Chapter

Evaluation of the Water Quality and the Eutrophication Risk in Mediterranean Sea Area: A Case Study of the Gulf of Gabès

Neila Annabi-Trabelsi, Mohammad Ali, Genuario Belmonte, Habib Ayadi and Wassim Guermazi

Abstract

The Gulf of Gabès, located in southern Tunisia, is a distinct and ecologically significant area in the Mediterranean Sea. Unfortunately, this dynamic marine ecosystem is experiencing cultural eutrophication, a process where water enrichment with nutrients like phosphorus and nitrogen salts leads to excessive algae growth, disrupting the ecological equilibrium and degrading water quality. In the Gulf of Gabès, key sources of nutrient pollution include industrial discharges, urbanization and agriculture. Eutrophication's effects here include harmful algal blooms, oxygen depletion, and declining water quality, upsetting the marine ecosystem's balance and impacting both fish and aquatic life. Nutrient enrichment interacts with trace metal pollution, overfishing and climate change. Future research must acknowledge and consider the complex interactions among these variables. Efforts in the Gulf of Gabès to address eutrophication involve tighter industrial regulations, enhanced agriculture and improved wastewater management, all crucial for preserving the marine environment's integrity and ensuring sustainability for the future.

Keywords: eutrophication, phosphorus, phytoplankton, zooplankton, algal blooms

1. Introduction

Cultural eutrophication poses a severe environmental and economic challenge in coastal marine ecosystems across the globe [1–3]. According to the European Union's definition, cultural eutrophication involves enriching water with nutrients, especially compounds of nitrogen and phosphorus, causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned [4]. This kind of pollution by nutrients is resulting from anthropogenic activities including industry, agriculture and sewage disposal [5]. The repercussions of cultural eutrophication extend to coastal ecosystem biodiversity and the services they give to society such as protection from coastal erosion and flooding, or fish production [6].

Eutrophication is mostly accompanied by hypoxia and an increase in the biomass of nuisance algal taxa [7]. In fact, eutrophication is an important factor contributing to the increased frequency and diversity of harmful algal blooms [8] and shifts in the zooplankton community [7]. Despite the fact the Mediterranean Sea is generally considered of good quality [9, 10] and classified as nutrient-poor and oligotrophic [11], eutrophication problems began emerging in the 1960s [12], mainly situated in areas of encircled gulfs and bays near big cities, in estuarine areas and near ports [13–17]. The Gulf of Gabès, situated on the southeastern coast of Tunisia, faces pollution from anthropogenic and industrial activities, and its coastal area showed signs of eutrophication [18]; continuous and increasing deterioration of the coastal waters of the Gulf was reported since the industrialization [19–21].

2. The Gulf of Gabès: main characteristics

Situated in southeastern Tunisia, the Gulf of Gabès, also known as "Petite Syrte", stretches from 9.5 to 12°E in longitude and from 33 to 35.5°N in latitude. It extends from "Ras Kapoudia" in the north to the Tunisian–Libyan border in the south, encompassing a coastline exceeding 400 km (**Figure 1**). It shelters various islands (Kerkenneh, Kneiss and Jerba) and lagoons (Boughrara and El Bibane).

It is characterized by a semiarid Mediterranean climate, shallow waters, weak currents, high salinity and high temperature. The Gulf's circulation is predominantly influenced by tides and anticyclonic winds [22].

The Gulf has the highest tidal range in the Mediterranean Sea (maximum >2 m), essentially due to the low slope of the continental shelf and the shallow depth, which maintains its horizontal dimensions close to the resonance phenomena [22, 23].

Since industrialization in 1970, the Gulf of Gabès has been heavily impacted by industrial wastes and described as one of the most human-impacted coastal areas in the Mediterranean Sea [21]. Diverse untreated pollutants from liquid and solid wastes discharged from industrial and domestic activities (crude phosphate treatment, chemical processing plants, tanneries and textile mills) have severely degraded the Gulf of Gabès [24, 25]. The phosphate fertilizer industry is mediated as the major source of pollution. The most important phosphate industry group (Tunisian Chemical Group: TCG) was set in Gabès city. Two other companies (SIAPE and GRANUPHOS) are located in Sfax city, and recently, another one (SIAPE II) has been launched in Skhira. The unregulated disposal of phosphogypsum (PG), a byproduct of the phosphate fertilizer industry, into the Gulf of Gabès at a daily rate ranging from 1000 to 13,000 tons, stands as the primary factor responsible for the deterioration of this ecosystem [26, 27].

3. Causes of eutrophication in the Gulf of Gabès

Phosphogypsum (PG) industrial effluents released into the Gulf of Gabès are notably acidic and carry elevated levels of fluoride and phosphate. Additionally, they contain variable concentrations of heavy metals such as cadmium, chromium, copper, zinc and lead, along with radionuclides [28, 29]. The study of El Kateb et al. [30] clearly established that the substantial discharge of PG is a leading cause of eutrophication in the Gulf of Gabès.

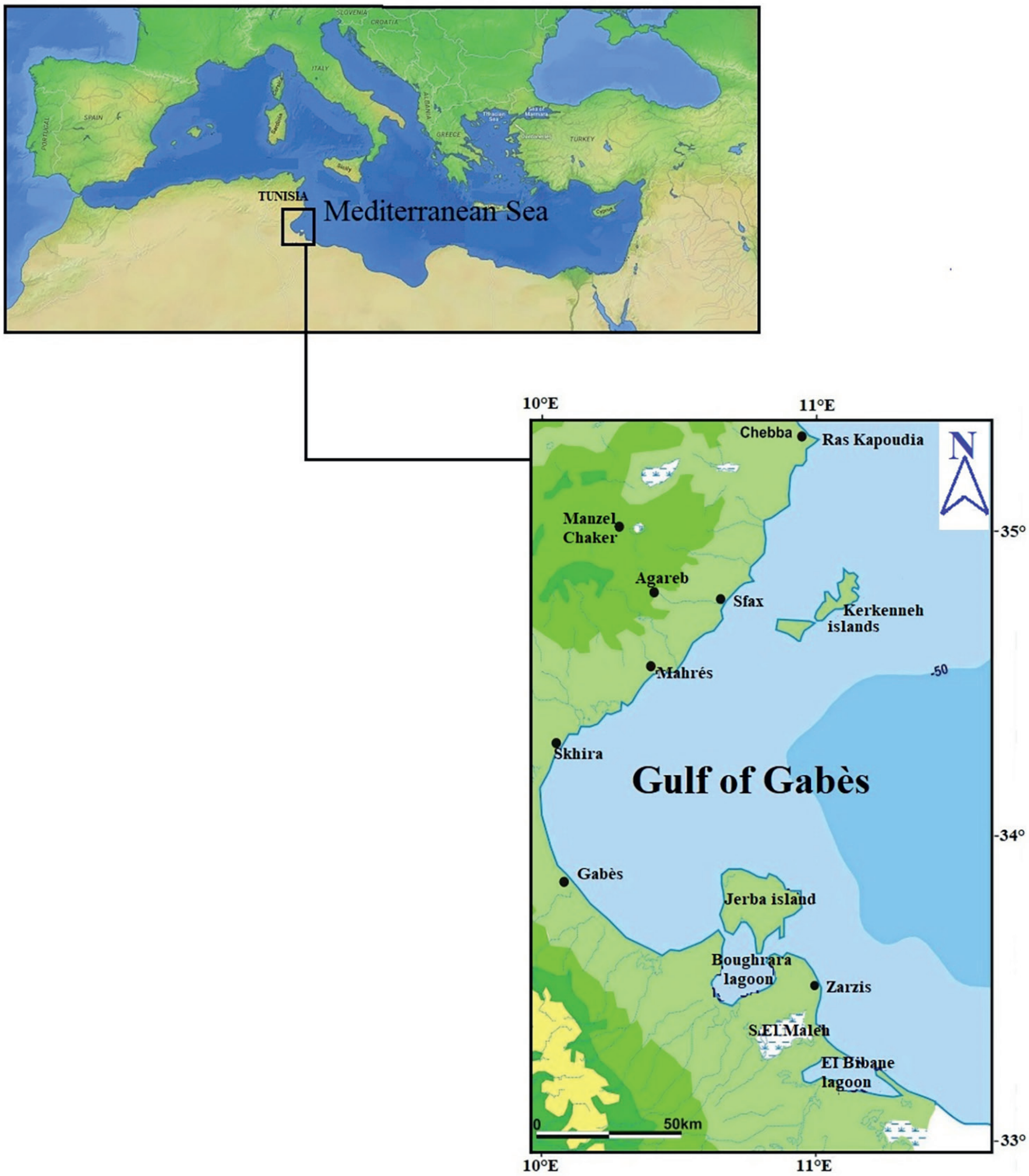

Figure 1.
Localization of the Gulf of Gabès.

While phosphorus is an essential element in the marine ecosystem, its excessive enrichment poses various challenges to biota, elevates the growth of organic matter, and consequently reinforces eutrophication [31, 32]. The high availability of inorganic phosphate along the coast of Gabès is also associated with agricultural use of land along the coast [33]. For phosphates, eutrophication is identified by phosphate levels exceeding 0.68 µmol l^{-1} [34]. Very high concentrations of phosphates are recorded in coastal areas of the Gulf of Gabès and reflect a eutrophic state. In fact, phosphate concentrations ranged from 0.51 to 8.52 µmol L^{-1} (mean ± SD = 2.98 ± 2.44 µmol L^{-1}) in the southern coast of Sfax [35]. They fluctuated between 1.25 to 2.97 µmol L^{-1} (mea n ± SD = 2.07 ± 0.62 µmol L^{-1}) in the northern coastal area of Sfax [36]. In the coastal waters of Gabès, phosphate concentrations ranged from 1.7 to 6.7 µmol L^{-1} (mean ± S D = 3.74 ± 1.65 µmol L^{-1}) [17].

The application of an Eutrophication Index (E.I.) [37] was used by [17] in order to assess the eutrophication status of the coastal waters of Gabès. This index takes into consideration nitrites, nitrates, ammonium, phosphates and Chlorophyll-a. If E.I. is above 1.51, water quality is bad. Values of E.I. calculated in the Gulf of Gabès were > 2.16, indicating a high ecological alteration of the marine ecosystem [17].

Ammonium stands out as the predominant form of dissolved inorganic nitrogen, followed by nitrates, in the coastal waters of the Gulf of Gabès [17, 35, 36]. This dominance is a typical characteristic of untreated anthropogenic wastewater input [38].

The range (min–max) and mean values of dissolved inorganic nitrogen forms (ammonium, nitrates and nitrites) recorded in the Gulf of Gabès are given in **Table 1**, confirming the widespread status of eutrophication in the coastal waters of the Gulf of Gabès.

4. Signs of eutrophication in the Gulf of Gabès

Eutrophication yields a range of consequences impacting water quality, ecosystems, human health and economic activities [39].

Changes in coastal ecosystem states due to coastal eutrophication include:

- Presence of low dissolved oxygen and formation of hypoxic or "dead" zones (oxygen-depleted waters) particularly on the bottom [6, 40]. Hypoxia and anoxia significantly affect living resources and can cause severe damage to fisheries [41].

- A shift in the composition of phytoplankton species toward more tolerant and opportunistic species [42], creating favorable conditions for the proliferation of harmful algal blooms [43].

- A decrease in zooplankton diversity [44] as larger-sized taxa are replaced by smaller ones [45, 46].

- Loss of marine biodiversity of the aquatic community [47, 48] and the dominance of gelatinous organisms [49, 50].

	Southern coast of Sfax [35]	Northern coast of Sfax [36]	Coast of Gabès city [17]
Ammonium (μmol L^{-1})	3.47–38.06 (13.26 ± 1.85)	2.99–7.75 (5.01 ± 1.71)	2.8–20.6 (8.73 ± 5.41)
Nitrates (μmol L^{-1})	1.09–26.53 (7.56 ± 1.5)	1.71–11.44 (3.07 ± 2.95)	3.1–6.0 (0.6 ± 0.1)
Nitrites (μmol L^{-1})	0.02–4.83 (0.82 ± 1.29)	0.04–2.64 (0.37 ± 0.8)	0.4–0.7 (3.07 ± 2.95)

Eutrophication is recognized for ammonium when values are above 2.2 μmol L^{-1} [34].
Eutrophication is recognized for nitrates when values are above 1.19 μmol L^{-1} [34].

Table 1.
Minimum, maximum and mean values of dissolved inorganic nitrogen forms in the Gulf of Gabès ± standard deviation from previous studies.

- A reduction in subaquatic vegetation due to excessive macroalgae and microalgae growth reduces light penetration [40, 51].

The Gulf of Gabès has exhibited these characteristic signs of eutrophication exacerbated by trace metals pollution over the last decades.

4.1 Degradation of water quality in the Gulf of Gabès

The seawater temperature range from 13°C during winter to 26°C in the summer [52]. The mean annual salinity is notably high, around 38 psu, and may surpass 39 psu during summer [53]. The lowest recorded salinity (36 psu) and pH (7.6) were observed in the spring in areas adjacent to discharges from TCG and urban wastewaters [17].

Various studies have highlighted deteriorations in water quality, including turbidity [18, 30, 54] and depletion in seawater oxygen levels [30, 55].

4.2 Decline of *Posidonia oceanica* in the Gulf of Gabès

The characterization and evaluation of specific responses to eutrophication in seagrasses offer a valuable tool for detecting changes in water quality in coastal areas, especially considering they are among the most widespread organisms in coastal waters [56, 57]. Eutrophication has been cited as a primary factor leading to the global decline of seagrass populations [58]. Therefore, *Posidonia oceanica* is suggested for use as a bioindicator to assess the health status of coastal habitats [59, 60]. The surface alkaline phosphatase activity in the seagrass *P. oceanica* can be used as a biomarker of eutrophication [57].

At the beginning of the twentieth century, the littoral beds of the endemic Mediterranean seagrass *P. oceanica* almost entirely covered the sea floor in Gulf of Gabès [61]. However, the present condition of *P. oceanica* indicates an ongoing decline in its meadows and its localized disappearance from multiple areas within the central part of Gabès Gulf [62]. Consequently, a noticeable decline in associated fish production has been consistently observed since 1990 [63]. The loss of the native vegetation cover in the Gulf of Gabès is estimated at 90%, with the *P. oceanica* beds being replaced by the opportunistic green algae *Caulerpa prolifera* in deeper zones [64]. This decline is a global phenomenon and is supposed to be primarily induced by eutrophication [65]. In addition to the effects of eutrophication, the warming of the sea may lead to synergistic effects and an increased rate of loss for these valuable ecosystems [66, 67]. The decline of *P. oceanica* in the Gulf of Gabès is linked to pollution from the phosphate industries [33, 62].

4.3 Phytoplankton and harmful microalgae blooms in the Gulf of Gabès

In the coastal region of the Gulf of Gabès, the phytoplankton community is composed of seven major groups: Dinophyceae (108 taxa), Bacillariophyceae (58 taxa), Cyanobacteria (5 taxa), Dictyochophyceae (1 taxon), Euglenophyceae (1 taxon), Coccolithophorideae (1 taxon) and Chlorophyceae (1 taxon) [68]. Within the identified species, ten have been recognized as potentially toxic, including *Alexandrium minutum*, *Coolia monotis*, *Karenia selliformis*, *Protoceratium reticulatum* [68], *Amphidinium carterae*, *Dinophysis caudata*, *Prorocentrum lima*, *Prorocentrum minimum*, *Pseudonitzchia* sp. [17] and *Ostreopsis* cf. *ovata* [69].

Since 1990, multiple blooms of toxic dinoflagellates have been detected in the Gulf of Gabès [70–73]. Harmful algal blooms (HABs) of *A. minutum* formed in areas subjected to anthropogenic eutrophication such as Sfax Harbor and in confined lagoons in the Gulf [71]. The sudden *A. minutum* blooms along the nearshore of the Gulf of Gabès are complex, but phosphorus appears to be the key driving factor [71].

In 1994, *K. selliformis* was responsible for a significant intensive fish kill, estimated at 200 tons in the Gulf of Gabès [74, 75]. The occurrence of this taxon in the Gulf is related to high nitrate levels and is supported by elevated temperatures [76]. Typically, late summer and autumn are the periods of high bloom frequency of this taxon [70].

The abundance of Cyanobacteria in the Gulf of Gabès was positively correlated with inorganic nitrogen [70]. Blooms of *Trichodesmium erythraeum* were initially observed in July 1988 [77]. *T. erythraeum* blooms occurred approximately 2.11 times per year during the period from 1988 to 2013 [78]. Damages resulting from the toxic algal blooms cannot be considered resolved by reducing their populations. Indeed, numerous toxic Dinophyceae produce cysts at their blooming, successively accumulating in the sediments where they wait for the return of favorable conditions to germinate [79]. The encystment phenomenon is regular and frequent in the Gulf of Gabès but affects a low variety of species. During two decades of monitoring, eight different groups of cysts were recorded in the Gulf, with the dominance of ones of potentially toxic species [80, 81]. Even in the absence of algal inoculation from neighboring geographic areas, such toxic species can re-appear by the germination of the cysts in the sediments each time the conditions are favorable. Thus, the management of coastal areas has to carefully consider this "potential" harmful injection, even in the absence of algal blooms in the water column for many years.

4.4 Copepoda in the Gulf of Gabès

Zooplankton assemblages in the Gulf of Gabès were primarily dominated by copepods, accounting for 69–83% of the total zooplankton abundance [82]. A total of 52 species of Calanoida, 30 Cyclopoida and 11 Harpacticoida species were reported in the Gulf of Gabès [83, 84]. Notably, Cyclopoida, particularly Oithonidae (mainly *Oithona nana*), dominated copepod communities in the Gulf of Gabès [17, 35, 36, 82, 85]. We suggest that with increasing eutrophication over decades, a general shift to smaller-sized Copepoda with egg sacs, particularly the cyclopoid Oithona nana, was observed in the Gulf of Gabès. The success of *Oithona* spp. in eutrophicated and disturbed ecosystems is mainly due to their remarkable adaptability to changing environments than other species [86] as they are typical ecological generalists [83, 84]. In fact, the dominance of this species can be linked to a change in the food spectrum (and/or the fact that it does not spawn eggs into the water column). The possession of egg sacs is considered as an advantage in eutrophicated ecosystems that evolve hypoxic/anoxic bottom waters [7]. Spawned eggs that fall into the sediments may be prevented from hatching due to reduced oxygen levels. Therefore, the combination of a successful reproductive strategy, an omnivorous diet, and lower metabolic demands likely underlines the prominence of *Oithona* in the Gulf of Gabès [85, 87].

5. Conclusion

As documented by a number of investigations, eutrophication is a serious problem for the biodiversity in the Gulf of Gabès. However, since the Gulf also experienced chemical pollution by trace metals, and overfishing, eutrophication may not have been the only factor. The enrichment of nutrients, especially phosphorus, interacts with these factors and, in addition, with climate change. Due to cumulative anthropogenic pressures, integrated management of the coastal marine environment of the Gulf of Gabès remains necessary to re-direct the ecosystem functioning toward a healthier status and a restoration of ecosystem services [88, 89] possibly compromised. Efforts in the Gulf of Gabès to contain eutrophication involve a policy of environmentally sustainable development, with tighter industrial regulations, enhanced agriculture and improved wastewater management. The heavy socio-economic impact of such a policy is only apparent. In fact, the decision should be sustained by detailed studies on the economic convenience of such an approach, with a precise monetization of what the present situation subtracts in terms of ecosystem services to society. The restoration of good environmental status, in addition, would not be a cost for managers because open gulfs (such as the Gabès one) should be easily re-populated. Living organisms, in fact, can go elsewhere when local conditions are adverse or can undergo a lethargic condition, waiting for the return of suitable conditions in the sediments for years [90, 91]. The re-covering of a good environmental status (and the re-launch of ecosystem services) could be, consequently, a fast process.

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