Marine Pollution Bulletin 162 (2021) 111846

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Macrobenthic communities in the tidal channels around the Gulf of Gabès, Tunisia

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ARTICLE INFO

Keywords:
Mediterranean Sea
Macrofauna
Seasonal changes
Ecological status
Anthropogenic pressures

ABSTRACT

A yearlong seasonal survey was carried out during 2016–2017 at 26 stations representing four tidal channels of the north-western part of the Gulf of Gabès (Tunisia). The area studied (characterized by a maximum tidal range of 2.3 m) was subjected to diverse anthropogenic pressures: from the phosphate industry and its metallic pollution, unauthorized bottom trawling in shallow water (known locally as 'Kiss'), and organic pollution from the nearby urbanized areas. A total of 23,506 invertebrates representing 311 taxa were collected. Dominant taxa were the polychaetes with 51.4% of the individuals collected and 39.3% of the taxa, the amphipods (18.6% and 15.5%), the tanaids (12.3% and 2.6%), and the molluscs (11.5% and 18.3%). The mean annual abundances varied widely from one channel to another: from 300 to 3700 ind·m^{-2}. The stations located in deeper waters exhibited greater variability. Measurements of abundance revealed seasonal changes with maximum values in winter, spring, and lower numbers in summer. Each tidal channel was characterized by specific features in the fauna. The macrofauna were dominated by the polychaete *Cirratulus cirratus* (mainly in spring) and the amphipod *Microdeutopus anomalus* (mainly in winter), whilst both of the tanaids, *Apseudopsis gabesi* (the first sighting reported for the area) and *A. mediterraneus*, were found to be abundant in winter in at least one of the four channels. Species are mainly deposit feeders, herbivorous and omnivorous. The analyses on spatial and temporal changes of the macrofauna population revealed variations according to the composition of the fauna increasing or falling along the channels and as a function of seasonal changes. In spite of a high level of anthropogenic activities, the Ecological Status (ES) assessment (applying the AMBI and M-AMBI indices) attributed High or Good ES for 10 stations, Moderate ES for 11 stations and five stations showed a poor ES at least during one season. Sampling subtidal stations in the future to survey long-term degradation of such ecosystems of the coastal environment of the Gulf of Gabès in Tunisia is proposed.

1. Introduction

In their recent literature review of the morphological, climatic, physical oceanographic, biogeochemical and fisheries features describing the Gulf of Gabès, Bejaoui et al. (2019) noted few studies on the benthic communities. They were thus confined to publications by Seurat and Le Danois from the 1920s and 1930s (Seurat, 1924; Le Danois, 1925) with respect to the intertidal habitats and the studies of De Gaillande (1970) and Poizat (1970) at the beginning of the 1970s who reported on the subtidal benthic sandy habitats, and Ktari-Chakroun and Azouz (1971) who focused on the effect of trawling on the typography of the seabed.

However, Bejaoui et al. (2019) had seemingly overlooked publications by Zaouali (1993) and Ben Mustapha et al. (1999) covering the macrofauna of the shallow waters of the Gulf of Gabès. Likewise, their review omits the most recent work on the benthic habitats of the western and southern parts of the Gulf of Gabès, such as those on the macrobenthos organisms in the sandy beach macrofauna (Perez-Domingo et al., 2008), those covering the intertidal zones colonised by *Zostera noltei* sea grass around the Kneiss Island (Mosbahi et al., 2015, 2016b, 2017a, 2017b), and those relating to the Boughrara lagoon in the south of the gulf near Djerba Island (Khedhri et al., 2015, 2017). Other related

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https://doi.org/10.1016/j.marpolbul.2020.111846
Received 26 May 2020; Received in revised form 16 October 2020; Accepted 13 November 2020
Available online 20 November 2020

studies were dedicated to the impact of human activities on the benthic communities such as bait digging (Mosbahi et al., 2015), clam harvesting (Mosbahi et al., 2016a), and the dredging operations in the channel between the major port of Sfax and the offshore Kerkennah Islands (Aloui-Bejaoui and Afli, 2012). Moreover, there are also studies devoted to the effects of multiple stressors on the subtidal communities in the shores near Sfax (Mosbahi et al., 2019) and also in the Bay of Skhira (Boudaya et al., 2019). These works suggest that the pollution effects remained moderate and only had a local impact on the benthic structure, in spite of consistent emissions going back several decades.

Many studies have sought to assess the level of contamination of the sediment or of the seawater around the Gulf of Gabès. Some of these have been focused on marine species including zooplankton in relation to the nearby phosphate industry and the relating discharge of metals (cadmium, chromium, copper, mercury, lead and zinc). Others have considered the effect of hydrocarbon contamination (Louati et al., 2001; Chouba and Mzoughi-Aguir, 2006; Mezghani-Chaari et al., 2011; Serbaji et al., 2012; Hammas et al., 2013; Zaghden et al., 2014; El Zrelli et al., 2015, 2017, 2018; Ayadi et al., 2015, 2016 and reference therein; Rabaoui et al., 2017; Drira et al., 2017; El Kateb et al., 2018; Naifar et al., 2018; Bejaoui et al., 2019). These studies were mostly relating to the marine environment around the contaminating source but some were carried out further away such as around Djerba Island and focussed on a patrimonial species such as *Posidonia oceanica*.

The study by Rabaoui et al. (2015) focussed on the relationship between the diversity and structure of the benthic macrofauna in the presence of the heavy metal concentrations in four shallow water sites around the Gulf of Gabès. They showed that the central part of the gulf was the most polluted and contained the most-affected benthic communities.

Studies on the macrofauna of the habitats of soft-bottom organisms are linked both to those living in the water column and those in the sediment, and are known to be excellent indicators of the level of pollution. In recent times, studies using Foraminifera as an indicator of pollution has been promoted in several coastal zones ranging from the Atlantic-Mediterranean system to the Gulf of Gabès (Aloulou et al., 2012; Ayadi et al., 2015, 2016; El Kateb et al., 2020). El Kateb et al. (2020) indicated a severe impact along the central part of the Gulf of Gabès near the phosphate industry in Skhira and also along the western coast of Djerba Island, but good conditions prevailed around the eastern part of Djerba Island.

There might thus seem to be a large number of studies on the pollution in the Gulf of Gabès. Some of them are devoted on the effects of pollution on the biota including the soft-bottom macrofauna, but few take into account seasonal pattern of the fauna neither benthic habitat of the tidal channels.

This last factor arises from one of the oceanographic peculiarities of the Gulf of Gabès: unlike much of the Mediterranean Sea, there is the presence of tidal range which is one of the largest observed other than the north of the Adriatic (Bejaoui et al., 2019). The tidal range reaches 2.3 m with a spring tide, which has two main consequences on the benthic habitats. Firstly, the low tide leads to the presence of an expanded intertidal zone especially around Kneiss Island, which is populated by rich benthic communities, which are exploited by the fish at high tide and birds at low tide (Mosbahi et al., 2015, 2016a, 2017a, 2017b). For this reason, the Kneiss ecosystem had been recognized as a Ramsar Zone and more than 50 marine bird species inhabit the area in winter. The second consequence of the tidal action is the presence of tidal channels, networks which play an essential role in the functioning of the tidal ecosystem as they serve as the major flow paths for water, sediments and nutrients between the intertidal and subtidal zones (Bali and Gueddari, 2011; Bejaoui et al., 2019). These tidal features are often exploited by the fishermen working from small boats equipped with bottom trawling systems known locally as 'Kiss': such illegal activity in shallow tidal channels at high tide can have a negative impact on the benthic habitats. These tidal channels can also concentrate pollution originating from land sources, often in relation to the phosphate fertilizer industry around the Bay of Skhira.

The objectives of this paper are: 1) to expand the knowledge of the structure of the benthic habitats in the tidal channels of the Gulf of Gabès; 2) to update the ecological status (ES) of the benthic communities in relation to local human activities, and 3) to compare the structure and ecological status in this particular ecosystem with other similar shallow areas, especially lagoons, around the Mediterranean Sea.

2. Materials and methods

2.1. The area studied

The Gulf of Gabès is a shallow region of sea located along the southern coast of Tunisia that covers an area of around 36,000 km^2. It is characterized by a pronounced annual water temperature cycle (13 °C in winter to 29 °C in summer) (Hattab et al., 2013; Bejaoui et al., 2019) and an unusually high tidal range reaching 2.3 m, amongst the highest observed in the Mediterranean Sea (Bejaoui et al., 2019). In the shallower regions of the Bay of Skhira (1.5–20 m depth) at the western end, of the Gulf of Gabès, the sediment was dominated by fine and medium sand near the coast, whereas muddy sand occurred in the deeper waters (Brahim et al., 2015). Sand, sandy mud and muddy sands dominated in waters of 10–50 m depth, whereas the deepest zone (50–200 m) was covered mainly by sandy mud (El Lakhrach et al., 2012).

In the current study, four tidal channels were selected as representative of the influence of local human activities across the north-western part of the Gulf of Gabès: the Maltine Channel (CML), the Kneiss Islands Channel (CK), the Ben Khlaf Channel (CP) and the Mimoun Channel (CM), this last channel being in the north-eastern part of the Kerkennah Islands (Fig. 1). All details and descriptions of these channels have been reported by Fersi et al. (2018).

2.2. Sampling and laboratory procedures

Sampling stations were positioned along lines running from the shallow upstream to the deeper downstream parts of four tidal channels (Fig. 1). Seven stations were set up in the Ben Khlaf and Mimoun Channels, and six in the Maltine and Kneiss Channels making a total 26 stations. Sediments were collected with a 0.1 m^2 Van Veen grab sampler: four replicates were taken at each station representing a total surface of 0.4 m^2. This was repeated in March (spring), July (summer) and September 2016 (autumn) and in January 2017 (winter). The sediment was sieved on a 1-mm mesh; after sorting, the individual organisms collected were identified (under a binocular microscope), specifying to the lowest taxonomic level possible. Species names were checked using the World Register of Marine Species list (http://www.marinespecies.org) as available on 15 October 2017.

A fifth grab sample was used to provide sediment for granulometric and organic matter analyses relating to each station: this was repeated for the four seasonal campaigns. Likewise, at each station and for each season, measurements of sea water temperature using a thermometer (WTW LF 196), of its salinity with a salinometer (WTW LF 196), and of its pH with a pH meter (WTW 3110) was carried out close to the seabed (Fersi et al., 2018). The transparency of the water was quantified using a Secchi disc (Fersi, 2019).

Applying the classification procedure described by the trophic guild analysis as proposed by Mosbahi et al. (2017a, 2017b, 2018), Fersi et al. (2018) and Boudaya et al. (2019), the identified taxa were classified into five trophic categories as follows: Suspension feeders (S), Deposit Surface feeders (DS), Herbivorous (HE), Sub-Surface Deposit feeders (SDF), and Omnivores (O), the later including predators and necrophagous.

For granulometric analysis, sediment from each sample was homogenized and wet-sieved through mesh sizes of 1000, 500, 250, 125 and 63 μm over 10 min. These results were classified as: 1) silt and clay (<63 μm), 2) sand (63–1000 μm), and 3) gravel (>1000 μm), this last

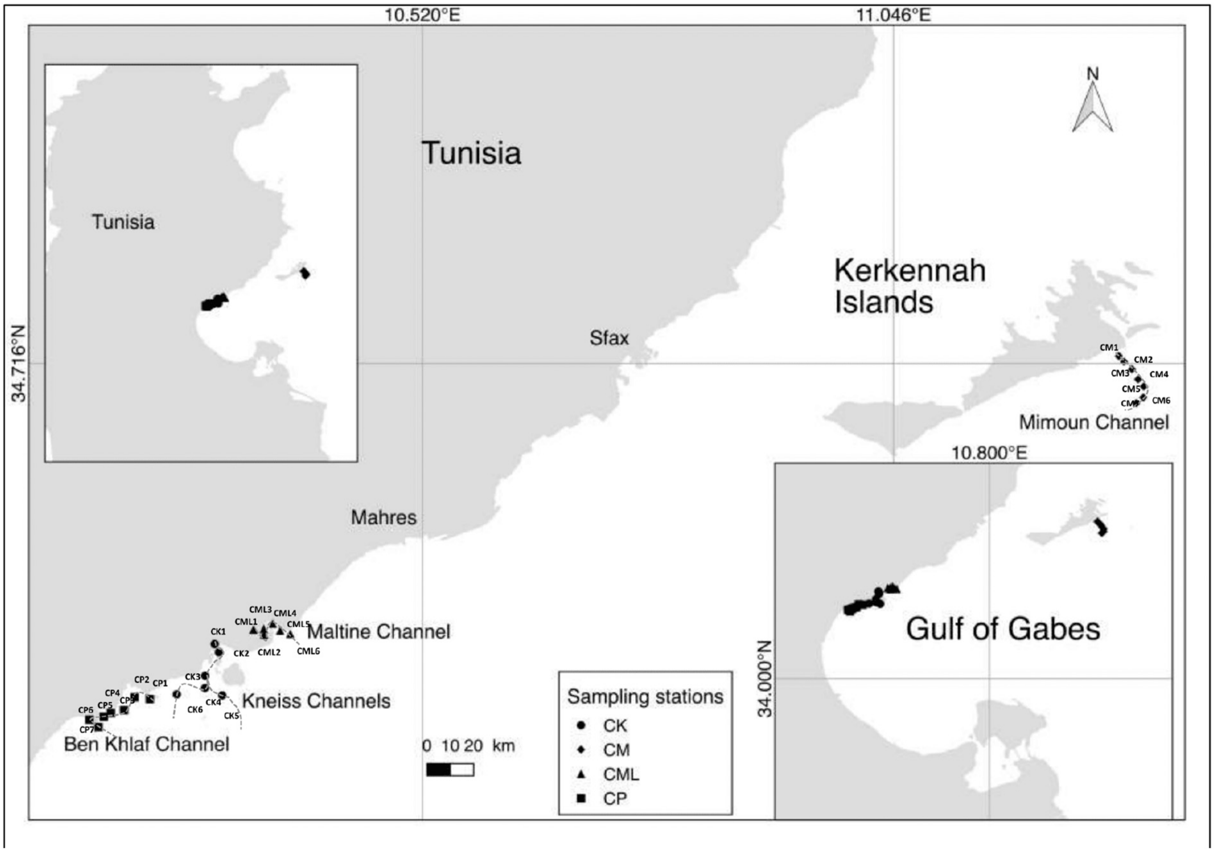

Fig. 1. Map of the study area showing the location of sampling stations in the four channels traversing the Gulf of Gabès.

including coarse sand, gravel and shell debris.

The organic matter content was measured on dried samples by the method, 'loss on ignition' at 450 °C for 4 h (Fersi et al., 2018).

2.3. Benthic indices

Collected data were used to calculate the species abundance (A) (quoted as the number of ind. 0.4 m^{-2} or the number of ind. 1 m^{-2}) and to determine the most commonly used biodiversity indices for each station, the taxonomic richness (TR), the Shannon-Weaver diversity index (H′) in $\log_2$, and Pielou's evenness (J) for each of the 26 stations representing the four channels. Data analysis was carried out using the PRIMER® software package (version 6) from Plymouth Routines in Multivariate Ecological Research (Clarke and Gorley, 2006).

To quantify the ecological quality status (ES) of samples from each of the 26 stations several benthic indices were applied, including the H′ and J values. High values for H′ and J indicate a rich community where no dominant species were present, whereas low values were typical of impoverished communities or those dominated by a single or relative few species. The five ES classes set out by the European Water Framework Directive have been used here: blue or unpolluted sites, good (green) for slightly polluted sites, moderate (yellow) for moderately polluted sites, poor (orange) for heavily polluted sites, and bad (red) for extremely polluted or azoic sites. The thresholds for H′ and J values were those previously defined by Dauvin et al. (2017).

Further analysis was performed using the AZTI Marine Biotic Index (AMBI) developed by Borja et al. (2000) and M-AMBI (Multivariate AMBI) proposed by Borja et al. (2004) then detailed by Muxika et al. (2007). AMBI used the proportions of ecological groups in terms of their responses to a gradient of organic matter enrichment. The AMBI was calculated using the software of AZTI on 30 June 2019. The taxa were classified into five Ecological Groups (EG): EG-I (blue) taxa very sensitive to organic enrichment and habitat disturbance, that are usually present only in unpolluted environments; EG-II (green), taxa indifferent to enrichment or disturbance; G-III (yellow), taxa tolerant of levels of organic matter enrichment that might occur under normal conditions, where their populations could be stimulated by such perturbation; EG-IV (orange): second-order opportunistic species and EG-V (red), first-order opportunistic species that are able to resist a high level of disturbance. The M-AMBI was calculated using the software of AZTI on 15 September 2020, according to high conditions recommended for the Italian waters for existing undisturbed sites by Carletti and Heiskanen (2009), i.e. AMBI: 0.5, TR: 30 and H′: 4.

2.4. Statistical analyses

Data relating to temperature, salinity, pH, water transparency, sediment type and organic matter contents were all treated using two-way ANOVA to test for differences in each channel and across the season. Prior to this test, environmental data were pre-processed by homogenization using a Shapiro-Wilk normality test and a Bartlett test. The Tukey Honestly Significant Difference test was applied when ANOVA analysis suggested significant differences.

The two-way ANOVA was used to investigate spatio-temporal changes (between channels and seasons) in terms of taxonomic richness (TR) and total abundance of the macrofauna in the Gulf of Gabès. Once again, a Shapiro-Wilk normality test and a Bartlett test for homogeneity of variances were applied to the data. The Tukey Honestly Significant Difference test was applied when the ANOVA analysis revealed significant differences.

The spatial and temporal changes with respect to all of the macrofauna taxa (the abundance matrix) were analysed separately by the group-average sorting classification, using a hierarchical clustering procedure (CLUSTER mode) based on the Bray-Curtis similarity index with a Log (X + 1) transformation of abundance values. To discern within different groups which species primarily accounted for the observed difference of the whole group, SIMPER (SIMilarity PERcentage) routines were performed using a decomposition of Bray-Curtis similarity on log transformed abundance data (Clarke and Gorley, 2006).

The CLUSTER and BEST analyses and permutation tests were all carried out using the PRIMER® v6 software package (Clarke and Gorley, 2006). The software package R was used to perform ANOVA analysis and the Shapiro, Bartlett and Tukey tests.

To establish correlations between the relative position of the 26 stations, and the 11 abiotic parameters, the datasets were compared using the method of Principle Components Analysis (PCA). Moreover, a PCA established the relative position of the 26 stations according to the mean abundances of the taxa.

3. Results

3.1. Environmental parameters

Table 1 sets out the mean annual values of the environmental parameters of the 26 stations of the four tidal channels. Raw data were taken from in Fersi et al. (2018) and Fersi (2019).

No differences were discerned between the water temperatures in the tidal channels: the mean annual sea temperature fell in the range of 21.8 and 23.8 °C recorded across the stations (Table 1). The water temperature greatly changed with season with minimum values recorded during the winter (12–13 °C) and maximum in summer and autumn (27–28 °C) (Table 2). In spring the water temperatures were generally lower in the two tidal channels CK and CM than observed in the CML and CP channels.

Water salinity varied from 36 to 47, and was significantly higher in the CML channel (mean salinity > 40.0) than at the three other sites (mean salinity ranging from 37.5 to 44.5, Table 1), but especially with respect to the CM channel during spring samples, although there were no significant changes in this respect across the seasons (Table 2).

The pH values of the water samples were higher at the CK and CML channels than at the two other sites (Table 1), these values being lowest in inter, higher in the autumn and highest in summer and spring; the pH values of water from the CML channel were significantly higher than those measured in the three other sites (Table 2).

Table 2
Results of the ANOVA tests on environmental parameters. Gravel (>1000 μm), sand (63–1000 μm), silt and clay (<63 μm); OM: Organic Matter; channels, CP: Ben Khlaf, CML: Maltine; CK: Kneiss; CM: Mimoun. Seasons, Win: winter; Spr: spring; Sum: summer; Aut: autumn. Df: degree of freedom; F: test values; P: probability.

		Df	F	P	Tukey test
Gravel	Season	3	0.27	0.85	
	Station	3	13.18	<0.001	CK; CP ≠ CM; CML
Sand	Season	3	0.08	0.97	
	Station	3	12.65	<0.001	CK; CP ≠ CM; CML
Silt-Clay	Season	3	0.90	0.44	
	Station	3	2.05	0.11	
Salinity	Season	3	1.87	0.14	
	Station	3	29.39	<0.001	CML ≠ CM; CP; CK
Temperature	Season	3	2192.81	<0.001	Win ≠ Spr; Sum; Aut Spr ≠ Aut; Sum
	Station	3	16.36	<0.001	CP ≠ CK; CM; CML
Ph	Season	3	23.46	<0.001	Aut; Win ≠ Spr; Sum
	Station	3	5.68	<0.01	CML ≠ CM
Transparency	Season	3	1.21	0.31	
	Station	3	2.40	0.07	
OM	Season	3	12.17	<0.001	Win ≠ Spr; Sum; Aut
	Station	3	1.13	0.34	
	∑	88			

Water transparency was linked with the water depth at the sampling station, the transparency being higher in samples from the CM channels than in the others (Table 1), but there were no significant changes with season or any difference between the channels (Table 2).

The organic matter content in sediment samples was high at all time of the year in the three shallow stations CP6, CML1 and CK1 and in the wintertime for the deeper station CK6. Values were significantly higher in winter, but there were no significant difference between these stations whilst the two stations CM1 and CM2 showed high mean values (Table 2).

The stations located in the shallowest waters are mainly characterized by sand, whilst gravel was found at the intermediate-depth stations,

Table 1
Main characteristics of the sampling stations in the four tidal channels (mean ± standard deviation). Gravel (>1000 μm), sand (63–1000 μm), silt and clay (<63 μm); OM: Organic Matter; channels: CP: Ben Khlaf, CML: Maltine, CK: Kneiss, CM: Mimoun.

Station	Depth (m)	Gravel (%)	Sand (%)	Silt-clay (%)	Salinity (psu)	Temperature (°C)	PH	Transparency	OM %
CP 1	3.5	2.0 ± 1.2	84.8 ± 10.4	12.6 ± 10.5	39.7 ± 0.8	23.1 ± 7.4	8.0 ± 0.2	1.2 ± 0.3	2.8 ± 3.0
CP 2	2.8	1.7 ± 1.6	96.6 ± 2.2	1.5 ± 0.6	39.6 ± 0.6	23.4 ± 7.4	8.1 ± 0.3	1.1 ± 0.4	0.9 ± 0.6
CP 3	3.2	76.3 ± 15.9	18.5 ± 11.0	4.8 ± 5.2	39.2 ± 0.4	23.4 ± 7.1	8.2 ± 0.3	1.6 ± 0.4	2.4 ± 2.2
CP 4	6.1	7.9 ± 3.5	87.8 ± 4.7	3.8 ± 2.4	39.0 ± 0.4	23.5 ± 7.2	8.2 ± 0.2	1.5 ± 1.1	1.1 ± 0.5
CP 5	7.6	3.7 ± 2.5	83.6 ± 6.3	12.3 ± 5.9	38.9 ± 0.4	23.7 ± 7.3	8.2 ± 0.2	2.2 ± 0.8	1.9 ± 1.0
CP 6	11.9	2.1 ± 1.1	62.4 ± 3.5	34.9 ± 2.7	38.8 ± 0.4	23.6 ± 7.2	8.2 ± 0.2	3.8 ± 0.6	7.3 ± 1.2
CP 7	0.9	2.0 ± 1.3	95.3 ± 2.5	2.4 ± 1.2	39.0 ± 0.6	23.8 ± 7.3	7.3 ± 0.8	1.2 ± 1.2	1.9 ± 1.9
CML 1	1.0	22.2 ± 8.6	49.8 ± 13.5	27.6 ± 4.8	44.5 ± 1.9	22.5 ± 6.9	8.3 ± 0.3	0.6 ± 0.1	9.3 ± 1.3
CML 2	2.1	57.2 ± 9.6	35.4 ± 13.6	7.0 ± 9.3	42.8 ± 1.9	22.3 ± 6.6	8.4 ± 0.4	1.4 ± 0.5	3.1 ± 3.9
CML 3	2.1	67.6 ± 10.7	26.4 ± 12.9	5.8 ± 6.5	42.7 ± 1.9	22.2 ± 6.3	7.9 ± 1.1	1.2 ± 0.1	1.7 ± 1.2
CML 4	3.1	80.6 ± 13.1	17.8 ± 11.9	1.5 ± 1.2	41.6 ± 0.3	22.3 ± 6.4	8.4 ± 0.3	1.6 ± 0.1	1.5 ± 1.9
CML 5	4.4	4.3 ± 4.1	93.5 ± 4.4	1.7 ± 0.9	41.0 ± 0.8	22.4 ± 6.3	8.3 ± 0.3	1.7 ± 0.2	1.4 ± 2.2
CML 6	3.7	30.7 ± 7.5	66.9 ± 6.7	2.0 ± 1.6	40.1 ± 1.0	22.8 ± 6.3	8.3 ± 0.3	1.6 ± 0.5	1.5 ± 1.9
CK 1	2.0	1.6 ± 1.9	89.8 ± 3.6	8.5 ± 2.7	39.8 ± 1.0	22.9 ± 7.7	8.2 ± 0.2	1.4 ± 0.4	4.2 ± 2.1
CK 2	8.5	18.1 ± 6.2	78.5 ± 7.2	3.1 ± 1.6	39.5 ± 1.2	22.2 ± 8.4	8.3 ± 0.3	1.6 ± 0.6	0.7 ± 0.2
CK 3	5.3	2.3 ± 1.8	90.3 ± 6.0	6.9 ± 4.3	39.4 ± 1.3	21.8 ± 8.3	8.3 ± 0.4	2.4 ± 1.1	2.4 ± 2.0
CK 4	7.4	17.5 ± 2.2	78.5 ± 3.2	3.6 ± 1.7	39.1 ± 0.6	21.9 ± 8.4	8.3 ± 0.4	2.2 ± 1.0	1.6 ± 1.6
CK 5	5.3	2.6 ± 2.5	94.9 ± 4.6	2.5 ± 4.6	39.1 ± 0.6	22.3 ± 7.6	8.3 ± 0.4	2.7 ± 0.4	1.7 ± 2.0
CK 6	8.3	4.0 ± 3.9	80.9 ± 4.7	14.4 ± 3.5	39.1 ± 0.5	22.3 ± 7.8	8.2 ± 0.3	1.9 ± 0.6	5.8 ± 4.6
CM 1	3.3	24.1 ± 4.3	67.7 ± 6.8	7.6 ± 3.3	40.5 ± 1.6	22.3 ± 7.0	8.1 ± 0.3	2.5 ± 0.4	5.8 ± 7.7
CM 2	3.3	14.6 ± 2.2	78.1 ± 5.7	6.6 ± 7.4	40.1 ± 1.9	22.8 ± 6.1	8.0 ± 0.3	1.8 ± 0.5	5.2 ± 6.5
CM 3	3.6	35.8 ± 5.9	57.4 ± 1.1	6.1 ± 5.1	40.0 ± 1.1	22.4 ± 6.5	8.0 ± 0.3	2.1 ± 0.6	4.9 ± 5.9
CM 4	4.1	62.8 ± 5.7	36.5 ± 5.3	0.4 ± 0.2	39.4 ± 2.7	21.8 ± 7.7	8.0 ± 0.3	2.2 ± 0.5	1.7 ± 2.9
CM 5	10.0	61.6 ± 8.0	36.6 ± 8.9	1.5 ± 0.9	37.8 ± 1.1	22.9 ± 5.7	8.0 ± 0.3	3.8 ± 0.3	1.8 ± 2.4
CM 6	13.5	75.7 ± 5.7	21.6 ± 3.3	2.4 ± 4.0	37.7 ± 1.1	22.6 ± 5.5	8.0 ± 0.2	3.0 ± 0.4	2.5 ± 3.3
CM 7	15.0	5.7 ± 1.2	86.7 ± 5.9	6.8 ± 5.6	37.5 ± 1.2	22.6 ± 5.6	7.9 ± 0.1	3.2 ± 0.6	5.4 ± 6.2

and the deeper stations were dominated by fine sediment (Table 1). The sediment from station CP6 contained a higher percentage of fine particles (muddy sand), whereas that from CP2 had a higher percentage of sand and CML 4 a higher percentage of gravel (Table 1). There was no seasonal difference in the percentage of fine particles between the stations (Table 2). Moreover, the percentage of sand and gravel were significantly different between the two channels CML and CM which have a higher percentage of gravel whereas sediment in the CK and CP channels was dominated by sand.

3.2. General patterns of the fauna

Macrophytes and macroalgae were present in most of the stations of the four tidal channels (Fersi et al., 2018). *Cymodocea nodosa* and *Zostera noltei* were mainly present in the shallow stations while *Posidonia oceanica* was found in the deeper stations including the deepest station CM7 at 15 m depth.

A total of 23,506 specimens representing 311 taxa were collected from the 26 stations across the four seasons. Amongst them, four zoological groups dominated: the polychaetes representing 51.4% of specimens and 39.3% of the taxa, the crustaceans (34% and 20%) these comprising essentially amphipods (18.6% and 15.5%), tanaids with 12.3% and 2.6%, and the molluscs (11.5% and 18.3%). The other groups together represented 6.2% of the specimens retrieved and 25.4% of the species.

Amongst the 311 taxa counted, the number was relatively similar in the four channels, with 183 taxa recorded in CM, 177 in CK, 165 in CP and 150 in CML.

For the four tidal channels, the TR was greatest at around 100 taxa per 0.4 m^2 in winter, and lowest in summer (Fig. 2). The TR was high all around the year at in the CM channel (between 80 and 100 taxa per 0.4 m^2), and low in the CML channel, especially during summer and autumn. The winter values were generally higher than the summer values (Table 3).

Across the four tidal channels it was the sampling stations in the deeper water that exhibited greater diversification than the shallower stations that were mainly on fine sand, whereas the stations in intermediate depths, mainly on gravel sediment, exhibited the poorest (Fig. 3). Nevertheless, there was no significant difference of TR between the stations themselves (Table 3).

In term of abundance values (count per 0.4 m^{-2}), high values were observed in the spring along the CK tidal channel, and to a lesser degree in winter along the CP channel. Very low abundances numbers were noted for the CM channel throughout the year, for the CK and CML channel in the summer and the CP channel in the autumn (Fig. 2; Table 6). Spring abundance values were significantly higher than those for the summer and autumn, and values for the CK channel were significantly higher than those for the CM (Table 3).

As observed for the measurements of TR, abundance values were higher in the deepest and the shallowest stations, whereas the stations located in intermediate depths where the poorest, especially along the CM channel (Fig. 3; Table 6). Moreover, there was significant difference in abundance values observed for the CK and CM stations located along the CK and CM channels (Table 3).

Measurements of H′ and J showed a wide range of values from 0 (no fauna) to 4.95 for H′ and 0 to 0.98 for J respectively. H′ and J were low in the CML channel, whereas they show high values in the CM channel. High values of J were observed in the CP channel, but the corresponding H′ values were low. Values of this parameter were also low in the CK channel.

Across the four seasons, the deposit surface feeders were dominant in the sediments of the CK channel, this dominance being shared with omnivorous species in the CM channel, whilst herbivorous and deposit surface feeders species dominated in CML channel and omnivorous in CP channel (Fig. 4). On the other hand, suspension feeders and the sub-surface deposit feeders represented only a low percentage of the trophic groups (Fig. 4).

Table 3
Results of two-way ANOVA (season/station factors) with Tukey test on Taxonomic richness, abundance, J: Pielou evenness, H′ Shannon diversity and AMBI. Channels CP: Ben Khlaf, CML: Maltine; CK: Kneiss; CM: Mimoun. Season, Win: winter; Spr: spring; Sum: summer; Aut: autumn. Df: degree of freedom; F: test values; P: probability.

		Df	F	P	Tukey test
Taxonomic richness	Season	3	3.51	<0.05	Winter ≠ summer
	Station	3	1.89	0.12	
Abundance	Season	3	5.63	<0.01	Spring ≠ summer; autumn
	Station	3	5.01	<0.01	CK ≠ CM
J	Season	3	0.69	0.56	
	Station	3	12.88	<0.001	CM ≠ CML; CK; CP
H′	Season	3	2.22	0.09	
	Station	3	9.54	<0.001	CM ≠ CML; CK; CP
AMBI	Season	3	2.24	0.08	
	Station	3	2.09	0.11	
	∑	98			

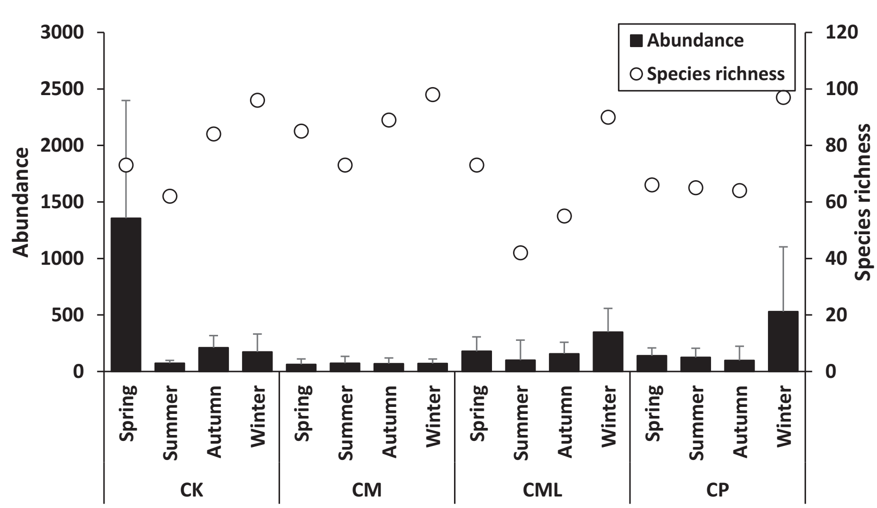

Fig. 2. Mean abundance figures of the total macrofauna (■) (with standard deviation) and of the total species richness (○) per 0.4 m^2 in each of the four channels (CK: Kneiss; CM: Mimoun CML: Maltine; CP: Ben Khlaf) which were sampled across the four seasons running from spring 2016 to winter 2017.

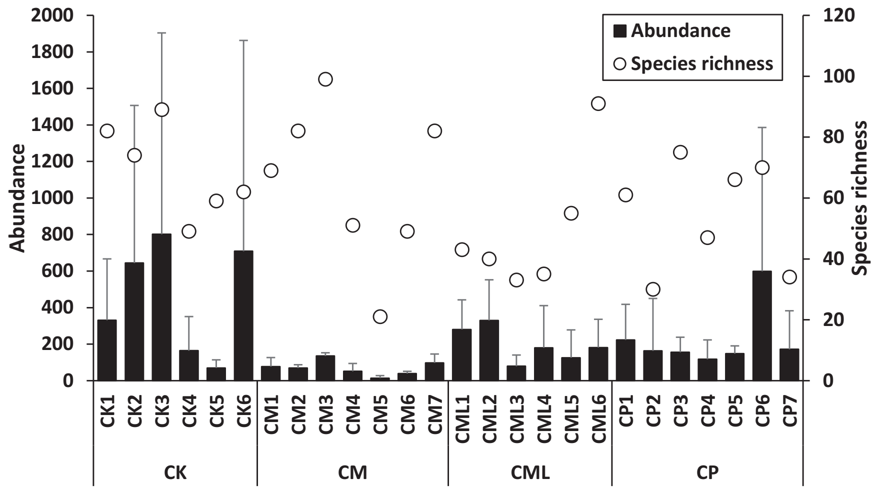

Fig. 3. Mean abundance figures of the total macrofauna (■) (with standard deviation) and of the total species richness (○) per 0.4 m^2 at the 26 sampling stations covering the four channels (CK: Kneiss; CM: Mimoun CML: Maltine; CP: Ben Khlaf) sampled four times from spring 2016 to winter 2017.

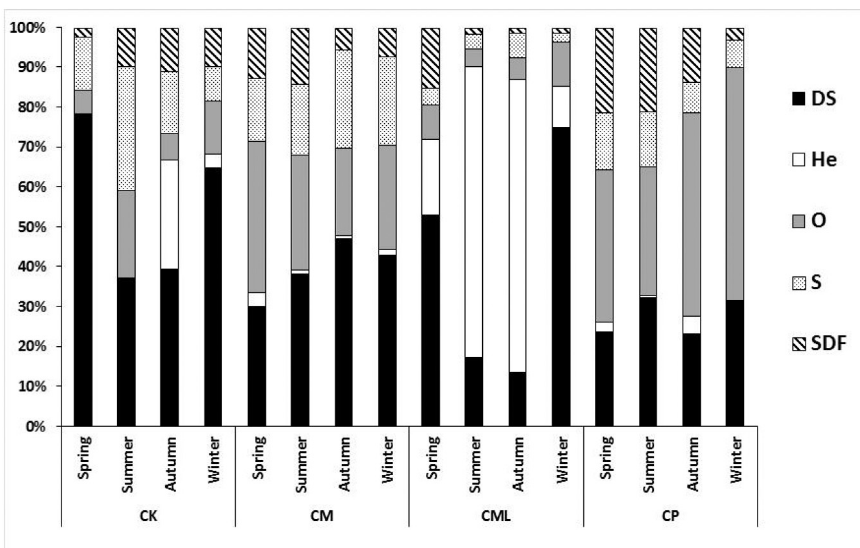

Fig. 4. The proportion of the different trophic groups in the macrofauna retrieved from the four channels during the four sampling seasons from spring 2016 to winter 2017. Channels - CK: Kneiss, CM: Mimoun, CML: Maltine, CP: Ben Khlaf. Trophic groups - DS, Deposit Surface feeders; HE, Herbivorous; O, Omnivores including predators and necrophagous; S, Suspension feeders; SDF, Sub-Surface Deposit Feeders.

3.3. Spatial pattern of the benthic assemblages

A dendrogram based on the mean abundance data after a Log (X + 1) transformation of the data from the 26 stations showed a level of 38% of similarity separating the stations into three groups of one and five groups of two or more (Fig. 5). The individual stations were: CM5 (characterized by the tanaid *Apseudopsis ostroumovi* and the amphipod *Microdeutopus anomalus*), CM4 (the polychaete *Cirratulus cirratus* and the bivalve *Pinctada imbricata radiata*), and CK5 (the ophiurid *Amphipholis squamata* and *M. anomalus*). The first group of 2 or more stations (Fig. 5) concerned the shallowest stations of the Ben Khlaf Channel (CP2 and CP7) (*Apseudopsis gabesi* and *Iphinoe serrata*). The second group comprised the five CML stations along the Maltine Channel (*M. anomalus* and the gastropod *Cerithium scabridum*). The third group included the five CM stations (*M. anomalus* and *C. cirratus*) of the Mimoun Channel plus one station (CML6), which was the downstream station of the Maltine Channel set on coarse sand. The fourth group gathered the five CK stations of the Kneiss Channel (the polychaetes *C. cirratus* and *Sabella pavonina*), and the fifth group comprised the five other CP stations of the Ben Khalf Channels (the tanaids *Apseudopsis gabesi* and *A. mediterraneus*).

Overall, 85% of the stations were grouped according their location in the four tidal channels.

3.4. Seasonal pattern of the benthic fauna

A dendrogram based on the mean abundance data after a Log (X + 1) transformation relating to the four seasons and the four tidal channels revealed a level of 36% of similarity separating the stations into three groups of one, and three of two or more. The individual stations were, Summer-CML (the gastropods *Cerithiopsis tubercularis* and *C. cirratus*), Spring-CK (*C. serratus* and *S. pavonina*) and Spring-CML (the amphipods *Microdeutopus anomalus* and *M. gryllotalpa*). The first group of two or more stations (Fig. 6) comprised seven season-channels: three from CP, two from CK and two from CML (*M. anomalus* and *C. cirratulus*). The second group comprised four season-channels: CK in summer and those of CM except in spring (the polychaetes *C. cirratus* and *Piromis eruca*). The third group covered both the spring measurements at CM and CP and was characterized by the polychaetes *Paradoneis armata* and

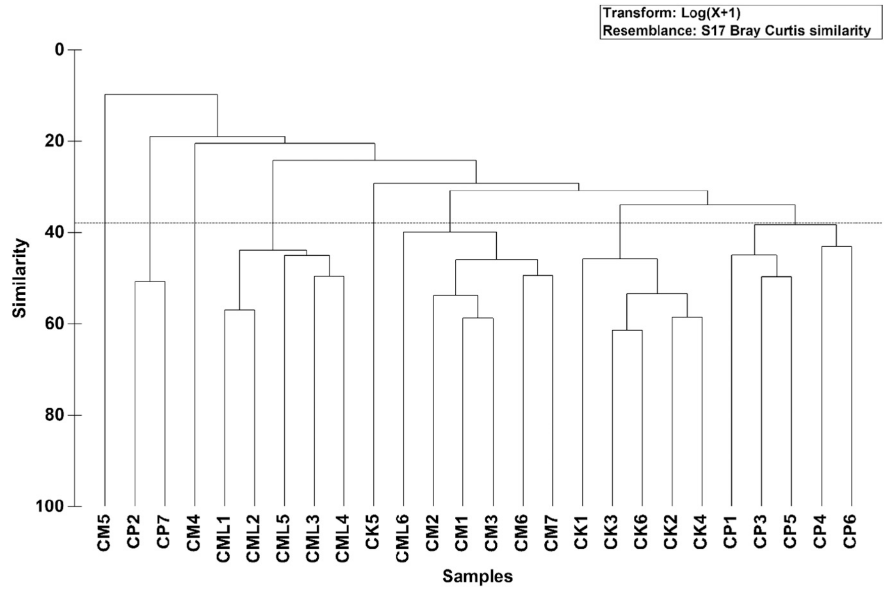

Fig. 5. Cluster dendrogram showing the distribution of mean abundances of species (for each of the four seasons and at each of the 26 stations) as a function of the Bray-Curtis similarity index following a Log (X + 1) transformation of the abundances values of the 311 taxa. Channels, CK: Kneiss; CM: Mimoun CML: Maltine; CP: Ben Khlaf.

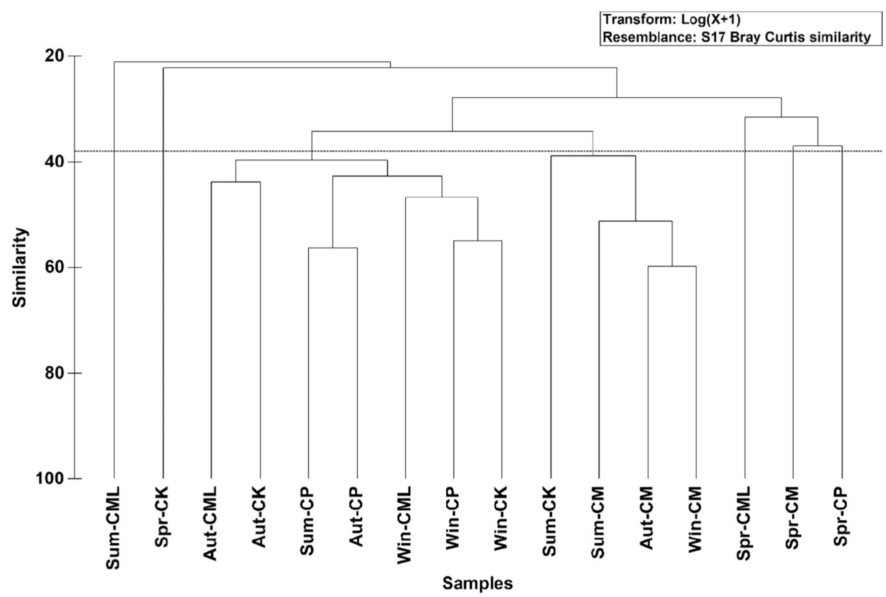

Fig. 6. Cluster dendrogram showing the distribution of mean abundances of species (at all stations sampled, in each of the four channels and for the four seasons) as a function of to the Bray-Curtis similarity index following a Log (X + 1) transformation of the abundances of the 311 taxa. Channels, CK: Kneiss; CM: Mimoun CML: Maltine; CP: Ben Khlaf. Seasons, Win: winter; Aut: autumn; Sum: summer; Spr: spring.

Lumbrineris latreilli.

This analyse reveals a variable seasonal effect, high abundance in the CK channel in spring, yet higher abundances in the other channels in winter than observed in other seasons especially in summer when the abundances were very low. Again two species dominated the fauna: the polychaete *C. cirratus*, and the amphipod *M. anomalus*.

In summary, both of the analyses on spatial and temporal factors show a predisposition of the fauna to reflect the composition of that existing in each channel (either upstream or downstream) and seasonal changes.

Table 4 lists the 10 dominant species found in each of the four tidal channels, which together represent only 23 species. Each channel showed certain particularities: CK was dominated by polychaetes, which were amongst the five top species found here; CM was dominated by polychaetes and amphipods; CML was dominated by amphipods and gastropods whereas channel CP was dominated only by peracarids (amphipods, tanaids and cumaceans).

The polychaete *Cirratulus cirratus* was dominant in two channels with very high abundance in the CK, and low abundance in CM. The amphipod, *Microdeutopus anomalus*, dominated in CML and both tanaid *Apseudopsis gabesi* and *A. mediterraneus* in the CP channel (Table 4). The mean annual abundances varied widely between the channels, reaching 3700 ind$\cdot$m^2 for CK, 1600 ind$\cdot$m^2 for CP, 1500 ind$\cdot$m^2 for CML yet only 300 ind$\cdot$m^2 for CM.

In spring, the polychaete *Cirratulus cirratus* dominated largely in terms of the abundance of the macrofauna of the four tidal channels

Table 4
Mean abundance (A, per 1 m^2) of the ten dominant species in the four tidal channels (CK: Kneiss; CM: Mimoun. CML: Maltine; CP: Ben Khlaf).

CK		CM		CML		CP	
Taxa	A	Taxa	A	Taxa	A	Taxa	A
Cirratulus cirratus	2523	*Cirratulus cirratus*	69	*Microdeutopus anomalus*	480	*Apseudopsis gabesi*	439
Sabella pavonina	453	*Microdeutopus anomalus*	61	*Cerithium scabridum*	293	*Apseudopsis mediterraneus*	387
Orbinia sertulata	128	*Piromis eruca*	33	*Cerithiopsis tubercularis*	181	*Iphinoe serrata*	112
Melinna palmata	100	*Elasmopus rapax*	19	*Monocorophium acherusicum*	175	*Apseudopsis annabensis*	98
Hediste diversicolor	82	*Chondrochelia savignyi*	19	*Microdeutopus gryllotalpa*	117	*Monocorophium acherusicum*	92
Monocorophium acherusicum	73	*Glycera fallax*	18	*Cirratulus cirratus*	77	*Cirratulus cirratus*	80
Microdeutopus anomalus	67	*Golfingia (Golfingia) elongata*	17	*Apseudopsis gabesi*	40	*Iphinoe trispinosa*	77
Scoletoma impatiens	67	*Pinctada imbricata radiata*	16	*Abra alba*	37	*Sabella pavonina*	75
Abra alba	63	*Loripes orbiculatus*	16	*Scoloplos armiger*	33	*Lumbrineris latreilli*	74
Tricolia speciosa	58	*Melinna palmata*	15	*Notomastus latericeus*	31	*Microdeutopus anomalus*	66

Table 5
Mean abundance (A) per 1 m^2 of the ten dominant species in the four seasons.

Spring		Summer		Autumn		Winter	
Taxa	A	Taxa	A	Taxa	A	Taxa	A
Cirratulus cirratus	2325	*Cerithiopsis tubercularis*	179	*Cerithium scabridum*	285	*Microdeutopus anomalus*	427
Sabella pavonina	333	*Cirratulus cirratus*	77	*Cirratulus cirratus*	151	*Apseudopsis gabesi*	383
Microdeutopus anomalus	125	*Sabella pavonina*	71	*Sabella pavonina*	85	*Apseudopsis mediterraneus*	289
Melinna palmata	107	*Microdeutopus anomalus*	51	*Microdeutopus anomalus*	75	*Monocorophium acherusicum*	210
Monocorophium acherusicum	92	*Chondrochelia savignyi*	45	*Apseudopsis gabesi*	62	*Cirratulus cirratus*	198
Hediste diversicolor	82	*Lumbrineris latreilli*	29	*Tricolia speciosa*	59	*Iphinoe serrata*	106
Hilbigneris gracilis	79	*Elasmopus rapax*	26	*Cymadusa filosa*	55	*Apseudopsis annabensis*	93
Microdeutopus gryllotalpa	73	*Protocirrineris chrysoderma*	24	*Orbinia sertulata*	52	*Iphinoe trispinosa*	90
Scoletoma impatiens	67	*Orbinia sertulata*	24	*Abra alba*	45	*Sabella pavonina*	79
Orbinia sertulata	65	*Monocorophium acherusicum*	22	*Lamellaria perspicua*	37	*Abra alba*	71

(Table 5). In summer at a lower density, the gastropod *Cerithiopsis tuberculatus* was the dominant species, and in the autumn, another gastropod, *Cerithium scabridum*, dominated. In winter, the fauna was dominated by the amphipods *Microdeutopus anomalus* and *Monocorophium acherusicum*, and the tanaids, *Apseudopsis gabesi* and *A. mediterraneus* (Table 5).

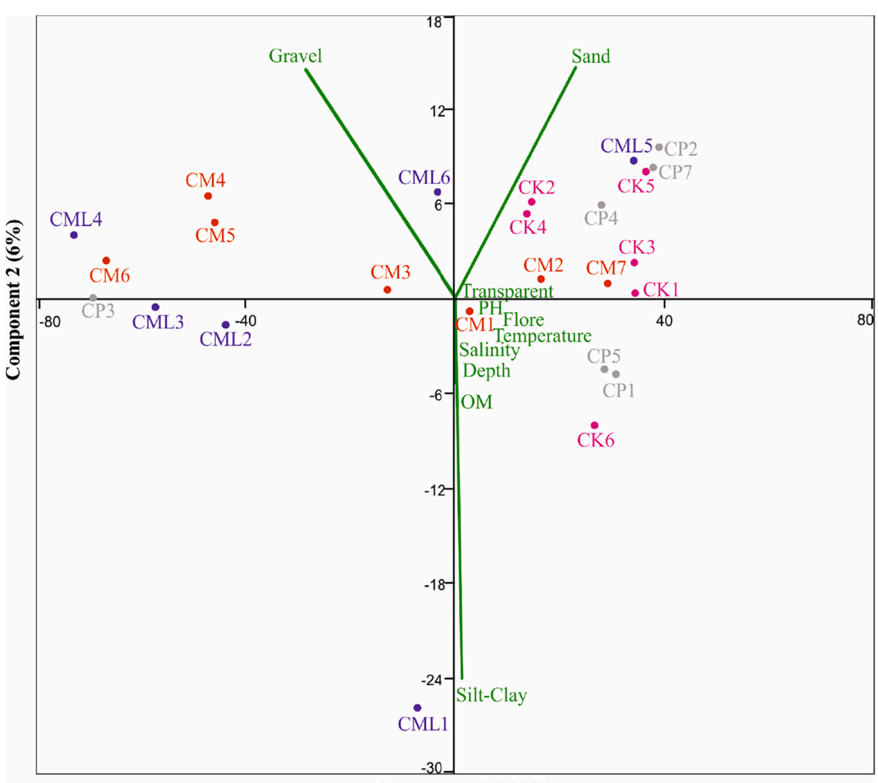

Fig. 7. Principal Component Analysis (PCA) (axis 1 and 2) relating to the position of the 26 stations and the mean values of the environmental parameters.

3.5. Relationships between fauna composition and environmental parameters

The principal component analysis (PCA) performed for the 26 stations looking at the influence of each environmental parameter (e.g. sediment type: gravel, sand, silt-clay, organic matter; water conditions: salinity, temperature, pH, and transparency) on the biological variables (Flora) showed that few environmental factors greatly influenced the biological components (Fig. 7). The first principal component explained 92% of the inertia and the second 6%. The sediment type was the most discriminant factor with the opposition of sand to gravel on the first axis. Stations with high percentage of sand were on the positive part of the axis, while those with high percentage of gravel were on the negative part of the axis (see Table 1). The second axis opposed the high percentage of silt-clay as in the stations CML1 and CP6 to the Sand-Gravel pole (Table 6). The other parameters were at the centre of the analysis and did not contribute to the separation of the stations (Fig. 7).

Considering now the mean abundances of the taxa, the first principal component explained 74.7% of the inertia and the second 12.2% (Fig. 8). Only few species contributed to the separation of the stations, with the opposition of stations CK1, CK2 and CK3 dominated by the polychaetes *Cirratulus cirratus* and *Sabella pavonina* to the others stations and taxa. On the second axis, the station CP6 characterized by the tanaid *Apseudopsis gabesi*, the stations CP2 and CP5 and the tanaid *Apseudopsis mediterraneus*, the cumacean *Iphinoe trispinosa* and the polychaete *Lumbrineris latreilli* were opposed to the rest of the taxa mainly the amphipod *Microdeutopus anomalus*, and the polychaetes *Scoletoma impatiens* and *Scoloplos armiger*, and the other stations.

3.6. Ecological status of the benthic habitat

Considering now the proportion of taxa falling into each of the five Ecological groups, showed that most of the sampling stations were dominated by EG-I and EG-II taxa, the exceptions being five of the six stations in the CK channel (Fig. 9). The proportions of the sensitive species (classified as EG-I) was greatest at station CP2 whereas the lowest amount was found at station CK6. Conversely the proportion of the opportunistic taxa (EG-IV) was low or non-existent for most of the stations with the exception of five stations in the CK channel, where the sediment was highest in organic matter content, especially station CK6 (Table 1): in this case, the fauna were dominated by polychaetes *Cirratulus cirratus*.

The AMBI scoring corresponded to High Ecological Status (for five stations), Good (nineteen stations) and Moderate for the two stations CK2 and CK6 (Fig. 8). The moderate status related to spring sampling at CK2, and CK6, and station CML5 (Table 6). The M-AMBI scoring showed that 16 stations on 26 presented at least one moderate ES (Table 6). Five values classified the CK2, CK6, CML4, CML5 and CP2 in spring or summer with a poor ES (Table 6). Considering the parameter H′, the poor and moderate ES corresponded only to spring and summer samples, whereas the CML stations exhibited a degraded ES, status throughout the year which is confirmed by the J value (Table 6).

Table 6
Values of the Taxonomic Richness (TR) and Abundance (A) per 0.4 m^2, Shannon diversity (H′), Pielou's evenness (J), AMBI, Ecological Status (High: blue, Good: green, Moderated: yellow, poor: orange and bad: red) of the 26 stations from the four tidal channels (CK: Kneiss; CM: Mimoun. CML: Maltine; CP: Ben Khlaf) in the four seasons (Spr: spring; Sum: summer; Aut: autumn, Win: winter).

Stations	TR				A				H′				J				AMBI				M-AMBI			
	Spr	Sum	Aut	Win	Spr	Sum	Aut	Win	Spr	Sum	Aut	Win	Spr	Sum	Aut	Win	Spr	Sum	Aut	Win	Spr	Sum	Aut	Win
CK1	31	18	28	37	818	52	251	204	3.00	3.15	3.27	4.25	0.60	0.76	0.68	0.81	2.67	0.53	1.26	1.72	0.61	0.68	0.73	0.77
CK2	22	11	31	39	1923	41	357	255	1.37	2.50	2.61	4.38	0.31	0.72	0.53	0.83	3.83	1.50	2.25	1.94	0.36	0.52	0.64	0.78
CK3	22	17	33	55	2442	103	226	436	1.90	2.96	3.86	4.37	0.42	0.72	0.77	0.75	3.04	1.76	1.59	2.08	0.45	0.59	0.78	0.84
CK4	27	18	15	11	443	95	53	66	3.30	3.32	3.07	2.79	0.69	0.80	0.79	0.81	2.25	2.51	2.21	1.25	0.63	0.57	0.57	0.58
CK5	9	20	27	9	77	64	123	16	2.25	3.57	3.88	2.95	0.71	0.82	0.82	0.93	0.25	1.29	1.51	0.47	0.55	0.68	0.75	0.64
CK6	21	15	28	19	2435	85	252	63	1.31	2.35	3.71	3.68	0.30	0.60	0.77	0.87	4.04	3.07	1.25	1.81	0.34	0.45	0.76	0.65
CM1	25	31	12	37	62	121	15	112	4.36	3.87	3.51	4.76	0.94	0.78	0.98	0.91	1.25	1.33	2.00	1.30	0.77	0.78	0.59	0.84
CM2	34	20	38	26	93	52	72	60	4.61	3.63	4.96	4.18	0.90	0.84	0.94	0.89	1.68	1.07	1.02	1.10	0.81	0.70	0.92	0.74
CM3	41	30	41	47	150	116	150	125	4.72	4.24	4.29	4.95	0.88	0.87	0.80	0.90	1.36	1.97	1.89	1.92	0.89	0.76	0.82	0.85
CM4	13	4	24	26	26	5	94	81	3.40	1.92	3.58	3.97	0.92	0.96	0.78	0.84	1.27	1.50	1.23	1.69	0.63	0.43	0.72	0.70
CM5	3	11	9	6	3	34	10	10	1.58	2.29	3.12	2.52	1	0.66	0.98	0.97	1.00	2.38	0.75	0.90	0.45	0.46	0.65	0.56
CM6	16	15	20	19	50	22	44	41	3.78	3.73	3.91	3.77	0.94	0.95	0.90	0.89	1.47	2.36	1.50	1.46	0.64	0.60	0.70	0.68
CM7	27	42	34	26	60	165	100	66	4.08	4.57	4.34	4.2	0.86	0.85	0.85	0.89	1.86	1.80	1.88	2.09	0.74	0.89	0.78	0.69
CML1	14	18	10	18	376	458	165	124	1.90	1.23	1.05	3.31	0.50	0.29	0.32	0.80	1.36	0.33	1.44	1.37	0.55	0.55	0.46	0.64
CML2	21	10	14	9	288	66	348	612	2.94	1.35	0.81	1.58	0.67	0.40	0.21	0.50	2.31	0.41	1.46	0.81	0.59	0.53	0.47	0.53
CML3	7	4	16	13	66	7	155	89	2.08	1.95	1.18	2.29	0.74	0.97	0.29	0.62	1.73	1.93	1.42	1.11	0.44	0.40	0.51	0.60
CML4	11	1	9	24	96	1	105	519	1.96	0	1.80	2.56	0.57	0	0.57	0.56	1.05	3.00	1.31	1.51	0.50	0.36	0.51	0.61
CML5	15	8	18	39	72	23	56	352	2.89	2.27	3.64	3.38	0.74	0.76	0.87	0.64	3.44	3.20	2.17	1.42	0.46	0.38	0.63	0.75
CML6	48	13	31	53	172	42	114	399	4.84	3.23	4.12	4.58	0.87	0.87	0.83	0.80	1.01	1.93	1.94	1.66	0.95	0.56	0.76	0.87
CP1	10	16	21	39	150	108	121	514	2.18	3.04	3.37	3.56	0.65	0.76	0.77	0.67	1.97	0.89	0.84	1.87	0.49	0.63	0.72	0.72
CP2	6	9	6	17	38	14	9	593	1.62	2.95	2.42	1.84	0.63	0.93	0.93	0.45	2.88	1.07	2.00	2.58	0.34	0.56	0.48	0.44
CP3	38	35	14	33	226	214	49	135	4.25	4.17	3.06	4.09	0.81	0.81	0.80	0.81	1.80	2.30	1.71	1.29	0.80	0.78	0.56	0.77
CP4	27	14	3	15	204	51	4	211	3.62	2.92	1.50	1.92	0.76	0.77	0.95	0.49	2.42	1.68	0.37	2.69	0.65	0.56	0.52	0.44
CP5	15	31	13	29	115	199	111	167	2.73	3.66	2.50	3.86	0.70	0.74	0.67	0.79	2.71	2.34	1.68	2.03	0.49	0.70	0.55	0.70
CP6	14	24	31	43	104	161	363	1768	2.46	3.27	3.39	2.93	0.64	0.71	0.68	0.54	2.07	1.61	2.46	2.31	0.50	0.67	0.67	0.66
CP7	-	-	10	28	-	-	23	321	-	-	2.48	2.88	-	-	0.75	0.60	-	-	2.02	2.01	-	-	0.51	0.61

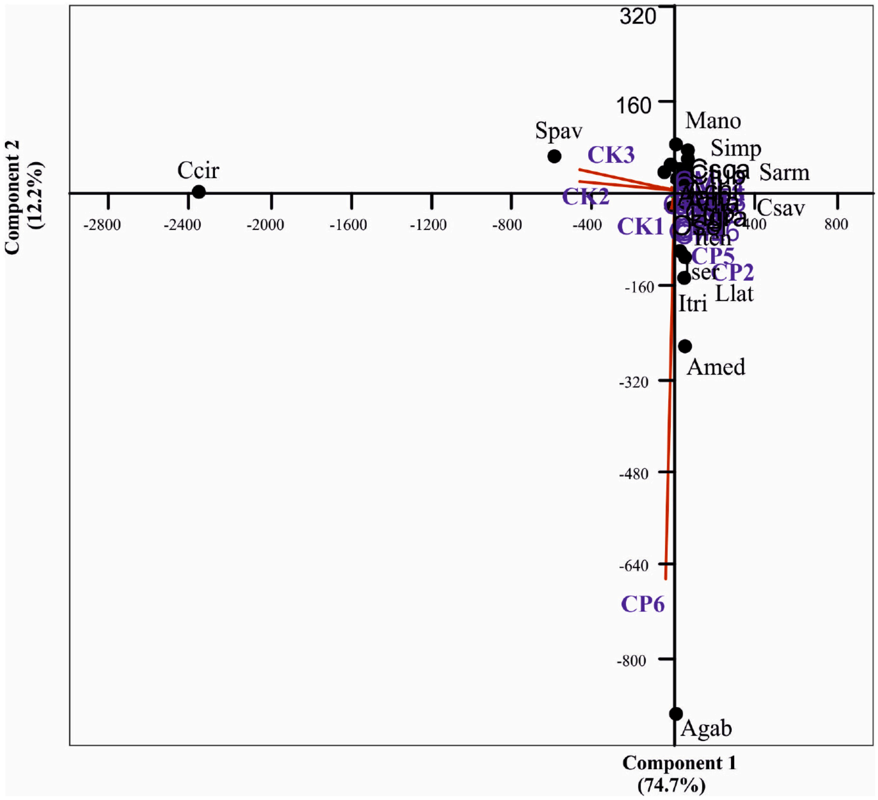

Fig. 8. Principal Component Analysis (PCA) (axis 1 and 2) relating to the mean Abundance of the macrofauna accounted in the 26 stations and the environmental parameters. Ccir: *Cirratulus cirratus*, SPav: *Sabella pavonina*; Mano: *Microdeutopus anomalus*; Simp: *Scoletoma impatiens*; Sarm: *Scoloplos armiger*; Csav: *Chondrochelia savignyi*; Llat: *Lumbrineris latreilli*; Iphi: *Iphinoe trispinosa*; Amed: *Apseudopsis mediterraneus* and Agab: *Apseudopsis gabesi*.

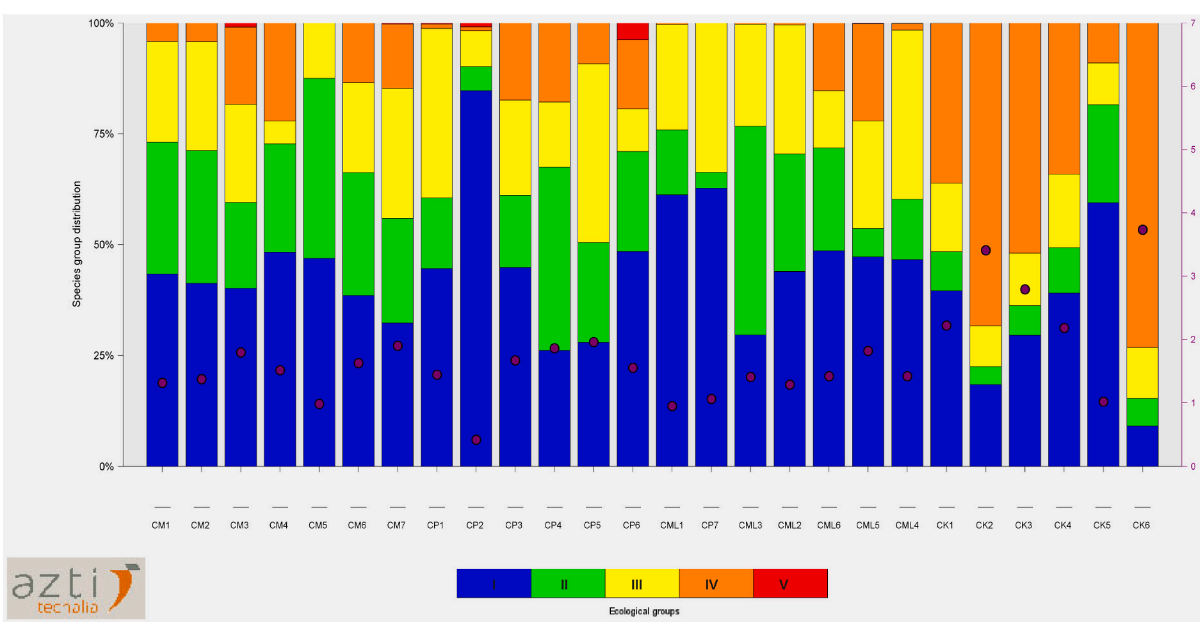

Fig. 9. Mean proportion of taxa classified under the five Ecological Groups. EG-I (blue), EG-II (green), G-III (yellow), EG-IV (orange) and EG-V (red) with the value of the AMBI index (black point on each of the 26 stations located along the four tidal channels). AMBI statuses: High: $0.0 < \text{AMBI} \leq 1.2$; Good: $1.2 < \text{AMBI} \leq 3.3$; Moderate: $3.3 < \text{AMBI} \leq 4.3$; Poor $4.3 < \text{AMBI} \leq 5.5$; Bad: $5.5 < \text{AMBI} \leq 7.0$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

The current study provides the first description of the macrofauna of the tidal channels traversing the Gulf of Gabès, along with information of the sedimentary texture of these channels and the interactions between the abiotic/edaphic factors and the marine invertebrates. The annual cycle of observations give an overview of the state of the benthic habitats in the channel in 2016–2017 in relation to anthropogenic pressures in this area.

4.1. Biodiversity and spatio-temporal composition of the macrobenthic fauna in the tidal channels

In this study, 311 taxa of benthic macrofauna were found and recorded. These taxa were distributed across four main taxonomic groups. Amongst them, the polychaetes dominated in both number of taxa and abundance. Taxonomic Richness and the abundance of fauna were greatest in the upstream and downstream portion of each channel based on sand and muddy sand, rather than the central portion of the tidal channels. This was probably due to the presence of strong water currents midway along each channel and to the presence of coarse sediment and shell debris in these same medium areas along with the absence of macrophytes. The Taxonomic Richness in these channels was amongst the highest found on any subtidal benthic soft-bottom communities along the Tunisian coasts. In the Bay of Skhira, Boudaya et al. (2019) reported a total of 239 taxa from 28 subtidal stations sampled once in April 2010, whilst Mosbahi et al. (2019) estimated a Taxonomic Richness of only 106 from a seasonal sampling of 12 stations in Sfax shallow waters (2015–2016). For the subtidal shallow habitats around the Gulf of Gabès, El Lakhrach et al. (2012) collected 205 species of mega-benthos invertebrates with the dominance of echinoderms (38%). In the Gulf of Tunis Ayari and Afli (2003) recorded a total of 214 invertebrate species with the dominance of polychaetes (63%), whilst Diawara et al. (2008) reported a total of 189 macro-zoobenthic species retrieved from the Tunis lagoon.

In the port of Sidi Youssef in the west of Kerkennah Islands, ten locations ranging from 0.9 to 5.65 m in depth were sampled by Scuba divers in the spring of 1997 (Aloui-Bejaoui and Afli, 2012). 77 taxa were identified but at a very low abundance ranging from 6 to 96 ind·m^{-2} which was probably due to dredging operations in the navigational channel: a dominance of polychaetes and bivalves and low abundances of crustacean and amongst them amphipoda, were reported. A similar observation was made in our study, which included the Mimoun Channel in the south-east of the Kerkannah Islands: at this location, the abundances were found to be the lowest (300 ind·m^{-2}).

The mean abundance of the macrofauna from the intertidal zone around the Kneiss Island was relatively high at 3895 ind·m^{-2} (Mosbahi et al., 2015), and similar to this of the abundance of macrofauna in the Kneiss tidal channel with 3800 ind·m^{-2}: this is higher than that found in the three other channels (ranging from 300 to 1600 ind·m^{-2}). The dominant species living in this *Zostera noltei* seagrass were polychaetes (*Euclymene oerstedii*, *Perinereis cultifera*, *Cirratulus cirratus*), amphipods (*Ampelisca brevicornis*, *Elasmopus rapax*, *Gammarus insensibilis* and *Lysianassa pilicornis*), and bivalves (*Loripes lucinalis* and *Ruditapes decussatus*) (Mosbahi et al., 2015). Only the polychaete *Cirratulus cirratus* was present amongst the top abundant species in both intertidal and subtidal systems.

The abundances of the macrofauna of the mediolittoral zones in three beaches surrounding the Gulf of Gabès varied between 550 and 1190 ind·m^{-2} (Perez-Domingo et al., 2008), with the dominance of the amphipod *Bathyporeia guilliamsoniana*, the polychaete *Scolelepis mesnili* and the bivalve *Donax trunculus*. This finding was similar to those observed in other sandy beaches of the Mediterranean and along the north-eastern Atlantic coasts (Perez-Domingo et al., 2008).

In order to estimate the effect of the phosphogypsum outfall on the macrofauna in the Bay of Skhira, Boudaya et al. (2019) had sampled in April 2010, 28 stations in four lines running inshore-offshore. Results showed that the stations nearest the source were the most disturbed. The mean spring abundance was 2705 ind·m^{-2}, which was higher than the mean annual abundance of the CP channel (1600 ind·m^{-2}), which is in the same part of the Gulf of Gabès. The dominant species were the polychaetes (*Melinna palmata*, *Lumbrineris tetraura*, *Cirratulus cirratus*), the bivalves (*Pinctada imbricata radiata*, *Scrobicularia plana*), the amphipods (*Cymadusa filosa*, *Dexamine spiniventris*, *Elasmopus rapax*, *Leucothoe incisa*) and the sea star *Astropecten spinulosus*. All of these species were found in the tidal channels in the present study. In the shallow coastal zone to the south of Sfax, Mosbahi et al. (2019) had sampled during one year (April 2015–January 2016), from 12 stations located along four inshore-offshore pollution gradient lines and identified three main groups of fauna, and the four locations near the coast that were the most affected by human activities exhibiting low taxonomic richness values (7–20) and low mean annual abundances (467–525 ind·m^{-2}). An intermediate zone (with for stations) gave intermediate values for TR (20–27) and abundances (709–855 ind·m^{-2}), and four offshore stations showed the highest values of TR (25–29) and abundances (827–1656 ind·m^{-2}). In this region the fauna was dominated by polychaetes, crustaceans and molluscs: most of the dominant species were polychaetes such as *Lumbrineris tetraura*, *Amphicteis gunneri*, *Euclymene oerstedii*, *Melinna palmata*, *Cirratulus cirratus*, or amphipods *Cymadusa filosa*, *Dexamine spiniventris*, *Gammarus insensibilis*, *Elasmopus rapax*, *Leucothoe incisa* or the bivalve *Scrobicularia plana*.

Afli et al. (2013) had previously studied the macrofauna along the western coast of the bay of Tunis (10 stations) and around Djerba Island in the south of Tunisia (11 stations). The maximum abundance measured was 2900 ind·m^{-2}, but most the stations showed numbers lower than 500 ind·m^{-2}. The species diversity was greater in the Bay of Tunis than around Djerba Island. The benthic macrofauna in the lagoon of Boughrara (south of the Djerba Island) was separately studied at 13 stations in 2009–2010 by Khedhri et al. (2015). The abundance found varied from a minimum of 66 to 7792 ind·m^{-2} during the summer and 5094 ind·m^{-2} in the autumn. Application of AMBI classified all the stations as having a ‘high’ ecological status except one station, which was only classified as ‘good’.

Ayari and Afli (2003) reported their first quantitative data from 30 stations from the Bay of Tunis in March 2013. Four main benthic populations had been identified with mean abundance values between 620 and 4685 ind·m^{-2}. The polychate *Melinna palmata* and the tanaid *Apseudes talpa* dominated the macrofauna. In a later study, Afli et al. (2008), demonstrated in several coastal and lagoons systems in the North of Tunisia (the Bay of Tunis, the Lagoon of Bizerte and the coastline of Dkhila in the Bay of Hammamet: 26 stations), a low Taxonomic Richness, that was associated with a moderate abundance with a maximum of 470 ind·m^{-2} in the Lagoon of Bizerte, 620 ind·m^{-2} in the Bay of Tunis and 1520 ind·m^{-2} along the coast of Dkhila. In the same area in the North of the Tunisia, Afli et al. (2009) had also studied two other lagoon systems: the southern lagoon of Tunis and the lagoon of Ghar El-Melh where the salinity was very high in summer (~50). The abundance was consistently higher in the southern lagoon of Tunis (1279–7547 ind·m^{-2}) than in the Lagoon of Gahr El-Mah (362–959 ind·m^{-2}).

The sediment of the lagoon of Bizerte is made up by sand habitats and numerous macrophyte meadows showing high abundances of amphipods with the dominance of *Cymadusa filosa*, *Dexamine spinosa*, and *Elasmopus rapax* (Khammassi et al., 2019), which were also abundant in the tidal channels of the Gulf of Gabès (Fersi et al., 2018). The fauna found in the tidal channels of the Gulf of Gabès, was similar to those found in Tunisian and Mediterranean lagoons, the main characteristic being the presence of high abundances of Tanaids. Other than the polychaetes (with the dominance of *Cirratulus cirratus*, *Sabella pavonina*; *Hediste diversicolor* and *Melinna palmata*), and the amphipods (with the dominance *Microdeutopus anomalus*, and *M gryllotalpa*, *Elasmopus rapax*, and *Monocorophium acherusicum*), the characteristic of the fauna in the tidal channels was the high abundance of the tanaids of the genus *Apseudopsis* accounting for four known species and the description of one new species *Apseudopsis gabesi* Esquete, 2019 (Esquete et al., 2019). The richness of the tanaid species was notable with the presence of four other species amongst the eight separately recorded by Fersi et al. (2019) in this study for the Tunisian. Most of the recorded *Apseudopis* spp. where found in the Ben Khlaf (CP) channel (94% of the specimens collected in the four channels). Furthermore, 82% of these specimens were also sampled in winter. Only *A. mediterraneus* was found in the same area by Boudaya et al. (2019) during a spring sampling campaign. *Apseudes talpa* was the only species of tanaid recorded along the coast of Tunisia in large numbers in the mud habitat *Melinna palmata-Apseudes talpa* in the Bay of Tunis (Ayari and Afli, 2003; Afli et al., 2009). The diversity and high abundance of tanaids in tidal channels of the Gulf of Gabès are noteworthy. Amongst the tanaids, *Apseudopsis latreillii* was the single species present at very high abundances amongst the soft-bottom habitats, such as in the northern part of Cotentin peninsular (Normandy, France), in the English Channel (20 to 23,000 ind·m^{-2}), which are amongst the highest recorded values anywhere in the world (Andres et al., 2020).

Many studies have been carried out in other lagoons around the Mediterranean and the macrofauna sampled in the tidal channels of the Gulf of Gabès appeared to be typical of such lagoons. On the other hand, the low contribution of molluscs, especially the bivalves, may be in relation to strong tidal currents in the channels. In the Merja Zerga lagoon (Morocco, Atlantic), the subtidal zone was composed of a coarser sediment and higher Taxonomic Richness than the intertidal zone; in this lagoon three benthic communities dominated by the bivalves were distinguished: *Cerastoderma edule*, *Scrobicularia plana* in both subtidal and intertidal zones, and *Ruditapes decussatus* in the subtidal zone (Bazairi et al., 2003). Chaouti and Bayed (2017) studied the seasonal changes of the macrofauna at ten stations located in the small Smir lagoon (3 km^2), in the northwest of Morocco. The fauna was made up from 42 species, dominated by crustaceans, polychaetes, and molluscs whilst, the polychaete *Hediste diversicolor*, the two isopods *Sphaeroma hookeri*, *Cyathura carinata*, and the two amphipods *Monocorophium acherusicum* and *Melita palmata* accounted for more than 90% of the individuals collected. In this lagoon system, the sediment was not considered as a temporal structuring factor whereas salinity and temperature, particularly in summer, were factors determining the seasonal pattern of composition and abundance of the community. As in the current study, the abundances were higher in winter and spring (430–860 ind·m^{-2}) than observed in summer (47 ind·m^{-2}). In another small lagoon in the eastern part of the Algerian coast (Mellah lagoon, 9 km^2), the fauna was dominated by the two polychaetes (*Capitella capitata* and *Spio decorata*), two crustaceans (*Microdeutopus gryllotalpa*, *Monocorophium insidiosum*) and the mollusc (*Loripes lucinalis*) with a mean abundances of 1640 ind·m^{-2} and a total taxonomic richness of 50 (Draredja et al., 2012). In the northern part of the western basin of the Mediterranean Sea, in the muddy sand of the lagoon of Prévost (France), Guélorget and Michel (1979) recorded very high abundances (12,000 ind·m^{-2}) at the beginning of the autumn period and very low abundances in summer (200 ind·m^{-2}) with a dominance of polychaetes (*Capitella capitata*, *Heteromastus filiformis*, *Owenia fusiformis*), molluscs (*Scrobicularia plana*, *Polititapes aureus*, *Tapes decussatus*), and amphipods (*Monocorophium insidiosum*, *Gammarus insensibilis*).

The benthic community in the 50 km^2 lagoon of Lesina (Apulia, Italy, in the southern Adriatic Sea,) was studied taking samples from July 2000 to June 2001 from 24 stations (Nonnis Marzano et al., 2003a). The taxonomic richness was given as 53 with abundances dominated by polychaetes (*Cirratulus cirratus*, *Cirriformia tentaculata*, *Hediste diversicolor*), molluscs (*Ecrobia ventrosa*, *Cerastoderma glacum*, *Abra segmentum*) and crustaceans, mainly isopods and amphipods, including *Monocorophium insidiosum*, *Microdeutopus gryllotalpa*, and *Gammarus aequicauda*. The maximum abundance value was observed in winter (2000 ind·m^2) and the minimum in summer (1000 ind·m^{-2}). In the Karavasta lagoon (Albania, Adriatic Sea, 41 km^2) 64 taxa were recorded from 14 sampling stations in April 2004 on the soft-bottom habitat, with the dominance of polychaetes, molluscs and crustaceans (Nonnis Marzano et al., 2003b). The bivalves *Abra segmentum* and *Cerastoderma glaucum* were the most common species, and the amphipod fauna collected in this lagoon was very similar to those fund in the tidal channels of the Gulf of Gabès (Fersi et al., 2018).

The dominant amphipod species in the tidal channels of the Gulf of Gabès were *Microdeutopus anomalus* and *M. gryllotalpa*, *Monocorophium acherusicum*, *Dexamine spinosa*, *Cymadusa filosa* and *Elasmopus rapa*: these are characteristic of areas with detritus accumulation, and are associated with the occurrence of sea grass meadows as found in many lagoons around the Mediterranean Sea (Fersi et al., 2018). As the dominant amphipods were dominated by herbivorous grazers and detritus feeders, living mainly on algae and sea grasses, the accumulation of herbivorous species linked to the accumulation of macro-particulate detritus explains the dominance of this trophic group in the Maltine Channel (Fig. 4). Furthermore, this trophic group was also dominant in the Kneiss and Mimoun channels. On the other hand, the omnivores dominated in the Ben Khalf channel (Fig. 4), where the suspension feeders and the sub-surface deposit feeders were weakly represented suggesting that most of these species depended on food particles in the water column or deposited at the surface of the sediment.

4.2. Ecological status of the tidal channels of the Gulf of Gabès

In spite, of the pressure from numerous anthropogenic activities in the Gulf of Gabès, the Ecological Status (assessed by AMBI and M-AMBI Indices) revealed that the benthic habitats appeared to be mainly in a good ecological condition with the exception of the Kneiss Channel where the macrofauna was dominated by the opportunistic species *Cirratulus cirratus* (Table 6). The diversity indices H′ and J indices suggested a more degraded environment (Table 6), not only in the Kneiss Channel, but also at most of the stations along the Maltine and the Ben Khalf channels. Analogous more degraded ES were estimated with M-AMBI mainly during the spring and summer periods, again when the polychaete *C. cirratulus* dominated the macrofauna abundances.

Similarly, in the ten stations at the port of Sidi Youssef in the Kerkennah Islands, AMBI classified all of the stations as having a high ecological status (Aloui-Bejaoui and Afli, 2012). In the lagoon of Boughrara in the south of the Gulf of Gabès, Khedhri et al. (2015) reported a high ecological status at all except one sampling station.

In the North of the Tunisia, the effects of human activities appeared to be more localised such as the heavily polluted zones in the Bizerte lagoon, the mouth of the Hamoum wadi and the harbours areas (Afli et al., 2008). In the study by Rabaoui et al. (2015), the AMBI method was used to classify the 18 stations distributed across the four areas: Kerkennah Island, Mahres, Gabès and Zarzis located around the Gulf of Gabès. Good or High ecological status was ascribed with the highest values corresponding to the central parts of the Gulf where the most heavy metal pollution had also been measured.

Amongst the 28 stations sampled in the Skhira Bay by Boudaya et al. (2019), the AMBI protocol distinguished 13 offshore stations with good or high ES, 13 stations with a moderate ES, and two stations (near the phosphor-gypsum outflow) with a poor ES. Nevertheless, in the current study, the same AMBI method was able to identify a pollution gradient falling away from the coast. Similarly, an inshore-offshore pollution gradient was clearly identified by AMBI in the shallow coastal zone south of Sfax (Mosbahi et al., 2019).

All these results were similar, in spite of the very high and diverse anthropogenic human pressures around the Gulf of Gabès and near to the coastal and lagoon Tunisian ecosystems. Based on the AMBI procedure, the benthic communities were classified with a high or good ecological status with the exception of those located near to outflows of industrial and urban wastes. Two questions arise for this observation. Firstly, was the AMBI procedure sufficiently sensitive to distinguish the negative effects of the human activities in this area? In other words, were the species present in the Gulf of Gabès not classified in the appropriate ecological groups? It was noted, for example, that some species found in the Gulf of Gabès that are classified in EG-III should be in classified in EG-IV. However, it was noticed that AMBI and M-AMBI indices based on the polluo-sensitivity of the macrobenthic species had been designed to assess organic pollution on the sediment and not pollution by other elements such as heavy metals. The second question is whether the effects of human activities were softened with respect to the benthic macrofauna when considered at the scale of the whole area of the Gulf of Gabès: the fish trawling and the pollution effects remaining local?

Nevertheless, urban wastes contributed to the eutrophication of the water in the shallowest coastal zones with the appearance of opportunistic macro-algae and the concurrent deterioration of the sea grass areas and especially of the *Posidonia oceanica* meadows (Ben Brahim et al., 2010; Bonacorsi et al., 2013; El Zrelli et al., 2018). *P. oceanica* is a very sensitive species to pollution and the increase of turbidity in the shallowest parts of the Gulf of Gabès had accelerated the reduction of seabed area covered by *Posidonia oceanica*; a process which had begun at the beginning of the 1960s. On the other hand, the meadows around the Kerkennah Islands, where there is little human impact (other than overfishing) are in a better ecological status (Zaouali, 1993; Ben Brahim et al., 2010). All the same, Hattab et al. (2013) have described a decline in fish catchment. All of these results suggest that the higher impact on benthic habitat should be the over-fishing rather than from the general pollution of the coastal ecosystem, and that impact of human activities remained local. Moreover, the tidal currents in the tidal channels of the Gulf of Gabès could dilute the pollution effects due to the mixing and oxygenation of both the sea water and the sea bottom sediment. The same currents might actively contribute to the dispersion of pollutants from these particular environments in to the Mediterranean Sea.

4.3. Future perspectives

The present study was to locate the sampling stations following a line running from the coast to the open sea in four representative tidal channels in the Gulf of Gabes in the southern Tunisian coast. These tide channel systems, where the sediment type was the main factor structuring the macrobenthic communities, had been never been studied before; they were exposed to different man-made impacts (pollution from chemical and organic effluents, over-fishing). In the case of small operations, fishermen use illegal bottom trawling methods in shallow tidal channels at depths of 5 m or less, at high tide. Such systems adversely affect not only on the juveniles of fish and shrimps, but also damage the benthic habitats such as *Posidonia oceanica* meadows (Ben Brahim et al., 2010). Recently, (in October 2018) a team of inspectors counted the vessels equipped with the prohibited gear to provide a realistic estimation of the total number of illegal trawlers operating in the Gulf of Gabès. The mesh size of the nets used is much smaller than on a commercial trawler, which makes them less selective and produces large amounts of by catch. Between 400 and 500 such trawlers were identified in the main ports around the Gulf of Gabès (https://fishact.org/2018/12/).

Several initiatives for future work might be considered. The first is the complete inventory of macro-zoobenthic species present in the Gulf of Gabès incorporating the present study with other recent researches on benthic habitats in the Gulf of Gabès; this would complement those given for all invertebrates (Afli, 2005) and for Polychaetes (Ayari et al., 2009) and for alien species (Ounifi Ben Amor et al., 2016).

In spite of numerous studies on benthic organisms in the Gulf Gabès over the last two decades, there is still a lack of studies in the shallow areas close to the major centres for the phosphate industries

Another approach will be to estimate the total biomass of benthic organisms collected during this study and thus to assess the rate of benthic production in the tidal channels. It will be also interesting to sample fish trawled in the tidal channels by the fishermen for the purpose of analysing stomachs contents to estimate the proportion of the macrobenthos species in their diet. Consequently, it may be possible to develop food web models for this tidal channel ecosystem as has previously been done for the whole of the Gulf of Gabès to identify the maturity of this ecosystem (Hattab et al., 2013).

Finally, it might be worth carrying out a pluri-annual monitoring at selected stations along these tidal channels to follow the long-term evolution of macrofauna in the absence of human activities and especially from industrial discharges.

CRediT authorship contribution statement

Jean-Claude Dauvin, supervision, preparation and redaction of the paper

Abir Fersi, sampling identification of species, first analyses and review of the paper

Jean-Philippe Pezy, statistical analyses and review of the paper

Ali Bakalem, identification of species and review of the paper

Lassad Neifar, supervision and review of the paper

Declaration of competing interest

No conflict in interest.

Acknowledgments

The authors wish to acknowledge with thanks the financial support received from the Universities of Sfax (Tunisia) and Caen-Normandie (France) for two periods of collaboration in 2016 and 2017. The authors also wish to thank Sami Fersi and the local fishermen of Kerkennah and Kneiss for their help during the sampling. The fauna matrix is available by mail to jean-claude.dauvin@unicaen.fr. Finally, they wish to thank Colin Burton his very useful revision of the English manuscript, the three reviewers and the editor of Marine Pollution Bulletin for their useful comments and suggestions on the first version of this paper.

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