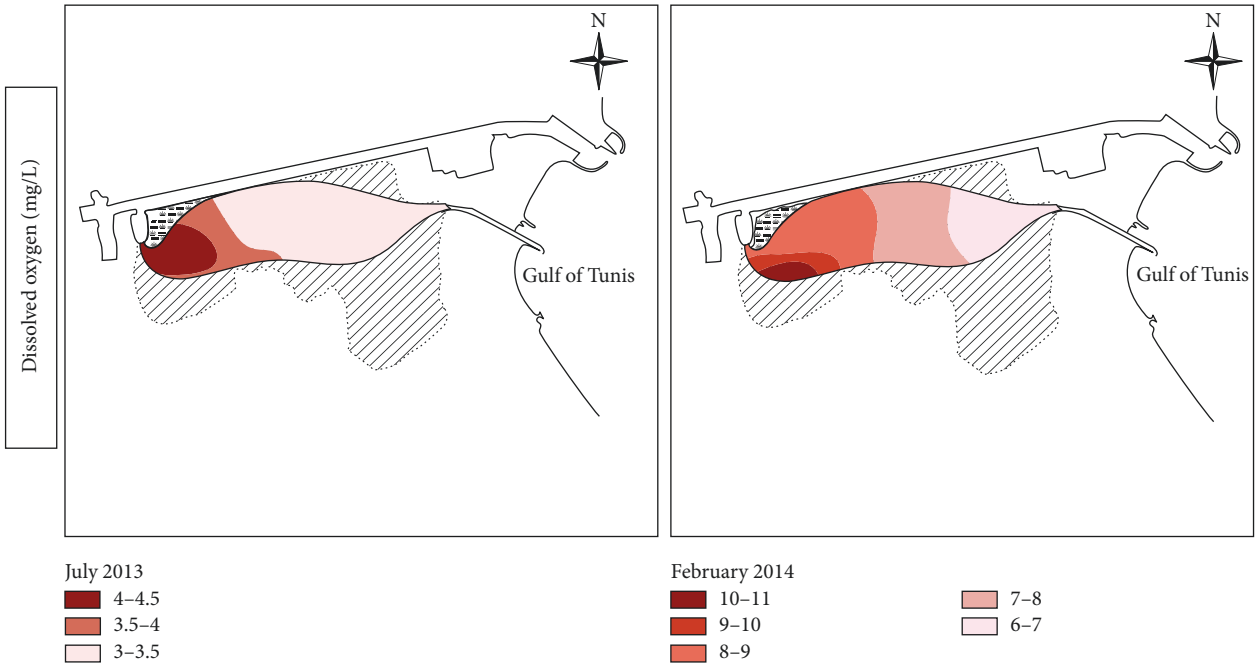

Figure 5: Dissolved oxygen distribution map of the South Lagoon of Tunis.

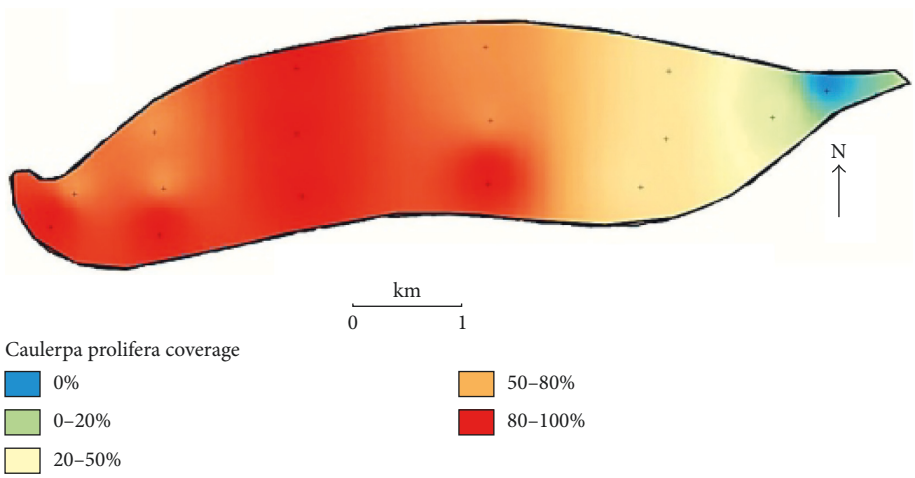

Figure 6: The distribution of *Caulerpa prolifera* in the South Lagoon of Tunis in summer 2014 [38].

In our case, the lagoon catchment area is exclusively occupied by urban or industrial zones which mean that the high rate of nitrate intake in the lagoon is not derived from agricultural activities. Therefore, the nitrate is formed in the lagoon by nitrification of NH_4^+ that may enter the lagoon directly, from urban or industrial N-breang wastewater as anthropogenic sources, or could be produced in situ by remineralization of organic matter.

Spatial variation maps of nitrate contents show that the distributions are influenced by liquid discharges on the south side of the lagoon, showing a positive gradient from south to north. The highest levels are those sampled near the discharge site. As they move away, the contents decrease and become homogenous in the rest of the study area which means the western and eastern parts of the lagoon (Figure 7). Furthermore, it is important to stress that NH_4^+ and NO_2^- nitrification can start even towards the lagoon and will consequently increase the NO_3^- concentration intake in the sampled water [39, 43].

The orthophosphate contents vary from 1.60 mg/L to 2.4 mg/L in July and from 1.6 mg/L to 2.94 mg/L in February (Table 1). Orthophosphate content variations are caused by primary production uptake and can be affected by various processes like adsorption and phosphate desorption and buffering action of sediments under environmental condition change (temperature and dissolved oxygen) [44, 45].

The cross-plot orthophosphate-total dissolved inorganic nitrogen (DIN) did not show any correlation ($r^2 = 0.13$ for July campaign and $r^2 = 0.40$ for February campaign) for sampled water (Figure 8). In shallow coastal ecosystems such

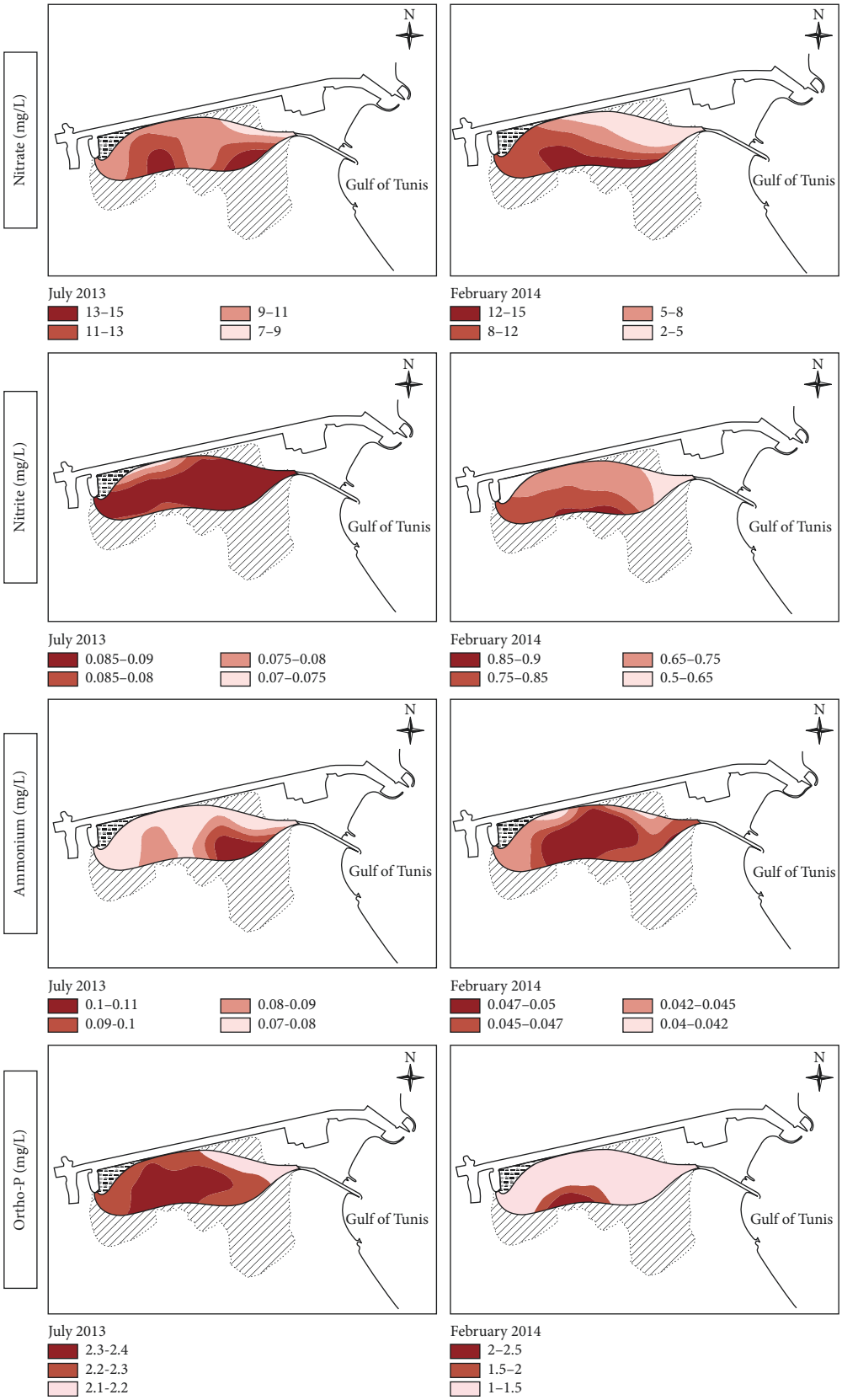

Figure 7: Nutrient distribution maps of the South Lagoon of Tunis.

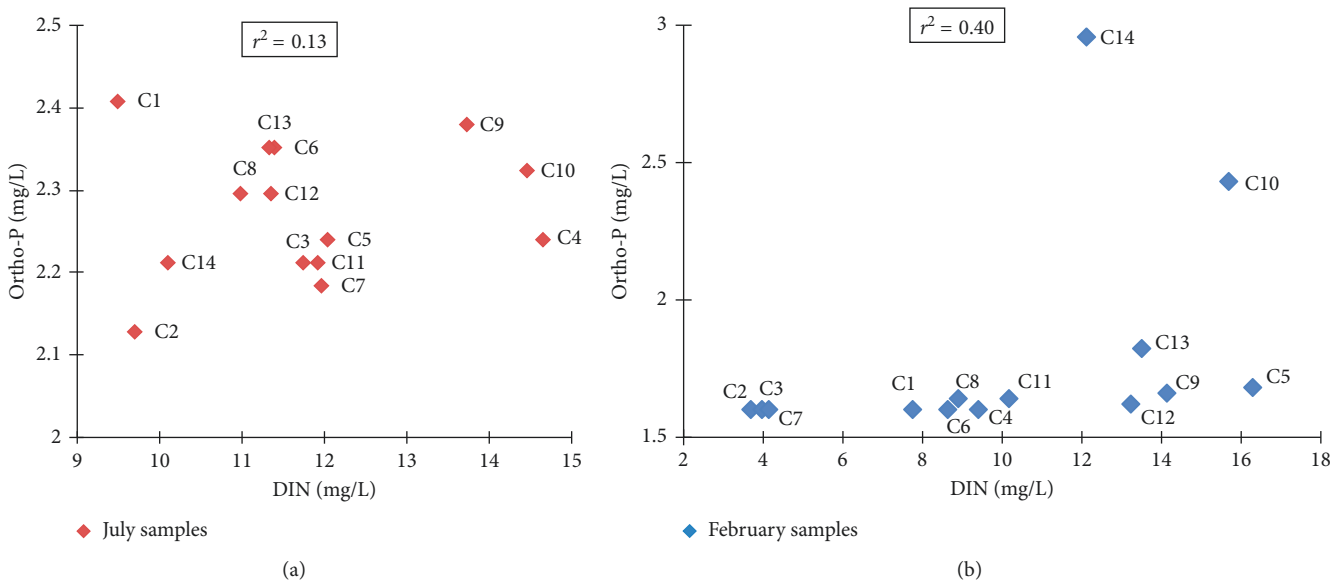

Figure 8: Plot of ortho-P by NID.

as the South Lagoon of Tunis, remineralization of the organic matter in the sediment and/or in suspended particles could often be a major source of dissolved inorganic nutrients in the water column [46–48]. Although this study was not designed to investigate the role of sediments as an internal source of nutrients to the water column, their influence in the nutrient's regeneration was apparent. In summer, mineralizing of organic matter at the sediment interface is accelerated, leading to a supplementary nutrient release to the water column [49–52].

Just like nitrate, the spatial distributions of ammonium and ortho-P contents show that the highest levels are recorded in the south side of the lagoon. Nitrite contents are homogeneous in July, whereas a positive gradient is noticed going from the south part to the north part in February. This distribution can be attributed mostly to urban wastewater and runoff (Figure 7).

3.2.1. Ratio NID/Ortho-P. The N/P ratio is often used in the prediction of the limiting nutrient for phytoplankton production. Despite the advances, nutrients limitation in coastal water is still an open question. There is an ongoing debate regarding the choice of the form of phosphorus and nitrogen used for calculating Redfield ratio [53], using the total form or just the inorganic form.

For the present study, in N/P ratio computation, the dissolved inorganic nitrogen (DIN) and orthophosphorus (ortho-P) are used [54–56]. In algal cells, the approximate ratio of nitrogen to phosphorus mass (Redfield ratio) is 7.2 : 1 (grams) or 16 : 1 (atoms).

Figure 9 shows the calculated molar ratios of DIN/ortho-P for all data. It varies between 3 and 4.9 for the July campaign and between 1.7 and 7.3 for the February campaign. The low N : P molar ratios (less than 16 : 1) suggest N-limitation in the sampled water. Nonetheless the N-limitation of coastal ecosystems (lagoon) might not necessarily be applied, especially when they are under high anthropic pressure [57].

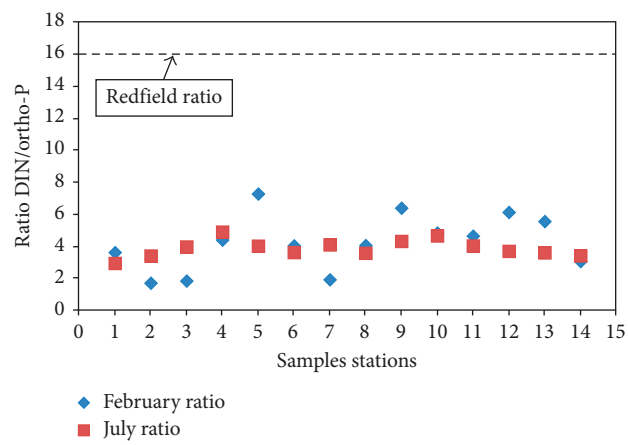

Figure 9: Ratio N/P for the South Lagoon of Tunis water samples.

3.3. Chlorophyll a. The chlorophyll a contents range from 1.11 to 3.32 μg/L in July and from 0.99 to 2.66 μg/L in February. Pheopigmant contents vary from 4.42 to 8.76 μg/L and from 0.6 to 2.72 μg/L, respectively, in July and February. Pheopigmant contents are higher than the chlorophyll a in July, which coincide with the end of the growth cycle of macroalgae and seagrass and their decomposition.

The spatial distribution of pheopigmants in the same period is almost the opposite distribution of the chlorophyll a. The highest concentrations of chl a are in the west and the southeastern part of the lagoon where the depth varies from 1.8 to 2.4 m. However, the lowest concentrations are in the East side of the lagoon where the water depth varies from 3.8 to 5.1 m (Figure 10). Positive gradient is established with the incoming water from the east side of the lagoon to the west side.

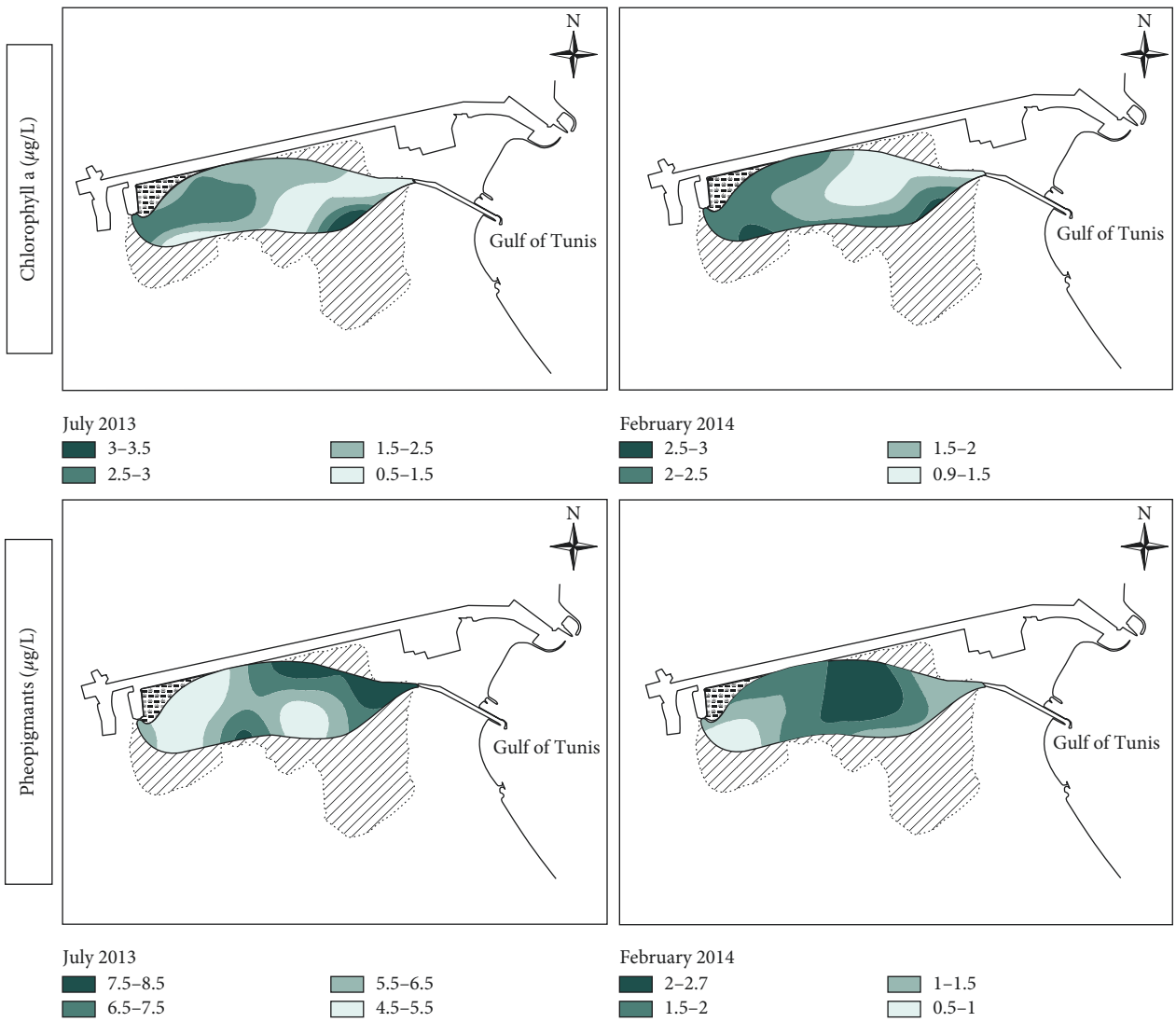

Figure 10: Spatial distribution maps of chlorophyll a (μg/L) and pheopigmants (μg/L) in surface water of the South Lagoon of Tunis.

3.4. Statistic Study. In order to classify the trends of this coastal lagoon, a detection of significant relationships between indices (differences of environmental parameters and nutrients) and samples was tested.

3.4.1. Correlation Matrix. Pearson's correlation coefficient matrix of the physicochemical parameters, nutrients, chlorophyll a, and pheopigmant contents was calculated (Table 2). The following results are drawn:

(i) Significant negative correlation between ammonium and dissolved oxygen contents ($r^2 = -0.87$), which conclude that ammonium is controlled by ammonification.

(ii) Negative correlation between nitrite and ammonium ($r^2 = -0.87$) and positive correlation between dissolved oxygen and nitrite ($r^2 = 0.79$), which indicates a continuous process of nitrosation.

(iii) Nitrate does not show any correlation with nitrite, ammonium, and dissolved oxygen that can be explained by an external input of nitrate in the lagoon water from urban/industrial water discharge.

(iv) Ortho-P concentrations were positively correlated with temperature ($r^2 = 0.64$), indicating phosphate release from sediments of the lagoon.

(v) Significant positive correlation between pheopigmants and temperature ($r^2 = 0.91$) and negative correlation with dissolved oxygen ($r^2 = -0.88$) show a high rate of pheopigmants in July matching the end of algal growth cycle. Those parameters correspond to the eutrophic condition in the dry season.

(vi) Turbidity presents a positive correlation with temperature ($r^2 = 0.85$), SPM ($r^2 = 0.85$), and pheopigmants ($r^2 = 0.78$). These parameters correspond to the eutrophic condition in the dry season. On the contrary, turbidity and transparency have an antagonist behavior ($r^2 = -0.45$) and high value of turbidity causes low visibility of lagoon water.

Table 2: Pearson correlation matrix of water quality variables of the South Lagoon of Tunis.

Variables	T°C	pH	O_2	Salinity	SPM	NH_4^+	NO_2^-	NO_3^-	Ortho-P	Chl a	Pheo	Turbidity	Transparency
T°C	**1**	−0.04	**−0.93**	**0.74**	0.68	**0.90**	**−0.97**	0.31	**0.64**	0.12	**0.91**	**0.85**	−0.39
pH		**1**	0.32	0.32	0.02	−0.18	−0.02	0.41	0.27	0.20	−0.09	0.12	−0.09
O_2			**1**	−0.57	−0.65	**−0.87**	**0.89**	−0.15	−0.54	−0.06	**−0.88**	**−0.78**	0.35
Salinity				**1**	0.50	0.64	−0.72	0.41	0.66	0.10	0.72	0.58	−0.42
SPM					**1**	0.49	−0.60	0.04	0.23	0.11	0.63	**0.85**	**−0.51**
NH_4^+						**1**	**−0.87**	0.31	0.57	0.07	**0.87**	**0.70**	−0.37
NO_2^-							**1**	−0.38	−0.65	−0.14	**−0.87**	**−0.79**	0.34
NO_3^-								**1**	0.48	0.12	0.31	0.23	0.07
Ortho-P									**1**	0.07	0.61	0.46	−0.07
Chl a										**1**	0.20	0.15	0.12
Pheo											**1**	**0.78**	−0.31
Turbidity												**1**	−0.45
Transparency													**1**

3.4.2. Principal Components Analysis: PCA. To evaluate the temporal and spatial variations of the studied parameters (physicochemical parameters and nutrients) in the Southern lagoon of Tunis, a principal component analysis (PCA) was applied.

The used variables are temperature, pH, dissolved oxygen content, salinity, suspended particulate matter (SPM), turbidity, transparency, NH_4^+, NO_2^-, NO_3^-, ortho-P, chlorophyll a (chl a), and pheopigmants (pheog).

Three components were extracted, which explained 75.57% of the total variance. The first factor (PC1) accounting for 54.65% of the total variance is strongly correlated primarily with dissolved oxygen (0.91) and nitrite (0.95) on the positive side and negatively correlated with water temperature (−0.99) and with ammonium (−0.89) and pheopigmants (−0.93), showing the inverse relationship between temperature and dissolved oxygen and between nitrite and ammonium (Table 3). It is also defined by less important salinity and SPM. HPO_4 is also correlated with PC1 (Table 3). Therefore, PC1 mainly represents the seawater marine influence from the gulf of Tunis, which has an important effect on the lagoon with continuous flushing, buffering, and dilution effect.

PC2 explained that 13.97% of the total variance was principally represented by pH and nitrate (Table 3). Additional 9.52% of the total variance was explained in PC3 and was represented by transparency.

The correlation circles of both components (PC1 and PC2) (Figure 11) show that chlorophyll a and nitrate have the same behavior explaining that the nutrient intake stimulates algae growth. Then, pheopigmants-temperature-ammonium-SPM and turbidity have the same behavior, indicating the eutrophic state in the July campaign.

The loading plot of the two factors (PC1/PC2) (Figure 11) shows the presence of two different groups:

(i) Group I included the July samples. They are dominated by ammonium, turbidity, SPM, pheopigmants, temperature, and salinity.

(ii) Group II included the February samples, at which the dominance of dissolved oxygen is determined.

PCA analysis shows a clear seasonal variation. Indeed, February samples are well oxygenated and the July samples present eutrophicated characters.

Table 3: Results of principal component analysis are shown as correlation values between the variables and the principal components for the first three principal components (PC1–PC3).

	PC1	PC2	PC3
T°C	**−0.99**	−0.07	0.08
pH	−0.04	**0.81**	−0.51
O_2	**0.91**	0.31	−0.21
Salinity	**−0.79**	0.30	−0.16
SPM	**−0.72**	−0.26	−0.43
NH_4^+	**−0.89**	−0.13	0.23
NO_2^-	**0.95**	−0.02	−0.12
NO_3^-	−0.37	**0.71**	0.18
Ortho-P	−0.68	0.44	0.25
Chl a	−0.14	0.31	−0.05
Pheo	**−0.93**	−0.06	0.16
Turbidity	**−0.88**	−0.08	−0.24
Transparency	0.45	0.27	**0.68**

3.4.3. Cluster Analysis. Hierarchical clustering based on the Euclidean distances as similarity coefficient allows the relationship investigation between the observations of the variables of a dataset, in order to recognize the existence of groups. It is applied to detect spatial similarity for sampling site grouping. In our study, 3 clusters that present similar characteristic features are identified (Figure 12):

(i) *Cluster I* is represented by samples taken from the west side of the lagoon in the July campaign (S4, S8, S9, S11, S12, and S14).

(ii) *Cluster II* concerns the July samples taken in the east side of the lagoon (S1, S2, S3, S5, S6, S7, S10, and S13).

(iii) *Cluster III* characterizes the samples collected in the February campaign, that can be subsided in two subclusters:

  (i) Samples located in the eastern part of the lagoon (S1, S2, S3, S6, and S7).

  (ii) Samples collected in the western part of the lagoon (S4, S5, S8, S9, S10, S11, S12, S13, and S14).

This classification allow us to divide the lagoon in two parts according to the physicochemical parameters: the eastern part under the influence of seawater coming from the gulf characterized by the lowest levels of temperature, pH,

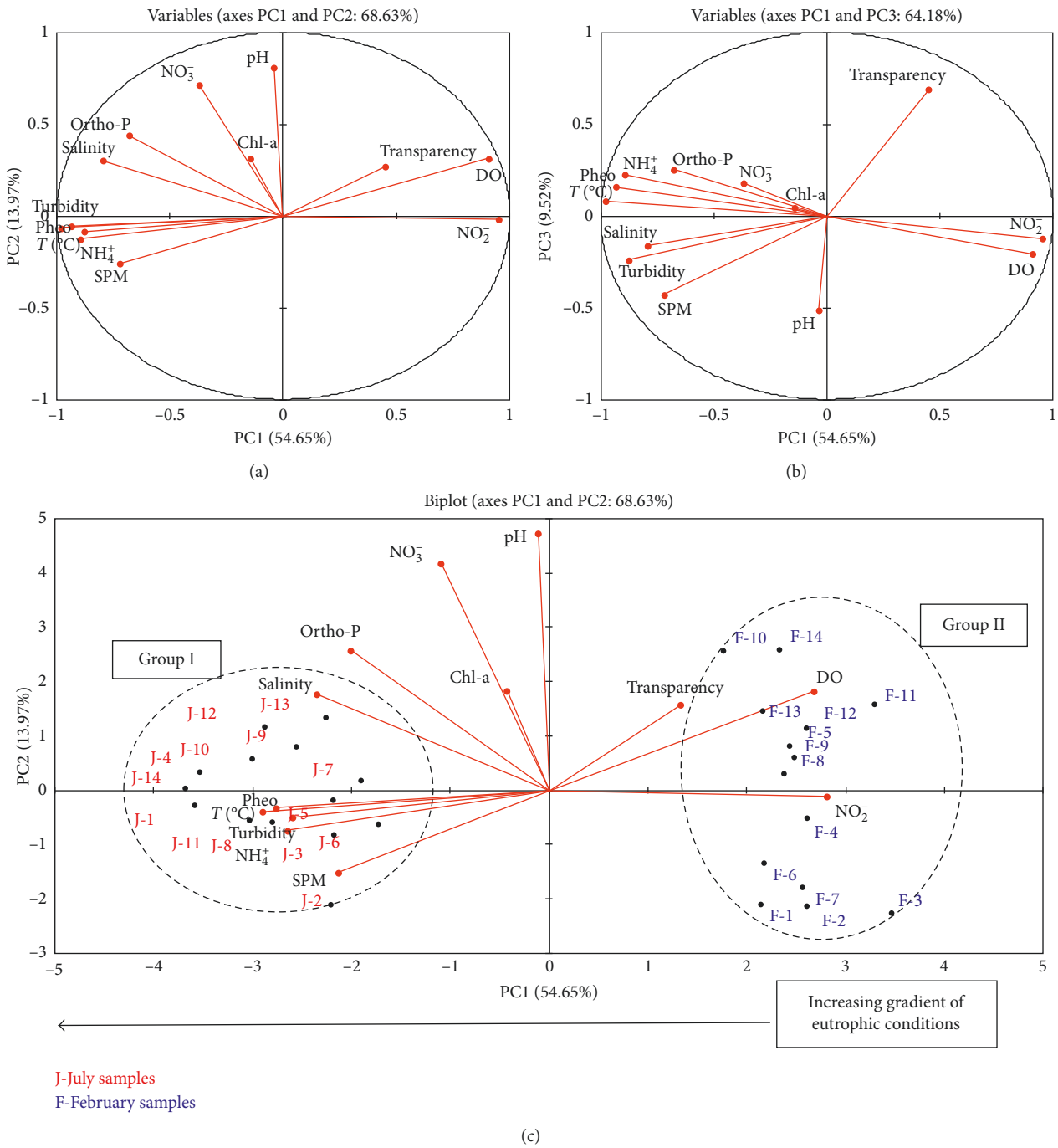

Figure 11: Circle of correlation on (PC1 and PC2) and (PC1 and PC3) and spatial distribution of variables and individuals in the axes system PC1 and PC2.

salinity, and dissolved oxygen contents and the western part with the highest levels of these parameters.

Water coming from the Canal of Rades exerts a continuous flashing on the lagoon. However, this dilution effect is limited in the east side of the lagoon. To road the outlet gate (on the west) the lagoon water are enriched.

3.5. Trophic State Assessment. In these last years, the concern of managers and scientists has grown and different classifications of the trophic state of coastal water based on nutrients and oxygen thresholds have been settled [58–60].

The morphology of the South Lagoon of Tunis has totally changed during the last decades (before and after the restoration project). For this propose, a comparative analysis, evaluating the restoration project impact on physico-chemical parameters and the nutrient contents of the lagoon, seems to be extremely interesting to check the good functioning of the restored ecosystem. In order to track the

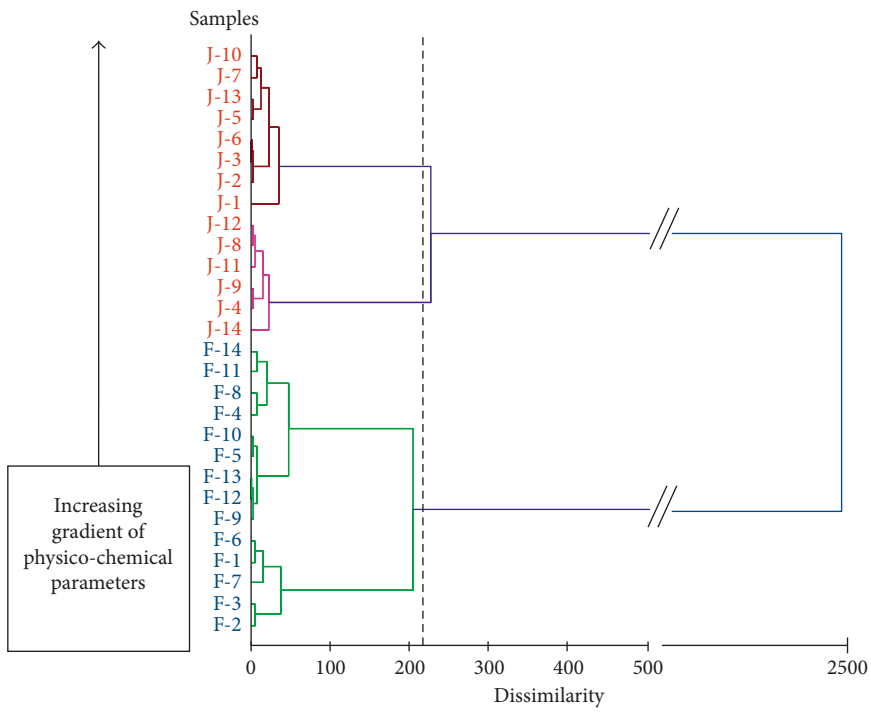

Figure 12: Dendrogram for the South Lagoon of Tunis samples.

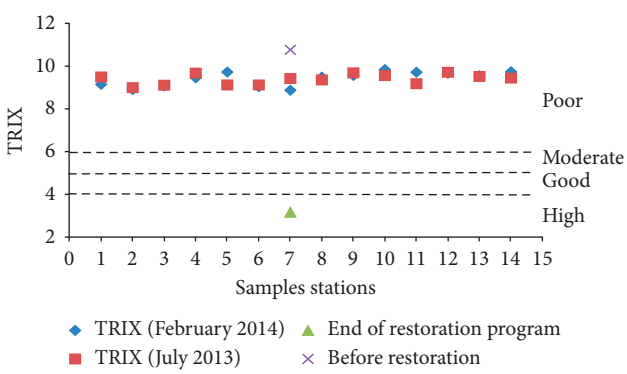

Figure 13: Variation of TRIX index [21] for the South Lagoon of Tunis.

evolution of the trophic conditions in the South Lagoon of Tunis, the TRIX [21] was selected.

Figure 13 shows the water trophic status in the South Lagoon of Tunis before, during, and after the restoration work. Before restoration, Ben Souissi [22] showed that nitrates/phosphorus and chl a rates reached high levels in the South Lagoon of Tunis. The lagoon water quality was categorized as "poor" according to TRIX index calculated from the mean monthly values. The best trophic state was registered during the restoration work; the lagoon was categorized as "high". In the present work, the TRIX values ranged from 8.9 to 9.9. Despite the hydrodynamic system improvement in the lagoon, the lagoon water quality was categorized as "poor".

The trophic status of marine coastal ecosystem assessment is based on measurements of combinations of biotic and abiotic variables [21] as well as the main elements (e.g., inorganic and organic N and P) and molecules (organic matter, chlorophyll a concentrations) that had been used as indicators of biomass in the water column [61]. However, the increase in the primary production levels is not the only factor controlling the trophic status of a marine ecosystem. There is also transparency, sunshine, and water circulation which are considered as important factors too [62]. For example, increased levels of primary production can also be associated with the accumulation of large amounts of detrital organic materials [63].

During the restoration of the South Lagoon of Tunis, a new hydraulic design was required. The hydrological parameters show an improvement of the physicochemical parameters, due to the newly produced hydrodynamic, permanent seawater exchanges, the water residence time reduction, the lagoon water volume increase, and a continuous flushing.

The engineering work improved the quality but did not fully reach the expected results. The South Lagoon of Tunis still records a poor water quality classification. As shallow marine ecosystems, the arid climate (characterized by a high evaporation rate and temperature) and the continuous intake of nutrients can modify the structure and the biology of the water column at very short time intervals (from minutes to hours). Despite dredging the bottom sediment of the lagoon, the South Lagoon of Tunis is still contaminated by organic matter and records a high rate of nutrients even after management work. These elements may, under precise conditions [64–66], be released and might be diffused from the water-sediment interface.

Moreover, in the anoxic phase that could happen in the lagoon due to the high summer temperature; the exchange

with the sea seems to be ineffective for flushing to decrease nutrient contents.

4. Conclusion

The purpose of this manuscript was to give an assessment of the lagoon status using geochemical and statistical approaches. The results indicate that the spatial distribution of temperature, salinity, and pH is under the control of water circulation in the Southern lagoon of Tunis. They show a slight increase from the east to the west.

The lagoon water shows a high level of nutrients (NO_3^-, NO_2^-, NH_4^+, and ortho-P) compared to the incoming water from the sea. This is essentially due to natural (nitrification, release from the sediments, and primary production) and anthropogenic (wastewater and runoff) sources.

Based on nutrient contents, DO, and chlorophyll a, TRIX proposed by Vollenweider et al. [21] was calculated. It demonstrated that the lagoon has reached the eutrophic status with a poor water quality index. The trophic status of the South Lagoon of Tunis is worrying and requires a serious intervention.

PCA identified two groups (winter sampling campaign/summer sampling campaign), the eutrophic status of the lagoon water is highlighted in July campaign. The CHA analysis allowed us to divide the lagoon into two parts (east and the west parts) where the west side is richer in nutrients and in physical-chemical parameters compared to the east side.

The current status of the lagoon requires serious interest, given its vulnerability and fragile balance, in order to avoid the failure of the engineering works (if a status-quo is maintained).

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

This work was partially presented in international conference days: ICEWE 2017.

Conflicts of Interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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