ISSN 1573-160X, *PHYSICAL OCEANOGRAPHY*, Vol. 33, Iss. 2, pp. 319-338 (2026)
Original Russian Text © D. A. Kremenchutskii, E. A. Kotelyanets, 2026,
published in *Morskoy Gidrofizicheskiy Zhurnal*, 2026, Vol. 42, Iss. 2, pp. 275–293

Original article

Heavy Metals in Suspended Matter in the Northern Black Sea

D. A. Kremenchutskii ✉, **E. A. Kotelyanets**

Marine Hydrophysical Institute of RAS, Sevastopol, Russian Federation
✉ *d.kremenchutskii@mhi-ras.ru*

Abstract
Purpose. The purpose of the study is to obtain quantitative characteristics of the spatial variability of heavy metal concentrations in suspended matter, as well as to assess the relationship between this variability and the hydrological and hydro chemical characteristics of the northern Black Sea waters.
Methods and Results. Data on the volume and mass concentrations of heavy metals (Pb, Zn, Ni, Fe, Cr, V, Co) in the Black Sea suspended matter obtained during the 133rd cruise of R/V *Professor Vodyanitsky* were used. A total of 44 water samples were collected at 33 stations and processed. The data on metal content were obtained using X-ray fluorescence analysis.
Conclusions. The volume and mass concentrations of the analyzed metals in suspended matter varied spatially within two orders of magnitude. Elevated volume concentrations of heavy metals were observed in the northeastern part of the study area, whereas lower values were typical in its southwestern part. The spatial variability in mass concentrations of heavy metals exhibited a more complex pattern. Elevated values of Pb, Zn, and Ni were noted in the deep part of the sea, while lower values were observed in the coastal area. Elevated values of Fe and V were typical of the shelf section from Cape Meganom to Cape Chauda, and lower values were typical of the deep-sea part. Higher and lower concentrations of Cr and Co were observed both on the shelf and in the deep-sea part of the study area. In the deep part of the sea, the mass and volume concentrations of metals both increased and declined with depth. In the upper part of the thermocline, the volume (Pb, Ni, Fe, Cr, V, Co) and mass (Fe, Cr, V, Co) concentrations of most heavy metals rose by a factor of 1.1–47.1. On the shelf in the near-bottom layer, the volume (Zn, Fe, Cr, V, Co) and mass (Zn, Fe, V, Co) concentrations of most heavy metals also grew by a factor of 1.1–137. Principal component analysis showed that the spatial variability of volume and mass concentrations of Fe, V, Co, and Cr is related to the impact of the lithogenic factor (coastal abrasion, inflow of the Sea of Azov waters, and atmospheric transport), the variability of Zn and Ni is driven by the influence of the biogenic factor (phytoplankton production, adsorption on organic matter), and the Pb variability is related to the hydrodynamic factor (mixing depth variability).

Keywords: heavy metals, Black Sea, suspended matter, spatial variability

Acknowledgments: The authors are thankful to the captain and crew of R/V *Professor Vodyanitsky* for their assistance in onboard operations, as well as to the members of the hydrology and currents group for providing temperature and salinity data. Water samples were taken at the Collective Use Center R/V *Professor Vodyanitsky* of FSBSI FRC A.O. Kovalevsky Institute of Biology of the Southern Seas. The study was carried out within the framework of the state-assigned research themes of FSBSI FRC MHI FNNN-2024-0001 and FNNN-2024-0016.

For citation: Kremenchutskii, D.A and Kotelyanets, E.A., 2026. Heavy Metals in Suspended Matter in the Northern Black Sea. *Physical Oceanography*, 33(2), pp. 319-338.

Introduction

Heavy metals (HMs) are a group of chemical elements with a relatively high atomic mass or density (usually exceeding 5 g/cm^3) that exhibit a tendency for bioaccumulate [1–3]. The most studied HMs in aquatic ecosystems include Pb, Zn, Ni, Fe, Cr, V, and Co. The interest in Pb and Cr is due to the fact that these metals are toxic to living organisms even at low concentrations [4–6]. The influence of the other metals (Zn, Ni, Fe, V, Co) play a dual role: at low concentrations, they are essential micronutrients required for the normal functioning of certain living organisms; however, at elevated concentrations, they can disrupt physiological and biochemical processes and induce metabolic changes in aquatic organisms [6–11].

HMs enter the marine environment through various processes: coastal abrasion, dry and wet atmospheric deposition, river runoff, and direct discharge of industrial waste [12–14]. Marine pollution by petroleum products is another important source of HMs [13, 15]. In the marine environment, HMs are distributed between dissolved and suspended forms. Settling suspended particulate matter plays a crucial role in the vertical transport of HMs; the sedimentation of adsorbed HMs on suspended matter is the primary mechanism for their removal from the water column [16, 17]. Thus, data on HM concentrations in suspended particulate matter are necessary to assess the rate and time of their removal from the water column. This underlines the relevance of the present study.

The Black Sea, being a semi-enclosed basin with limited water exchange, represents a unique natural system particularly sensitive to anthropogenic impact [18]. Results from recent studies indicate an increase in HM concentrations in the bottom sediments of the Black Sea shelf [19, 20], which may also suggest an increase in their concentration in the water.

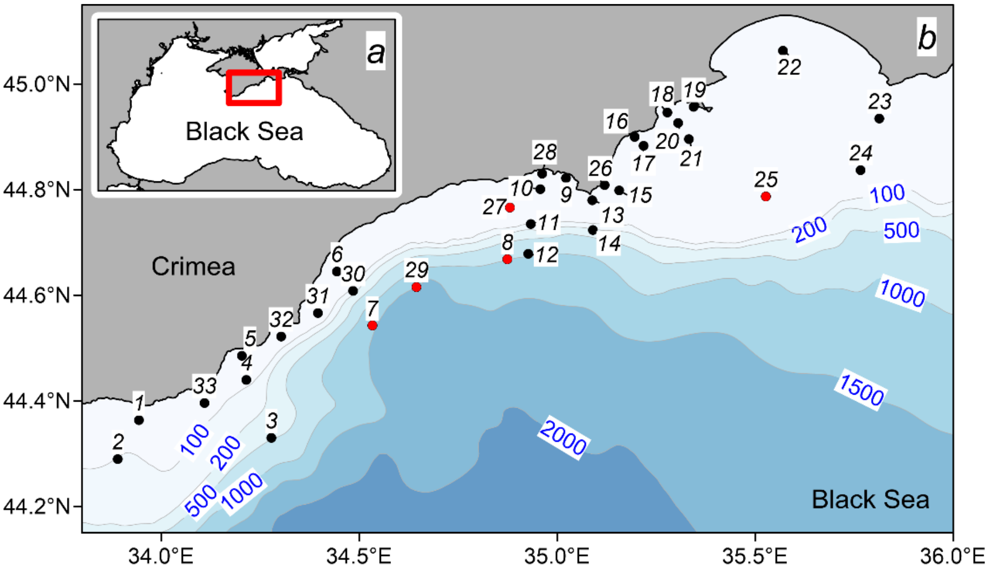
It should be noted that many studies focus on HM concentrations in aquatic organisms [10, 13, 21], bottom sediments [13, 22, 23], and dissolved forms in seawater [13, 14, 21, 24, 25] in the Black Sea. At the same time, data on HM concentrations in suspended particulate matter are very limited [21, 26–29], and for the area presented in this work, they are absent from the available literature. This highlights the novelty of the present study.

The purpose of the study is to obtain quantitative characteristics of the spatial variability of heavy metal concentrations in suspended matter, as well as to assess the relationship between this variability and the hydrological and hydro chemical characteristics of the northern Black Sea waters.

Materials and methods

Sampling

Field data were obtained during the 133rd cruise of the R/V *Professor Vodyanitsky* (September 11 – October 3, 2024). Seawater samples were collected in plastic containers using a SP15P-B-6-95 pump (Finish Thompson Inc., USA), which prevents sample contamination by heavy metals. A total of 44 water samples were collected from 33 stations. The station layout is shown in Fig. 1. At each station, seawater sampling was carried out at a depth of 3 m. At stations *7*, *8*, *25*, *27*, and *29*, an additional 2–3 samples were collected from depths of up to 66 m to obtain data on the vertical distribution of the analyzed parameters. The depths for water sampling were selected directly during the work, using data on the vertical temperature profile.



F i g. 1. Study area (*a*) and the location of seawater sampling stations there (*b*). Red dots indicate the station locations where vertical profiles were obtained

Determination of total suspended matter (TSM) concentration

The methodology for TSM determination is based on RD 52.24.468-2019 “Mass concentration of suspended solids and dry residue in water. Gravimetric measurement procedure.” The main difference was that new and used filters were dried in a drying oven for 24 hours, which reduced the number of drying-and-weighing cycles to one.

Concentration of suspended matter was determined using a vacuum filtration system with membrane filters made of cellulose nitrate (pore diameter 0.45 μm) on board the ship immediately after sample collection. From 3.35 to 20.45 L of seawater were filtered through a single filter. The volume of water filtered depended on the concentration of suspended matter and was preliminarily assessed visually by the filtration rate. The filtered water was collected in 5 L plastic containers. The volume of water passed through a single filter was determined by gravimetry under minimal rolling conditions, using electronic scales with an accuracy of 1 g. Upon completion of filtration, the filter was packed in a plastic Petri dish and stored at –20 °C until drying in the drying oven. The concentration of suspended matter in water was calculated as the ratio of the difference between the filter masses after and before water filtration to the volume of water filtered.

Determination of heavy metal concentrations

In this study, measurements were performed for the following heavy metals: Pb, Zn, Ni, Fe, Cr, V, and Co. Their concentration on the filter was determined by X-ray fluorescence analysis using a SPECTROSCAN MAKS-GVM spectrometer (SPECTRON JSC, Russia). The spectrometer was calibrated using calibration sample sets GH-1 and GH-2 (SPECTRON JSC, Russia). The SpectrQuant software (SPECTRON JSC, Russia) was used to control the spectrometer operation and obtain quantitative values of HM content on the filter. The measurement error averaged 17% for Pb, 4% for Zn, 6% for Ni, 2% for Fe, 5% for Cr, 3% for V, and 36% for Co. The minimum measurable content was 0.01 μg for Pb and Zn, 0.02 μg for Cr, 0.03 μg for Ni and Co, 0.05 μg for V, and 0.06 μg for Fe.

Values of volume-based metal concentration in suspended matter were calculated by normalizing the metal content values on the filter by the volume of water passed through the filter. Values of mass concentration of metals in suspended matter were obtained by normalizing their volume-based concentration in suspended matter by the concentration of suspended matter.

Hydrological data

Temperature and salinity measurements during the cruise were performed using IDRONAUT Ocean Seven 320 plus CTD profilers (Idronaut S.R.L., Italy) and Seasun CTD48 (Sea & Sun Technology GmbH, Germany). The measurement errors for temperature and salinity did not exceed 0.002 °C and 0.01, respectively.

The mixing layer depth (MLD) was determined from the vertical temperature profile by identifying the horizon at which the temperature decrease relative to the surface layer reached 0.5 °C.

Statistical analysis

Calculations were carried out using SPSS Statistics (IBM Corporation). Pearson correlation coefficients were used to assess relationships between the studied parameters, allowing for the identification of linear dependencies between quantitative variables. Correlation coefficient values were considered statistically significant at a confidence level of at least 95% ($p \leq 0.05$), which ensured the reliability of the identified relationships and reduced the probability of chance associations.

To assess the applicability of multivariate statistical analysis methods, the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy was calculated for two datasets. The first dataset included data on volume-based HM concentration, suspended matter concentration, station depth (*StD*), and mixing layer depth. In the second dataset, volume-based HM concentration data were replaced with data on mass concentration. Data on the vertical distribution of these parameters were excluded from both datasets. The KMO values were 0.65 and 0.53 for the first and second datasets, respectively, indicating a satisfactory level of sampling adequacy and suggesting the suitability of the datasets for further analysis using principal component analysis (PCA). Additionally, Bartlett's test of sphericity was applied to test the hypothesis of no correlations among variables. The obtained significance values ($p < 0.001$ in both cases) indicate the presence of statistically significant relationships among the analyzed parameters, which is a necessary condition for using PCA and confirms the appropriateness of its application.

PCA was used to identify latent factors determining the joint variability of HM concentrations. To enhance clarity and facilitate the interpretation of the obtained factors, orthogonal Varimax rotation was applied, aimed at maximizing the variance of factor loadings. The use of this rotation method allows for a clearer delineation of the contribution of individual variables to factor formation and aids in their interpretation in terms of physical and geochemical processes.

Results and discussion

Distribution of heavy metals in the upper mixed layer of the sea

The volume-based concentration (μg/L) of the discussed HMs varied spatially over a wide range: < 0.01–0.24 for Pb; < 0.03–2.61 for Zn; < 0.01–0.12 for Ni; 1.07–36.71 for Fe; < 0.02–0.24 for Cr; < 0.02–0.36 for V; < 0.02–0.25 for Co. The obtained data are consistent with those presented in the available literature on the Black Sea (Table 1): 0.002–0.307 for Pb; 0.002–1.103 for Zn; 0.01–4.3 for Ni; 0.13–148 for Fe; 0.04–1.47 for Cr; 0.0003–0.87 for V; 0.0007–0.11 for Co.

The mass concentration (μg/g) of HMs, like the volume-based concentration, varied spatially within two orders of magnitude: < 11–819 for Pb; < 16–6240 for Zn; < 19–390 for Ni; 10999–115930 for Fe; < 20–663 for Cr; < 59–1220 for V; < 38–877 for Co. The reported concentration values are consistent with published data (Table 1): 2–251 for Pb; 6–2630 for Zn; 2–2200 for Ni; 130–130000 for Fe; 24–1867 for Cr; 1–97 for V; 0.4–39 for Co.

The spatial variability of the volume-based concentration of HMs exhibited a complex distribution pattern (Fig. 2). Elevated and often maximum concentration values for the discussed HMs were observed in the northeastern part of the study area, namely on the shelf from Cape Meganom to Cape Chauda. Reduced concentration values were characteristic of the southwestern part of this area. An exception was Zn, for which elevated values were observed in the deep-sea part of this area and in the coastal zone near Sudak. Notably, for all HMs, reduced values were observed both on the shelf and in the deep-sea part.

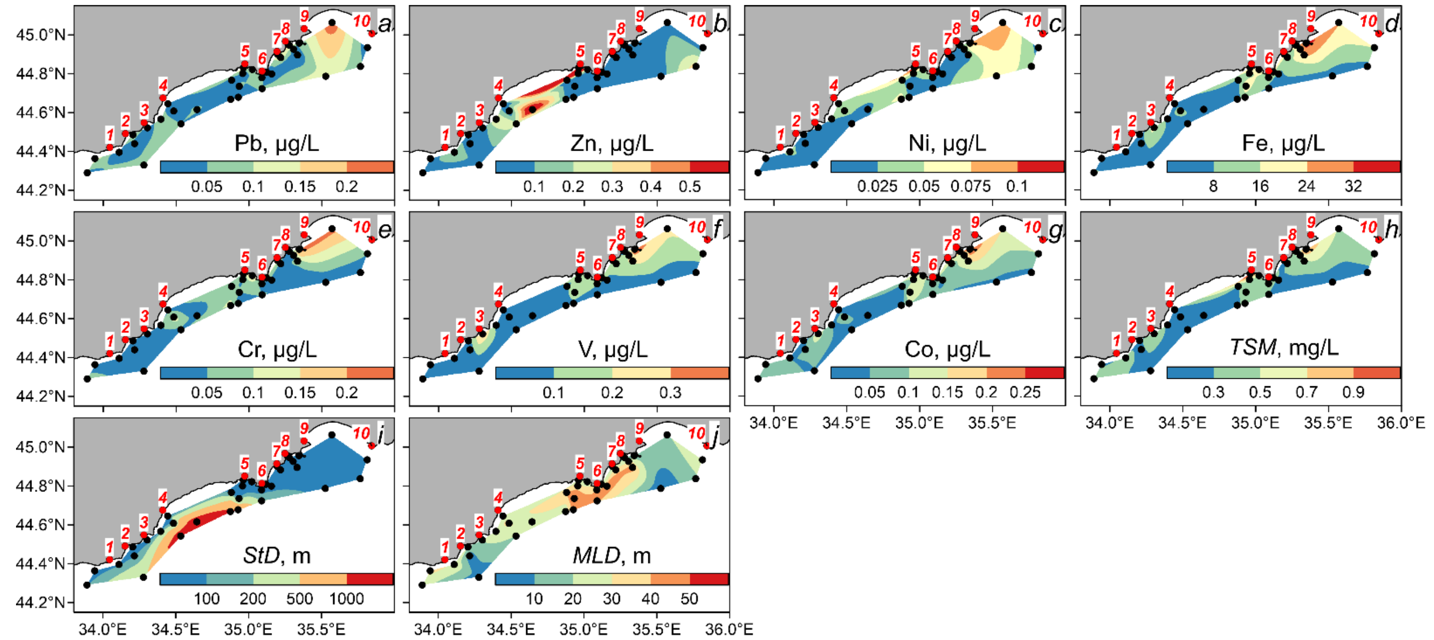
The identified features of the spatial variability of volume-based HM concentration are consistent with data obtained for other areas of the Black Sea. According to the results of a study conducted on the northwestern shelf of the Black Sea presented in [29], the volume-based concentration of Fe in suspended matter in surface waters decreased from the shelf to the continental slope from 3.9 to 0.6 μg/L, respectively. In [28], data on the variability of volume-based HM concentration in suspended matter at the 10–20 m horizon along a transect from the Bosphorus Strait to the deep-sea part of the Black Sea are presented. Comparing the data obtained at the station in the strait with those from the deep-sea part, a decrease in concentrations for all HMs can be observed. When comparing data obtained only from the deep-sea part of this transect, it can be noted that the concentration of Zn, Fe, and V tends to decrease with distance from the shore.

Fig. 3 shows the spatial distributions of the discussed mass concentration values of HMs. Elevated values of Pb, Zn, and Ni were noted in the deep-sea part of the sea, while reduced values were observed in the coastal area. Elevated values of Fe and V were characteristic of the shelf section from Cape Meganom to Cape Chauda, while reduced values were characteristic of the deep-sea part. The spatial variability of Cr and Co was more complex: elevated and reduced values were observed both on the shelf and in the deep-sea part of the study area. Notably, maximum or near-maximum mass concentration values for most HMs (Pb, Fe, Cr, V) were recorded on the shelf near Kurortnoye settlement.

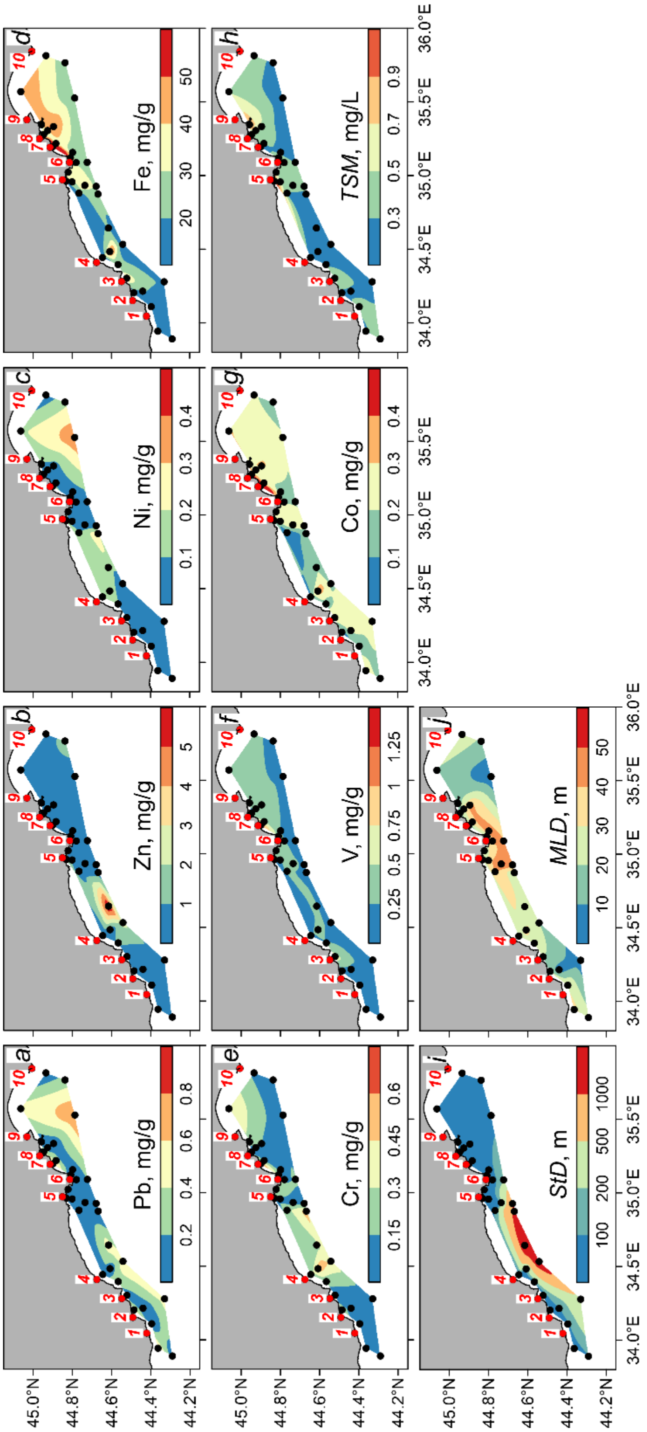
T a b l e 1

Data on the volume and mass concentration of heavy metals (HM) on suspended matter in the waters of the Black Sea

HM	Volume concentration, µg/L				Mass concentration, µg/g				
	This study	[28]	[21]	[27]	This study	[28]	[30]	[27]	[31]
Pb	< 0.01–0.24	0.006–0.27	0.074	0.002–0.307	< 11–819	7–110	17.0	2–121	15–251
Zn	< 0.03–2.61	0.002–0.91	1.103	0.009–0.496	< 16–6240	6–100	67.0	12–359	20–2630
Ni	< 0.01–0.12	0.008–4.3	0.071	0.001–0.123	< 19–390	6–2200	47.0	2–36	–
Fe	1.07–36.71	0.27–193	–	0.13–148	10999–115930	164–5933	35200.0	116–130000	130–13100
Cr	< 0.02–0.24	0.04–1.47	–	–	< 20–663	24–1867	92.0	–	48–1161
V	< 0.02–0.36	$0.3 \cdot 10^{-3}$–0.87	–	–	< 59–1220	1–14.0	97.0	–	–
Co	< 0.02–0.25	$0.7 \cdot 10^{-3}$–0.11	0.005	< 0.001–0.026	< 38–877	0.4–13	17.3	0.38–39	–



F i g. 2. Spatial variability of concentrations of various metals in suspended matter (*a* – *g*) and suspended matter concentration (*h*) at 3 m depth, as well as station depth (*i*) and mixing layer depth (*j*) for the analysis of HM volume-based concentration. Numbers indicate the following geographical objects: *1* – Alupka, *2* – Yalta, *3* – Gurzuf, *4* – Alushta, *5* – Sudak, *6* – Cape Meganom, *7* – Kurortnoye settlement, *8* – Koktebel settlement, *9* – Feodosia, and *10* – Cape Chauda



F i g. 3. The same as in Fig. 2, at HM mass concentration

Table 2

Paired correlation coefficients between the volume concentration of heavy metals (μg/L), suspended matter concentration (mg/L), station depth (m) and mixing depth (m)

Parameter	Pb	Zn	Ni	Fe	Cr	V	Co	*TSM*	*StD*	*MLD*
Pb	1.00	0.21	0.32	0.14	0.18	0.03	0.26	0.10	–0.17	–0.31
Zn	–	1.00	0.56	0.13	0.05	–0.02	0.16	0.55	0.10	–0.07
Ni	–	–	1.00	0.38	0.56	0.28	0.30	0.49	–0.09	–0.25
Fe	–	–	–	1.00	0.65	0.90	0.92	0.76	–0.39	0.03
Cr	–	–	–	–	1.00	0.60	0.48	0.38	–0.11	–0.18
V	–	–	–	–	–	1.00	0.76	0.60	–0.39	0.02
Co	–	–	–	–	–	–	1.00	0.74	–0.35	–0.01
TSM	–	–	–	–	–	–	–	1.00	–0.36	0.05
StD	–	–	–	–	–	–	–	–	1.00	–0.01
MLD	–	–	–	–	–	–	–	–	–	1.00

Note: Statistically significant correlation coefficients are highlighted in red

The results of the correlation analysis indicate the presence of statistically significant relationships between the spatial variability of volume-based concentrations of individual HMs (Table 2). Such a relationship was observed in the pairs Fe – Ni (r = 0.38), Fe – Cr (r = 0.65), Fe – V (r = 0.90), Fe – Co (r = 0.92). This may be due to both the adsorption of these metals onto Fe [27, 28] and the similarity of their geochemical behavior, where concentration variability is determined by the same physicochemical processes. The absence of significant relationships between Fe and Pb, Zn may indicate differences in the sources or sinks of these metals in the study area. The spatial variability of the volume-based concentration of most HMs (Zn, Ni, Fe, Cr, V, Co) is linked to the spatial heterogeneity of the suspended matter concentration field: the correlation coefficient values are 0.55 (Zn), 0.49 (Ni), 0.76 (Fe), 0.38 (Cr), 0.60 (V), and 0.75 (Co). Thus, the more suspended matter contained in a unit volume of seawater, the higher the concentration of HMs in the suspended matter. Statistically significant negative correlation coefficients between water depth and the volumetric concentration of Fe (r = –0.39), V (r = –0.39), Co (r = –0.35), and suspended matter (r = –0.36) may indicate that the source of these metals (e.g., coastal abrasion) in the study area is located in the shelf zone.

The analysis results (Table 3) indicate the presence of statistically significant relationships between changes in the mass concentration of Fe in suspended matter and those of Cr (r = 0.56), V (r = 0.92), and Co (r = 0.86). The absence of a statistically significant relationship between Fe and Zn or Ni may be due to the fact that these two heavy metals (Zn and Ni) have local sinks – they are actively consumed by phytoplankton [32]. The absence of a statistically significant relationship between Fe and Pb may be due to differences in the sources of these metals. Lead enters the marine environment primarily from the atmosphere [33], but atmospheric flux is not the only source of iron in the marine environment. Notably, only for Pb is there a statistically significant correlation with changes in suspended matter content ($r = -0.41$): an increase in suspended matter concentration is accompanied by a decrease in the mass concentration of Pb on the suspended matter. This is likely related to a dilution effect: the concentration of suspended matter is higher on the shelf than in the deep-sea part due to the presence of additional material sources.

Table 3

Paired correlation coefficients between the mass concentration of heavy metals (μg/g), suspended matter concentration (mg/L), station depth (m) and mixing depth (m)

Parameter	Pb	Zn	Ni	Fe	Cr	V	Co	*TSM*	*StD*	*MLD*
Pb	1.00	0.31	0.30	0.10	0.12	0.06	0.35	–0.41	0.14	–0.40
Zn	–	1.00	0.20	–0.22	0.07	–0.15	–0.16	–0.11	0.63	–0.08
Ni	–	–	1.00	0.09	0.34	0.10	0.00	–0.23	0.13	–0.33
Fe	–	–	–	1.00	0.56	0.92	0.86	0.09	–0.26	–0.01
Cr	–	–	–	–	1.00	0.52	0.37	–0.19	0.25	–0.13
V	–	–	–	–	–	1.00	0.71	0.08	–0.29	0.02
Co	–	–	–	–	–	–	1.00	–0.04	–0.13	–0.12
TSM	–	–	–	–	–	–	–	1.00	–0.36	0.05
StD	–	–	–	–	–	–	–	–	1.00	–0.01
MLD	–	–	–	–	–	–	–	–	–	1.00

Note: Statistically significant correlation coefficients are highlighted in red

Vertical distribution of HMs. Vertical profiles of volumetric and mass metal concentrations are shown in Fig. 4.

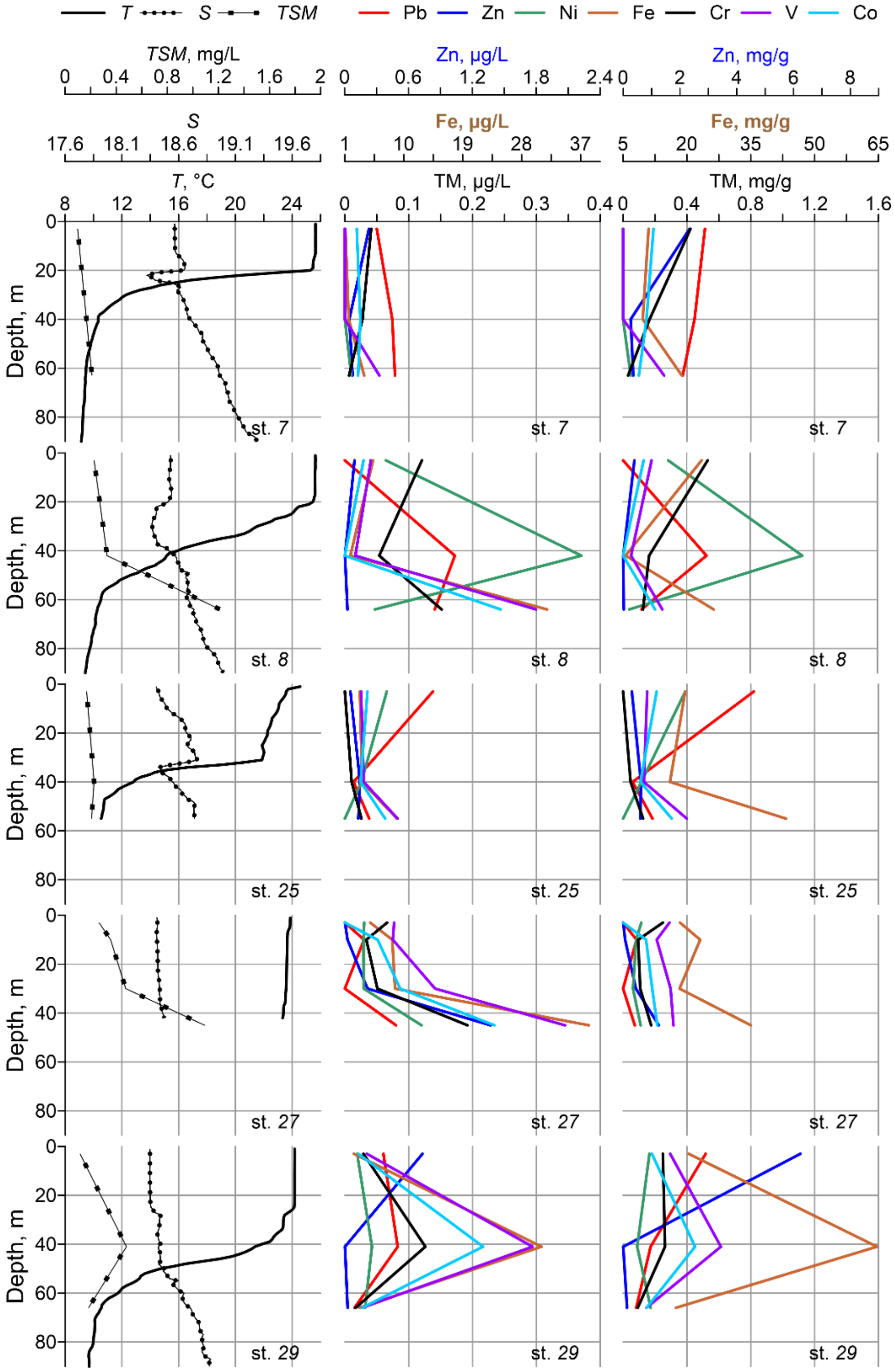
At stations located in the deep-sea part of the Black Sea (st. *7*, *8*, *29*), a decrease with depth (comparing data from horizons at 3 and 63–66 m) was observed for the volume-based and mass concentrations of Zn by 3.1–29.4 and 6.6–47.1 times, respectively, along with an increase in the volume-based concentration of Fe by 1.3–6.0 times and Co by 1.1–8.3 times. The mass concentration of Fe in suspended matter either increased with depth (by 1.1–1.7 times) or decreased (by 1.2 times). Regarding Co, its mass concentration increased by a factor of 1.6 and decreased by 1.2–1.9 times. The volume-based concentration of other HMs both increased and decreased with depth: by 1.6 and 4–14 times, respectively, for Pb; by 1.6 and 1.4 times for Ni; by 1.3 and 1.7–6.25 times for Cr; and by 5–7.4 and 1.3 times, respectively, for V. The mass concentration of these metals also both increased and decreased with depth: by 12 and 1.4–6.3 times, respectively, for Pb; by 1.1–5 and 7.3 times for Ni; and by 1.4–26 and 2 times for V. The mass concentration of Cr increased only with depth by 2.7–13.5 times.

The obtained results are in good agreement with published data. Analyzing the data presented in [28], a trend towards a decrease with depth in volume-based concentration of Pb, Zn, Ni, V, and Co can be noted.

On the shelf (st. *25* and *27*), an increase with depth was observed for the volume-based and mass concentrations of most metals: by 2.4–137 and 2–125 times, respectively, for Zn; by 2.7–7.8 and 1.9–2.2 times for Fe; by 3.2–4.5 and 1.1–2.6 times for V; by 1.8–23 and 1.5–21 times for Co. The volume-based concentration of Cr showed an increase with depth by 2.9–3 times, while its mass concentration increased by a factor of 13 at st. *25* and decreased by a factor of 1.4 at st. *27*. The volume-based and mass concentrations of Pb increased by 8 and 7 times, respectively, at st. *27* and decreased by 3.6 and 4.4 times at st. *25*. The volume-based and mass concentrations of Ni at the same stations increased by 4 and 39 times and decreased by 7 and 1 times, respectively. The increase in the volume-based concentration of HMs in suspended matter with depth observed for most HMs is likely due to an increase in suspended matter concentration. As shown above in the analysis of spatial variability in the upper mixed layer, an increase in suspended matter concentration is accompanied by an increase in the volume-based concentration of HMs in the suspended matter. The increase in mass concentration of HMs may be due to their adsorption onto suspended matter during its settling. The maximum concentration of suspended matter in the bottom layer may be related to a decrease in its settling velocity due to reduced water dynamics.

According to the results of a study conducted on the northwestern shelf of the Black Sea presented in [29], the volume-based concentration of Fe in suspended matter increases from the surface layer to the bottom layer by 5–46 times. The authors of [27] noted the presence of a maximum concentration of Co, Ni, and Zn in the bottom layer, which was associated with the maximum concentration of Fe and explained by the adsorption of these HMs onto it.

The results of the correlation analysis (Tables 4 and 5) indicate the presence of a strong positive relationship between the vertical distribution of volume-based concentrations of Fe and Cr ($r = 0.86$), Fe and V ($r = 0.99$), Fe and Co ($r = 0.98$), and Fe and suspended matter concentration ($r = 0.89$). The mass concentration of Fe correlates only with V ($r = 0.98$) and Co ($r = 0.85$). This result indicates a common pattern in the behavior of Fe, V, and Co in the study area. A relationship between the vertical distribution of volume-based concentrations of Fe and Co was noted in [26], whose authors indicated that this is due to the adsorption of Co onto Fe.



F i g. 4. Vertical distribution of temperature, salinity, suspended matter concentration, and the volume-based and mass concentrations of heavy metals at different stations

Table 4

Paired correlation coefficients between the volume concentration of heavy metals (µg/L) and concentration of suspended matter (mg/L)

Parameter	Pb	Zn	Ni	Fe	Cr	V	Co	*TSM*
Pb	1.00	0.01	0.59	0.26	0.16	0.21	0.29	0.34
Zn	–	1.00	0.06	0.44	0.45	0.42	0.37	0.40
Ni	–	–	1.00	0.05	0.21	0.03	–0.01	0.19
Fe	–	–	–	1.00	0.86	0.99	0.98	0.89
Cr	–	–	–	–	1.00	0.84	0.81	0.82
V	–	–	–	–	–	1.00	0.97	0.89
Co	–	–	–	–	–	–	1.00	0.89
TSM	–	–	–	–	–	–	–	1.00

Note: Statistically significant correlation coefficients are highlighted in red

Table 5

Paired correlation coefficients between the mass concentration of heavy metals (µg/g) and concentration of suspended matter (mg/L)

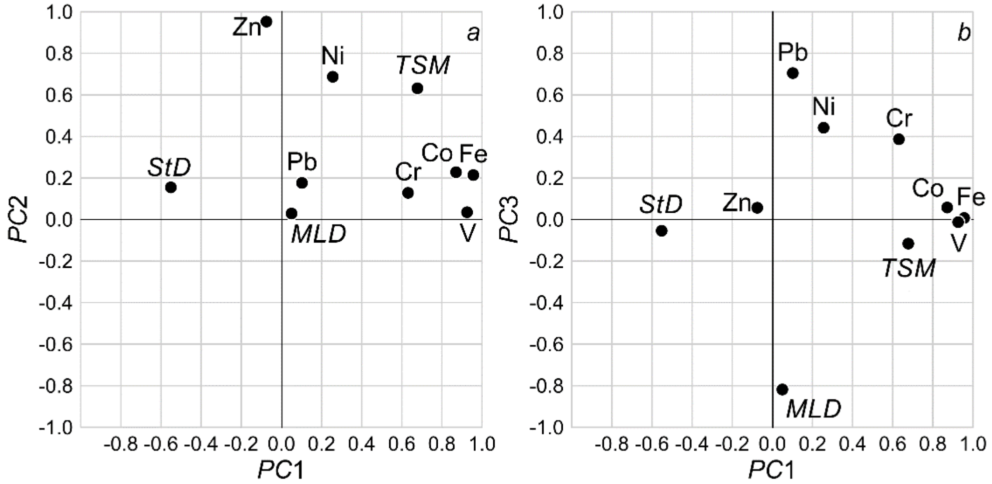
Parameter	Pb	Zn	Ni	Fe	Cr	V	Co	*TSM*
Pb	1.00	0.33	0.37	–0.31	–0.14	–0.38	–0.01	–0.38
Zn	–	1.00	–0.11	–0.10	0.27	0.01	0.07	–0.21
Ni	–	–	1.00	–0.33	–0.01	–0.30	–0.43	–0.10
Fe	–	–	–	1.00	0.08	0.90	0.85	0.33
Cr	–	–	–	–	1.00	–0.03	0.05	–0.12
V	–	–	–	–	–	1.00	0.65	0.32
Co	–	–	–	–	–	–	1.00	0.21
TSM	–	–	–	–	–	–	–	1.00

Note: Statistically significant correlation coefficients are highlighted in red

The influence of the thermocline on the vertical distribution of HMs should be noted separately. At st. *29*, the midpoint of the profile is located in the upper part of the thermocline. In the thermocline layer, compared to the 3 m horizon, an increase in volume-based concentration was observed for all metals except Zn: Pb by a factor of 1.4; Ni by 2.2; Fe by 13; Cr by 4.3; V by 8.5; Co by 10.3 times. The concentration of Zn decreased by a factor of 73. The increase in volume-based metal concentrations may be due both to an increase in suspended matter concentration by a factor of 4.1 and to metal adsorption during its settling. Evidence supporting the latter is the increase in the mass concentration of Fe by 3.2; Cr by 1.1; V by 2.1; and Co by 2.5 times. The mass concentration decreased for Pb by 3 times, for Zn by 62, and for

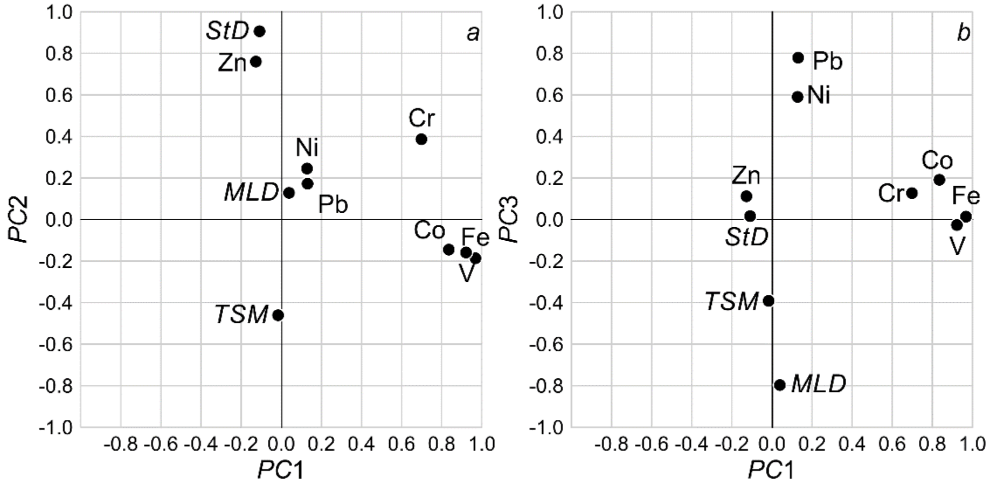
Ni by 1.9 times. The decrease in mass concentration of these metals may be due to both their active consumption in the upper layers and a dilution effect due to the increase in suspended matter concentration. The accumulation of suspended matter in the thermocline is associated with increasing density [34]. Notably, in the lower part of the thermocline (st. *8*), with an increase in suspended matter concentration by a factor of 1.5, an increase in volume-based concentration was observed only for Ni (by 5.8 times) and Pb (by 17 times). A significant increase (up to two orders of magnitude) in the concentration of individual metals at specific horizons in the photic layer was noted in the data from [28].

Principal component analysis. Analysis of volume-based HM concentration data using PCA allowed for the identification of 3 components (Fig. 5). The first component explains 43.1% of the variability in the analyzed series, the second – 17.3%, and the third – 12.3%. The first component is associated with the variability of Fe, V, Co, Cr, and suspended matter concentration and likely reflects the influence of the natural lithogenic factor (coastal abrasion, intrusion of Sea of Azov waters, atmospheric transport) [7, 26–28]. The second component is associated with Zn, Ni, and suspended matter concentration and likely reflects the influence of the natural biogenic factor (phytoplankton production, adsorption onto organic matter). The third component is associated with Pb and mixing layer depth and likely reflects the influence of hydrodynamic processes: Pb enters the marine environment with atmospheric aerosols; the decrease in volume-based Pb concentration with increasing mixing layer depth suggests its dilution in a larger volume.



F i g. 5. Graphical representation of the first and second (*a*), and the first and third (*b*) components for HM volume-based concentrations

Analysis of mass HM concentration data using PCA also allowed for the identification of 3 components (Fig. 6). The first component explains 31.7% of the variability in the analyzed series, the second – 23.7%, and the third – 12.6%. The association of the extracted factors with the analyzed parameters did not fundamentally change compared to the results described above, which further confirms the validity of the assumptions made about the nature of the processes controlling the spatial variability of HM content in suspended matter in the area under consideration.



F i g. 6. Graphical representation of the first and second (*a*), and the first and third (*b*) components at HM mass concentration

Conclusions

This paper presents the results of analyzing field data on the spatial variability of volume-based and mass concentrations of heavy metals (Pb, Zn, Ni, Fe, Cr, V, Co) in suspended particulate matter, obtained in the northern part of the Black Sea. The values of volume-based and mass concentrations of the analyzed metals varied spatially over a range of two orders of magnitude. Elevated and often maximum volume-based concentration values for these heavy metals were observed in the northeastern part of the study area, while reduced values were characteristic of the southwestern part. The spatial variability of the mass concentration of heavy metals exhibited a more complex pattern. Elevated values of Pb, Zn, and Ni were noted in the deep-sea part of the sea, while reduced values were observed in the coastal area. Elevated values of Fe and V were characteristic of the shelf section from Cape Meganom to Cape Chauda, while reduced values were characteristic of the deep-sea part. Elevated and reduced concentrations of Cr and Co were observed both on the shelf and in the deep-sea part of the study area.

In the deep-sea part, the mass and volume-based concentrations of the analyzed metals either increased or decreased with depth (comparing the 3 m layer with the

63–66 m layer). In the upper part of the thermocline, an increase in volume-based (Pb, Ni, Fe, Cr, V, Co) and mass (Fe, Cr, V, Co) concentrations was observed for most heavy metals by a factor of 1.1–47.1. An increase by a factor of 1.1–137 in volume-based (Zn, Fe, Cr, V, Co) and mass (Zn, Fe, V, Co) concentrations of most heavy metals was also noted on the shelf in the bottom layer. Such an increase is due to the combined influence of at least two processes – accumulation of suspended matter due to reduced water dynamics and adsorption of these metals onto the settling suspended particulate matter.

Using PCA, it was shown that the spatial variability of volume-based and mass concentrations of Fe, V, Co, and Cr is associated with the influence of the lithogenic factor (coastal abrasion, intrusion of Sea of Azov waters, dust transport); the variability of Zn and Ni is due to the influence of the biogenic factor (phytoplankton production, adsorption onto organic matter); the variability of Pb is due to the influence of the hydrodynamic factor (variability of the mixing layer depth).

REFERENCES

1. Singh, R., Gautam, N., Mishra, A. and Gupta, R., 2011. Heavy Metals and Living Systems: An Overview. *Indian Journal of Pharmacology*, 43(3), pp. 246-253. https://doi.org/10.4103/0253-7613.81505
2. Stancheva, M., Makedonski, L. and Peycheva, K., 2014. Determination of Heavy Metal Concentrations of Most Consumed Fish Species from Bulgarian Black Sea Coast. *Bulgarian Chemical Communications*, 46(1), pp. 195-203.
3. Singh, V., Singh, N., Rai, S.N., Kumar, A., Singh, A.K., Singh, M.P., Sahoo, A., Shekhar, S., Vamanu, E. [et al.], 2023. Heavy Metal Contamination in the Aquatic Ecosystem: Toxicity and Its Remediation Using Eco-Friendly Approaches. *Toxics*, 11(2), 147. https://doi.org/10.3390/toxics11020147
4. Kamila, S., Shaw, P., Islam, S. and Chattopadhyay, A., 2023. Ecotoxicology of Hexavalent Chromium in Fish: An Updated Review. *Science of the Total Environment*, 890, 164395. https://doi.org/10.1016/j.scitotenv.2023.164395
5. Srivastav, A., Srivastav, S.K. and Upadhyay, R.K., 2024. Physiological and Behavioral Effects of Lead Poisoning in Aquatic and Marine Animals: Review. *World Journal of Pharmacy and Pharmaceutical Sciences*, 13(6), pp. 171-185. https://doi.org/10.20959/wjpps20246-27390
6. Ramos-Filho, A.M., Rodrigues, P.D.A., De Oliveira, A.T. and Conte-Junior, C.A., 2025. A Systematic Review on Contamination of Marine Species by Chromium and Zinc: Effects on Animal Health and Risk to Consumer Health. *Journal of Xenobiotics*, 15(4), 121. https://doi.org/10.3390/jox15040121
7. Bruland, K.W., 1983. Trace Elements in Seawater. In: J. R. Riley and R. Chester, eds., 1983. *Chemical Oceanography.* London: Academic Press. Vol. 8, pp. 157-220.
8. Mason, A.Z. and Jenkins, K.D., 1995. Metal Detoxification in Aquatic Organisms. In: A. Tessier and A. D. R. Turner, eds., 1995. *Metal Speciation and Bioavailability in Aquatic Systems*. London: John Wiley & Sons Ltd., pp. 479-608.

9. Jitar, O., Teodosiu, C., Nicoara, M. and Plavan, G., 2013. Study of Heavy Metal Pollution and Bioaccumulation in the Black Sea Living Environment. *Environmental Engineering and Management Journal*, 12(2), pp. 271-276. https://doi.org/10.30638/eemj.2013.032

10. Chelyadina, N.S., Popov, M.A., Pospelova, N.V. and Smyrnova, L.L., 2022. Effects of Heavy Metals on Sex Inversion of the Mussel *Mytilus Galloprovincialis* Lam., 1819 in Coastal Zone of the Black Sea. *Marine Pollution Bulletin*, 185, part A, 114323. https://doi.org/10.1016/j.marpolbul.2022.114323

11. Gokul, T., Kumar, K.R., Prema, P., Arun, A., Balaji, P. and Faggio, C., 2023. Particulate Pollution and Its Toxicity to Fish: An Overview. *Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology*, 270, 109646. https://doi.org/10.1016/j.cbpc.2023.109646

12. Mitryasova, O., Koszelnik, P., Gruca-Rokosz, R., Smirnov, V., Smirnova, S., Bezsonov, Y., Zdeb, M. and Ziembowicz, S., 2020. Features of Heavy Metals Accumulation in Bottom Sediments of the Southern Bug Hydroecosystem. *Journal of Ecological Engineering*, 21(3), pp. 51-60. https://doi.org/10.12911/22998993/118299

13. Manev, I., Kirov, V. and Neshovska, H., 2020. Heavy Metals Accumulation in Black Sea Ecosystems: Seawater, Sediment, Algae, Benthic Organisms. *Tradition and Modernity in Veterinary Medicine*, 5, 2(9), pp. 88-99.

14. Butnariu, M., 2022. Heavy Metals as Pollutants in the Aquatic Black Sea Ecosystem. In: G. H. Dar, R. A. Bhat, H. Quadri, K. M. Al-Ghamdy and K. M. Hakeem, eds., 2022. *Bacterial Fish Diseases*. Academic Press, pp. 31-57. https://doi.org/10.1016/B978-0-323-85624-9.00003-8

15. Nemirovskaya, I.A., Zavialov, P.O. and Khramtsova, A.V., 2022. Hydrocarbon Pollution in the Waters and Sediments of the Kerch Strait. *Marine Pollution Bulletin*, 180, 113760. https://doi.org/10.1016/j.marpolbul.2022.113760

16. Haraldsson, C. and Westerlund, S., 1991. Total and Suspended Cadmium, Cobalt, Copper, Iron, Lead, Manganese, Nickel and Zinc in the Water Column of the Black Sea. In: E. Izdar and J. W. Murray, eds., 1991. *Black Sea Oceanography.* NATO ASI Series, 351. Dordrecht: Springer, pp. 161-172. https://doi.org/10.1007/978-94-011-2608-3_9

17. Lewis, B.L. and Landing, W.M., 1991. The Biogeochemistry of Manganese and Iron in the Black Sea. *Deep Sea Research Part A. Oceanographic Research Papers*, 38, pp. S773-–S803. https://doi.org/10.1016/S0198-0149(10)80009-3

18. Konovalov, S.K. and Murray, J.W., 2001. Variations in the Chemistry of the Black Sea on a Time Scale of Decades (1960–1995). *Journal of Marine Systems*, 31(1–3), pp. 217-243. https://doi.org/10.1016/S0924-7963(01)00054-9

19. Korablina, I.V., Barabashin, T.O. and Katalevsky, N.I., 2021. Heavy Metals in the Bottom Sediments of the Black Sea Northwestern Shelf in Recent Years. *Physical Oceanography*, 28(5), pp. 549-566. https://doi.org/10.22449/1573-160X-2021-5-549-566

20. Gurov, K.I., Kotelyanets, E.A., Zhuravleva, A.A. and Kremenchutskii, D.A., 2025. Radionuclides and Heavy Metals in the Kerch Strait Sediments: Spatial Distribution, Fluxes and Pollution Loads. *Continental Shelf Research*, 285, 105386. https://doi.org/10.1016/j.csr.2024.105386

21. Pospelova, N.V., Egorov, V.N., Proskurnin, V.Yu. and Priymak, A.S., 2022. Suspended Particulate Matter as a Biochemical Barrier to Heavy Metals in Marine Farm Areas (Sevastopol, the Black Sea). *Marine Biological Journal*, 7(4), pp. 55-69. https://doi.org/10.21072/mbj.2022.07.4.05

22. Gurov, K.I., Kurinnaya, Yu.S. and Kotelyanets, E.A., 2021. Features of Accumulation and Spatial Distribution of Microelements in Bottom Sediments of the Crimea Coastal Regions. In: T. Chaplina, ed., 2021. *Processes in GeoMedia – Volume III*. Cham: Springer Geology, pp. 119-130. https://doi.org/10.1007/978-3-030-69040-3_12

23. Kremenchutskii, D.A. and Gurova, Yu.S., 2023. Factors Forming the Spatial Distribution of Natural and Man-Made Radionuclides in the Bottom Sediments of the Kamyshovaya Bay, Sevastopol. *Physical Oceanography*, 30(5), pp. 652-665.

24. Zavialov, P.O., Zavialov, I.B., Izhitskiy, A.S., Izhitskaya, E.S., Konovalov, B.V., Krementskiy, V.V., Nemirovskaya, I.A. and Chasovnikov, V.K., 2022. Assessment of Pollution of the Kerch Strait and Adjacent Black Sea Area Based on Field Measurements of 2019–2020. *Oceanology*, 62(2), pp. 162-170. https://doi.org/10.1134/S0001437022020175

25. Chuzhikova-Proskurnina, O.D., Proskurnin, V.Yu., Tereshchenko, N.N. and Kobechinskaya, V.G., 2022. Heavy Metals in the Coastal Waters of Russian Sector of the Black Sea and the Sea of Azov. *Ecosystems*, (31), pp. 111-122 (in Russian).

26. Lewis, B.L. and Landing, W.M., 1992. The Investigation of Dissolved and Suspended-Particulate Trace Metal Fractionation in the Black Sea. *Marine Chemistry*, 40(1–2), pp. 105-141. https://doi.org/10.1016/0304-4203(92)90050-K

27. Tankéré, S.P.C., Muller, F.L.L., Burton, J.D., Statham, P.J., Guieu, C. and Martin, J.-M., 2001. Trace Metal Distributions in Shelf Waters of the Northwestern Black Sea. *Continental Shelf Research*, 21(13–14), pp. 1501-1532. https://doi.org/10.1016/S0278-4343(01)00013-9

28. Yiğiterhan, O., Murray, J.W. and Tuğrul, S., 2011. Trace Metal Composition of Suspended Particulate Matter in the Water Column of the Black Sea. *Marine Chemistry*, 126(1–4), pp. 207-228. https://doi.org/10.1016/j.marchem.2011.05.006

29. Lenstra, W.K., Hermans, M., Séguret, M.J.M., Witbaard, R., Behrends, T., Dijkstra, N., Van Helmond, N.A.G.M., Kraal, P., Laan, P. [et al.], 2019. The Shelf-to-Basin Iron Shuttle in the Black Sea Revisited. *Chemical Geology*, 511, pp. 314-341. https://doi.org/10.1016/j.chemgeo.2018.10.024

30. Rudnick, R.L. and Gao, S., 2014. Composition of the Continental Crust. In: H. D. Holland, K. K. Turekian, eds., 2014. *Treatise on Geochemistry: Second Edition*. Oxford: Elsevier, vol. 4, pp. 1-51. https://doi.org/10.1016/B978-0-08-095975-7.00301-6

31. Denisov, V.I. and Latun, V.V., 2018. Flows of Chemical Elements in Suspended Matter Fluxes in the Shallow Area of the Black Sea Shelf (According to the Sediment Traps Data). *News of Higher Educational Institutions. North Caucasian Region. Series: Natural Sciences*, 4(200), pp. 77-85 (in Russian).

32. Chan, C.-Y., Zheng, L. and Sohrin, Y., 2025. The Behaviour of Nickel, Copper, Zinc, and Cadmium in the Subarctic Pacific Ocean: East–West Differences. *Journal of Oceanography*, 81(2), pp. 149-162. https://doi.org/10.1007/s10872-025-00746-y

33. Rahaman, W., Chanakya, I.V.S., Ray, I., Tarique, M., Fousiya, A.A., Das, R. and Misra, S., 2024. Anthropogenic Lead (Pb) Deposition History of the Western Indian Ocean from Coral-Based Pb/Ca Ratio and Pb Isotope Records. *Science of The Total Environment*, 955(10), 177312. https://doi.org/10.1016/j.scitotenv.2024.177312

34. Tian, Z., Liu, Y., Zhang, X., Zhang, Y. and Zhang, M., 2022. Formation Mechanisms and Characteristics of the Marine Nepheloid Layer: A Review. *Water*, 14(5), 678. https://doi.org/10.3390/w14050678

Submitted 27.08.2025; approved after review 03.09.2025;
accepted for publication 28.01.2026.

About the authors:

Dmitrii A. Kremenchutskii, Senior Researcher, Marine Hydrophysical Institute of RAS (2 Kapitanskaya Str., Sevastopol, 299011, Russian Federation), CSc. (Geogr.), **ORCID ID: 0000-0002-8747-6612**, **ResearcherID: AAC-1673-2020**, **SPIN-code: 1695-9378**, d.kremenchutsky@gmail.com

Ekaterina A. Kotelyanets, Junior Researcher, Marine Hydrophysical Institute of RAS (2 Kapitanskaya Str., Sevastopol, 299011, Russian Federation), **ORCID ID: 0009-0007-1921-3566**, **Scopus Author ID: 36059344400**, **ResearcherID: AAA-8699-2019**, **SPIN-code: 4390-5829**, plistus@mail.ru

Contribution of the co-authors:

Dmitrii A. Kremenchutskii – writing of the original draft, visualization, methodology, investigation, and conceptualization

Ekaterina A. Kotelyanets – review and editing of the article, formal analysis, and data curation

The authors have read and approved the final manuscript.
The authors declare that they have no conflict of interest.