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MARINE CHEMISTRY

Current Evolution of the Salt Composition of Waters in the Western Basin of the South Aral Sea

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Abstract—Hydrochemical studies were carried out in the western basin of the South Aral Sea, within Uzbekistan, during the expedition in 2019. Water samples were collected in the deep-water part of the western basin from various horizons. The maximum depth of the lake at the time of sampling was 30 m. This work is a part of studies of the evolution of residual water bodies of the Aral Sea. It describes the evolution of the chemical composition of the Aral-Sea water observed in the lake since the beginning of its desiccation and continuing to the present time in all residual water bodies of the Aral Sea. It is established that currently the deep-water part of the western basin of the South Aral Sea has a salinity of ~140‰ and occupies an intermediate position between the brackish North Aral Sea and the hypersaline Chernyshev Bay of the South Aral Sea. The salinity of the lake increases every year and has seasonal changes along with fluctuations in the lake level. It is found that the density increases by 1.2 kg/m^3 both in the surface and bottom layers with increasing salinity by each 1‰.

Keywords: evolution of the water composition, basic ion composition, component composition, water metamorphization, hyperhaline lake, Aral Sea, salt lakes, South Aral Sea, hydrochemical properties

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INTRODUCTION

The hydrochemical parameters are important indicators of the state of a body of water. Studying the hydrochemical characteristics of the Aral Sea makes it possible to understand the mechanisms of the formation of brines, evaporates, and sediments in hypersaline lakes of this type, as well as to predict the state of salt lakes depending on environmental changes.

The hydrochemical regime of the Aral Sea, like that of any other basin, is closely related to its physical and geographical position. It is influenced by geography, geology, climatology, water dynamics, continental runoff, and other factors [18, 29]. In the past few decades, regional changes in the environment have affected the mineral composition of the Aral-Sea waters. The Aral Sea was formed more than 10 thousand years ago and in the middle of the 20th century until the 1960s had the fourth largest area among inland water bodies. This closed endorheic lake is located in an arid zone with a semi-arid climate and a moisture index (IM) of 0.07 in the existing range for arid regions of 0.05–0.2 [9]. We report the history of the formation of individual water bodies of the Aral Sea in [3]. It may be briefly noted that the level of the sea before the 1960s fluctuated around 53.5 m above the level of the World Ocean [6]. It decreased to 30 m in 2004, [35] and to 26 m by 2010 [10]. According to our calculations, in 2019 it was ~18 m above the World Ocean level. To date, the sea level has dropped by 36 m (56%).

According to various sources [6, 10], the maximum sea depth at its deepest part (Station A2) was 66–68 m until the 1960s. In 2000, it was 46.5 m [35]; in 2014, 34 m; in 2015, 32.6 m [28]; in October 2017, 29.5 m [4]. Currently the western basin of the South Aral Sea is the deepest of the remaining individual bodies of water. According to our data, its depth was 30 m in May 2019. The northern end of the South Aral Sea, the Chernyshev Bay, turned into an almost isolated reservoir, although it is still connected to the main part of the basin by a channel.

The average salinity of the seawater in the period from 1949 to 1960 was 9.0–10.8‰ [10]. Its increase in the western basin of the South Aral Sea in the period from 1960 to 2010 had a different intensity: from 2 to 14‰ per year, and on average 7‰. In the period from 2014 to 2017, the salinity on the surface was 126–140‰ [4].

The decrease in the sea's area resulted in the formation of desert areas (playa) around the body of water. Such playas are formed via the shrinking of lakes and their drying out. At present, playas occupy more than 60000 km^2 in Central Asia. The playa area of the Aral Sea exceeds 30000 km^2. They contribute to the appearance and intensification of salt and dust storms, which negatively affect the ecology and health

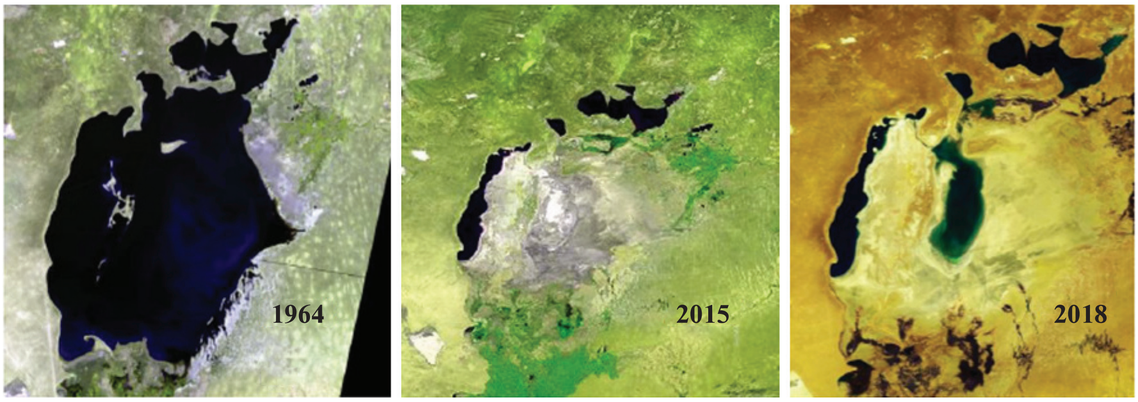

Fig. 1. Satellite images of the state of the Aral Sea in 1964 [24], 2015, and 2018 [25].

of the population in the region [19, 20, 32, 33]. Storms raise sediments from the drained bottom of the Aral Sea, represented by precipitated particles that contain many sulfates, chlorides, pesticides, heavy metals and other elements, once brought into the lake by rivers [23, 26]. The scale of dust carry-over from the dried bottom of the Aral Sea is estimated by various authors as 15 to 75 million tons per year or higher [19]. In turn, residual lakes are the catchment points for a certain amount of dust particles, thereby reducing the negative impact of dust and sandstorms on the environment [30].

Degradation of the sea has long been of scientific interest, and there are more than 1000 publications describing these studies. The consequences of the Aral Sea drying up were the following: climate change in the Aral-Sea region, decline of the economy and the fishing industry, a catastrophic decrease in the biodiversity of the natural ecosystems of the sea itself and river delta regions, as well as an increase in the frequency and strength of salt and dust storms [23, 26].

The drying up of the sea caused an increase in water salinity and a change in the ratios of the components of its chemical composition. The reasons for the drying up of the Aral Sea are assumed to be anthropogenic (80%) and climatic (20%); the latter are associated with a general increase in aridity throughout Central Asia [11, 14]. The Aral-Sea region is characterized by wide variability of the IM index. Some researchers believe that the climatic factor plays a decisive role there. This is explained [9] by the “inland dry phase of the climate”, which exacerbated the processes of desertification in the Aral region in the 20th century, along with the anthropogenic impact.

The drying up of the sea changed the morphometric characteristics of the Aral-Sea waters. This resulted in profound transformations of the hydrological, physical, and chemical regimes in its separate parts [8]. Figure 1 shows satellite images that clearly demonstrate changes in the area of the Aral Sea as a result of its drying up from 1964 to 2018.

Our study is aimed at hydrochemical investigation of the largest and deepest part of the Aral Sea. The results of studies of the western and eastern basins of the South Aral Sea in earlier periods were described in [10, 34]. The concentrations of major ions, salinity, total alkalinity, pH, water density in the water samples from the studied body of water are analyzed, and the relationship between these parameters is revealed.

A separate task is to compare the data obtained with historical data, and to study the evolution of the ionic composition of the Aral-Sea waters under changing hydrological conditions. Using the data obtained during the expedition in 2019, we analyze the distribution of the components of the main ionic composition over a depth from 0 to 30 m.

EXPERIMENTAL

Investigation of the water was carried out in the deepest part of the western basin of the South Aral Sea at Station A2, where hydrochemical and hydrophysical studies are regularly carried out by researchers of the Institute of Oceanology, Russian Academy of Sciences. The location of Station A2 is shown in Fig. 2, and its coordinates are given in Table 1. This table shows the coordinates of sampling stations in the period from 2014 to 2017 as well. The results of these studies were published earlier in our paper [4].

Water samples from the Aral Sea were delivered to the laboratory in a hermetically sealed plastic container for analysis within 3–7 days. Sampling and storage of the samples was carried out in accordance with the standards in [9].

The total alkalinity (A_T) was measured via acid–base titration, according to [15, 16]. After analysis of the pH and total alkalinity, the samples were filtered through a GFF 0.7-μm membrane filter and placed in glass containers with a volume of 100–250 mL. The chlorine content and the concentration of major ions (sulfate, calcium, and magnesium) were measured by potentiometric titration. A Metrohm 905 Titrando

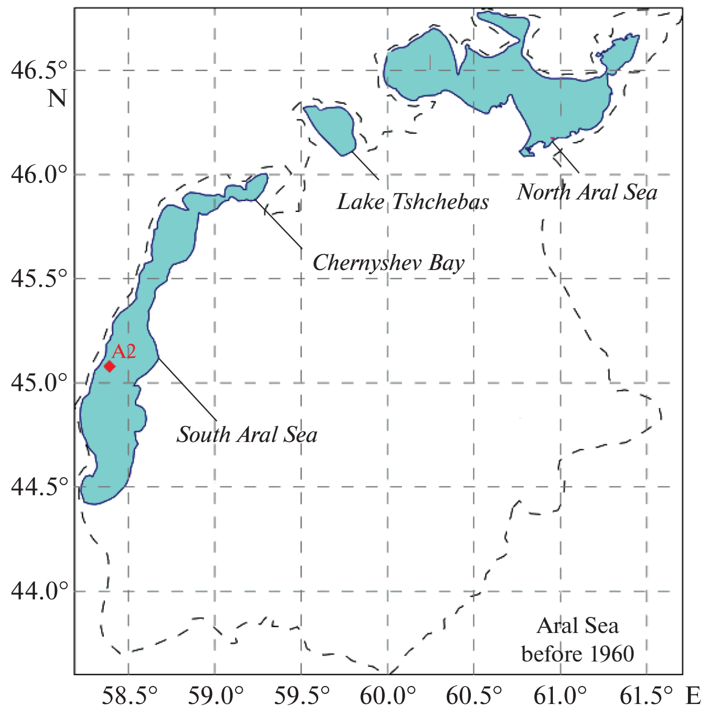

Fig. 2. Scheme of the current Aral Sea and location of the A2 sampling station.

automatic potentiometric titrator with indicator electrodes selected in accordance with the type of occurring reaction and the detected ion was used for this purpose. The methods of analysis of the concentrations of major ions in hypersaline bodies of water are described in detail in [4]. The mean-square deviations of the concentrations of the studied ions did not exceed the values reported in Table 2. The analysis of each sample was carried out 3–6 times, depending on the detected ion. The potassium-ion concentrations were measured gravimetrically. The concentration of sodium ions was determined as the difference between anions and cations in mol/kg and recalculated to ‰.

The optimal sample volume for each analysis was determined empirically, depending on the ion to be analyzed. If necessary, the samples were diluted with deionized water with an electrical conductivity of ≤0.2 μS/cm, prepared using a laboratory deionizer, during analysis.

The total dissolved inorganic carbon was calculated from the total alkalinity and expressed as HCO_3^- [31]. The salinity of the studied samples was determined by summing the contents of major ions. Measurement of the salinity of waters of hypersaline bodies of water using standard hydrophysical measuring equipment results in huge errors due to a difference in their ion–salt composition from the "canonical" oceanic one [6, 8, 21]. The salinity of seawater is the sum of all minerals dissolved in 1 kg of seawater, provided that all bromine is replaced with an equivalent content of chlorine, all carbonates are converted to oxides, and all organic matter is removed [6, 31]. Therefore, the method of summing the concentrations of major ions can be considered as the most reliable for analyzing salinity, especially in water bodies with an ionic composition that is different from the oceanic one. In addition, the calculation of salinity using the chlorine coefficient cannot be applied as well due to a constant

Table 1. Coordinates of water-sampling stations in the western basin of the South Aral Sea in 2014–2019

Station	Maximum depth in the point of sampling, m	Depth of sampling, m	Year of sampling	Month of sampling	Coordinates
A2	34.1	34	2014	October	45°4′46.1″ N 58°23′25.1″ E
	29.2	29	2017	October	
	30.1	30	2019	May	
Near the coast	0.5	0	2016	April	45°5′37.13″ N 58°20′22.94″ E
			2017	October	

Table 2. Mean-square deviations of the analyzed hydrochemical parameters of water in the western basin of the Aral Sea in 2019, ‰ and % of the average value

Depth	Ca^{2+}		Mg^{2+}		K^{+}		Cl^{-}		SO_4^{2-}		HCO_3^{-}		pH		A_T	
m	‰	%	‰	%	‰	%	‰	%	‰	%	‰	%		%	mmol/kg	%
0	0.02	3.0	0.02	0.2	0.05	2.1	0.28	0.4	0.08	0.4	0.005	1.1	0.01	0.1	0.24	2.0
15	0.03	4.1	0.03	0.2	0.04	1.7	0.08	0.1	0.05	0.2	0.001	0.2	0.03	0.4	0.07	0.6
25	0.01	1.7	0.05	0.5	0.05	1.9	0.41	0.6	0.05	0.2	0.002	0.4	0.01	0.2	0.22	1.9
30	0.04	5.3	0.02	0.2	0.02	0.8	0.14	0.2	0.16	0.7	0.014	3.1	0.04	0.5	0.18	1.9

change in the ratio of ions in the Aral Sea [2]. Other methods of measurement of the salinity in the Aral Sea, such as the gravimetric method (by the weight of the dry residue after evaporation of the sample), as well as the method of measurement of the speed of sound, are described in [13].

The density of the water column is usually obtained from the calculated data of the hydrophysical CTD probe, i.e., by the equation of state, which, leads to significant deviations from the real values of the salinity, and, consequently, density, in bodies of water with an ion–salt composition different from that of the ocean. In this study, we measured the density of the Aral-Sea water using an Anton Paar DMA 5000 M density meter. The error in measurement of the water density is $\pm 10^{-6}$ g/cm^3 [17]. The density was measured at 21°C and atmospheric pressure. 3–4 measurements were performed for each sample. The standard deviation in some cases reached 0.06 kg/m^3, but more often was 0. The average value was taken as the result.

The temperature during sampling in 2019 was measured using a CastAway CTD hydrophysical probe.

RESULTS

Hydrochemical data obtained upon expeditions to the Aral Sea in 2019 compared to earlier data for 2014–2017 [4] are reported in Table 3.

It is evident from Table 3 that in the three-year period from 2014 to 2017, the level of the Aral Sea in the studied area decreased by 4.8 m. Most likely, the sea experiences seasonal fluctuations, which can be observed by comparison of the depths in October 2017 and in May 2019. The water level was almost one meter higher in May 2019, than that in October 2017, while the salinity was lower by 3%. This is probably due to the spring inflow of continental runoff. The salinity in the studied period from 2014 to 2019 ranged from 126 to 140‰. The relative ratios of major ions in the Aral Sea during this period fluctuated depending on the level of the water body and its salinity.

In 2019, the SO_4/Cl weight ratio ranged within 0.30–0.35 at the surface and within 0.34–0.35 in the bottom layer. The Ca/Na ratio was slightly lower at the bottom (0.023–0.025). There was a slight increase in the content of hydrocarbon ions in the bottom layer. The HCO_3/Cl ratio was 0.007 in all water samples obtained from different horizons (Table 3). The salinity in the bottom layer in 2019 was higher than that in the surface layer by 2.4%.

The graph (Fig. 3) shows the distribution of major ions in the water column from the surface to the bottom. From a depth of 15 m and below and at a salinity of ≥137‰, a change in the relative content of major ions is detected. The content of chloride ions is 1.2% lower, and the content of sulfates is 14.7% higher in the bottom layer than in the surface layer. The content of sodium ions is higher by 4.6% and potassium ions by 7.0% in the bottom layer than that in the surface layer. The content of calcium and magnesium ions in the bottom layer is lower than that on the surface by 5.0 and 4.5%, respectively. Changes in the ionic composition at depths below 15 m indicate chemical stratification in the water column.

It should be noted that in previous years of our research, the chemical stratification was much more pronounced than in 2019 and was often accompanied by the presence of hydrogen sulfide in the lower layer [10]. For example, according to our observations in 2017 compared to 2019, the difference in the relative content of ions in the surface and bottom layers was 6.4% for chlorides and 20% for sulfates, whereas in 2019, it was 1.2% for chlorides and 14.7% for sulfates under conditions of almost the same salinity (Table 3).

The pH value in 2019 was in the range of 7.82–7.86, indicating a slightly alkaline reaction of the medium, and did not change significantly with depth. The total alkalinity in the bottom layer was higher by 4% in comparison with the surface layer, while the salinity was higher by 2.4%.

Laboratory measurements of the Aral-Sea water using a precision density meter allowed us to obtain density values at the temperature recorded upon sampling (in situ) at depths of 0, 10, 20, and 30 m. Figure 4 shows the profiles of the temperature and density over the depth from 0 to 30 m in 2019. It is evident that the water density increases with decreasing temperature for the temperature values measured upon sampling (in situ). The increase in density is caused by an increase in salinity, but this process is not linear. For

Table 3. Hydrochemical characteristics of waters from the western basin of the Aral Sea (2014–2019, station A2)

Year	Station	Depth, m		pH	A_T**, mmol/kg	ρ at 21°C, g/cm^3	S**, ‰	Anions, ‰, %			Cations, ‰, %			
		sampling	max at the sampling point					Cl^-	SO_4^{2-}	HCO_3^-	Na^+	K^+	Ca^{2+}	Mg^{2+}
2014*	A2	0	34.0	8.25	12.059	1.097569	126.30	64.1*** *50.8*	21.33 *16.9*	0.44 *0.4*	26.97 *21.4*	2.16 *1.7*	1.32 *1.1*	9.97 *7.9*
		34				1.101968	No data							
2016*	Near the coast	0	0.5	7.94	13.428	1.104338	127.63	64.70 *50.7*	20.01 *15.7*	0.44 *0.3*	31.16 *24.4*	No data	0.83 *0.7*	10.46 *8.2*
2017*	A2	0	29.2	8.26	14.249	1.114072	140.06	68.50 *48.9*	23.88 *17.1*	0.57 *0.4*	33.24 *23.7*	2.08 *1.5*	0.91 *0.7*	10.87 *7.8*
		29		8.15	13.561	1.115151	140.62	64.11 *45.6*	28.75 *20.5*	0.62 *0.4*	34.04 *24.2*	1.95 *1.4*	0.94 *0.7*	10.21 *7.3*
	Near the coast	0	0.5	8.39	13.946	1.114072	140.22	68.60 *48.9*	23.75 *16.9*	0.66 *0.5*	33.40 *23.8*	2.09 *1.5*	0.95 *0.7*	10.78 *7.7*
2019	A2	0	30.1	7.86	11.236	1.108926	135.49	69.14 *51.0*	20.47 *15.1*	0.46 *0.3*	31.84 *23.5*	2.31 *1.7*	0.79 *0.6*	10.95 *8.1*
		15		7.82	10.180	1.108964	136.57	69.01 *50.5*	21.26 *15.6*	0.46 *0.3*	32.32 *23.7*	2.36 *1.7*	0.79 *0.6*	10.84 *7.9*
		25		7.82	11.657	1.109927	138.68	68.27 *49.2*	23.39 *16.9*	0.48 *0.4*	33.22 *24.0*	2.35 *1.7*	0.80 *0.6*	10.64 *7.7*
		30		7.83	11.688	1.111261	138.72	68.30 *49.2*	23.49 *16.9*	0.46 *0.3*	33.32 *24.0*	2.14 *1.6*	0.76 *0.6*	10.71 *7.7*

* The data for 2014–2017 are taken from [4]; ** S is the salinity; A_T is the total alkalinity; *** hereinafter, the first line shows the values in ‰, and second line (italics), in % of the salinity of the sample.

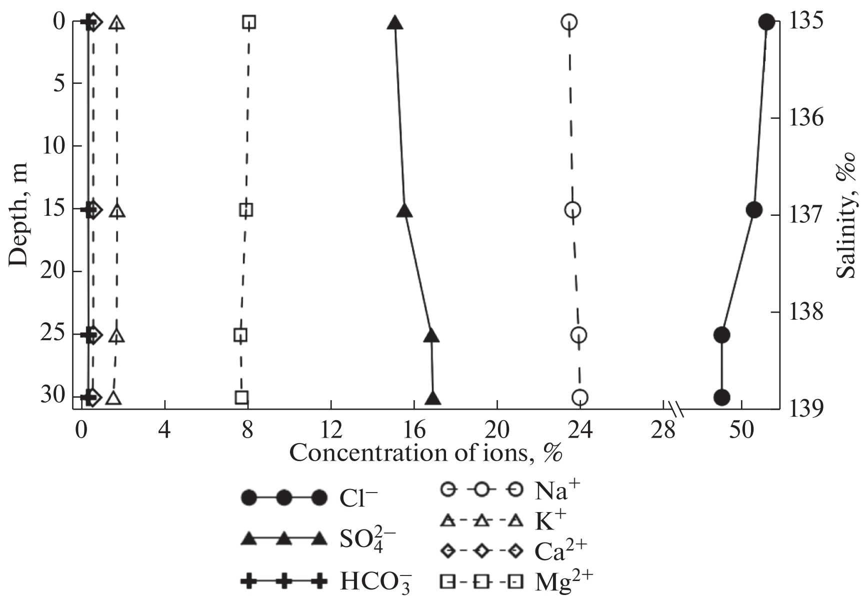

Fig. 3. Distribution of the major ions with depth in the western basin of the South Aral Sea at Station A2 in 2019.

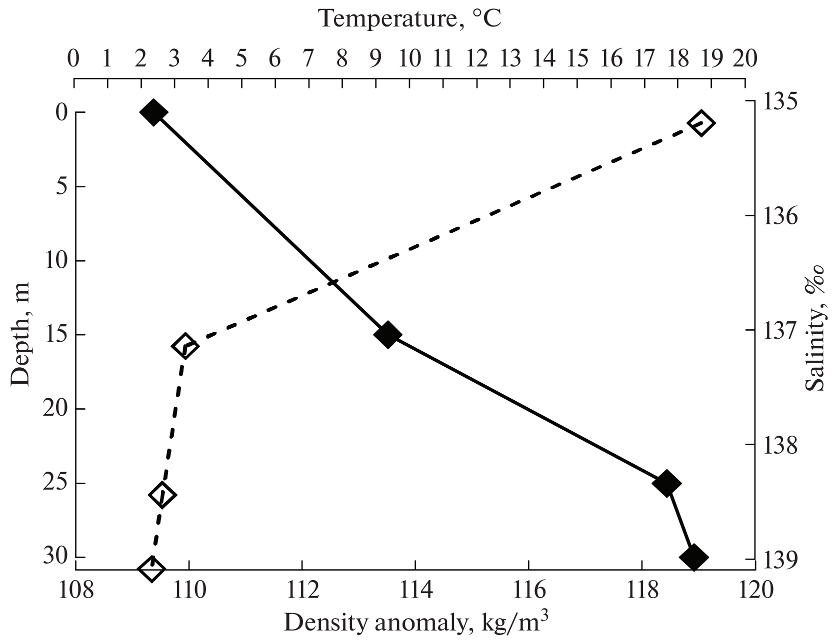

Fig. 4. Profiles of the density (full rhombs and solid line) and temperature (empty rhombs and dotted line) of the Aral Sea water in May 2019 at a depth of 0–30 m.

example, the difference in salinity for the samples taken from the surface and from a depth of 15 m was 1.08‰, while the difference in density was 4.10 kg/m^3. The difference in the density values for the samples from depths of 15 m and 25 m was 4.9 kg/m^3, while the salinity in the sample from 25 m exceeded the salinity in the sample from 15 m by 2.1‰. The difference between the density values in the samples from 25 and 30 m was only 0.4 kg/m^3, while the difference in salinity was 0.04‰. Thus, there is a sharp increase in density and a decrease in temperature in the water layer from 0 to 15 m.

There are significant differences in the ionic composition between the lower horizons (25–30 m) and the upper layer (0–25 m). This provides evidence for the presence of two-layer chemical stratification in the

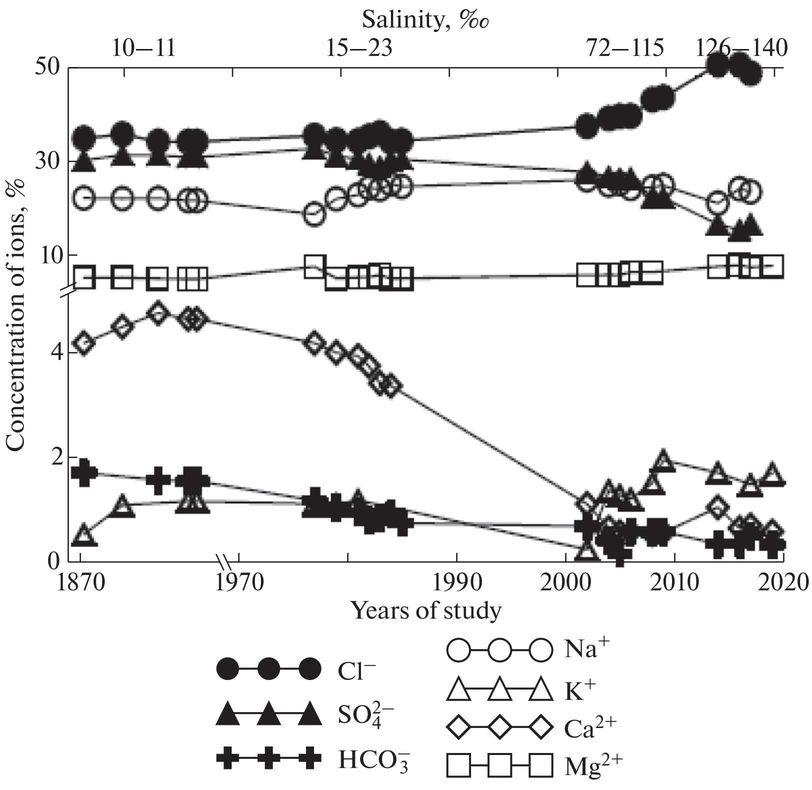

Fig. 5. Evolution of the major-ion composition in the period of monitoring from 1870 to 2019, according to our results and the data from [1, 4–6, 8, 10].

water column of the lake in May 2019. The data on the density and temperature allow us to suggest the presence of chemical and thermohaline, as well as density stratification in May 2019. Stratification of the water column was previously observed for this part of the Aral Sea and was much more pronounced, as was reported in our papers [10, 28].

DISCUSSION OF THE RESULTS

The history of exploration of the Aral Sea begins in 1870 and the first results were reported in [5]. Figure 5 shows the published historical data on the ionic composition of the Aral-Sea water, which mainly presents data on the surface layer of the sea. Data on the concentrations of the components of the major-ion composition of the Aral Sea in the period up to 1902 were taken from [5]; until 1952, from [6]; 1980–1985, from [1, 8]; 2002–2009, from [10]; for 2014 and 2017, from [4]; and for 2019, from this study. The graph shows that the changes in the ratios of the major ions became more pronounced from the 1970s.

The evolution of the salt composition of closed water bodies in general, and for the Aral Sea, in particular, is a complex process that depends on such conditions as water and air temperature, air humidity, and concentration of the salt solution. These factors affect the order of the precipitation of salts and their re-dissolution from the precipitate. At the same time, salts may transform from one to another under the influence of these conditions [7, 18]. The process of evolution of the Aral-Sea waters is of particular interest due to the unique initial ionic composition of its waters. Metamorphization of the Aral-Sea waters in the 1980s resulted in a change in their type [10]. The Aral-Sea waters initially belonged to the sodium-sulfate type, which is intermediate between the sodium-chloride type of oceanic waters and calcium-bicarbonate type of continental ones. They had a sulfate/chlorine molar ratio of 0.68 and a weight ratio of 0.9 [6]. By October 2005, the weight ratios were 0.67 in the surface layer and up to 0.82 in the bottom layer [10]. In April 2017, these ratios were 0.35 in the surface layer and 0.45 in the bottom layer [4], and according to our latest data, in May 2019, it was 0.30 in the surface layer and 0.34 in the bottom layer. Thus, there is an annual decrease in the relative content of sulfates in the composition of the Aral-Sea waters.

Figure 5 shows no significant changes in the salt composition of the waters up to the 1970s. However, the salinity of the Aral Sea already increased by this time; this most likely resulted in an intensive decrease in the content of calcium and magnesium carbonates, which started to precipitate in the Aral Sea at a salinity of 10‰ and higher [10]. Simple and complex sodium and magnesium carbonates are precipitated even in the early stage of lake-water accumulation [18]. However, the content of these salts is not very high, and the analysis of bottom sediments showed that by 2008, over 50 years of drying of the Aral Sea, the contribution of magnesium carbonates was only 2% of all precipitated salts [10]. Thus, it may be assumed that the precipitation of magnesium carbonate occurred in the period from 1960 to 1970.

Significant changes in the evolution of the chemical composition have become noticeable since the 1980s (Fig. 5), when the salinity exceeded 22‰ and the precipitation of salts started, most likely predominantly in the form of calcium sulfate. It was previously shown that the precipitation of sulfates in the water of the Aral Sea begins at a salinity of 22–23‰ [6, 8] or 25–26‰ [2]. A decrease in the relative content of calcium ions, along with sulfates, is evident in Fig. 4 at a water salinity of ~23‰. The precipitation of gypsum $CaSO_4 \cdot 2H_2O$ most likely occurred at that time (after 1985). It is evident from Fig. 5 that the calcium content (white rhombs) decreases sharply below the 3-% limit.

The relative content of major ions in the water of the western basin of the Aral Sea changes from year to year as well (Fig. 5). By 2019, compared with the period before 1960, the relative content of chlorine ions increased by a factor of 1.5; sodium, by a factor of 1.05; potassium, by a factor of 3.2; and magnesium, by a factor of 1.5. The content of other components decreased: sulfates, by a factor of 2; hydrocarbonates, by a factor of 5; and calcium ions, by a factor of 7. With increasing mineralization by more than 20‰ (in the period after 1981), a sharp increase in the sodium content became noticeable. It slightly decreased after the 2000s, when the salinity of the water reached ~100‰. The content of magnesium ions remained rather stable and even increased when the brine reached a salinity of more than 110‰.

The relative content of magnesium, as well as potassium, in the surface layer of the water of the South Aral Sea has remained quite stable for many years. Potassium is usually precipitated in salty lakes as minerals like kainite $KCl \cdot MgSO_4 \cdot 3H_2O$, sylvite KCl, and carnallite $KMgCl_3 \cdot 6H_2O$. These salts are formed in modern salty lakes via precipitation from residual brine during the period of drying or at the "dry lake" stage in the upper part of the salt deposit [7, 18]. Potassium and magnesium are the most conservative cations. They persisted in the water column of the Aral Sea as well, even when the water salinity in the Chernyshev Bay reached 240‰ in 2016 [3].

As a result, when the water level decreased by 56%, the relative content of chlorides in the water of the western basin of the South Aral Sea increased by a factor of 1.5; sodium, by a factor of 1.05; potassium, by a factor of 3.2; and magnesium, by a factor of 1.5. The contents of sulfates, hydrocarbonates, and calcium decreased by factors of 2, 5, and 7, respectively.

Although in this study we did not analyze the gas composition of the Aral-Sea waters, research by scientists of the Institute of Oceanology showed the presence of hydrogen sulfide and methane mainly in the bottom horizons of the residual water bodies. It was accompanied by the presence of anaerobic conditions in deep sea waters, which have a significant effect on the hydrochemical regime and geochemistry of waters [12, 28, 34]. It can be briefly noted that at the end of 2002, hydrogen sulfide H_2S was first discovered in the Aral Sea, at Chernyshev Bay, which is the northern end of the South Aral Sea. A summary of monitoring for the H_2S content in 2002–2010 was presented in [10].

The depth of anoxic-layer occurrence in the western basin of the South Aral Sea varied over a wide range (from 15 to 35 m), and the H_2S concentrations ranged from 5 to 80 mg/L. In 2012, samples from a depth of 30 m and more exhibited the distinct smell of H_2S and the complete absence of O_2; in 2013, the upper limit of H_2S was at 18 m [12]. The presence of hydrogen sulfide was detected in the bottom layers in 2014 and 2017, but its concentration was not studied. In May 2019, there were no tangible signs of hydrogen sulfide in the samples under study. It is known that, for example, in the spring and summer of 2004, the presence of hydrogen sulfide in the bottom layer was not detected as well, which was associated with deep convection events in the winter period in 2003–2004 [10].

Study of the water density of the Aral Sea

In our study [3], the values of the density and salinity were reported for two hypersaline and one slightly saline water body of the Aral Sea, namely the Chernyshev Bay of the South Aral Sea, Lake Tshchebas, and the North Aral Sea, and an extrapolation was presented to compare the changes in the physical-chemical properties of the studied water bodies that occurred from the beginning of the lake drying out. The data for extrapolation for the North Aral Sea, Chernyshev Bay, and Lake Tshchebas were taken from [4, 10, 22, 28]. We added extrapolation of the density and salinity data for water in the deep-water part of the western basin of the South Aral Sea for the period of 2014–2019 to the graph from [3] for a more complete understanding of the evolution of the Aral-Sea water (Fig. 6). This graph reflects the course of the physicochemical evolution of waters of individual water bodies of the Aral Sea, including the western basin of the South Aral Sea.

The graph shows that the changes in the ionic composition were followed by significant changes in the physical characteristics of the waters of individual water bodies of the Aral Sea, and the trend lines predict their likely further state under conditions existing at present. When the studied bodies of water reach the maximum salinity, the value recorded in Chernyshev Bay (242‰), the deviation between the density values with Lake Tshchebas would be 30 kg/m^3; with the

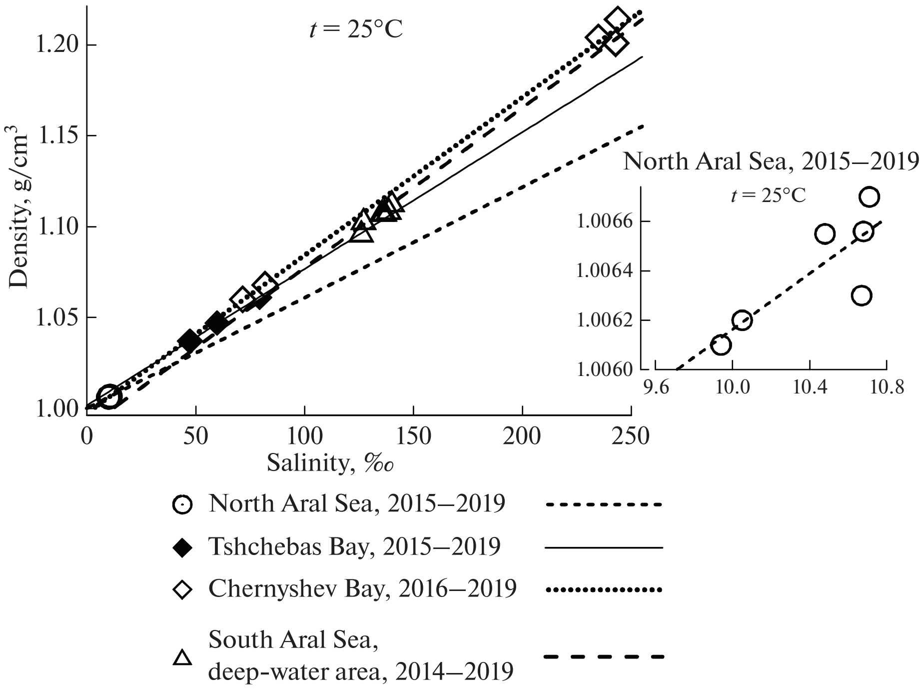

Fig. 6. Dependence of the density on the salinity of water at a temperature of 25°C in different water bodies of the Aral Sea 2014–2019.

North Aral Sea, 70 kg/m^3 [3]; and with the deep-water part of the South Aral Sea, 9 kg/m^3. Therefore, we can conclude that the deep-water part and Chernyshev Bay, being parts of the South Aral Sea, acquired their own physical-chemical properties in the course of the sea drying out, different from other individual water bodies of the Aral Sea, as well as from each other.

Such differences are explained by the different hydrological regimes of these water bodies, their depths, areas, and remoteness from the continental runoff. The currently existing separate parts of the Aral Sea began to differ in terms of their hydrochemical characteristics, as well as in the hydrophysical parameters in the course of evolution. The density of water, the temperature of evaporation and freezing in each water body are now different.

CONCLUSION

The hydrochemical characteristics of waters from the western basin of the Aral Sea were obtained during an expedition in 2019. The salinity of the water was analyzed, but its measurement with standard hydrophysical equipment for electrical conductivity leads to significant errors due to a difference in the ionic composition of the water from that of the ocean. Studies of the density of the Aral-Sea water using high-precision equipment made it possible to analyze its distribution in the water column from the surface to the bottom and to detect the presence of density stratification.

It was found that the sea level experiences seasonal fluctuations up to 1 m, which is accompanied by a change in the salinity of the lake and should result in a pronounced seasonal variation in the ion–salt composition.

It was shown that significant changes occurred in the content of the components of the major ionic composition, as well as the salinity and density in the course of evolution of the Aral-Sea waters during its drying out. Thus, when the water level decreased by 56%, the relative content of chlorides in the water of the western basin of the South Aral Sea increased by a factor of 1.5; the content of sodium ions, by a factor of 1.05; the content of potassium ions, by a factor of 3.2; and the content of magnesium ions, by a factor of 1.5. On the contrary, the content of sulfates, hydrocarbonates, and calcium, decreased by factors of 2, 5, and 7, respectively. The evolution of the ionic composition of waters from the deep-water part of the South Aral Sea continues to the present day. It entails changes in the physical properties of water, such as the density and salinity, and affects evaporation rates and the freezing point of water as well.

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