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Archives of Environmental Protection
Vol. 50 no. 3 pp. 100–108

PL ISSN 2083-4772
DOI:10.24425/aep.2024.151689

Wetland Ramsar site in Tunisia (Soliman brackish lagoon): status, threats, and protection

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Keywords: bacteria, bioindicator, clean water, nemathodes, pollution, Ramsar wetlands

Abstract: The Ramsar wetlands are crucial for global ecology. They are essential for preserving the balances of ecosystems. The aim of this work is to prevent the current situation of Sebkha of Soliman (880 ha; 36°43'N, 010°29'E; Nabeul, Tunisia) from deteriorating further. It is one of the few wetlands that receives water from both the sea, Wadi, and a wastewater treatment plant. According to a study of the organic pollution in the Sebkha's waters and sediments conducted in March 2022, there are high concentrations of suspended matter, that exceed 80 mg/L. The total organic matter exceeds 110 g/kg DW, and the biological oxygen demand exceeds 56 mg O_2/L. Additionally, there are more than $24*10^3$ bacteria per liter., We also identified mineral pollution primarily caused by nitrate (2.4 g/kg DW), phosphorus (2.42 g/kg DW), and iron (40 mg/L). Pollution is dispersed over three areas: the least polluted area is near the sea, the most polluted area is in the center of Sebkha, and the area farthest from the sea has medium pollution levels. The distribution of pollutants in the Sebkha is influenced by the contribution of pollutants and the self-purification by seawater.

Introduction

Wetlands are systems that are both ecologically sensitive and adaptive. Wetland ecosystems are ecologically and functionally significant elements of the water environment, with potentially an important role to play in achieving sustainable river basin management (Directorate-General for Environment 2003). Despite great progress and global awareness following the Ramsar Convention in 1971, many wetlands are still threatened by extinction. Approximately 50% of the world's wetlands have been lost since 1900 (Gell et al. 2016). The global extent of wetlands declined from 64% to 71% during the 20th century, and losses continue worldwide, as estimated. Wetlands are often considered as wasteland and harmful for human development. They are even used as landfills (Kaushalya 2020). Political processes frequently overlook wetlands with significant potential value.

Soliman's coastal plain, situated at the southern end of the Gulf of Tunis, is representative of the largest nearly natural coastal plain in the area and includes a lagoon, salt marshes, and dunes (Chekirbane et al. 2016). The importance of the site was emphasized by its designation as Ramsar site No. 1713 (most recent RIS information: 2007) (Ramsar Sites Information Service 2016). Site TN 011 (Fishpool and Evans 2001) is considered a Bird Life site and an important area for the conservation of birds (ZICO/IBA) (National Census Reports East Atlantic Africa 2017). The citations highlight the significance of the site for two crucial species, the marbled teal and the taunting gull, as well as its role as a nesting place and migratory stop (Sustain-COAST WP2 2020, Amari and Azafzaf 2001). It is a rare place in the area that retains water throughout the summer (Tunisia's Second National Communication Under The United Nations Framework Convention on Climate Change (UNFCCC) 2013).

It is an important refuge for water birds, hosting breeding populations such as the marbled duck (*Marmaronetta angustirostris*), the white stork (*Ciconia ciconia*), the Mediterranean gull (*Ichthyaetus melanocephalus*), the Sandwich tern (*Sterna sandvicensis*), and the collared pratincole (*Glareola pratincola*) (Annotated List of Wetlands of International Importance 1998). Medicinal, aromatic, halophilic, nitrophilic Forage plants, and dune fixators are found in Sebkha of Soliman, which is typical of wetlands (Mili 2016, Hidri et al. 2022). The flora is dominated by halophyte plants from the *Halocnemum* and *Arthrocnemum* genera, as well as *Salicornia arabica* L. (Zarrouk et al. 2003). Submerged species like *Ruppia* and wild species like wild tobacco, which grow in polluted soils, are the dominant vegetation of the lagoon (Hails 1997). Halophilic vegetation is present in the lagoon and depression areas with the most salty soils (El Hidri et al. 2013, Hammami et al. 2016).

Sebkha of Soliman is among the few places in the region that conserve water throughout the year. It shelters populations coming from the Sebkha of Sijoumi and other nearby wetlands.

Table 1. The annual contributions of Wadi el Bey.

	Average annual contribution (Mm^3 / year)	Solid contribution (Ton / year)	Low flow (m^3 / s)	Average flow annual- winter (m^3 / s)	Annual flood flow (m^3 / s)
Wadi el Bey	15.18	55 215	0.10	2	34

Table 2. Sources of pollution of the Sebkha of Soliman.

Type of pollution	Nature of polluting products	Sources
physics thermal	hot water discharge	industry
organic	carbohydrates, lipids, proteins, Ammonia, nitrate	
chemical fertilizers, metals and metalloids, pesticides, organochlorine, detergents, hydrocarbons	nitrate, phosphate, mercury, cadmium, lead, aluminum, arsenic ... insecticides, herbicides pcb, solvent	urbanization (tourist area of borjcedria), industry (food, textile, medical.), domestic effluent, transport
microbiological	bacteria	mushroom breeding urban effluent
biological		hunting

The *Larus geneien*, a *wintering gull*, has a population of 500 to 1,600 individuals (threshold of 1%: 230 individuals) (Evans and Fishpool 2001). The white stilt *Himantopus himantopus* was observed during the nesting period, and it is possible that other delimicole species were observed during the migration period (Tinarelli 1987). There are two operating regimes at Sebkha of Soliman (Khouni et al. 2021). The hydrological regime that is influenced by the floods of the Wadi of El Bey, and the hydrographic regime that is triggered by the tide through the pass that connects it to the sea. A study found that the waters have extremely high nutrient concentrations and the sediments are contaminated with metallic elements (Cd, Cu, Ni, Pb, and Zn) (Khadhar et al. 2013).

The Sebkha of Soliman is a crucial component in the self-purification process of wastewater from the El Bey river. This wetland, with an area of approximately 460 km^2, is exposed to a variety of anthropogenic activities(Gdara et al. 2017). Rainwater from the Wadi El Bey watershed flows through the Sebkha, contributing, along with the massive influx of water treated by the Soliman sewage treatment plant, to its year-round flooding. The sustainability of this coastal water area is a rare feature of the Tunisian coast in general and the Cap Bon Plain in particular, especially given the significant transformations resulting from actions implemented as part of the National Strategy on Water Mobilization.

Thewatershed of the Sebkha includes the urban agglomerations of Bou Algoub, Glombria, Beni Khaled, Menzel Buzelfa and Soliman, as well as several important industrial and agricultural units. Various types of drainage into Wadi El Bey exert significant pressure on water quality throughout the Wadi, Sebkha, and coastal water systems (Fig.1). Table 1 shows the annual contributions that have flowed into Wadi El Bay, making it the most polluted tributary due to industrial wastewater (Mhamdi et al. 2016). This tributary accounts for 60% of the hydro-pollution load from some urban agglomerations. The main sources of pollution in Wadi el Bay include tanneries, stationery shops, breweries, tomato processing plants and slaughterhouses (Table 2). To protect the beach, the municipality decided to build a sand barrier at the height of the Sebkha spillway every summer. The Soliman brackish lagoon and other coastal regions are subject to a significant environmental impact, even in protected areas such as Lake Ichkeul located in northeastern Tunisia (N Africa) and the southern Mediterranean Sea (Brik et al., 2022).

Methodology

Sampling site

In the study area, five stations were selected based on their proximity to discharge points. Figure 1 shows the location of these five stations. Water and sediment samples were taken in March 2022 from four stations at the Sebkha of Soliman and one station at the Mediterranean Sea. Table 3 shows the coordinates of the sampling points. The Sebkha of Soliman, also called Sebkhat el Melah, is a flooded wetland with a total area of about 225 hectares (Coastal Protection and Development Agency 2002). There are 5 sampling points: the first sampling point is located at the Artificiel outlet (36°44’11.9”N 10°28’39.6”E); the second sampling point is located at the Marine Channel (36°43’47.3”N 10°29’03.7”E);the third sampling point is located at the Western confined sector effluent (36°44’01.8”N 10°28’54.7”E);the fourth sampling point is located at the

Table 3. The sampling points were chosen taking into account in particular the different effluents observed around the Sebkha of Soliman.

Site	Coordinates	Status
1	36°44'11.9"N 10°28'39.6"E	Artificiel outlet
2	36°43'47.3"N 10°29'03.7"E	Marine Channel
3	36°44'01.8"N 10°28'54.7"E	Western confined sector effluent
4	36°43'35.2"N 10°30'25.3"E	Scattered agricultural and urban residues
5	36°44'08.6"N 10°28'21.8"E	Mediterranean sea

Scattered agricultural and urban residues site (36°43’35.2”N 10°30’25.3”E); and the fifth sampling point is located at the Mediterranean sea site (36°44’08.6”N 10°28’21.8”E) (Figure 1, Table 3). The main factors that explain the zoning of the lagoon area are: (i) the artificial outlet, which allows the maintenance of a permanent water bed, (ii) the freshwater inputs of the Soliman treatment station, and (iii) the natural filling of the lagoon (Prudêncio et al. 2010).

Characterization of the basic climate features that may shape the hydrology of the area

The hydraulic functioning of the Sebkha of Soliman depends on the balance between alimentation and evapotranspiration. Marine inputs are dominant, whereas either rainfalls (annual mean: 457 mm) or the very scarce and episodic fluvial contributions come from Oued El Bey. The total balance is clearly negative because evapotranspiration exceeds 1400 mm by year (Prudêncio et al. 2007). It also depends on marine waters through the artificial inlet and groundwater flows from the El Bey and Sidi Said aquifers (Ruiz et al. 2006). The climate of the Mediterranean Soliman region during March 2022 is characterized by a temperature of around 14°C, precipitation levels reaching up to 141 mm, humidity up to 77%, and wind speeds of around 23 mph. In this work, we have tried to evaluate the degree of pollution in the Sebkha under climatic conditions during spring that favor the minimization of pollution, particularly, with low temperatures and fast winds, which promote the self-purification of water in the Sebkha.

Case study on actual water samples from different sites

To evaluate the water, five outlet samples from each of the sites were vacuum-filtered through a 0.45 µm filter, and the dissolved phase was analyzed during screening. The samples were taken from the upper fringe of the infralittoral stage, accessible by swimming (up to 2 m deep).

Conservation, transport, and storage of samples

The AS950 Portable Sampler’s lightweight design was used to collect samples over 24 hours, with interval of 5 min (200 mL/ 5 mn). All samples obtained for analysis are representative of the entire stream composition. The cleaning and preparation of relocated equipment included washing with hot water and phosphate-free detergent, followed by hot and cold-water rinsing, distilled water rinsing, andmultiple rinses with the actual water being sampled. The method for storage and transformation was described in the “Protocol for the Sampling and Analysis of Industrial/Municipal Wastewater Version 2.0,”

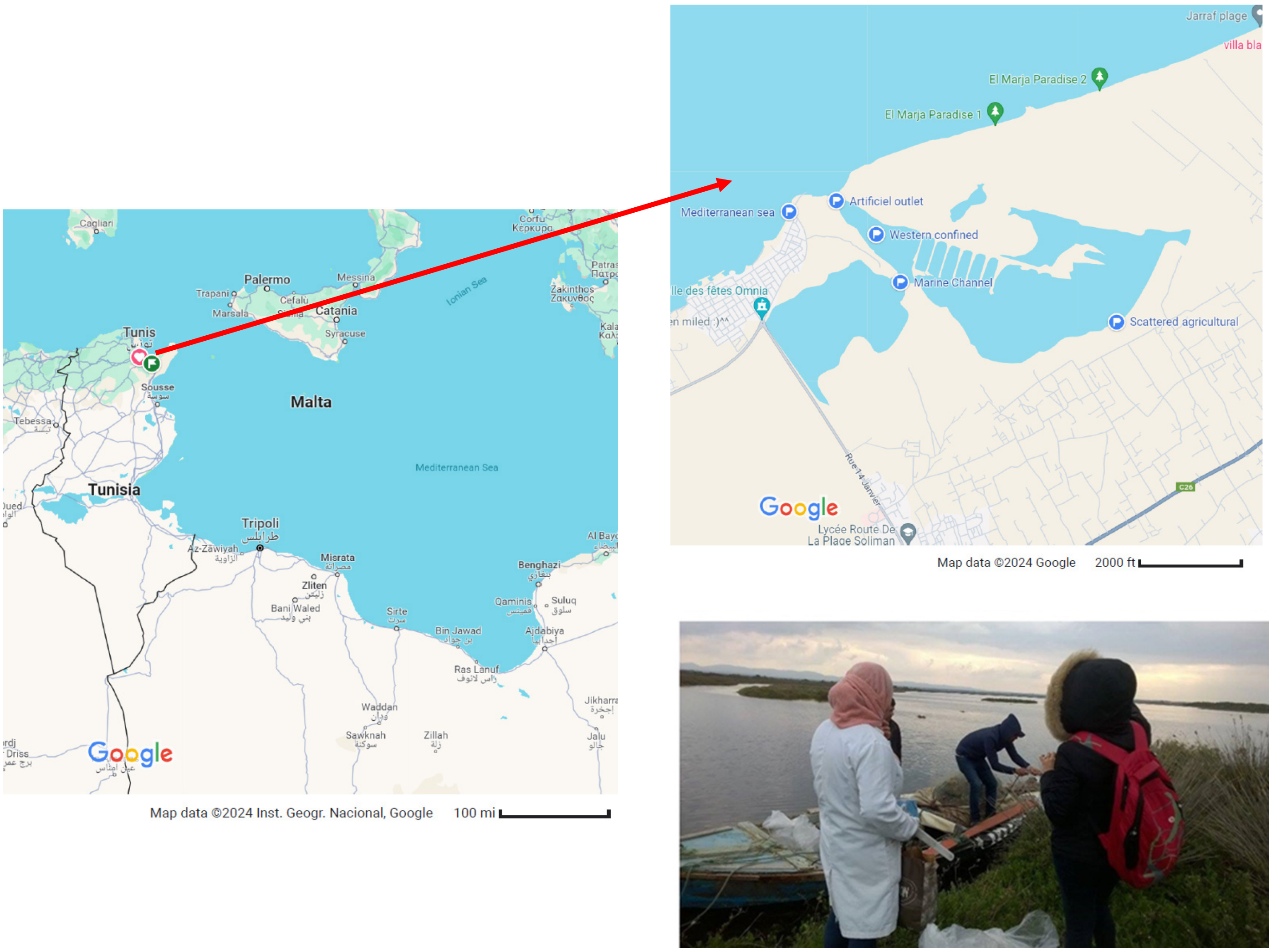

Figure 1. The sampling site. Water and sediment samples were taken in March 2022 at four stations at the Sebkha of Soliman and one station at the Mediterranean Sea.

January 1, 2016, Ontario Ministry of the Environment and Climate Change Laboratory Services Branch. Water samples were collected, transported to a dark, cool warehouse, and analyzed immediately upon return to the laboratory.

Physico-chemical parameters of water samples

For the characterization of samples, we analyzed and evaluated the following parameters: pH, salinity, biochemical oxygen demand (BOD), and suspended matter (MES). pH was measured using pH meter (type 3510 pH-Meter). Salinity was determined using a conductivity meter. Biochemical oxygen demand (BOD), which is the amount of oxygen necessary to oxidize organic matter by biological means, was measured according to the nanometric method based on the principle of the WARBURG respirometer. Suspended matter (MES) was determined by filtration one liter of water using Whatman Millipore filters (0.45 µm), and the residue was dried at 105 °C for 2 h (Xi and Zhang 2011).

Analysis of bacterial density in water

The microbial load of samples was determined using the probable number (NPP) technique. This technique involves three main stages: dilution, inoculation, and reading.

Case study on actual sediments samples from different sites

Natural sediment, including the meiobenthos, was collected from 5 sampling points: the Artificial outlet, the Marine Channel, the Western confined sector effluent, the Scattered agricultural and urban residues site, and the Mediterranean Sea site. Plexiglas cores (area 10 cm2) were used to collect sediments up to 15 cm below sediment surface. Following collection, sediments were transferred from the sampling device to sample containers of appropriate size and construction for the requested analyses. Samples for meiofaunal analysis were passed through a 1 mm mesh to exclude larger macrofauna and retained using a 40-µm sieve. Once extracted, the organisms were stained with Rose Bengal (0.2 gl^{-1}). When the grain size was too fine to allow separation of the organisms from the sediment, density gradient centrifugation was used to extract meiofauna. Meiofaunal organisms were then counted under a binocular microscope (Somerfield and Warwick 2013).

Characteristics of sediment samples

The organic matter (OM) was determined using the incineration method. The measurement of loss on ignition (LOI) indicates the organic matter content and organic carbon content (Corg). To determine the OM level, the sediment samples were burned at 400 °C. During combustion,the organic matter is destroyed and released in the form of carbon dioxide (CO_2) and water vapor. After combustion, only the mineral fraction remained in the container.

Chemical determination of trace element contents by ICP-OES was performed according to the international standard ISO 17072-2 (2015). Digestion is carried out using a ternary acid mixture until complete mineralization. The residue was then deionized and analyzed by ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometry, Perkin Elmer Optima 8000). The filtrate was analyzed against reference solutions of metals with known concentrations at specific wavelength for each of the different elements (International Standard ISO 17072-2 2015).

Statistical analyses

Differences in the microbial community variables among control and treatments were tested using parametric one-way ANOVA tests. A posteriori paired multiple comparisons were performed using the Tukey HSD test when significant differences were $p < 0.05$.

Results and discussion

We have monitored five sampling stations, which are presented in Figure 1. The choice of sites is primarily based on their proximity to pollution sources in the Sebkha of Soliman (Table 3). Station 4 is the closest station to the agricultural area of Elmarja and the Soliman wastewater treatment plant. Station 2 is nearest to the flows of Wadi El Bey and Wadi Selten. Station 3 serves as the junction of the flow waters with Station 4. Stations 1 and 5 represent the coastal zone where the waters of the Sebkha meet seawater, with Station 5 being the furthest from the Sebkha.

The physicochemical characteristics of the water were determined to assess the level of water pollution. pH values ranged from 8.14 to 8.70. According to the standard for bathing water, which sets the pH between 6.5 and 8.5, the pH of the water of the Sebkha of Soliman is consistent with the Tunisian standard NT 106.02 (1989). Factors such as precipitation, runoff, and industrial or municipal spills influence the pH of the Sebkha. To assess the overall mineralization of the Sebkha waters, electrical conductivity was measured. The highest recorded value of conductivity, according to in-situ measurements, is about 1.852 $S.m^{-1}$, and the lowest is 0.494 $S.m^{-1}$, indicating high salinity that favors the establishment of halophilic species in the environment (Table 4). These station-level inconsistencies reveal a very noticeable variation in pollution levels in the Sebkha, Allowing us to track the progression of the pollution. We have identified the presence of mineral, organic, chemical, and biological pollution. Both sediments and water are impacted by this pollution.

We can identify three zones based on the amount of suspended matter in the water column. Zone 1 (Z1), which includes stations 1, 2, and 5, is the least polluted. The high pollution zone (Z2) is represented by station 3, while the moderate pollution zone (Z3) is represented by station 4 (Fig. 2). Three significant areas of organic pollution in the water of the Sebkha of Soliman can be seen when considering the biological oxygen demand (Fig. 3, Table 4). Sites 1 and 2 are part of Zone 1, which appears to be the least polluted. Station 3 in Zone 2 is the region most affected by organic pollutants. Site 4 represents Zone 3, which is moderately polluted and located the furthest from the sea (Fig. 4, Table 5).

The treatment plant and the Wadis are considered to be the primary sources of the contamination and accumulation of pollution observed at Zone 2. By examining the microbial load, it is evident that the waters are contaminated with organic material. Sites 2, 3, and 4 in Zone 2 have a high bacterial load. The coastline with a low bacterial load is represented by Zone 1, which includes sites 1 and 5 (Fig. 5, Table 5). Additionally, by examining the distribution of benthic meiofauna abundance

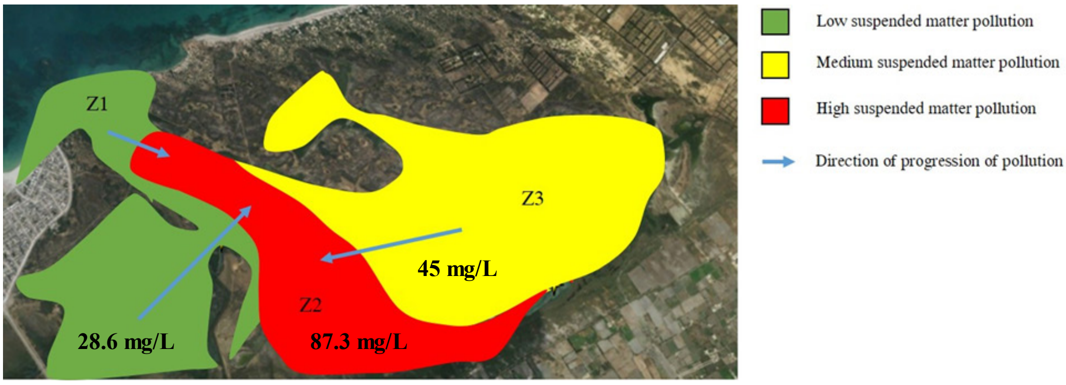

Figure 2. Progression of suspended matter pollution in in the water of the Sebkha of Soliman. Low pollution (Z1), high pollution (Z2) and medium pollution (Z3).

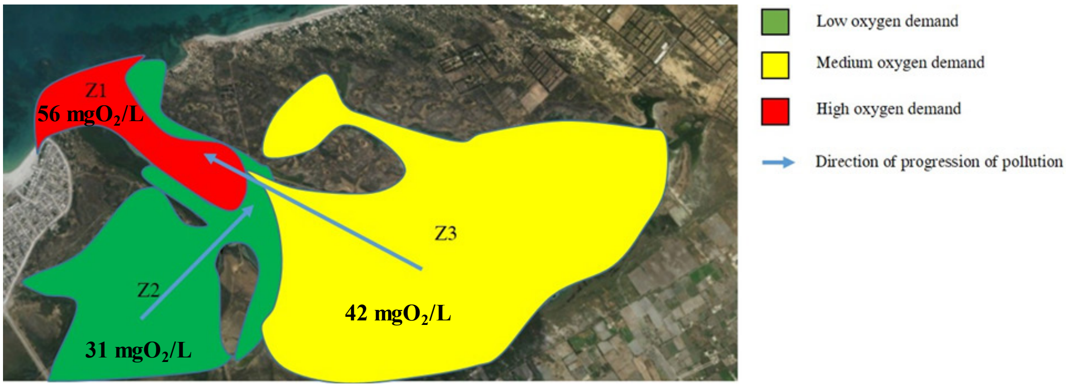

Figure 3. Progression of oxygen demand in the water of Sebkha of Soliman. Low pollution (Z1), high pollution (Z2) and medium pollution (Z3).

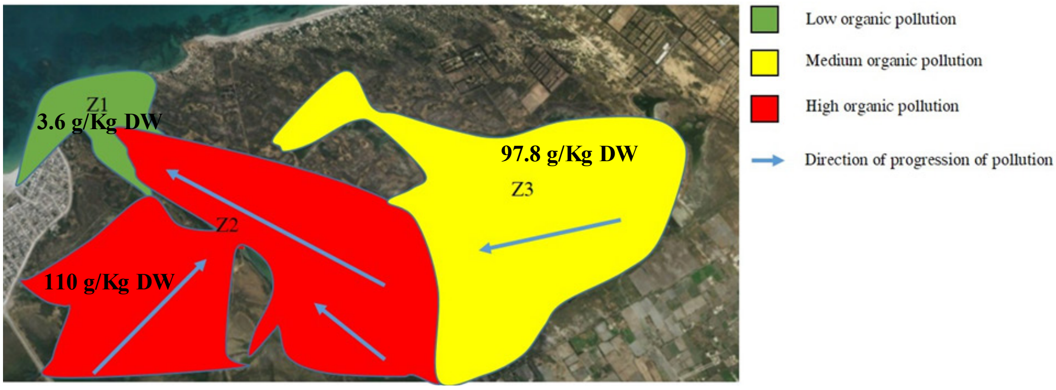

Figure 4. Progression of organic pollution in the sediment of Sebkha of Soliman. Low pollution (Z1), high pollution (Z2) and medium pollution (Z3).

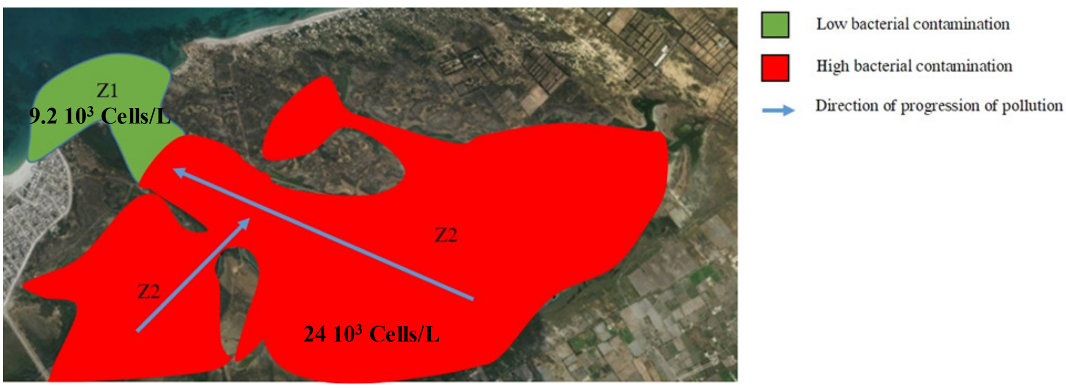

Figure 5. Progression of bacterial pollution in the water of the Sebkha of Soliman. Low pollution (Z1) and high pollution (Z2).

in sediment, we were able to distinguish three zones (Fig. 6, Table 6): Zone 1, with a high abundance, is situated at site 5, which corresponds to the coastline; Zone 2, with a medium abundance, is situated at sites 1 and 4. Sites 2 and 3 of the Sebkha are located in Zone 3, which is the poorest in meiofaunaabundance . It appears that strong organic pollution has a serious impact on the benthic meiofauna in Zone 3.

The mineral pollution is mostly concentrated in the region that is the furthest from the sea and the closest to the La Marja agricultural region and the Soliman wastewater treatment plant. This pollution, which is predominantly found at zone 3, is caused by discharges of fertilizers, pesticides, fungicides, and herbicides as well as pollutants from treatment plant effluents (Fig. 7 and 8, Table 5). Various studies have emphasized the role that pesticides and fertilizers play in the contamination of water, particularly by nitrates and phosphorus (Khan et al. 2017, Singh and Craswell 2021, Moloantoa et al. 2022, Steinhoff-Wrześniewska et al. 2022). Additionally, domestic and urban water from the treatment plant contaminates the Sebkha with nitrate and phosphorus (Fijałkowski et al. 2011, Mažeikienė and Šarko 2023, Bunce et al. 2018). At sites 1 and 5 (Z1), we observed that phosphorus and nitrate pollution levels were not high (0.041 and 0.179 g/Kg DW, respectively).

The cleansing properties of seawater could be the cause of these outcomes. A sediment-accumulating capacity for these categories of pollutants could contribute to the high accumulation at Station 3. When we examine the sources of pollution, we can identify the direction that pollutants take from Zone 3, Site 4, to the sea (Z1). Zone 2, which has low concentrations of these pollutants produced by the waters from Wadi El Bey and Wadi Selten, converges towards Zone 1. These pollutants include pesticides, fungicides, herbicides, and other chemical products derived from the waters of the fertilizer-rich Wadi of the Grombelia agricultural area. In addition, we notice discharges from industrial areas of effluents containing traces of nitrate and phosphorus. Certainly, each of these pollution sources has contributed to accelerating the Sebkha's rate of pollution. Despite the importance of the marine current in the purification process of the Sebkha, this does not prevent the concentration of this pollution in Station 4, Zone 3, the furthest from the sea.

The process of self-purification of the Sebkha following the flow of marine waters represents a primary mechanism of depollution. Disorders of the Sebkha ecosystem are caused by human intervention in controlling the entry of seawaters to the Sebkha, the flow of the Wadi El Bey and Wadi Selten, and the discharge of treatment plant waters into this wetland. These findings are confirmed by additional studies (Zabłocki et al. 2022, Perumanath et al. 2023, Hnativ et al. 2023), which demonstrate how a change in self-cleaning power can aggravate the environmental hazard and quicken the pace of contamination. In order to maintain the Sebkha's current state or enhance the self-purification process, the ideal solution is to minimize polluting discharges.

When examining the Sebkha's metal pollution, we can identify two pollution areas. A zone of high metallic pollution is present in Zone 2, which includes Sites 2, 3, and 4, while Zone 1, which is closest to the sea and represents Sites 1 and 5, is only slightly polluted (Fig. 9, Table 7). This distribution hints at the impact of the industrial zone's contributions to the effluents of the Wadis on the accumulation of metals in Zone 2.

Table 4. Physicochemical characteristics of the water of Sebkha of Soliman.

Sites	GPS coordinates	pH	Conductivity (mS/cm)	BOD5 (mgO_2/L)	MES (mg/L)	Bacterial density (cells/L)
1	36°44'11.9"N 10°28'39.6"E	8.40	1.08	31	28.8	9.2. 103
2	36°43'47.3"N 10°29'03.7"E	8.70	1.653	31	30.2	24. 103
3	36°44'01.8"N 10°28'54.7"E	8.14	0.494	56	87.3	24. 103
4	36°43'35.2"N 10°30'25.3"E	8.41	1.171	42	45	24. 103
5	36°44'08.6"N 10°28'21.8"E	8.26	1.852	56	27	9.2. 103

MES, suspended matter; BOD5, dissolved oxygen

Table 5. Physicochemical characteristics of the sediments of Sebkha of Soliman.

Site	Total phosphorus TP, (g/Kg DW)	Total nitrogen TN, (g/Kg DW)	Total Organic Carbon, TOC (g/Kg DW)	Total organic matter, TOM (g/kg DW)
1	0.057	0.286	0.62	3.1
2	0.417	1.62	27.1	110
3	2.42	2.38	33.3	110
4	1.05	2.02	11.6	97.8
5	0.041	0.179	1.07	4.2

Table 6. Distrubtion of benthic meiofauna in sediments of Sebkha of Soliman.

Site	Nematodes (ind./cm²)	Oligochaetes (ind./cm²)	Copepods (ind./cm²)
1	99±6	26±2	10±2
2	9±2	7±1	2±1
3	12±2	8±2	1±1
4	98±8	22±4	22±4
5	9711±220	14±4	n.d

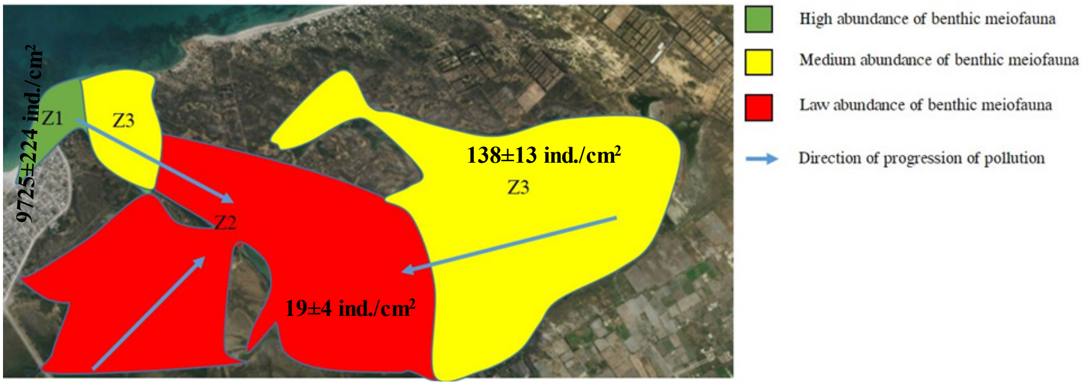

Figure 6. Abundance of benthic meiofauna in the sediment of the Sebkha of Soliman (ind./cm²). High abundance (Z1), medium abundance (Z2), and law abundance (Z3).

Figure 7. Progression of nitrate pollution in in the sediment of the Sebkha of Soliman. Low pollution (Z1), medium pollution (Z2) and high pollution (Z3).

Figure 8. Progression of phosphorus pollution in in the sediment of the Sebkha of Soliman. Low pollution (Z1), medium pollution (Z2) and high pollution (Z3).

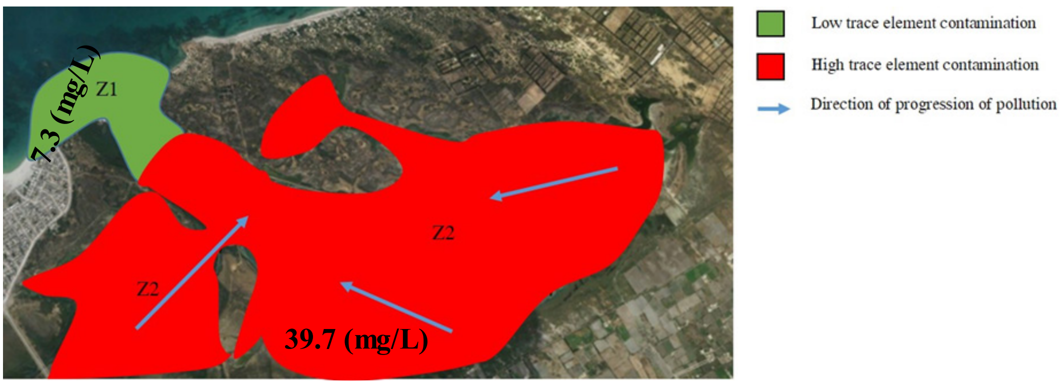

Figure 9. Progression of trace element pollution in the sediment of Sebkha of Soliman. Low pollution (Z1) and high pollution (Z2).

Conclusion

In this study, we examined the development of pollutionin the Sebkha of Soliman,a RAMSAR wetland. By analyzing total organic matter, biological oxygen demand, bacterial load, and abundance of benthic meiofauna, we have identified organic pollution. The accumulation of heavy metals, phosphate, and nitrate has also resulted in mineral pollution. The outcomes display the pollution's distribution over three key regions. An area with little pollution that is typically near the sea. A major pollution hotspot in the center. The area furthest from the sea, which has average pollution levels. The contributions of pollutants from the Wadis, the wastewater plant, and discharges from the agricultural area could be explain, at least in part, this distribution of pollution. On the other hand, the Sebkha's ability to self-purify due to the influence of seawater helps reduce the progression of pollution. Considering all of these findings, it is possible to prevent the propagation of pollution in the Sebkha by conserving the sea's purifying ability and treating water before releasing it into the Sebkha. To prevent the current situation from getting worse, continual monitoring and controls are necessary.

Table 7. Trace element concentrations in sediments of Sebkha of Soliman (mg/L).

Site	Cu (mg/L)	Fe (mg/L)	Cadmium (mg/L)
1	0.0031	7.332	n.d
2	0.015	39.36	n.d
3	0.014	39.73	n.d
4	0.006	40	n.d
5	0.002	7.268	n.d

Acknowledgements

The authors would like to thank the Deanship of Scientific Research at Shaqra University for supporting this work.

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