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WATER QUALITY AND PROTECTION: ENVIRONMENTAL ASPECTS

Microelement Composition of Bottom Sediments in Mekong River Delta, Republic of Vietnam

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Abstract—Mean concentrations of Zn, Cu, Pb, Cd, As, and Hg in water and bottom sediments of Mekong Delta (Socialist Republic of Vietnam) over low-water period of 2013 were evaluated. The space distribution of the chemical composition of bottom sediments shows a tendency toward an increase in the concentrations of the examined microelements toward the sea coastline. The mechanism of those changes was considered and attributed to a release of low-solubility compounds from water and with sorption of microelements on alluvium and sediment particles at the mixing of river and sea water. The value of surface water pH was suggested as an indicator of current and forecasted variations of the concentrations of some microelements in bottom sediments.

Keywords: bottom sediment, chemical composition, Mekong River delta, Socialist Republic of Vietnam
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INTRODUCTION

The chemical composition of bottom sediments (BS) of rivers is an important characteristic of the geoecological and geochemical conditions of water bodies and their drainage areas, and the corresponding data form an indispensable information resource for planning and implementing nature protection programs and measures for integrated use of territories, including for agriculture. This issue becomes especially important in the densely populated regions of Asia, i.e., in the Mekong R. basin, including territories belonging to China, Myanmar, Thailand, Laos, Cambodia, and Vietnam. The basin of this river, 795000 km^2 in area, is divided into the upper and lower parts. The lower reaches of the Mekong R. (the territories of Laos, Thailand, Cambodia, and Vietnam) alone, with an area of 606000 km^2 have a population of about 53 million [13, 14].

Obviously, the concentration of population as high as that, along with the industrial and agricultural potential cannot but have an effect on the state of the river's BS, which, involved in the agrogeochemical and water management cycles, affect the socioeconomic conditions of the entire region and, especially, Mekong Delta (Fig. 1).

Of particular interest is the microelement composition of BS, which characterizes the degree of BS pollution and its sanitary–toxicological properties. The objective of this study is to identify the regularities in the evolution of microelement composition of BS in the left part of Mekong Delta during low-water seasons.

METHODS OF STUDY

In accordance with classification of deltas [2], the Mekong nearshore area is classified as open protruded; and the mouth area, as multibranch with a delta, which has mostly formed under the effect of tides and waves. The Mekong Delta proper, with its complex structure, is represented by two sets of branches—Tienzang and Khauzang. The Khauzang set is represented by three large branches; and the Tienzang set, by six branches, the largest of which—Khamluong Branch—is the focus of this study. In January 2013, 12 BS samples were taken along a segment of this branch 75 km long (the samples were taken by Fung Tkhai Zyong and researchers from Dongtkhap University, Tsaolan City, Socialist Republic of Vietnam). In the same period, four BS samples were taken from arms of the Khamluong Branch and four samples, from other branches in the Mekong R. delta (Fig. 2; Table 1).

BS samples were taken with the use of a basal probe from the top layer ~0.2 m in thickness, BS stratification remaining undisturbed, in watercourse segments with a depth of up to 10 m: in the branches of Khamluong, Koch'en, and Kyadai, within 10–50 m from the left and right banks (the width of those watercourses during flood-free period is >1 km on the average and ~3 km at the mouth; water depth reaches 12–15 m); in

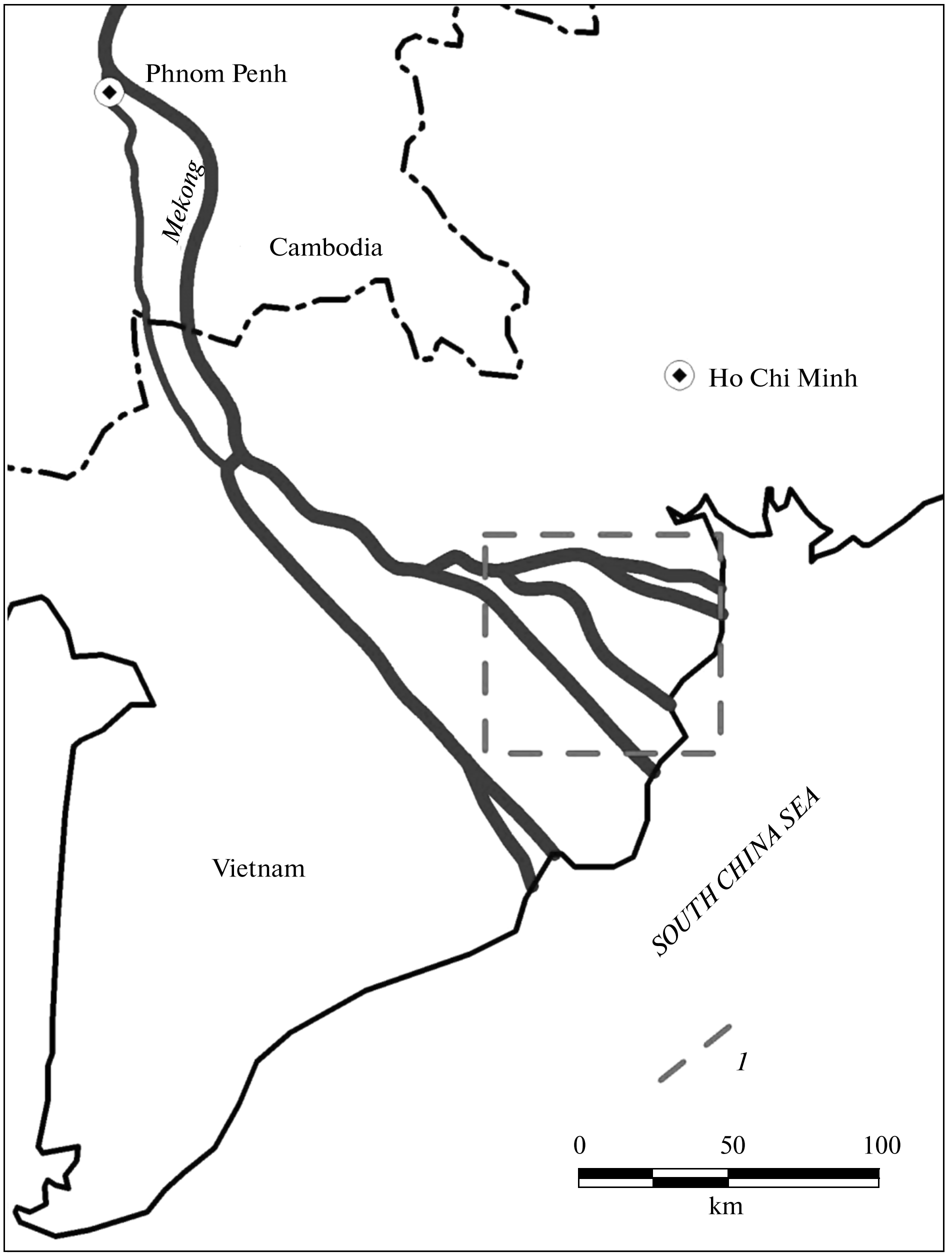

Fig. 1. Study area *1* in the lower reaches of the Mekong R.

arms of the branch of Khamluong, the samples were taken within 5–10 m from the bank. Parallel to that, river water samples were taken from a layer 0.3–0.4 m from the surface.

BS samples were placed in specially prepared vessels and delivered into the laboratory of Dongtkhap University, where they were dried at 25°C and disintegrated to a fraction with particle diameter of up to 0.5 mm. Acid extracts from BS were analyzed to determine the concentrations of Zn, Cu, Pb, Cd, As, and Hg by atomic-absorption method. In aqueous extracts from BS, the values of pH were determined by potentiometric method and specific electric conductivity, by conductometric method. The same methods were used to determine the respective characteristics of surface waters, samples of which were pre-filtered with the use of a paper filter with pore diameter of 1.5 μm.

RESULTS AND DISCUSSION

The examined BS samples from arms and branches of the Mekong Delta showed the following mean concentrations, mg/kg: 96.9 for Zn, 33.4 for Cu, 3.8 for Pb, 1.1 for Cd, 5.9 for As, and 0.10 for Hg. This is generally comparable (considering the determination errors) with the characteristics for some similar water

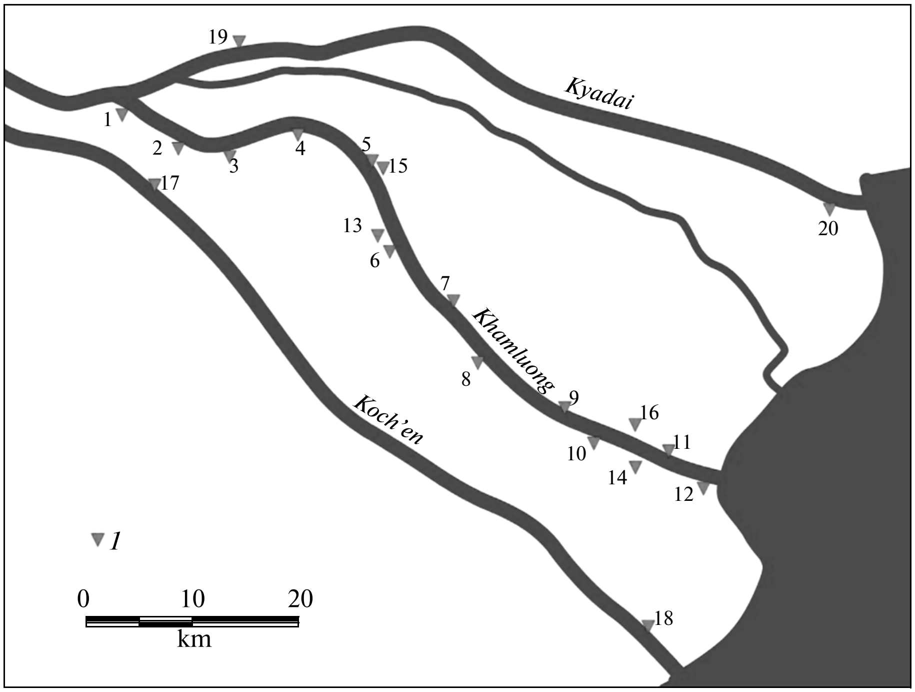

Fig. 2. Layout of water and BS sampling sites. Numbers 1–20 denote sampling points.

objects in Southeastern and Northern Eurasia [1, 5, 10, 11, 17]; however, when comparing this, one should take into account water runoff volume, water regime phase, the distance from the sampling section to the delta coastline, and the anthropogenic load (Table 2). To substantiate this thesis, we will consider in more detail the mechanism of the influence of the factors listed above on the concentrations of microelements in BS.

According to [2–4], the water objects under examination lie within the penetration zone of tides (up to 400 km) and reverse currents (110 km), which has a considerable effect on the hydrochemical regime of the delta and determines the penetration of brackish water over 40–50 km from the delta coastline (up to 70 km in some cases). Clearly, the latter value depends on the water regime in the mouth area and varies over both a many-year period and an individual hydrological year. In a simplified form, this dependence can be written as [2]:

$$S_x = S_m - (S_m - S_r)\exp\left(-k_s \frac{x}{h_0}\right), \quad (1)$$

where S_x is the mean water salinity at distance x from the initial section; S_m and S_r are the mean salinities of sea and river water, respectively; k_S is a constant, which characterizes the attenuation of flow velocity during sea and river water mixing; h_0 is flow depth at $x = 0$. Note that the concentration of dissolved salts M in river water is commonly inversely proportional to water discharge Q:

$$M = M_0\left(\frac{Q}{Q_0}\right)^{-\frac{k_M}{k_Q}}, \quad (2)$$

here, M_0 is the concentration of dissolved salts in a conventionally equilibrium state of the water–organic matter–rocks system, which can be conventionally assumed background; Q_0 is water discharge corresponding to M_0, k_M, and k_Q (specific rates of variation of the total dissolved salts and water discharge) [8, 9]. Therefore, the relationship (1), other conditions being the same, will better agree with observation data at water discharges $Q \approx Q_0$, as was the case during studies with sampling in early January after the end of the moist period with an average duration from May to October [12, 13]. Accordingly, the obtained data can be used as the first approximation to characterize the mean concentration of the microelements in question in BS of the Mekong Delta.

Analysis of observational data showed equation (1) to be applicable to the Khamluong Branch. In particular, the mean values of specific water electric conductance χ_w at a distance of x from a convectional section located at a distance L from the delta coastline can be described by the relationship:

$$\chi_{w,x} = \chi_m - (\chi_m - \chi_r)\exp\left(-k_\chi \frac{L-x}{h_0}\right), \quad (3)$$

where χ_m is the specific electric conductance of seawater, estimated at 974.5 mS/cm in accordance with the polynomial dependence between the specific electric conductance and salinity [6]; the specific electric con-

Table 1. Physicochemical and hydrochemical characteristics of water and aqueous extracts from BS in the Mekong R. delta on January 1–9, 2013 (A, δ_A are the arithmetic mean and its determination error; $\delta_A = \sigma/\sqrt{N}$, σ is standard deviation; N is sample size)

Site no.	Water object, distance from delta coastline	Water temperature, °C	pH		Specific water conductance, mS/cm	
			water	BS	water	BS
1	Khamluon R.,					
	75 km	30.2	6.96	6.59	1.99	0.31
2	70 km	29.3	7.13	6.87	2.47	1.11
3	64.5 km	32.6	7.22	7.44	6.13	2.87
4	57.2 km	29.6	7.35	7.04	7.72	0.92
5	44.5 km	28.9	7.44	7.23	18.19	2.22
6	41.6 km	29.2	7.54	7.34	27.90	4.31
7	35 km	28.6	7.61	7.57	107.10	4.36
8	28 km	28.4	7.71	7.63	164.50	4.35
9	20.5 km	29.0	7.75	7.62	169.30	4.70
10	15.2 km	29.6	8.01	7.80	189.40	4.96
11	9.2 km	29.3	8.12	7.88	202.70	4.94
12	4.2 km	28.7	8.15	7.98	209.20	5.57
13	Khamluon R. Branch					
	Song Ben Tre, 44 km	31.5	6.79	6.25	2.54	0.36
14	Song Ba Tri, 10.6 km	30.3	8.04	7.17	106.10	4.33
15	Song Vam Nuok Trong, 49.4 km	32.4	7.07	6.66	8.56	0.69
16	Song Rach Sau, 16 km	29.5	7.97	7.09	150.70	3.29
17	Koch'en R.					
	68.5 km	31.2	7.16	6.77	10.35	0.48
18	5.5 km	29.4	8.22	8.08	216.80	5.45
19	Kyadai R.					
	59.4 km	30.6	6.70	6.37	2.70	0.57
20	7 km	28.9	8.04	7.93	193.20	5.09
	A	29.9	7.55	7.26	89.88	3.04
	δ_A	0.3	0.11	0.12	19.61	0.44

ductance of river water χ_r was derived from the observation data for the upper section 75 km from the delta coastline (Table 1), and h_0 was evaluated at 4.5 m based on observation data with materials [15] taken into account; the values of k_χ and L were chosen to maximize the squared correlation relationship R^2 between the measured and calculated values of specific conductance.

In this case, we have $R^2 = 0.79$ at $k_\chi = -0.0124$ and $L = 82$ km, which allows the variable L to be interpreted as the distance of maximal manifestation of river water salinization in January 2013, though water salinity at the moment of sampling changed most abruptly in the reach 35–42 km from the delta coastline, and an appreciable change was recorded 65–75 km from it (Fig. 3); this facts approximately correspond to data in [3].

The relationship between specific electric conductance and water salinity (or the concentration of dissolved ions) is generally nonlinear, in particular, logarithmic. Therefore, the values of logarithms of concentrations of some substances can change linearly with the distance from delta coastline, as, for example, was the case for pH (Fig. 4).

The value of pH is an important characteristic of interaction in the water–rock system. In particular, an increase in pH is associated with the degree of water saturation with low-solubility compounds of metals

Table 2. Microelement concentrations in water, μg/dm^3, and acid extracts from BS, mg/kg, in Mekong R. branches on January 1–9, 2013 (n.d.a. means no data available)

Site number, water object	Zn		Cu		Pb		Cd		As		Hg	
	water	BS	water	BS	water	BS	water	BS	water	BS	water	BS
1	269.4	96.1	67.6	31.3	0.04	0.9	0.20	0.1	0.10	4.7	0.06	0.09
2	248.4	80.7	58.9	30.3	0.01	2.2	0.20	1.0	0.28	3.9	0.02	0.11
3	386.1	75.1	63.6	28.4	0.01	1.3	0.20	0.2	0.71	4.2	0.03	0.07
4	311.7	123.0	68.3	33.8	0.01	6.1	0.20	2.4	0.40	6.2	0.06	0.06
5	228.0	101.2	49.5	34.8	0.04	2.3	0.20	1.2	0.27	6.4	0.03	0.09
6	383.5	77.6	69.8	34.4	0.01	4.9	0.20	1.4	0.39	5.9	0.06	0.09
7	351.5	92.1	85.4	34.9	0.01	4.4	0.20	0.9	0.37	7.6	0.05	0.12
8	338.0	91.3	67.8	34.9	0.00	3.0	0.20	1.0	0.39	6.6	0.01	0.12
9	350.5	91.2	69.2	35.7	0.01	4.6	0.20	1.5	0.31	7.5	0.02	0.13
10	302.5	106.4	78.6	35.2	0.02	4.9	0.20	1.0	0.45	7.7	0.00	0.13
11	373.6	97.2	78.0	31.2	0.01	6.6	0.20	1.4	0.43	8.2	0.06	0.14
12	379.9	107.3	78.2	38.5	0.01	5.7	0.20	2.4	0.59	8.0	0.09	0.13
13	390.6	105.4	74.3	32.4	0.01	1.1	0.20	0.6	0.33	6.3	0.06	0.09
14	452.1	99.8	52.8	33.6	0.01	6.0	0.20	0.3	0.50	4.1	0.05	0.07
15	415.6	90.5	83.0	34.6	0.07	3.1	0.20	1.1	0.44	4.0	0.01	0.08
16	347.5	100.2	84.2	35.0	0.01	3.7	0.20	1.1	0.22	4.0	0.01	0.04
17	277.3	87.7	54.0	28.5	0.03	1.1	0.20	1.1	0.18	4.6	0.06	0.07
18	396.6	102.6	61.4	33.5	0.01	6.3	0.20	1.6	0.33	7.7	0.03	0.12
19	329.1	100.1	68.7	33.1	0.01	2.8	0.20	0.2	0.34	4.1	0.02	0.10
20	359.5	105.7	67.9	33.4	0.01	4.3	0.20	1.9	0.39	6.2	0.03	0.14
						A						
	344.6	96.6	69.1	33.4	0.017	3.8	0.20	1.1	0.370	5.9	0.038	0.10
						δ_A						
	12.9	2.5	2.3	0.5	0.004	0.4	0.00	0.1	0.030	0.4	0.005	0.01
Brahmaputra R. [17]	n.d.a.	78.3	n.d.a.	n.d.a.	n.d.a.	9.6	n.d.a.	0.5	n.d.a.	n.d.a.	n.d.a.	n.d.a.
Ganges R. [17]	n.d.a.	203.8	n.d.a.	n.d.a.	n.d.a.	22.8	n.d.a.	9.4	n.d.a.	n.d.a.	n.d.a.	n.d.a.
Coastal area, Hai Phong [1]	n.d.a.	140.43	n.d.a.	51.79	n.d.a.	63.22	n.d.a.	0.34	n.d.a.	1.16	n.d.a.	0.22
Saigon R. [10]	n.d.a.	157.0	n.d.a.	31.6	n.d.a.	23.8	n.d.a.	0.1	n.d.a.	n.d.a.	n.d.a.	n.d.a.
Onega Bay [5]	n.d.a.	30–60	n.d.a.	3–9	n.d.a.	≤3	n.d.a.	n.d.a.	n.d.a.	20–40	n.d.a.	n.d.a.
Kandalaksha Gulf [5]	n.d.a.	≤50	n.d.a.	30–50	n.d.a.	≤30	n.d.a.	n.d.a.	n.d.a.	20–30	n.d.a.	n.d.a.
Gulf of Ob [5]	2.13–10.0	67.5–161.0	0.44–1.9	10.4–25.5	0.55–1.64	14.8–30.4	0.05–0.14	0.09–0.34	n.d.a.	n.d.a.	n.d.a.	n.d.a.
Khatanga Bay [5]	1.9–4.4	29.3–114.0	0.33–0.87	10.4–27.0	0.27–0.79	16.8–31.4	0.05–0.08	0.14–0.5	n.d.a.	n.d.a.	n.d.a.	n.d.a.

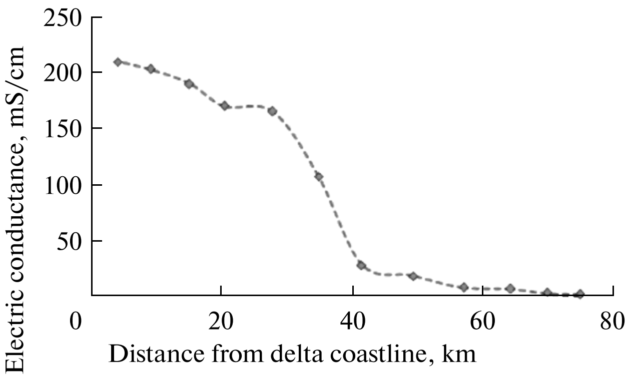

Fig. 3. Variations of specific electric conductance of Khamluong R. water.

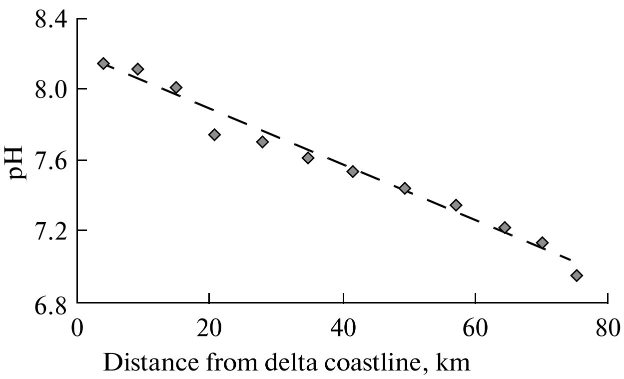

Fig. 4. Variations of water pH in the Khamluong Branch: pH $8.197 - 0.016x$, $R^2 = 0.98$.

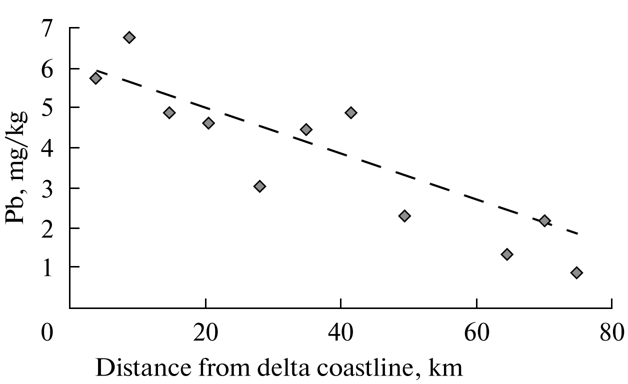

Fig. 5. Variations of Pb concentrations in BS of the Khamluong R.: $[Pb]_s = 6.178 - 0.058x$, $R^2 = 0.54$.

with humic acids, as well as carbonate and clay minerals, resulting in the removal from solution of some substances, accompanied by coprecipitation and sorption on particles of suspended sediments and deposits [6, 7, 11]. These effects contribute to an increase in the concentrations of some chemical elements in BS, depending on the ratio of the rates of sediment roiling and accumulation, microbiological processes, and the presence in the medium of organic acids, interaction with which is accompanied by the formation of stable organic–mineral complexes (in suspended and/or colloidal form) or, conversely, low-solubility compounds with metals. This mechanism is supposed to determine the character of spatial distribution of the examined microelements in BS in the Mekong Delta (Table 2).

In particular, a statistically significant decrease was established in Pb concentrations in BS of the Khamluong Branch with approaching the delta coastline (the square of the correlation relationship for the equation relating Pb and distance x: $R^2 = 0.54$, the critical value being 0.36), with some scatter of values due to variations of flow characteristics and the conditions of interaction in the water–rock–organic matter–gas system, including changes in the particle-size and chemical compositions of BS, flow velocities, concentrations of dissolved gases, water temperature, etc. (Fig. 5).

The assumptions made above are indirectly confirmed by the results of correlation analysis of the obtained data (Table 3), which suggest that a tentative estimate and forecast of changes in the concentrations of Pb, Cd, Cu, As, and Hg in BS in the Mekong Delta can be based on river water pH with regularities in the variations of physicochemical characteristics of the water body taken into account [12, 16].

CONCLUSIONS

The mean concentrations of Zn, Cu, Pb, Cd, As, and Hg in water and BS in the Mekong Delta during dry season of 2013 were obtained in this study. The spatial distribution of BS chemical composition showed a tendency toward an increase in the concentrations of the examined microelements with approaching the delta coastline. The mechanism of this change is supposedly associated with the release of low-solubility compounds from water and the sorption of microelements on the particles of suspended and deposited sediments during river and sea water mixing. The values of water pH can serve as an indicator of hydrochemical conditions in the delta, which can be used for the tentative assessment of the actual and anticipated concentrations of microelements in BS along the Mekong branches and within a year, as well as in the planning of water management and agricul-

Table 3. Statistically significant coefficients between physicochemical and geochemical characteristics of water and BS in the Mekong Delta (coefficients of correlation r under the condition that $r > 2\frac{1-r^2}{\sqrt{N-1}}$, N is sample size ($N = 20$); subscripts s and w denote BS and water samples, respectively)

Characteristic	pH_w	χ_w	Zn_s	Cu_s	Pb_s	Cd_s	As_s	Hg_s	pH_s	χ_s
pH_w	1.00	–	–	–	–	–	–	–	–	–
χ_w	0.91	1.00	–	–	–	–	–	–	–	–
Zn_s	–	–	1.00	–	–	–	–	–	–	–
Cu_s	0.47	0.50	0.44	1.00	–	–	–	–	–	–
Pb_s	0.78	0.68	0.42	0.53	1.00	–	–	–	–	–
Cd_s	0.52	0.45	0.43	0.49	0.60	1.00	–	–	–	–
As_s	0.58	0.68	–	0.50	0.57	0.55	1.00	–	–	–
Hg_s	0.43	0.64	–	–	–	–	0.72	1.00	–	–
pH_s	0.88	0.85	–	–	0.67	0.54	0.71	0.62	1.00	–
χ_s	0.92	0.89	–	0.50	0.71	0.41	0.66	0.59	0.93	1.00

tural measures, in particular, agrochemical works in the delta.

REFERENCES

1. Dang, Kh.N., The state of quality in surface-water deposits in coastal areas in Hai Phong (in Vietnamese), *Zhurn. Nauk i Morskoi Tekhnologii,* 2010, no. 3, pp. 33–52.
2. Mikhailov, V.N., *Gidrologicheskie protsessy v ust'yakh rek* (Hydrological Processes at Delta Mouths), Moscow: GEOS, 1997.
3. Mikhailov, V.N. and Arakl'yants, A.D., Specific features of hydrological and morphological processes in the mouth area of the Mekong River, *Water Resour.*, 2010, vol. 37, no. 3, pp. 253–267.
4. Nguen, V.K., *Ust'evye oblasti rek V'etnama* (Mouth Areas of Rivers in Vietnam), Odessa: Astroprint, 2004.
5. *Nedra Rossii* (Subsurface Resources of Russia), Mezhelovskii, N.V. and Smyslov, A.A., Eds., St. Petersburg: Gornyi inst., Mezhregion. tsentr po geol. kartografii, 2002, vol. 2.
6. *Okeanologiya. Khimiya okeana* (Oceanology: Chemistry of the Ocean) Bordovskii, O.K. and Ivanenkov, V.N., Eds., Moscow: Nauka, 1979.
7. Savichev, O.G., Effect of interaction in water–rock system on the formation of river water chemistry in the Ob basin, *Geogr. Prir. Res.*, 2009, no. 2, pp. 74–80.
8. Savichev, O.G., Background concentrations of chemicals in river water in the taiga zone of the Western Siberia, *Vestn. TGU*, 2010, no. 334, pp. 169–175.
9. *Spravochnik po gidrokhimii* (Reference Book on Hydrochemistry), Nikanorov, A.M., Ed., Leningrad: Gidrometeoizdat, 1989.
10. Khoang Tkhi Tkhan' Tkhui, Heavy metals in deposits in the Saigon R., Ho Chi Minh City, *Zhurn. Nauch. Razrabotok i Tekhnologii*, 2007, no. 1, pp. 27–37 (in Vietnamese).
11. Fedorov, Y.A., Ovsepyan, A.E., Dotsenko, I.V., and Korobov, V.B., Bottom sediments and their role in surface water pollution with mercury (with a special reference to the Northern Dvina river mouth and the Dvina Bay of the White Sea), *Russ. Meteorol. Hydrol.*, 2010, vol. 35, no. 9, pp. 611–618.
12. Hurt, B.T., Jones, M.J., and Pistone, G., Transboundary water quality issues in the Mekong River basin, *Mekong River Commission*, Water Studies Centre. Monash Univ., 2001.
13. Kumu, Matti., Lu, X.X., Rasphone, A., Sarkkula, J., and Koponen, J., River changes along the Mekong River: remote sensing detection in the Vietnam–Nong Khai area, *Quatern. Intern.*, 2008, vol. 196, pp. 1000–1012.
14. MacAliser, C. and Mahaxay, M., Mapping wetlands in the Lower Mekong Basin for wetland resource and conservation management using Landsat ETM images and field survey data, *J. Environ. Manage.*, 2009, no. 90, pp. 2130–2137.
15. Meshkova, L.V. and Carling, P.A., The geomorphological characteristics of the Mekong River in Northern Cambodia: a mixed bedrock–alluvial multi-channel network, *Geomorphology*, 2012, nos. 147-148, pp. 2–17.
16. Prathumratana, L., Sthiannopkao, S., and Kim, K.W., The relationship of climatic and hydrological parameters to surface water quality in the lower Mekong River, *Environ. Intern.*, 2008, no. 34, pp. 860–866.
17. Ramesh, R., Ramanathan, Al., Ramesh, S., Purvaja, R., and Subramanian, V., Distribution of rare earth elements and heavy metals in the surficial sediments of the Himalayan river system, *Geochem. J.*, 2000, vol. 34, pp. 295–319.

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