ASSESSMENT OF INSULAR VULNERABILITY IN SOUTH WESTERN MEDITERRANEAN COUNTRIES: CASE OF SIDI FREDJ IN ALGERIA

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Abstract. The article provides a comprehensive evaluation on vulnerability of the Sidi Fredj islet, located along the southern Mediterranean coast, based on environmental and socio-economic data. The study indicates that the areas of the islet near the coast, which are exposed to significant threats, are the most vulnerable due to anthropogenic pressures, such as marine pollution, waste accumulation and human discharges. The analyses reveal high levels of fecal and chemical contamination, necessitating rigorous environmental management to preserve this ecosystem. This work highlights the importance of implementing targeted conservation measures and sustainable management practices to mitigate the negative impacts of human activities on this islet. This study confirms the specific vulnerability of coastal island areas to environmental and socio-economic disturbances. The assessment approach incorporates various indicators, such as water salinity, pH, and heavy metals, alongside socio-economic factors like tourism intensity, urbanization rates, and local economic activities. By integrating these diverse elements, the study provides a holistic understanding of the islet's vulnerability. The results demonstrate that the methodological approach used in this study could serve as a model for similar assessments in other Mediterranean regions, offering valuable insights for managing and conserving vulnerable coastal ecosystems. This holistic approach not only highlights the critical points that require attention but also serves as a foundation for ongoing surveillance and adaptive management. This study may provide valuable insights for the management and conservation of vulnerable island ecosystems, highlighting the need for integrated and sustainable approaches to address environmental challenges.

Key words: Insular vulnerability, Algeria, Sidi Fredj, Mediterranean, Anthropogenic pressure

1. INTRODUCTION

The vulnerability of insular environments is a complex concept describing the fragility of these ecosystems when exposed to environmental and anthropogenic threats. It is often linked to a system ability for adapting to natural disturbances, climate changes, or the impact of human activities (Lambert *et al.*, 2019). Islands, despite varying in size, often exhibit specific vulnerability due to their isolation and dependence on external resources, making them sensitive to economic and environmental fluctuations (Kurniawan *et al.*, 2016). In the Mediterranean, insular environments play a crucial role in shaping and maintaining regional biodiversity, acting as ecological bridges between coastal and marine environments (Bevan *et al.*, 2013). Given the Mediterranean ecological significance, especially for biodiversity, islands like Sidi Fredj often serve as critical hotspots that support unique species and ecosystems. However, without effective management strategies that consider the interconnections between marine and terrestrial environments, these islets risk irreversible degradation. Sustainable tourism practices, habitat protection, and careful monitoring of human activities could play key roles in safeguarding such ecosystems (Daeden, 2015). Moreover, the surrounding coastal urbanization and the presence of a nearby thalassotherapy center contribute to the area pollution, affecting water quality and the health of local marine ecosystems. Previous assessments of insular environment vulnerability have used various methodological approaches adapted to different geographical contexts. For example, Caniani *et al.* (2016) and Zou and Yoshino (2017) used fuzzy logic models and spatial principal components to evaluate the impact of anthropogenic activities and environmental vulnerability. Additionally, He *et al.* (2018) and Yahia Meddah *et al.* (2023) proposed comprehensive ecological vulnerability assessments by amalgamating various environmental and socio-economic indicators to guide biodiversity conservation initiatives and environmental management. Studies have also specifically examined the vulnerability of tourist and coastal islands. For instance, Farhan and Lim (2012) studied ecological conditions in the Seribu islands in Indonesia, reporting severe impacts from overfishing and pollution. Kurniawan *et al.* (2016) assessed the vulnerability of small islands to tourist activities in the Gili Matra marine park in Indonesia, finding significant environmental degradation due to uncontrolled tourism. Rizzo *et al.* (2020) evaluated coastal vulnerability along the north-eastern sector of the island of Gozo in Malta, highlighting areas at high risk from erosion and sea-level rise. Ma *et al.* (2023) assessed the ecological vulnerability of islands and coral reefs in the South China Sea using remote sensing and reanalysis data, revealing critical threats from climate change and human activities. These works highlight the importance of adopting various methodologies tailored to local contexts to assess the vulnerability of insular environments. This study aims to approach vulnerability of the islet of Sidi Fredj. We integrated various data, including microbiological, physico-chemical, environmental, ecological, and socio-economic parameters. The aim of this study is to conduct a comprehensive evaluation of the ecological status of the insular ecosystem and to propose effective conservation and sustainable management strategies. This research also represents a pilot study, with two key objectives: first to explore the global significance of the islet, and the second, to test a novel methodology for assessing the vulnerability of insular ecosystems. Through this approach, our research seeks to provide a model for similar ecological assessments along the Algerian coast and in other Mediterranean regions.

2. MATERIAL AND METHODS

2.1. Study Area

The islet of Sidi Fredj, located in the central Algerian basin within the wilaya of Algiers, is approximately 650 m from the coast between the coordinates 36°45′30″N, 2°50′03″E and 36°45′33″N, 2°50′06″E. The islet has a coastal perimeter of 283 m and an area of 0.4 ha. It is characterized by volcanic rocks, with surrounding sea-beds primarily composed of fine sands and muddy sands (Bakalem, 2008).

Fig. 1. Map of the Study Area (Islet of Sidi Fredj).

The bathymetric profile ranges from 0.5 m near the islet to approximately 22 m offshore, creating complex underwater topography that influences marine life, currents, and geological processes (Fig. 2).

2.2. Sampling and sample processing

During the winter season (between the 1st and the 18th of February), sampling was conducted at 8 stations around the islet of Sidi Fredj, as shown in figure 1, to collect seawater and sediment samples. These samples were analyzed for various environmental parameters and ecology, including biodiversity.

Water samples were collected manually using pre-sterilized glass bottles for microbiological analysis. The bottles were submerged to a depth of approximately 30 cm below the water surface, then opened against the current. Once filled, the bottles were sealed underwater to avoid contamination (Rodier *et al.*, 2005). For suspended matter and nutrients, seawater samples were collected in polyethylene bottles pre-washed with an acid solution (10% HNO_3) and rinsed with distilled water. The samples were analyzed immediately, except for nutrient samples, which were refrigerated at +4 °C until analysis. Surface sediment samples were collected manually for the measurement of heavy metals and organic matter.

The geographical coordinates of the sampled stations are presented in the tabel 1.

Table 1. Geographical Coordinates of the Sampled Stations

Station	Latitude (E)	Longitude (N)
1	2° 50′3.92″	36° 45′32.14″
2	2° 50′7.11″	36° 45′32.14″
3	2° 50′7.11″	36° 45′30.08″
4	2° 50′3.92″	36° 45′30.08″
5	2° 50′5.58″	36° 45′30.08″
6	2° 50′7.11″	36° 45′33.21″
7	2° 50′3.92″	36° 45′33.2″
8	2° 50′7.11″	36° 45′30.96″
9	2°50′10″	36° 45′40″
10	2° 50′08″	36° 45′31″

2.2.1. Environmental components

General data on seawater quality (temperature, salinity, and pH) were obtained in situ using a WTW Cond 315i multiparameter probe and an OHAUS-STARTER2100 for pH measurements. The measurement of suspended matter is based on the filtration of a representative volume of seawater (1 liter).

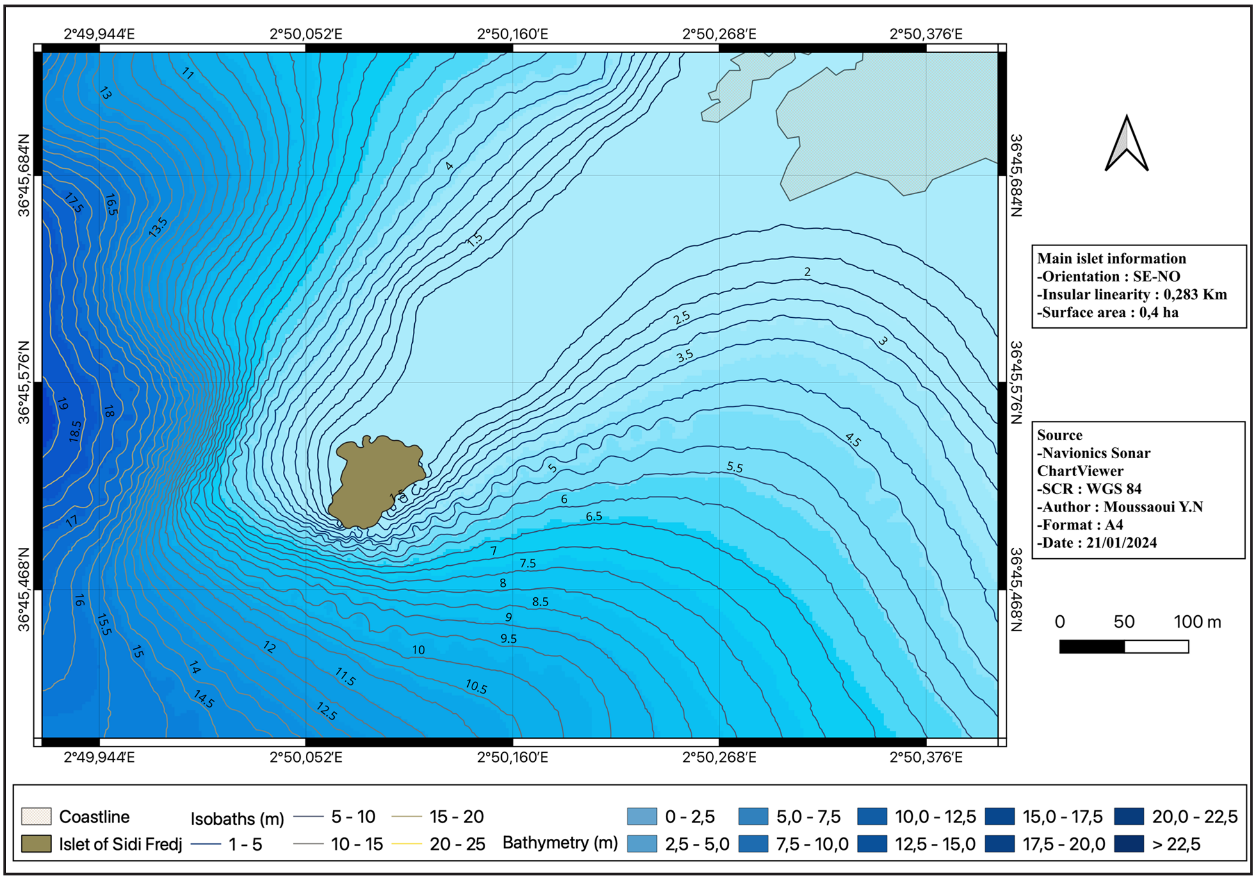

Fig. 2. Bathymetric map of Sidi Fredj islet.

Filtration was performed on a filtration ramp connected to a vacuum pump. The difference in weight of the filters before and after filtration provides information on the suspended particulate matter load (Rodier *et al.*, 2005). The analysis of nutrients (nitrate, nitrite, phosphate, and silica) was done using the colorimetric method on an automated SKALAR chain (Auto-analyzer SAN PLUS) (SKALAR, 1998). Sediment samples were frozen, then dried in a lyophilizer at -55°C and 0.1 bar for 48 hours. Part of the samples was incinerated using an oven at 600°C for 2 hours to burn off organic matter. The difference in weight before and after incineration represents the percentage of organic matter. Another part of the sediments was finely ground and sieved to 63 µm to isolate the fraction relevant for heavy metal analysis. Sediment mineralization was carried out according to the IAEA Protocol (1998). The resulting solution was analyzed using a PerkinElmer atomic absorption spectrometer (PinAAcle 900H).

The bacteria sought in seawater were total coliforms, fecal coliforms, and fecal Streptococci using the enumeration method. Other Enterobacteriaceae bacteria, such as *Salmonella*, which are indicators of proximity or old fecal contamination, were also sought. Samples were inoculated upon arrival at the laboratory. Enumeration of total coliforms, fecal coliforms, and fecal Streptococci in seawater samples was performed using the membrane filtration method (Rodier *et al.*, 2005). 100ml of seawater from each station was filtered through a 0.22 µm porosity filter. The filters were then placed on Petri dishes containing selective media for each bacterium. The result is expressed as Colony Forming Units per 100 ml of water analyzed (CFU/100 ml) (Beleneva, 2011; Rio *et al.*, 2017). The search for *Salmonella* was performed using a qualitative method involving two successive enrichments to inhibit the growth of other bacteria (Uchiyama, 2000; Hebbar *et al.*, 2015). A series of biochemical tests were conducted to confirm the presence or absence of *Salmonella*. Table 2 summarizes the different media (enrichment and isolation) used for each bacterium, as well as the incubation conditions and expected results.

The enumeration of coliforms and fecal Streptococci is performed according to ISO 7218: 2007. The formula used is as follows:

$$N = \frac{\sum C}{V \times 1{,}1d} \qquad (1)$$

where:

N: is the number of colony-forming units (CFU);

ΣC: is the total number of colonies counted on the two retained plates;

V: is the volume of inoculum applied to each plate in milliliters;

d: is the dilution factor corresponding to the first retained plate with the least diluted inoculum.

2.2.2. Ecological Components (Macrozoobenthos)

To study macrozoobenthos communities, significant amounts of sediment were collected, i.e. 8 grabs at stations 2, 3, 6, 9, and 10 using a Van Veen grab with a surface area of $0.1m^2$. Eight replicates were taken per station. The sediment samples were sieved through a 1mm mesh sieve. Subsequently, they were placed in glass jars and fixed with 10% formaldehyde to ensure optimal preservation, thus obtaining a representative and sufficient sample for ecological analyses.

Sediments are sorted into vials according to the different phyla found and identified down to the species level with specialist literature, where possible, to create an inventory of the zoobenthic biodiversity of the Sidi Fredj insular environment. The coordinates and information on nearby marine habitats were recorded to compile them into a map of the marine microhabitats of the insular environment by using QGIS software.

2.2.3. Socio-Economic Factors

Questionnaires were designed and distributed to residents in the Sidi Fredj region to gather information on the various anthropogenic activities affecting the insular ecosystem, including fishing, tourism, scuba diving, urban development, port activities, and waste discharge.

2.3. Statistical/Data analyses

2.3.1. Descriptive Statistics

The descriptive statistics applied in this study involved the calculation of means and standard deviations for the environmental and ecological parameters measured around the Sidi Fredj islet, including water temperature, salinity, pH, and suspended matter. These analyses provided an overview of the central tendency and variability of the data across the different sampling stations. All calculations were conducted using Excel, which facilitated efficient data processing and analysis.

Table 2. Enrichment, Isolation Media, and Incubation Conditions for Targeted Microbes

Microbes sought	Enrichment media	Isolation media	Incubation conditions	Expected results
Total Coliforms	/	Tergitol	24h at 37°C	Red-yellow colonies
Fecal Coliforms			24h at 44°C	Yellow colonies
Fecal Streptococci		Slanetz and Bartley	24h at 37°C	Brick-red colonies
Salmonella	SFB Broth	SS Agar (*Salmonella-Shigella*)	24h at 37°C	Transparent colonies with black centers

Additionally, the modeling and calculation of vulnerability indices were also performed in Excel, integrating normalized parameters to provide a comprehensive assessment of the islet's vulnerability, considering both environmental and socio-economic factors.

2.3.2. Method for identifying and mapping benthic habitats

The micro-distribution maps of marine habitats around the islet of Sidi Fredj were created using a combination of field methods. Sampling stations were selected to cover the diversity of present substrates, with each station geo-referenced using GPS to ensure accurate location. In addition to physical samples, underwater observations were carried out using videos and photographs taken on a (20m x 20m) grid, allowing for habitat characterization at each grid point. These visual data were complemented by field notes.

All this information was then integrated into a Geographic Information System (GIS) using QGIS software. Spatial interpolation was performed to produce a thematic map detailing the distribution of marine microhabitats. This combined method allows for precise visualization of the distribution of different marine habitats and provides a better understanding of the ecological structure of the islet.

2.3.3. Vulnerability Index

Assessing ecological vulnerability is a complex process, and there is no internationally recognized standard or guideline stipulating the specific number and type of parameters required to capture this vulnerability (He *et al.*, 2018). To evaluate this vulnerability, representative indices reflecting both natural and anthropogenic factors were selected based on a diagnostic of the islet. These indices were grouped into two categories: the Environmental Sensitivity Index (ESI), which incorporates environmental parameters, and the Socio-Economic and Anthropogenic Pressure Index (SEAPI), derived from questionnaire results. The overall index includes the data normalization using Chenery's structural transformation model (Chenery and Syrquin, 1975) and the determination of weights using multi-criteria decision analysis previously employed in environmental risk and ecological impact assessments (Liu *et al.*, 2015; Topuz and van Gestel, 2016). The index is calculated using the equation (2):

$$GVI = ESI + SEAPI \tag{2}$$

Each group index is represented by the multiplication of the weight with the score of each attribute, as described in equation (3):

$$\sum_{i=x=1}^{n} S_x W_i \tag{3}$$

where:
S_x: is the score of the attribute;
W_i: is the weight of the attribute;
***n*:** is the number of parameters used;
i: 1, 2, 3..., n.

To evaluate the vulnerability of the areas surrounding the islet of Sidi Fredj, a classification system is applied, categorizing vulnerability into distinct classes, ranging from low to extremely high levels, following the method proposed by Li *et al.* (2009). The resulting Global Vulnerability Index (GVI) values are then integrated into Geographic Information System (GIS) software, allowing the visualization of overall vulnerability of the insular environment through a thematic map.

3. RESULTS AND DISCUSSION

3.1. Environmental Analysis

The collected data shows an average temperature of [16.75±0.053 °C], with no significant variations between the different stations. These readings are consistent with the expected winter seasonal norms, reflecting typical temperatures for this period (Bachari, 2009). The average salinity is [36.31±0.30 PSU], in line with the Mediterranean standard of 36 to 37 PSU (Millot *et al.*, 2005). However, stations 5 and 7 exhibit a slight downward deviation, likely due to precipitation preceding the sampling. The average pH is [7.95±0.023], with stations 5, 6, and 7 showing slightly lower values, also attributed to heavy precipitation prior to the sampling (Table 3).

The suspended particulate matter (SPM) has an average concentration of [10.68 ± 2.27 mg/l], with higher values at stations 1, 5, 6, 7, and 8, due to greater turbidity and strong currents. These values remain within the standards set by WHO/UNEP (1995). Organic matter averages [4.13 ± 4.60%], in station 4 showing the highest values due to sediments rich in mollusk debris. This fraction is essential for the functioning of biogeochemical cycles by regenerating nutrients (Aminot and Kérouel, 2004). The concentrations of total carbon [3.81 ± 6.03%], total nitrogen [0.15 ± 0.04%], and total sulfur [0.012 ± 0.018%] are highest at stations 4 and 8. The analysis of heavy metals reveals high concentrations at station 8, followed by stations 4 and 2, with station 3 having the lowest levels of contamination.

The contamination factor indicates no pollution for Pb, Cu, and Zn and moderate pollution for Cd and Hg, according to the standards established by the Rhone Basin Agency (1990). The pollutant load index calculated indicates a general absence of intense heavy metal pollution at the Sidi Fredj site. NO_2^- [1.77 ± 2.71 µmol/l], NO_3^- [1.34 ± 2.09 µmol/l], PO_4^{3-} [0.64 ± 0.19 µmol/l], and SiO_2^- [7.25 ± 2.51 µmol/l] concentrations are elevated at stations 5, 6, and 7, due to high bacterial oxidation and coastal inputs. Nutrient analysis is an essential tool for characterizing and identifying water masses, as well as for understanding certain oceanographic phenomena such as water circulation, marine primary production, and sediment dispersion (Bachari, 2009). The results reveal average concentrations of total coliforms ranging between 2000 and 10300 CFU/100ml, exceeding the JORA (1993) standards of 500 CFU/100ml and the maximum limit of 10000 CFU/100ml, with station 3 having the highest concentration.

Fig. 3. Habitats and substrates found around the islet of Sidi Fredj: (**a**) *Posidonia oceanica*; (**b**) *Asparagopsis taxiformis*; (**c**) *Jania rubens*; (**d**) Exposed rock with a population of encrusting calcareous red algae and sea urchins (*Arbacia lixula*) (ERCA).

Fecal coliforms vary between 300 and 700 CFU/100ml, exceeding the guideline of 100 CFU/10 ml and the maximum value of 1000 CFU/100ml, with stations 1 and 4 showing the highest levels. Initial analyses on selective SS medium suggested the possible presence of *Salmonella* in samples from stations 2, 3, and 4, characterized by transparent colonies with a black center. However, after purification and further analyses (Gram staining, catalase test, TSI, and identification using the API 20E gallery), it was concluded that the microorganisms were actually *Raoultella ornithinolytica*. According to the technical sheet issued in 2013 by the Toulouse Center for Quality Control in Clinical Biology, this bacterium has pyogenic properties and is involved in opportunistic infections. Its pathogenic potential can cause bronchopulmonary infections, intra-abdominal infections, wound superinfections, urinary tract infections, and septicemia.

Table 3. Results of measured variables around Sidi Fredj islet.

Variables		S1	S2	S3	S4	S5	S6	S7	S8
Basic Parameters	Temperature (°C)	16.8	16.7	16.7	16.8	16.8	16.7	16.8	16.7
	Salinity (PSU)	36.6	36.5	36.6	36.5	35.95	36	35.9	36.4
	pH	7.97	7.95	7.97	7.97	7.93	7.92	7.92	7.97
	Suspended particulate matter (mg/l)	10.8	7.2	8.2	9.2	12.14	13.71	12.5	11.67
	Organic Matter (%)	-	1.02	1.44	10.89	-	-	-	3.16
CHNS (%)	Total Carbon	-	4.49	3.62	11.73	-	-	-	4.29
	Total Nitrogen	-	0.15	0.11	0.14	-	-	-	0.22
	Total Sulfur	-	0	0	0.01	-	-	-	0.04
	Total Hydrogen	-	0	0	0	-	-	-	0
Heavy Metals (µg/g)	Pb	-	1.23	0.82	1.95	-	-	-	3.46
	Cu	-	9.3	5.02	3.4	-	-	-	7.97
	Cd	-	0.144	0.065	0.103	-	-	-	0.23
	Hg	-	0.061	0.095	0.087	-	-	-	0.131
	Zn	-	39.38	19.38	44.97	-	-	-	61.07
Nutrients (µmol/l)	SiO_2^-	4.31	6.46	5.56	6.37	12.29	9.42	7.35	6.28
	PO_4^{3-}	0.73	0.65	0.66	0.34	0.45	0.98	0.64	0.63
	NO_2^-	0.01	0.03	0.02	0.04	5.52	3.46	1.54	0.05
	NO_3^-	0.03	0.04	0.04	0.05	7.06	4.66	2.15	0.1
Microbiology	Total Coliforms CFU/100ml)	8300	3400	10300	2000	-	-	-	-
	Fecal Coliforms CFU/100ml)	700	400	300	700	-	-	-	-
	Fecal Streptococci (CFU/100ml)	800	100	500	1400	-	-	-	-
	Salmonella	Absence	Absence	Absence	Absence	-	-	-	-

3.2. Ecological Assessment (Macrozoobenthos communities)

A total of 160 macrozoobenthic taxa belonging to seven major taxonomic groups have been identified. These taxa include Gastropoda (67 species), Bivalvia (35), Scaphopoda (2), Malacostraca (20), Thecostraca (4), Polychaeta (29), Echinodermata (2), and Cnidaria (1). The percentages are represented in figure 4.

Regarding macrozoobenthic density, variations were observed across the sampled stations. The highest density was recorded at station 9, with 3060 (ind./m^2), while the lowest was at station 6, with 490 (ind./m^2). Other stations exhibited densities of 1030 (ind./m^2) at station 2, 1820 (ind./m^2) at station 3, and 710 (ind./m^2) at station 10.

In terms of species dominance, *Spisula subtruncata* is the most abundant with 91 individuals, followed by *Cerithiopsis tubercularis* (27 individuals), *Glans trapezia* (22), *Bittium reticulatum* (21), and *Perforatus perforatus* (19). These dominant species, primarily bivalves and gastropods, play a crucial role in the structuring of benthic communities on the Sidi Fredj islet. Their high abundance suggests an adaptation to local conditions, highlighting their ecological importance in maintaining the diversity and stability of the benthic ecosystem in the study area.

Conus ventricosus and *Posidonia oceanica* are both classified as Least Concern (LC) on the IUCN Red List, indicating a stable status without immediate extinction threats. Meanwhile, *Paracentrotus lividus* benefits from legal protection under the Barcelona Convention (Annex III) and the Bern Convention due to its ecological significance.

Station 9, located near the thalassotherapy center, represents the highest number of species compared to all other stations, with a total of 75 species. We observe the presence of pollution indicator species at stations 6 and 9, such as *Cirriformia tentaculata*, *Cirratus cirratus*, and *Capitella capitata*, with a total abundance of 5 individuals.

The presence of these species confirms the high levels of organic matter and the significant bacterial load observed during the environmental study of the area. To better understand the studied insular ecosystem, a micro-distribution map of marine habitats around the islet of Sidi Fredj was created, revealing diverse benthic environments (Fig. 5).

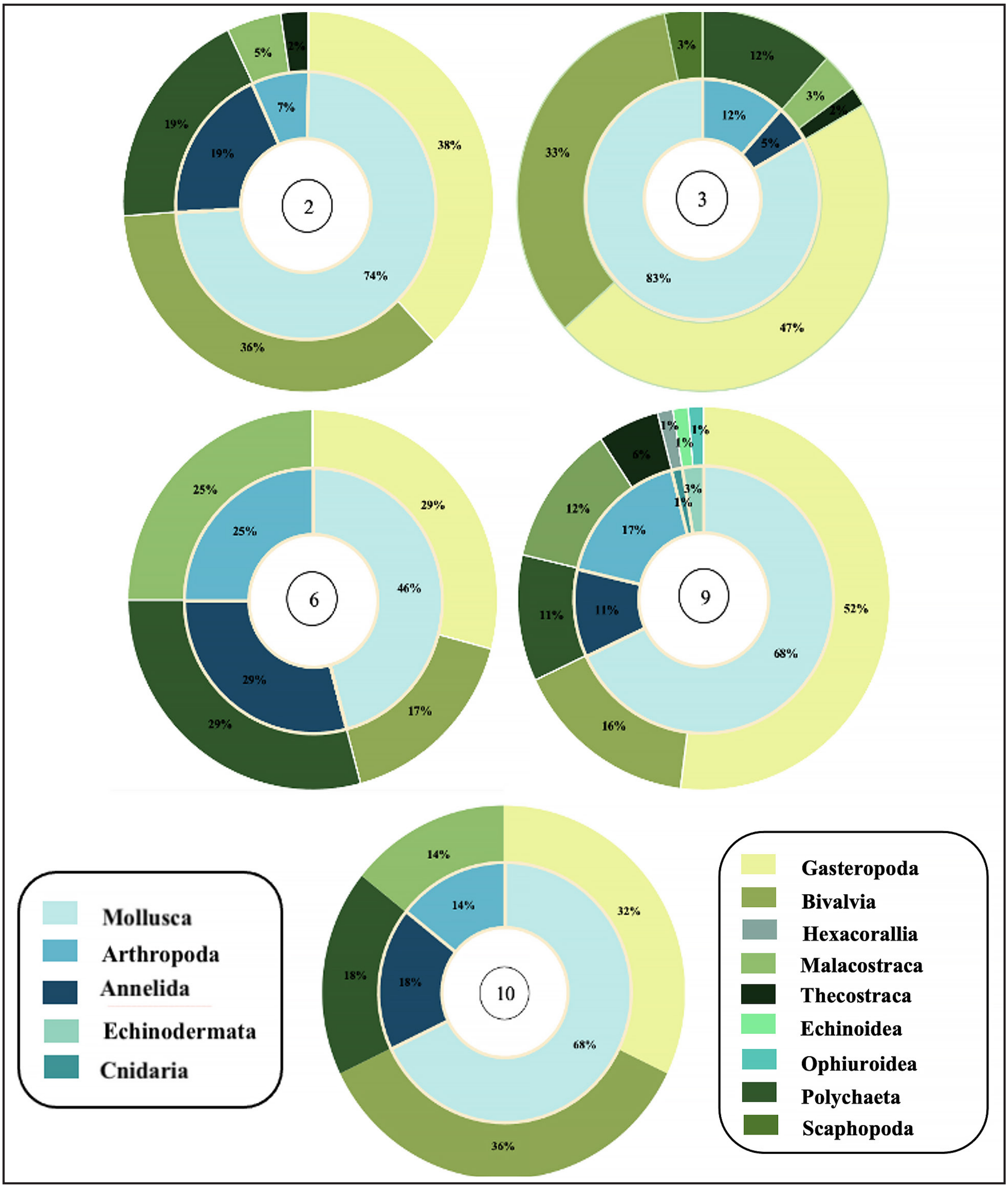

Fig. 4. Percentages of Macrozoobenthos identified at stations 2, 3, 6, 9, and 10.

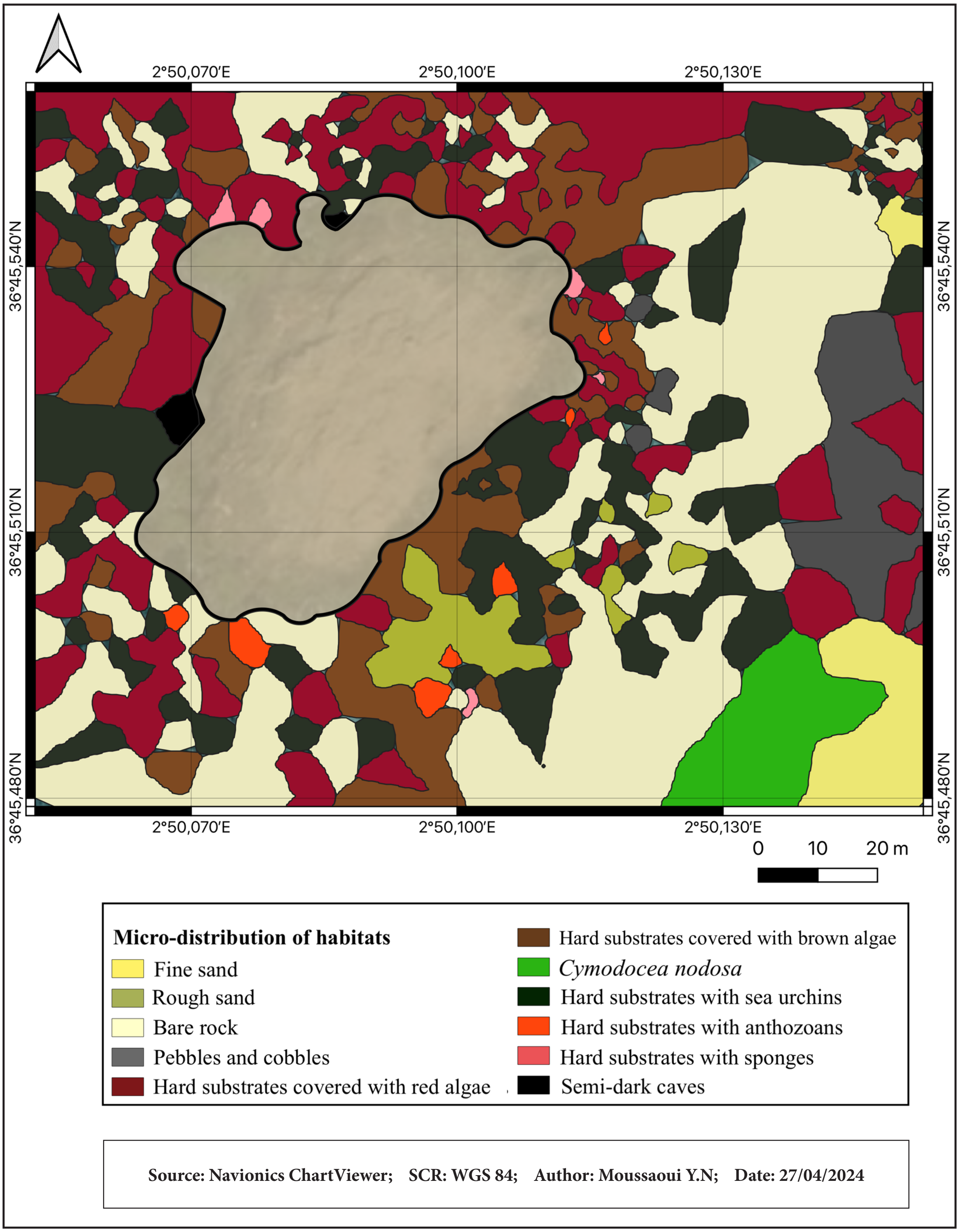

Fig. 5. Micro-habitat distribution map.

These include hard substrates covered with Ochrophytes, which are dominated by brown algae that support rich biodiversity. *Cymodocea nodosa* meadows are present, providing essential habitat for marine species and stabilizing sediments. Hard substrates with sea urchins, anthozoans, or sponges form complex ecosystems, hosting various invertebrates. Semi-dark caves offer shelter for species adapted to low light conditions. Fine and coarse sand areas support burrowing organisms and serve as feeding grounds. Bare rocks, pebbles, and cobbles provide surfaces for colonization, enhancing biodiversity. Lastly, substrates covered with Rhodophytes are characterized by red algae that create dense mats, offering food and shelter for numerous species.

3.3. Socio-Economic results

The questionnaire was distributed to residents of Sidi Fredj, primarily fishermen or individuals with a deep knowledge of the marine environment. Ten recreational fishermen were surveyed about the anthropogenic activities affecting the islet of Sidi Fredj. Three of them noted excessive tourist activity, with tourists frequently traveling to the islet for the day, and occasionally staying overnight. All surveyed fishermen are engaged in shore-based line fishing on the islet, and five also practice net fishing around the islet. Domestic waste discharge was clearly observed due to urbanization located a few meters from the beach. However, the fishermen confirmed the absence of trawlers, purse seiners, or seines around the islet. Port activities were identified as a source of pollution, particularly through hydrocarbon discharges and underwater noise, which disrupt marine fauna. Additionally, a thalassotherapy center located nearby was noted as a potential source of pollution due to the discharge of chemically treated wastewater, which could alter water quality. Lastly, subaquatic activity is well-developed in the region, due to the presence of several diving clubs that value the islet for its biodiversity and shallow bathymetry near the shore, making it accessible for beginner divers. Figure 6 illustrates the locations where these socio-economic activities are most frequent.

3.4. Vulnerability of the Insular Environment of Sidi Fredj

The combination of environmental and socio-economic results contributed to the calculation of socio-economic and environmental vulnerability, leading to the generation of a vulnerability map (Fig. 7).

The analysis of the vulnerability map of the islet of Sidi Fredj show in figure 7 a variation in environmental vulnerability around the islet. The area around station 4, which is the farthest from the coast, is classified as moderately vulnerable, reflecting limited human activity and the relative preservation of this zone.

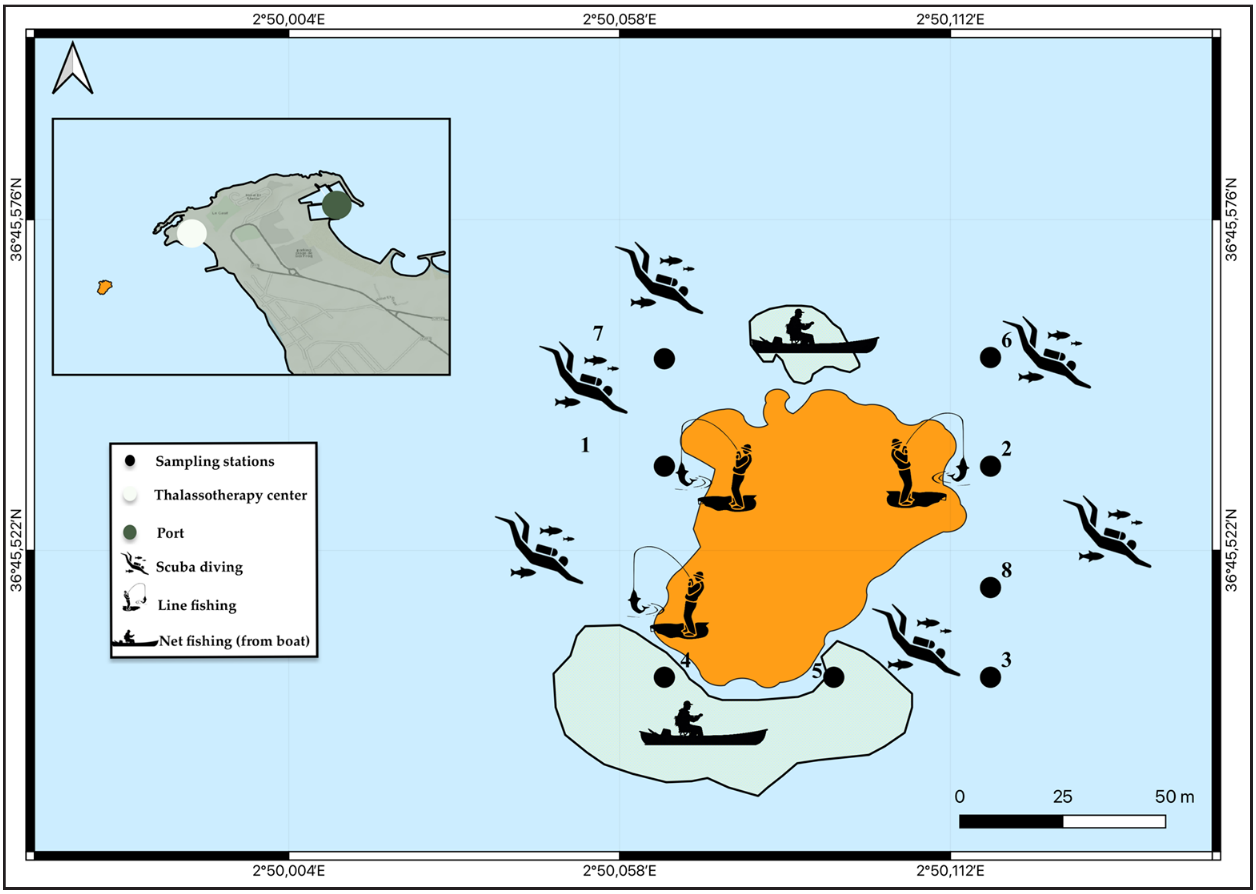

Fig. 6. Socio-economic pressure around Sidi Fredj islet.

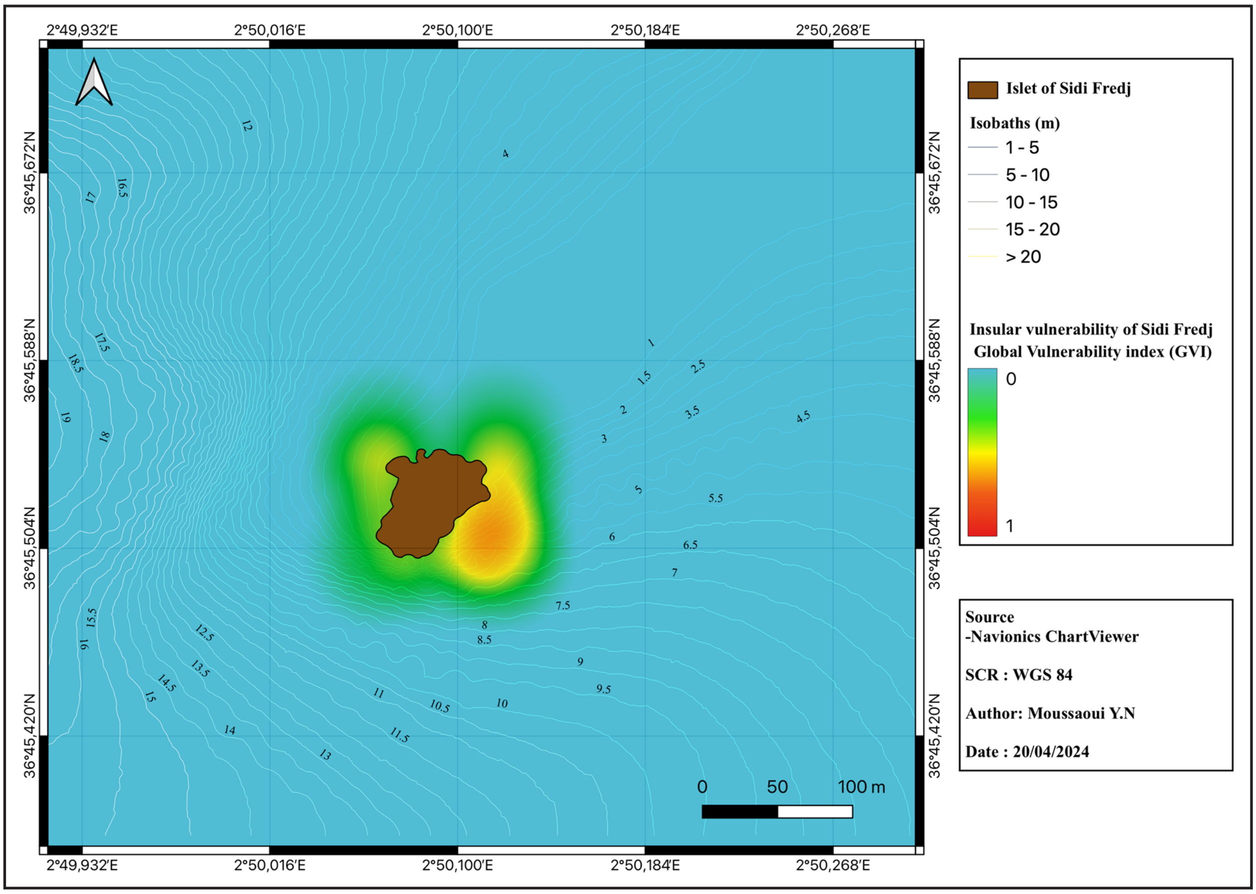

Fig. 7. Overall vulnerability map of Sidi Fredj islet.

In contrast, the area near the thalassotherapy center exhibits vulnerability ranging from moderate to higher values, indicating the impact of this infrastructure on the insular ecosystem. The presence of the hospital appears to have a moderate effect on the environment, likely due to discharges linked to healthcare activities. Stations located closer to the coast show an increasing intensity of vulnerability, ranging from low to high. This increase is directly linked to the intensity of human activities, including waste accumulation, industrial emissions, and high population density. These factors increase the environmental pressure on the islet, exacerbating the degradation of the coastal ecosystem. In summary, the map illustrates a clear correlation between increasing vulnerability and proximity to anthropogenic disturbances, highlighting the significant impact of human activities on the environmental health of the islet of Sidi Fredj.

4. CONCLUSION

The study of the vulnerability of Sidi Fredj islet revealed significant complexity due to environmental and anthropogenic pressures. The findings show that areas near human infrastructure and coasts are the most vulnerable. This vulnerability is primarily due to intense human activity, including waste accumulation, industrial discharges, and population density. In contrast, more remote areas appear to be relatively better preserved, reflecting the limited impact of direct human activities.

The methodological approach adopted in this study largely achieved its objectives. By integrating microbiological, physico-chemical, and ecological parameters, the study provided a comprehensive assessment of the islet's vulnerability. The results clearly indicate areas of high vulnerability and specific environmental pressures. This approach also underscores the importance of considering both direct and indirect anthropogenic impacts on insular ecosystems.

Looking forward, it is recommended to incorporate physical parameters such as erosion and hydrodynamics into vulnerability indices to obtain a more complete view of environmental risks and pressures. A more holistic approach that includes these additional factors will facilitate the development of more effective management and conservation strategies for vulnerable insular ecosystems.

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