Recep Tayyip Erdoğan Üniversitesi Fen ve Mühendislik Bilimleri Dergisi, 5(2) 159-172 2024
Recep Tayyip Erdogan University Journal of Science and Engineering, 5(2) 159-172 2024
ISSN: 2687-2315 / E-ISSN: 2757-7686

Assessing Water and Sediment Pollution in the Sea of Marmara Estuaries and Its Impact on Invertebrate Fauna

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Araştırma Makalesi/Research Article
Geliş Tarihi/Received: 08.10.2024
Kabul Tarihi/Accepted: 21.12.2024

Abstract

The Marmara Sea is a significant inland body of water affected by extensive industrialization, urbanization, and agricultural practices. This research examined the correlation between benthic invertebrate species and metal concentrations in both water and sediment across eight estuary stations in the Sea of Marmara. A total of 33 benthic invertebrate species were identified, including those from the phyla Arthropoda, Mollusca, and Annelida. For water analysis, the amounts of orthophosphate, nitrate+nitrite, ammonium, and silicate were low, indicating that the water quality fell under the "Class 1" standard. For metal analyses, Al, B, Cr, Cu, Fe, Mn, and Zn were quantified at low levels in water samples (Al: 4.1-16.5 µg/L; Fe: 2.8-11.61 µg/L). The sediment samples were examined for elements including Al, B, Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn, which were determined to be at low contamination levels by the Sediment Quality Guidelines (SQG). Aluminum (16.7-38.5 mg/kg) and iron (117.0-225.5 mg/kg) exhibited the highest quantities in the sediment. CCA analysis indicated that Mollusca species exhibited a positive correlation with Cu and Zn, but Polychaeta species were connected with Cr and Mn. The Bray-Curtis study of species distribution categorized the stations into two primary groups. The results demonstrate that pollution levels are minimal; yet, regular monitoring studies are essential for safeguarding the Marmara Sea ecology. Metal assessments indicate that the pollution burden in the region is manageable; nevertheless, regional disparities must be considered.

Anahtar Kelimeler: Pollution bioindicators, marine biodiversity, marine pollution, heavy metal

Marmara Denizi Haliçlerindeki Su ve Sediman Kirliliğinin Değerlendirilmesi ve Omurgasız Faunası Üzerindeki Etkisi

Öz

Marmara Denizi, yoğun sanayileşme, kentleşme ve tarımsal uygulamalardan etkilenen önemli bir iç su kütlesidir. Bu araştırma, Marmara Denizi'ndeki sekiz haliç istasyonunda bentik omurgasız türleri ile hem su hem de sedimandaki metal konsantrasyonları arasındaki ilişkiyi incelemiştir. Arthropoda, Mollusca ve Annelida filumlarından olanlar da dahil olmak üzere toplam 33 bentik omurgasız türü tespit edilmiştir. Su analizlerinde ortofosfat, nitrat+nitrit, amonyum ve silikat miktarları düşük bulunmuş olup, su kalitesinin "Sınıf 1" standardının altında olduğunu göstermektedir. Metal analizlerinde, su örneklerinde Al, B, Cr, Cu, Fe, Mn ve Zn miktarları düşük seviyelerde ölçülmüştür (Al: 4,1-16,5 µg/L; Fe: 2,8-11,61 µg/L). Sediman numuneleri Al, B, Cd, Cr, Cu, Fe, Mn, Ni, Pb ve Zn gibi elementler açısından incelenmiş ve bunların Sediman Kalite Kılavuzuna (SQG) uygun olarak düşük kirlilik seviyelerinde olduğu tespit edilmiştir. Alüminyum (16,7-38,5 mg/kg) ve demir (117,0-225,5 mg/kg) sedimanda en yüksek miktarları sergilemiştir. CCA analizi, Mollusca türlerinin Cu ve Zn ile pozitif bir korelasyon sergilediğini, ancak Polychaeta türlerinin Cr ve Mn ile bağlantılı olduğunu göstermiştir. Bray-Curtis tür dağılımı çalışması istasyonları iki ana gruba ayırmıştır. Sonuçlar, kirlilik seviyelerinin minimum düzeyde olduğunu göstermektedir; ancak Marmara Denizi ekolojisinin korunması için düzenli izleme çalışmaları gereklidir. Metal değerlendirmeleri bölgedeki kirlilik yükünün yönetilebilir olduğunu göstermektedir; yine de bölgesel farklılıklar göz önünde bulundurulmalıdır.

Keywords: Kirlilik biyo-indikatörleri, denizel biyoçeşitlilik, deniz kirliliği, ağır metal

Cite as;
Akdemir, T. (2024). Assessing water and sediment pollution in the sea of marmara estuaries and its impact on invertebrate fauna. *Recep Tayyip Erdogan University Journal of Science and Engineering*, 5(2), 159-172. DOI: 10.53501/rteufemud.1581428

1. Introduction

Sea of Marmara is an inland sea located within the borders of Türkiye, connecting to the Black Sea through the Bosphorus and to the Aegean Sea through the Dardanelles. With a total area of 11.500 km² and a volume of 3.380 km³, Sea of Marmara is characterized by a sharp topographic gradient due to the North Anatolian Fault passing through it. It is the convergence point of two different water masses, originating from the Black Sea and the Aegean Sea. Sea of Marmara is subjected to pressure from neighboring seas and intensive anthropogenic and industrial pollution sources in its vicinity. Coastal areas and aestuarines, essential components of natural resources, have become attractive for countries due to their rich living resources, despite the increasing industrialization, urbanization, transportation, and tourism. Urban wastewater, organic matter and nutrients from agricultural activities lead to changes in the ecological characteristics of these areas, causing eutrophication (Avcı, 2019; Tan, 2021).

Benthic invertebrates are indispensable components that sustain the integrity, functionality, and biodiversity of marine ecosystems. Their involvement in the food chain, regulation of water quality, habitat formation, nutrient cycling, and scientific significance are vital to maintaining the equilibrium and sustainability of these ecosystems. Whereas the benthic environment represents a fundamental compartment of any aquatic ecosystem. Sediments at the bottom of the water column represent the final sink for many anthropogenic pollutants, and can accumulate significant quantities of organic matter, which affects the oxygen content of bottom waters (Venturini et al., 2004; Albayrak et al., 2006). Heavy metals are pollutants, regardless of their source, and above certain limits they have a toxic effect on marine organisms (Akdemir and Dalgic, 2021). It is a well-established fact that aquatic invertebrates are capable of accumulating significant quantities of heavy metals in their tissues, yet they are able to survive in environments that are severely polluted (Dallinger and Rainbow, 1992; Rainbow, 2002; Chiarelli and Roccheri, 2014). From another aspect, especially Mediterranean mussel (Mytilus galloprovincialis) beds in the Sea of Marmara have been observed to contain hazardous substances, and the varied benthic invertebrate groups associated with these mussel beds are affected by environmental factors like salinity and mussel biomass. The presence of invasive species poses a minor but prospective harm to the ecosystem (Doğruyol et al., 2024; Çinar et al., 2020). As it is known Sea of Marmara represents a significant migratory corridor between the Black Sea and the Mediterranean for fish species, including those that feed on benthic invertebrates. Furthermore, fishing in the Sea of Marmara constitutes a significant contributor to the regional economy (Arat et al., 2021) In this regard, the contamination of these regions has implications extending beyond the invertebrate fauna inhabiting the estuaries. It also gives rise to concerns regarding the potential health risks associated with the consumption of food items at various points along the food pyramid.

Water and sediment pollution, invertebrate groups, fish populations, invasive species, and related subjects have been the focus of academic studies in Sea of Marmara in previous years (Öztürk, 2009; Tan, 2021; Daban, 2021; Balcıoğlu, 2014; Palaz et al., 2010). Particularly in recent years, issues such as the negative impact of mucus (marine mucilage) on fishing, tourism, and aquaculture, as well as the effects of the Istanbul Canal project, have become prominent. Eutrophication in the Sea of Marmara is evidenced by the impact of mucilage, leading to notable reductions in diverse invertebrate species in benthic habitats as a consequence of deoxygenation (Isinibilir et al., 2024).

The distinctive aspect of this study is its departure from the conventional monitoring approach and the study is designed (i) to identify the invertebrate groups living in the aestuarines of Sea of Marmara and (ii) to investigate the relationship between pollutants at these points and the living organisms..

2. Materials and Methods

2.1. Study area and sampling

Eight stations were selected as the study area from the coastal areas of Sea of Marmara and samplings were conducted. Station names, codes, coordinates, location information of the stations were given in Table 1. The map of the stations is presented in Figure 1.

Table 1. Location information of the stations

Code of Station	Station Names	Province	Coordinates
S1	Gemlik	Bursa	40.424 N 29.154 E
S2	Kınıklı	Tekirdağ	41.010 N 27.985 E
S3	Silivri	İstanbul	41.077 N 28.236 E
S4	Büyükçekmece	İstanbul	41.015 N 28.570 E
S5	Biga	Çanakkale	40.378 N 27.317 E
S6	Şarköy	Tekirdağ	40.607 N 27.102 E
S7	Moda	İstanbul	40.981 N 29.033 E
S8	Yalova-Sellimandıra	Yalova	40.659 N 29.240 E

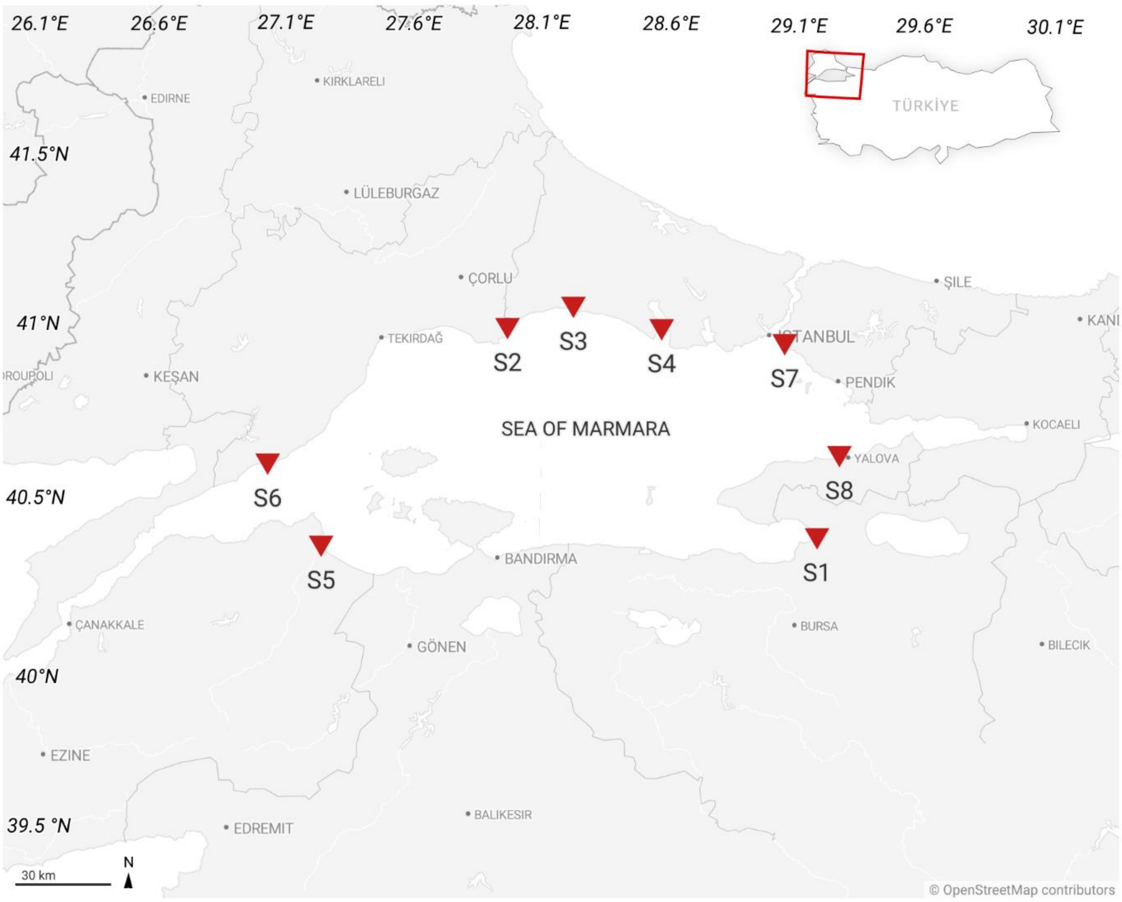

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Figure 1. Map of sampling points.

Water, sediment, and invertebrate samples were collected from each station during the samplings in September 2022. Sampling was performed at the estuarine, at depths of 0-3 meters, using free diving techniques. A surber sampler, prepared with a 20×20 cm square made of fine iron with a mesh size of 250 microns, was used to collect invertebrate groups. The sampling tool was placed in the selected habitat, the hard bottom was excavated with a spatula, and the sample was filled into the net (Andrulewicz et al., 2004; OSPAR Commission, 2012). The collected samples were transferred to plastic containers, fixed with 96% ethyl alcohol, and transported to the laboratory. After being freed from mud, individuals were sorted into groups, diagnosed, and stored again with 96% ethyl alcohol.

Sterile polypropylene amber bottles of 1 liter each were used for water samples. The bottles were filled with station water, kept cold without coming into contact with any chemicals, and transported to the laboratory. Measurements of orthophosphate, nitrate+nitrite, ammonium, and silicate were conducted at the Trabzon Central Research Institute. The study was performed utilizing a SEAL brand Auto-Analyzer (Seal X-Y-2 Sampler AA3, Seal Analytics). The techniques G-172-96 (Rev 11) for nitrate and nitrite, G-175-96 (Rev 13) for phosphate, and G-177-96 (Rev 9) for silicate were utilized. The minimum detection limits (MDL) were 0.01 µM for nitrate, 0.003 µM for nitrite, 0.02 µM for phosphate, and 0.1 µM for silicate.

For metal measurements, water samples were filtered through filter paper with a mesh size of 0.45 µm, pure nitric acid (suprapure) was added at a concentration of 65%, and the samples were delivered to the Recep Tayyip Erdoğan University Central Research Laboratory for measurement with Inductively Coupled Plasma-Optical Emission spectroscopy (ICP-OES) (US EPA, 1994).

Sediment samples collected from the same stations were transported to the laboratory without coming into contact with any chemicals and kept cold. An Ekman grab, with dimensions of 20×20 cm was used as the sampling tool. The samples were dried in an oven for 24 hours using a petri dish, sieved manually with a set of sieves (<0.063 mm) crushed to a homogeneous state, and placed in perfluoroalkoxy tubes. They were acidified with nitric acid (HNO3 Traceselect), hydrogen peroxide (H2O2 Traceselect), and hydrochloric acid (HCl) and delivered to the Recep Tayyip Erdoğan University Central Research Laboratory for measurement (Folk, 1974; US EPA, 1996; Gedik, 2018).

2.2. Quality assurance and control

Quality assurance and control were maintained through blank runs, triplicate analyses of each sample, and the comparison of measurements of the reference material created with the calibration standard. The limit of detection (LOD) was determined by taking three times the standard deviation of ten measurements of the blank solution, which was prepared following the guidelines set forth by the International Union of Pure and Applied Chemistry (IUPAC), and subsequently dividing this value by the slope of the calibration curve (Sirin et al., 2021). Also, the quantitation limit (LOQ) is defined as ten times the signal-to-noise ratio.

2.3. Statistical analyses

For the mapping of the sampled stations in Sea of Marmara estuarine ecosystems, the Datawrapper software package was used. Pearson correlation analysis was conducted to interpret the relationship between environmental parameters. Canonical Correlation Analysis (CCA) was applied to determine the relationship between environmental parameters and species (Ter Braak, 1995). Bray Curtis similarity analysis was employed to detect similarities between stations (Somerfield, 2008; Yoshioka, 2008).

3. Results and Discussion

3.1 Evaluation of benthic groups

In the sampling studies conducted along the coasts of Sea of Marmara, water, sediment, and aquatic invertebrate groups were collected from 8 river mouth stations. As a result of the diagnoses, a total of 33 benthic invertebrate species belonging to 7 phyla, namely Arthropoda, Mollusca, Annelida (Polychaeta), Platyhelminthes, Echinodermata, Nemertea, and Actinaria, were identified. A total of 390 individuals were obtained from all stations (Table 2), with the highest number of individuals recorded at station S8 (Yalova-Sellimandıra). The number of individuals at these stations constituted 30% of the total (Figure 2). The highest number of individuals belonged to the species Idotea balthica (Pallas, 1772) (50), Nereis zonata Malmgren, 1867 (37), and Apohyale crassipes (Heller, 1866) (32), respectively. When examining the phyla based on the number of species, it was observed that Mollusca and Polychaeta were the phyla with the highest species diversity, in that order.

Table 2. Species list and number of individuals recorded at each sampling station.

Phylum	Species	S1	S2	S3	S4	S5	S6	S7	S8
Arthropoda	*Pectenogammarus olivii* (H. Milne Edwards, 1830)	6				3			
	A. crassipes	9	5	18					
	Melita palmata (Montagu, 1804)							3	
	Gammarus subtypicus Stock, 1966	3							
	I. balthica		39	11					
	Anthura gracilis (Montagu, 1808)							1	
	Lekanesphaera monodi (Arcangeli, 1934)	1							
	Parapenaeus longirostris (Lucas, 1846)	1		2	2				3
Mollusca	*Tritia reticulata* (Linnaeus, 1758)	1							
	Steromphala adansoni (Payraudeau, 1826)				12			15	
	Bittium reticulatum (da Costa, 1778)				21			3	
	Rissoa scurra (Monterosato, 1917)				2				
	Tricolia pullus (Linnaeus, 1758)						4	7	5
	Patella caerulea Linnaeus, 1758						5	18	
	Modiolula phaseolina (R. A. Philippi, 1844)							2	
	Musculus costulatus (Risso, 1826)								2
	Mytilaster lineatus (Gmelin, 1791)						9		1
	Acanthochitona fascicularis (Linnaeus, 1767)						2	4	
Annelida (Polychaeta)	*Nereis pelagica* Linnaeus, 1758	1							
	Spirobranchus triqueter (Linnaeus, 1758)				25				
	Nereis splendida Grube, 1840					1			8
	Platynereis dumerilii (Audouin & Milne Edwards, 1833)								12
	Platynereis coccinea (Delle Chiaje, 1822)								8
	N. zonata	10						5	22
	Polyophthalmus pictus (Dujardin, 1839)			2					15
	Prionospio polybranchiata Fauvel, 1929								1
	Maldane sp.							1	
Platyhelminthes	*Pleioplana okusi* Bulnes, Kalkan & Karhan, 2009							3	25
	Leptoplana sp.								10
Echinodermata	*Amphipholis squamata* (Delle Chiaje, 1828)				3			3	
Nemertea	*Nemertea* sp.								5
	Lineus ruber (Müller, 1774)							8	
Actinaria	*Actinia equina* (Linnaeus, 1758)							2	

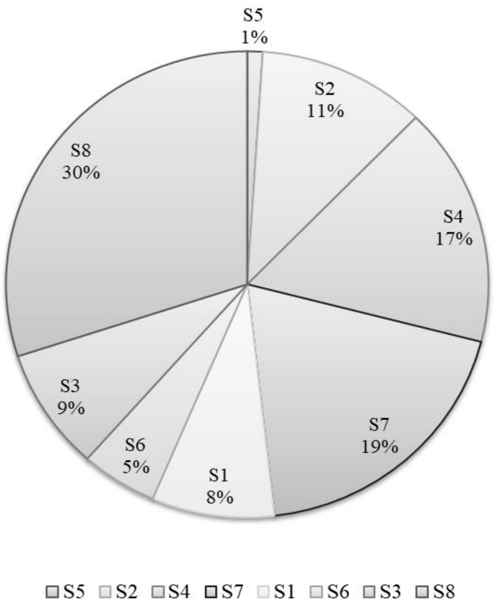

Figure 2. Percentages of individuals (%).

The percentage values for the number of individuals at stations are presented in Figure 2. According to the Bray-Curtis similarity analysis based on species distributions, two groups have been identified. Stations S8, S6, S4, and S7 form the first group, while stations S1, S2, S3, and S5 constitute the second group (Figure 3).

3.2. Evaluation of environmental parameters

The minimum and maximum values obtained for Orthophosphate were measured as 0.003-1.97 mg/L at stations S3 and S1, respectively. For Nitrite + Nitrate, the lowest concentration was 0.019 mg/L at stations S3 and S6, while the highest concentration was 2.89 mg/L at station S5. The minimum and maximum values for Ammonium were 0.01-6.18 mg/L, detected at stations S3 and S1, respectively. The minimum and maximum values for silicate, an important parameter to be measured in seas, were determined as 0.19-244.2 mg/L at stations S6 and S5. The parameters with average values given in Table 3 were evaluated according to SWQMR criteria, and it was determined that all parameters exhibited Class 1 water quality. Black Sea and Marmara coastal and transitional waters were evaluated for DIN (Nitrite + Nitrate +Ammonium) according to eutrophication criteria, and they were found to have an oligotrophic character. Although the concentrations obtained at station S1 are below the limit values, they are higher than the other stations in terms of organic pollution parameters specified in Table 3. During the study, organic and inorganic pollution factors were measured from water samples. Analyses were conducted for a total of 11 different parameters. The average and standard deviation values for Orthophosphate, Nitrite+Nitrate, Ammonium, and Silicate are provided in Table 3, and trace element results are given in Table 4.

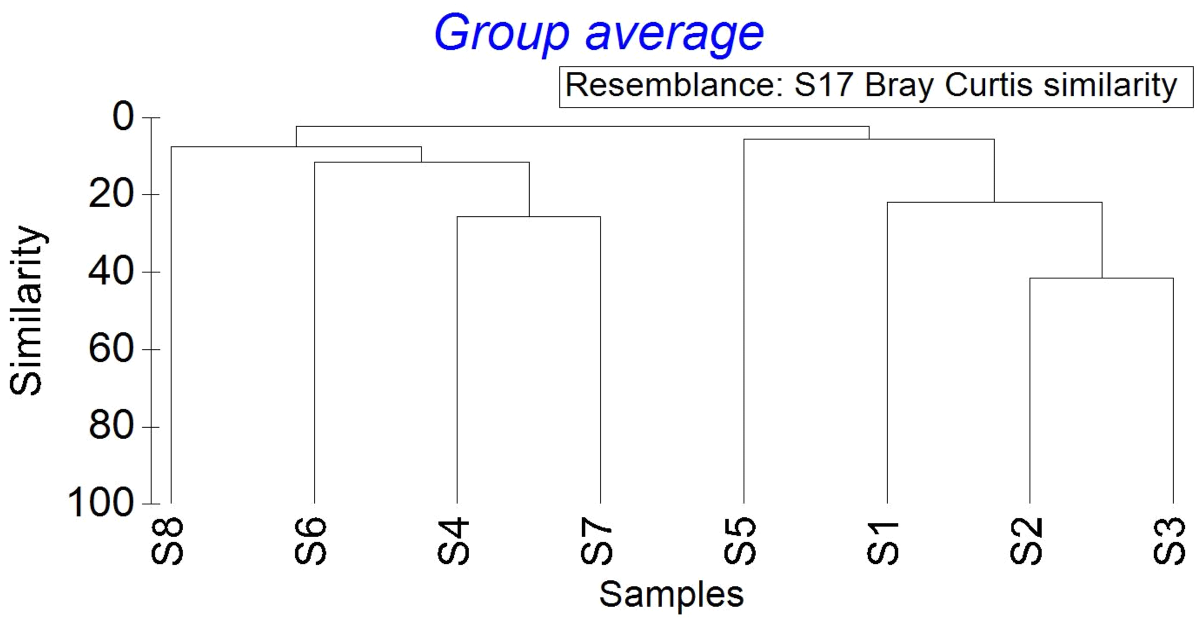

Figure 3. Clustering of stations according to Bray Curtis similarity analysis.

Table 3. Average and standard deviation values of water analyses (mg/L).

Station	o-PO_4	NO_3^{-2}+ NO_2^{-2}	NH_4	Si
S1	1.97±2.554	2.70±12.79	6.18±8.72	229.0±0.883
S2	0.068±0.056	2.49±2.93	1.26±0.042	5.60±3.403
S3	0.003±0	0.019±0.149	0.011±0	1.73±3.11
S4	0.014±0	0.175±0.073	0.072±0	0.27±0.223
S5	0.235±0.097	2.89±4.604	0.141±0.54	244.2±1.17
S6	0.008±0	0.019±0.056	0.062±0	0.193±0.182
S7	0.008±0.02	0.296±193	0.062±0	0.27±0.276
S8	0.062±0.155	0.12±0.22	0.028±0	0.545±0.75

Table 4. Results of metal(loid) analyses from water samples (µg/L)

Station	Al	B	Cr	Cu	Fe	Mn	Zn
S1	9.22 ± 0.269^{cd}	1.19 ± 0.032^{k}	0.34 ± 0.030^{d}	1.84 ± 0.224^{l}	6.04 ± 0.337^{f}	0.39 ± 0.025^{ef}	0.33 ± 0.027^{e}
S2	9.66 ± 0.327^{cd}	1.71 ± 0.035^{f}	0.35 ± 0.021^{d}	3.01 ± 0.125^{g}	7.55 ± 0.488^{de}	0.17 ± 0.009^{i}	0.56 ± 0.052^{c}
S3	8.64 ± 0.184^{de}	2.90 ± 0.041^{b}	0.26 ± 0.025^{ef}	1.46 ± 0.089^{n}	11.27 ± 0.873^{c}	0.33 ± 0.023^{f}	0.42 ± 0.036^{d}
S4	4.10 ± 0.246^{h}	1.12 ± 0.060^{l}	0.14 ± 0.016^{h}	4.03 ± 0.229^{c}	3.50 ± 0.187^{j}	0.16 ± 0.011^{i}j	0.47 ± 0.018^{d}
S5	7.15 ± 0.5204^{e}	1.12 ± 0.028^{l}	0.14 ± 0.013^{h}	4.92 ± 0.321^{b}	11.61 ± 0.744^{c}	0.26 ± 0.017^{g}	0.31 ± 0.026^{f}
S6	5.61 ± 0.227^{g}	1.05 ± 0.026^{m}	0.32 ± 0.028^{d}	1.66 ± 0.151^{m}	2.80 ± 0.224^{k}	0.52 ± 0.028^{d}	0.38 ± 0.028^{e}
S7	16.53 ± 0.429^{a}	3.44 ± 0.057^{a}	0.24 ± 0.018^{f}	3.39 ± 0.243^{f}	8.77 ± 0.512^{d}	0.41 ± 0.024^{e}	0.79 ± 0.068^{b}
S8	10.39 ± 0.401^{c}	1.69 ± 0.037^{f}	0.29 ± 0.034^{de}	2.09 ± 0.157^{k}	5.45 ± 0.369^{fg}	0.34 ± 0.032^{f}	0.62 ± 0.029^{b}

Different letters indicate that the difference between the groups is significant (P<0.05).

In the spectroscopic analyses conducted to determine the concentrations of heavy metals, As, Cd, Co, Hg, Mo, N, Pb and Sn were found to be below the measurable limit. Therefore, they have not been included in the statistical evaluations. Despite not being categorized as heavy metals, Al, B, and Fe were incorporated into environmental assessments because of their toxicological impacts. For the parameters Al, B, Cr, Cu, Fe, Mn, and Zn, the measured minimum and maximum values are as follows: 4,1-16,5 µg/L,1.05-3.44 µg/L, 0.14-0.35 µg/L, 1.46-4.92 µg/L, 2.80-11.61 µg/L, 0.16-0.52 µg/L, and 0.31-0.79 µg/L. Al, B and Fe listed with

In the Pearson correlation analysis conducted to determine the relationship between pollutant factors, a positive correlation was found between B-Orthophosphate and B-Ammonium. It was determined that Zn has a positive correlation with Cu and a negative correlation with Fe (Table 5).

CCA analysis was applied to determine the relationship between the environmental parameter results obtained from water samples and species. In the diagram, it was observed that Mollusca species were negatively affected by all parameters except Cu and Zn, showing a positive relationship with Cu and Zn. M. lineatus is the species closest to the center of the diagram, indicating its higher tolerance to pollutants. Polychaeta species are mainly clustered between Cr and Mn, showing negative correlations with other parameters except these two (Figure 4).

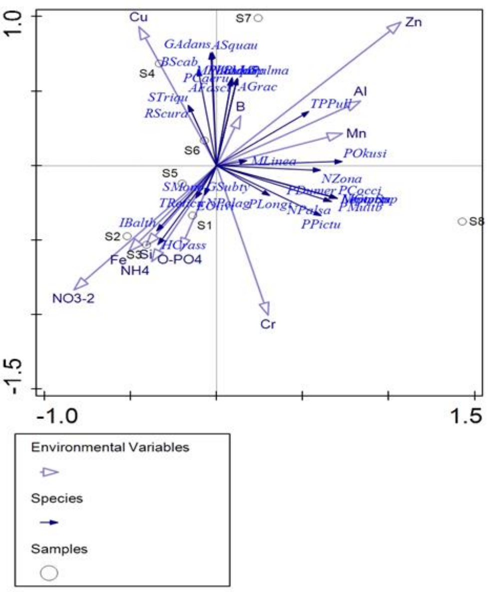

Figure 4. Relationship between environmental parameters and species data with CCA analysis (Water sample).

Table 5. Pearson correlation analysis results of the data obtained from water samples ($p<0.05$)

	o-PO_4	**NO_3^{-2}**	**NH_4**	**Si**	**Al**	**B**	**Cr**	**Cu**	**Fe**	**Mn**
o-PO_4	1									
NO_3^{-2}	0.566	1								
NH_4	0.977	0.587	1							
Si	0.705	0.799	0.602	1						
Al	0.017	**-0.02**	0.045	-0.12	1					
B	**0.006**	-0.24	**0.030**	-0.23	0.824	1				
Cr	0.32	0.084	0.44	-0.18	0.270	0.16	1			
Cu	-0.23	0.369	-0.28	0.310	-0.06	-0.26	-0.76	1		
Fe	-0.07	0.348	-0.12	0.339	0.378	0.486	-0.26	0.26	1	
Mn	0.19	-0.31	0.123	**0.005**	0.252	0.229	0.405	-0.58	-0.18	1
Zn	-0.42	-0.41	-0.35	-0.62	0.761	0.574	0.118	**0.043**	**-0.029**	-0.017

Table 6. Results of metal(loid) analyses from sediment samples (mg/kg).

Station	**Al**	**B**	**Cd**	**Co**	**Cr**	**Cu**	**Fe**	**Mn**	**Mo**	**Ni**	**Pb**	**Zn**
S1	26.28±0.316e	10.25±0.322de	0.02±0.004b	1.20±0.080h	1.79±0.094l	14.72±0.284n	201.4±2.684e	1.88±0.064i	1.78±0.038g	1.28±0.061^{ef}	0.007±0.002fg	25.41±0.689b
S2	26.18±0.209e	11.15±0.394d	0.04±0.005a	1.00±0.041i	1.99±0.048j	20.89±0.487i	186.4±2.587f	1.01±0.034m	1.32±0.074i	0.84±0.014^{h}	0.001±0.001f	20.50±0.768e
S3	33.26±0.342b	14.04±0.517b	0.01±0.002c	1.98±0.064d	2.36±0.069h	9.18±0.255p	225.5±3.185b	3.16±0.113c	2.69±0.086c	1.97±0.073^{bc}	0.009±0.001f	13.01±0.396j
S4	16.737±0.164m	6.67±0.198h	0.03±0.008ab	1.64±0.038f	1.57±0.084n	26.89±0.343c	117.0±1.876m	1.39±0.051k	1.87±0.057ef	1.22±0.047^{f}	0.018±0.004d	8.13±0.524l
S5	21.41±0.214i	9.18±0.288ef	0.01±0.003c	1.58±0.061g	0.94±0.057p	25.90±0.317d	176.9±1.458h	1.82±0.063i	1.98±0.051e	1.57±0.057^{d}	0.018±0.002d	17.30±0.637g
S6	19.37±0.149k	7.63±0.187g	0.009±0.002d	2.08±0.108d	3.64±0.108b	18.54±0.469k	140.5±1.678k	2.62±0.095e	3.15±0.099a	2.16±0.066^{b}	0.051±0.009a	24.96±0.889c
S7	38.54±0.365a	20.04±0.864a	0.01±0.002cd	3.19±0.079a	1.36±0.075o	24.21±0.282e	219.3±2.354c	3.02±0.096c	3.02±0.068ab	2.48±0.091^{a}	0.03±0.014b	15.67±0.712i
S8	25.98±0.243e	10.65±0.426de	0.02±0.002bc	1.11±0.052h	1.86±0.088k	17.63±0.369l	181.9±2.057g	1.96±0.027h	1.89±0.079f	1.47±0.069^{d}	0.002±0.001ef	24.32±0.664c
TEL			0.60		37.3	35.70				18.0	35.0	123.0
PEL			3.53		90.0	197.0				36.0	91.3	315.0
ERL			5.00		80.0	70.0				30.0	35.0	120.0
ERM			9.00		145.0	390.0				50.0	110.0	270.0

Table 7. Pearson correlation analysis results of the data obtained from sediment samples

.	Al	B	Cd	Co	Cr	Cu	Fe	Mn	Mo	Ni	Pb
Al	1										
B	0.938	1									
Cd	-0.27	-0.32	1								
Co	0.453	0.662	-0.66	1							
Cr	-0.15	-0.25	-0.27	**0.034**	1						
Cu	-0.44	-0.140	0.215	0.165	-0.49	1					
Fe	0.936	0.809	-0.24	0.237	-0.22	-0.53	1				
Mn	0.596	0.593	-0.87	0.761	0.309	-0.44	0.49	1			
Mo	0.301	0.403	-0.87	0.850	0.464	-0.16	0.136	0.900	1		
Ni	0.441	0.560	-0.91	0.893	0.259	-0.11	0.290	0.926	0.965	1	
Pb	-0.205	**0.001**	-0.64	0.683	0.480	0.261	-0.34	0.480	0.804	0.713	1
Zn	-0.018	-0.130	-0.11	-0.347	0.395	-0.33	0.129	-0.054	-0.06	**-0.05**	**0.028**

The measurements from sediment samples evaluated almost the same elements as the water samples, and results were obtained for 12 parameters at all stations. The minimum and maximum values for the measured parameters Al, B, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, Pb, and Zn are as follows: 16,7-38,5; 6.67-20.04; 0.009-0.04; 1.00-3.19; 0.94-3.64; 9.18-26.896; 117.0-225.5; 1.82-3.16; 1.32-3.15; 0.84-2.48; 0.001-0.051 and 8.123-25.41 mg/kg, respectively. The mean and standard deviation values are given in Table 6. When compared with Sediment Quality Guidelines (SQG), the obtained values indicate that all parameters are within the low-impact range, suggesting no significant contamination. In the correlation table, a positive correlation was observed between Cr-Co and Pb-B. It was determined that Zn has a positive correlation with Pb and a negative correlation with Ni.

4. Discussion

In previous studies conducted in this region, almost all benthic groups have been recorded. Dağlı et al. (2008), identified 17 polychaeta species belonging to 2 families from depths of 8-680 m in the Saros Gulf. Arısal (2012), identified 45 polychaeta species belonging to 21 families from depths of 0-30 m in the Kapıdağ Peninsula's littoral region. Avcı (2019), identified 68 polychaeta species belonging to 31 families from depths of 5-30 m in Büyükçekmece Bay. In this study conducted along the coasts of Sea of Marmara, 9 polychaete species were identified from depths of 0-3 m. The different depths sampled and the absence of seasonal sampling prevented reaching all of the species recorded in the literature.

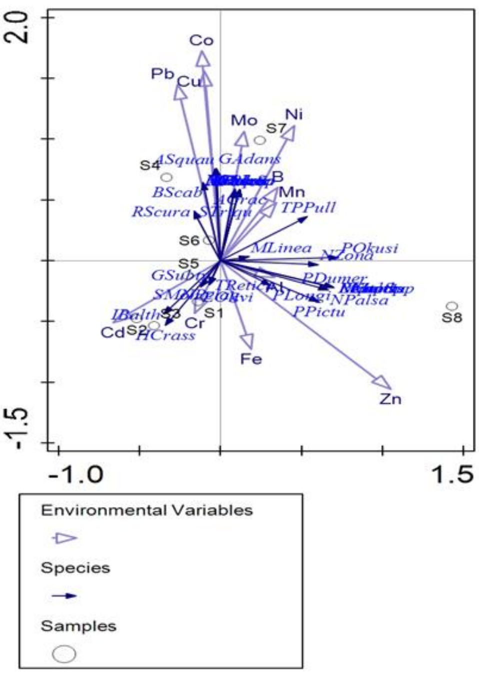

Figure 5. Relationship between environmental parameters and species data with CCA analysis (Sediment sample).

Türkçü et al. (2015), in their study investigating mollusca species in the Mytilus galloprovincialis facies in Sea of Marmara, identified 52 mollusca species belonging to 25 families. Bitlis et al. (2022), recorded 66 mollusca species belonging to 28 families from depths of 0.2-5 m in Kemer Bay. In the sampling from depths of 0-3 m along the coasts of Sea of Marmara, 10 species belonging to the Mollusca phylum were identified. The recorded species during the study consist of those previously identified in the literature, making the findings consistent with previous studies.

In the Istanbul Strait, connecting Sea of Marmara, Sowinsky (1897) identified amphipod and isopod fauna. Balkıs and Albayrak (1994) identified 20 amphipod species in their studies aimed at determining the benthic amphipods of the Istanbul Strait. Balkıs et al. (2002) compiled a species list for the Crustacea fauna of the Istanbul Strait. Kurun (2010), examined the benthic amphipoda fauna and distributions in Bandırma and Erdek bays for his doctoral study. Artüz (1967), Erden and Erim (1971), and Bilecik (1985), noted the presence of P. longirostris, a commercially important species in the northern parts of the Sea of Marmara. The P. longirostris species, being one of the dominant commercial shrimp species in Sea of Marmara and Aegean Seas, is also recorded in the straits. The species has been identified along Sea of Marmara coasts in various studies since the 1950s. In this study, P. longirostris was identified at stations in S1, S3, S4, and S8. The findings regarding this species are consistent with the literature. In the samplings from Sea of Marmara coasts, 8 species belonging to the Arthropoda phylum, including 4 Amphipods, 3 Isopods, and 1 Decapod, were identified. The recorded Crustacea species during the study consist of those previously identified in the literature, making the findings consistent with previous studies.

Öztoprak et al. (2014), recorded the presence of A. squamata species in the Black Sea and Sea of Marmara. This species was encountered at stations S7 and S4 along Sea of Marmara coasts. The detection of this species near the straits is consistent with previous studies.

Nemertea species were studied by Demir (1952) in the Istanbul Strait and Sea of Marmara, where 8 species were recorded. In the following years, they were also identified from the coasts of the Black Sea and the Aegean Sea.

One of the sea anemones known to prefer sandy and rocky bottoms and found in the Çanakkale Strait, connecting Sea of Marmara with the Aegean Sea, and the northern parts of Sea of Marmara, is A. equina. In 2022, this species was encountered at the S7 station along Sea of Marmara coasts. The findings support the existing literature. Silicate, which is found in the Earth's crust at a rate of 58% and plays a significant role in the formation of the cell wall of some marine organisms, is an important component of the seas. In a study investigating the effect of silicate, which is not present in high concentrations in seawater, on diatom growth, it was found that high silicate adversely affected growth (Büyükışık et al. 1994). In the doctoral study conducted by Kurun (2010), samples were taken from selected stations in the Sea of Marmara, and silicate values were measured between 1.37-55.97 micrograms/L. In comparison to the pre-mucilage period, silicate was found to be higher in 2022. In the analyzes conducted along Sea of Marmara coasts, the highest silicate concentrations were detected at stations S1 and S5. It was observed that the values at these stations were higher than in other studies.

In the Marine Quality Bulletin of Marmara, ÇSB (2018), it was determined that the concentration of nutrients in Sea of Marmara was highest in winter and lowest in spring. In the ecological quality assessment of coastal waters, it was evaluated that they were mostly of good/medium quality, and Çanakkale-Şarköy-Tekirdağ coasts were evaluated as good/very good quality. In a study by Tan (2021), evaluating the pressure-impact and eutrophication situations in the Gulf of the Marmara, it was determined that Gemlik Inner and Bandırma Gulfs were under high pressure, having eutrophic and hyper-eutrophic characteristics, while Gemlik Outer and Erdek Gulfs were under medium pressure with mesotrophic characteristics. Due to its association with the open sea, which is beyond the seasonal effects of the Susurluk River and Nilüfer Creek, Gemlik Outer Bay is reported to be farther from the pressure of pollutants, thus having higher water quality. The presence of intense industrial facilities in the Kocaeli and Bursa provinces may lead to a higher impact of pollutants at Station S1. However, the presence of two advanced treatment plants near the Gemlik Bay and a preliminary treatment plant with a deep discharge system in the Gemlik district has ensured the elimination of pollution load.

In a study conducted by Bozkurt Kopuz, and Kara (2020), on the beaches of the Sea of Marmara, heavy metal concentrations were detected, and they stated that these concentrations were not at dangerous levels for human health and aquatic life. Mülayim et. al. (2012), found that Pb, Cd and Hg contents in Sea of Marmara were higher than shale values at all stations, and other metals except Pb were at lower concentrations in the surface sediment. Algan et al. (2004), in a study comparing metal concentrations in the northern and southern shelves of Sea of Marmara, found that the concentrations were higher in the southern shelves. In the heavy metal measurements made from 8 stations selected from Sea of Marmara estuarines, it is seen that the pollutant load is at a minimum level, but since there are no periodic samples, no comparison can be made.

Surugiu (2011) pointed out that some species of Polychaeta can be used as indicators, with Nereis zonata being sensitive to organic pollution, while most polychaete species are opportunistic and can be found in abundance in eutrophic waters. In Figure 4 and Figure 5, a positive correlation between polychaete species such as P. dumerilii, N. palsa, N. zonata, P. pictus and metals like Fe, Zn, Mn, and Cr is observed. It is suggested that these species may exhibit tolerance to specific increases in the concentrations of these metals.

5. Conclusions

This study identified aquatic invertebrate species at 8 selected stations from the estuarines in Sea of Marmara. A total of 33 species were encountered. Pollutant loads were determined using water and sediment samples collected from the same points. Nutrient and heavy metal concentrations indicated that pollution loads were at a minimum during the sampling period at these points. However the lack of data on heavy metal accumulation in invertebrate tissues, owing to inadequate sample size, constrains the direct evaluation of pollution's biological effects. Subsequent research utilizing these data will yield significant insights into species' pollution tolerance and their impact on ecosystem dynamics. The estuary stations harbor organisms that have physiologically adapted to these areas. Therefore, conducting repeated sampling in these areas is important both to reach a greater number of species and to estimate the degree to which environmental parameters affect the population.

Author contribution

The author assumed responsibility for all aspects of the research process, including conceptualisation, formal analysis, data curation, writing and editing, supervision, project administration, and funding acquisition.

Acknowledgements

Samples were taken during the fieldwork FBA-2021-1269 project supported by Research Funds of the Recep Tayyip Erdogan University. I would like to thank Kadir Can ÇALIŞKAN for his help in sampling and Assoc. Prof. Dr. Hazel BAYTAŞOĞLU and Prof. Dr. Ahmet Mutlu GÖZLER for the identification of invertebrate species.

Financing Statement

Samples were taken during the fieldwork FBA-2021-1269 project supported by Research Funds of the Recep Tayyip Erdogan University.

Conflict of Interest Statement

The authors declare that they have no conflict of interest.

Ethical Standards

No Ethics Committee Approval is required for this study.

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