

RESEARCH ARTICLE

Trends in Changes of Hydrological and Hydrochemical Conditions of The Aral Sea Until 2030

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Abstract

Since 1961, as a result of intensive and irreversible withdrawal of river flow, primarily for irrigation, the inflow of water into the Aral Sea has sharply decreased, leading to a disruption of its hydrological and hydrochemical regime. Evaporation significantly exceeds water inflow, causing a steady drop in sea level, desertification of the surrounding areas, and degradation of the natural environment of the Aral Sea region. New continental ecosystems are forming on the exposed seabed, aeolian processes are intensifying, and deflation contributes to the spread of salts, worsening soil conditions. The environmental crisis is further complicated by the current geopolitical and socio-economic situation, necessitating new scientifically grounded approaches to minimize its consequences. Anthropogenic factors account for up to 95% of the inflow reduction, and by 2022, the sea's surface area had decreased to 14,000 km², its volume to 44 km³, and salinity had reached 123‰. Forecasts indicate a continued drop in sea level and the transformation of the Aral into a chloride brine lake with salt deposition, which could open up opportunities for salt extraction or balneological use.

KEYWORDS

Aral Sea, environmental crisis, inflow reduction, anthropogenic factors, evaporation, desertification, hydrochemical regime, salinity, aeolian processes, brine lake, Aral region, water balance, ecosystem degradation, ionic runoff, environmental transformation.

INTRODUCTION

Since 1961, due to a sharp increase in the irreversible withdrawal of runoff, mainly for irrigation purposes, the inflow of river water into the Aral Sea has significantly decreased. As a result, the sea's hydrological and hydrochemical regime has been severely disrupted. The decline in sea level continues steadily, as evaporation significantly exceeds inflow. This

negatively affects the transformation of the natural environment and the socio-economic conditions of the entire Aral region, especially in the lower reaches of the Amu Darya and Syr Darya rivers, where natural conditions are closely tied to the sea. This has led to the desertification of the non-irrigated zones of the deltas, encompassing new areas as the

Aral continues to dry up.

The drying coastline of the sea is a unique area newly exposed from under the Aral's waters, where the emergence, formation, and development of primary continental natural complexes are taking place, and components of the natural environment are being formed. Furthermore, the former seabed has become a site of aeolian processes, a phenomenon typical for desert zones. Deflation causes the removal of accumulated salts along with dust, which are deposited in surrounding soils due to the intensive evaporation of surface moisture.

The threat of further deterioration of the region's geosystems calls for the development of appropriate scientifically based measures. Moreover, the Aral and Aral region's environmental crisis is now unfolding under a new geopolitical and socio-economic context. All previously developed pre-project and scientific proposals largely remain unimplemented. Therefore, a new understanding and explanation of the situation are required to develop approaches to overcome the crisis or minimize its consequences.

METHODS

Since 1961, the inflow of river water into the sea has been systematically decreasing. Currently, the inflow through the Amu Darya has completely ceased, while the Small Aral Sea continues to receive about 3 km³/year through the Syr Darya. According to estimates by the Institute of Geography of the Russian Academy of Sciences, about 80% of the reduction in inflow to the sea is due to anthropogenic factors, while the remaining portion depends on river water availability, which has been low over the past decade. According to data from T.N. Vladimirova [3], A.V. Volodkin [4], and F.E. Rubinova [14], current anthropogenic water losses account for 92–95% of the total runoff losses.

The study of the hydrochemical regime of the Aral Sea in connection with the onset of intensive sea level decline has been the focus of a number of works. For instance, research on the non-stationary salinity regime was conducted by S.K. Revina and A.B. Zaklinsky [12]; N.K. Yelibayev [7]; A.N. Kosarev [8]; V.N. Bortnik [2]; F.E. Rubinova [14]; M.A. Yakubov [20]; E.I. Chembarisov [17]; S.R. Saidova et al. [15]; V.E. Chub [18], among others.

Studies on changes in hydrological and hydrochemical conditions in closed water bodies, particularly the Aral Sea,

were undertaken by a number of authors. Forecasts of potential future changes in sea level or individual elements of the water balance were conducted by A.V. Shnitnikov [19]; V.P. Lvov [9]; M.Kh. Baidal [1]; V.V. Golubtsov and O.A. Morozov [6]; K.I. Smirnova [16]; M.M. Rogov [13]; I.P. Gerasimov [5]; A.A. Rafikov [10], V.A. Rafikov [11], and others.

The analysis was based on long-term data on precipitation, evaporation, sea level, surface area, volume, and salinity, including predictive estimates of minimum and maximum scenarios for increased irreversible water withdrawal in the Amu Darya and Syr Darya river basins (Table 3).

RESULTS

The average annual precipitation between 1961–1985 was 124 mm, with the driest decade being 1971–1980, when annual precipitation dropped to 110 mm. From 1986–2022, the average dropped to 113 mm, with the driest years recorded from 2015–2022, averaging only 69 mm per year. Overall, for the period 1911–2022, the long-term average precipitation over the Aral Sea surface was 96 mm. The maximum precipitation, 235 mm, occurred in 2018, while the minimum, 67 mm, was recorded in 1944 [18].

The average annual evaporation from the sea's surface was 1,035 mm for 1961–1970. In the following periods, it measured 968 mm (1971–1980), 962 mm (1981–1985), 927 mm (1986–1990 and 1991–2000), and 972 mm for 2001–2021. Over the entire period of 1911–2022, the average annual evaporation was 898 mm, with a maximum of 1,206 mm in 2003 and a minimum of 781 mm in 1982.

Observational data show that the destabilization of the sea is caused by evaporation significantly exceeding total inflows. The average rate of sea level decline in 1961–1970 was about 21 cm/year (noting the anomalously high-flow year of 1969), 58 cm/year during 1971–1980, and 80 cm/year in 1981–1985. During 1986–1990, the decline averaged 74 cm/year, 49 cm/year in 1991–2000, and 56 cm/year from 2001–2022. As a result, the sea's area shrank to approximately 43,000 km² by 1986 and to 14,000 km² by 2022, while its volume decreased to 432 km³ and 44 km³, respectively. The sea's configuration changed significantly—large shallow bays in the eastern, southeastern, and southern parts of the Aral have completely disappeared. Former islands like Vozrozhdeniye, Barsakelmes, Lazarev, and the Muynak Peninsula are now part

of a unified geographic landmass along with the exposed seabed.

At the beginning of the Aral Sea's intensive decline (1971–1975), the salinity of the Small Aral Sea exceeded 12‰, while in the Large Aral it ranged from 12 to 12.5‰, with the highest concentrations observed in shallow eastern areas. Significant vertical salinity gradients were recorded in the estuarine zones and deeper western regions, where salinity increased with depth by 0.4–0.6‰. In spring 1981–1985, the salinity in the Large Aral Sea reached 19.7–20.5‰; in 1986–1990, it was 20.6‰; in 1991–2000, 37.6‰; and by 2001–2022, it had reached 108.5‰. Due to continued reduction and at times complete cessation of river inflow, the freshwater zones in the Amu Darya delta disappeared. Inflows from the Syr Darya resumed in 1992–1995.

In summer 1981–1985, the salinity of the Large Aral rose to 21‰; in 1986–1990, to 23‰; in 1991–2000, to 41.6‰; and in 2001–2022, it reached 123‰. In autumn, when river inflow decreases and convective water mixing begins, vertical salinity becomes nearly uniform. The rise in salinity in the western basin is less due to volume loss than due to the inflow of more saline brine from the eastern basin through the connecting strait. The salinity of the eastern basin is slightly lower, but this exchange contributes to density stratification in the west.

Between 2002–2022, the salinity difference between the base of the upper quasi-homogeneous layer and the bottom reached up to 12 g/kg (equivalent to a density difference of 9–10 kg/m³), with the halocline being about 20 m thick.

The salt composition of the "marine" water results from evaporative concentration, salt precipitation, and the inflow of riverine ionic load. At the onset of destabilization, the ionic flow into the Aral Sea increased from 23.8 million tons/year to 26.9 million tons/year during 1961–1970. This increase is explained by a sharp rise in total mineralization of the Syr Darya waters (almost doubling). The mineralization of the Amu Darya waters increased only slightly during this period. In later periods, due to a drastic reduction in water flow, the total ionic load decreased to 12.5 million tons/year in 1971–1980 and 2.23 million tons/year in 1981–1985. In 1986–1990, ionic flow was 1.79 million tons/year; in 1991–2000, it nearly dropped to zero at 1.01 million tons/year; and from 2001–2022, ionic inflow ceased entirely. Notably, during certain periods between 1991–2000 and 2001–2022, no ionic flow was recorded even along the Syr Darya. In the final period (2001–2022), the mineralization of Amu Darya waters rose to 3,671.8 mg/L and that of Syr Darya to 2,878.4 mg/L—according to measurements at the terminal cross-sections (Table 1).

Table 1.

The average long-term concentration of major ions, total mineralization, and ionic runoff of the Amu Darya and Syr Darya rivers for characteristic periods (according to data from the Hydrometeorological Services of Uzbekistan and Kazakhstan)."

Period	Unit of measurement	HCO_3^-	SO_4^{2-}	Cl^-	Ca^{2+}	Mg^{2+}	$Na^+ + K^+$	Total mineralization	Ion drain, million tons
River AmuDarya									
1986-1990	мг/л	136,2	912,1	675,6	161,8	111,3	352,4	2349,4	1,72
	%	10,3	21,4	17,3	17,1	11,3	12,6	100,0	
1991-2000	мг/л	127,3	1190,1	910,4	208,7	139,5	410,7	2986,7	1,01
	%	8,70	23,3	14,5	11,7	14,8	27,0	100,0	
2001-2022	мг/л	115,1	1395,3	1270,1	245,6	175,5	470,2	3671,8	-
	%	12,7	18,8	20,1	12,3	14,4	21,7	100,0	
River SyrDarya									
1986-1990	мг/л	171,3	1120,1	210,4	155,9	105,6	498,1	2261,4	0,07
	%	10,9	13,3	19,4	13,8	17,0	25,6	100,0	
1991-2000	мг/л	156,8	1240,3	245,3	170,8	121,5	628,9	2563,6	-
	%	12,0	19,1	18,3	15,5	11,8	23,3	100,0	

2001-2022	мг/л	139,9	1360,2	271,7	191,7	137,4	777,5	2878,4	-
	%	9,90	16,4	21,7	19,9	14,4	17,7	100,0	

The chemical composition of river waters flowing into the Aral Sea has transformed from hydrocarbonate-calcium to sulfate-sodium, indicating their direct metamorphosis. In the salt balance of the sea, the input of salts from atmospheric precipitation constitutes only a fraction of a percent, and their role in shaping water salinity is considered very insignificant. The underground inflow into the Aral Sea under current conditions does not exceed 0.1–0.3 km³/year, and the corresponding ionic runoff is also negligible.

Aeolian (wind-driven) input and removal of salts from the sea is associated with desertification. According to conducted estimates, the input of salts through atmospheric dust and wind-driven removal from the sea surface are unbalanced. Based on these estimates, windborne salt removal exceeds approximately 0.1–0.2 million tons per year. According to observations from 1990–2000, the average amount of salt deposited per 1 km² of the desiccated sea floor was estimated

at 5.4 thousand tons. The average annual amount of salts deposited on the dried seabed for the periods 1986–1990, 1991–2000, and 2001–2022 was estimated at 5.3, 4.8, and 6.09 million tons, respectively.

The amount of carbonate and sulfate salts precipitated due to concentration by seawater during 1986–1990 was 8.26 million tons, with annual fluctuations ranging from 0 to 15.0 million tons. In subsequent periods (1991–2000, 2001–2022), this amount totaled 9.87 and 10.12 million tons, respectively, with annual fluctuations ranging from 6.13 to 12.3 million tons.

The results of estimates for the minimum and maximum scenarios of increased irreversible water withdrawals in the Amu Darya and Syr Darya river basins, excluding long-term river flow regulation by reservoirs, are presented in Table 2, which provides assessments for the case of 50% water flow reliability.

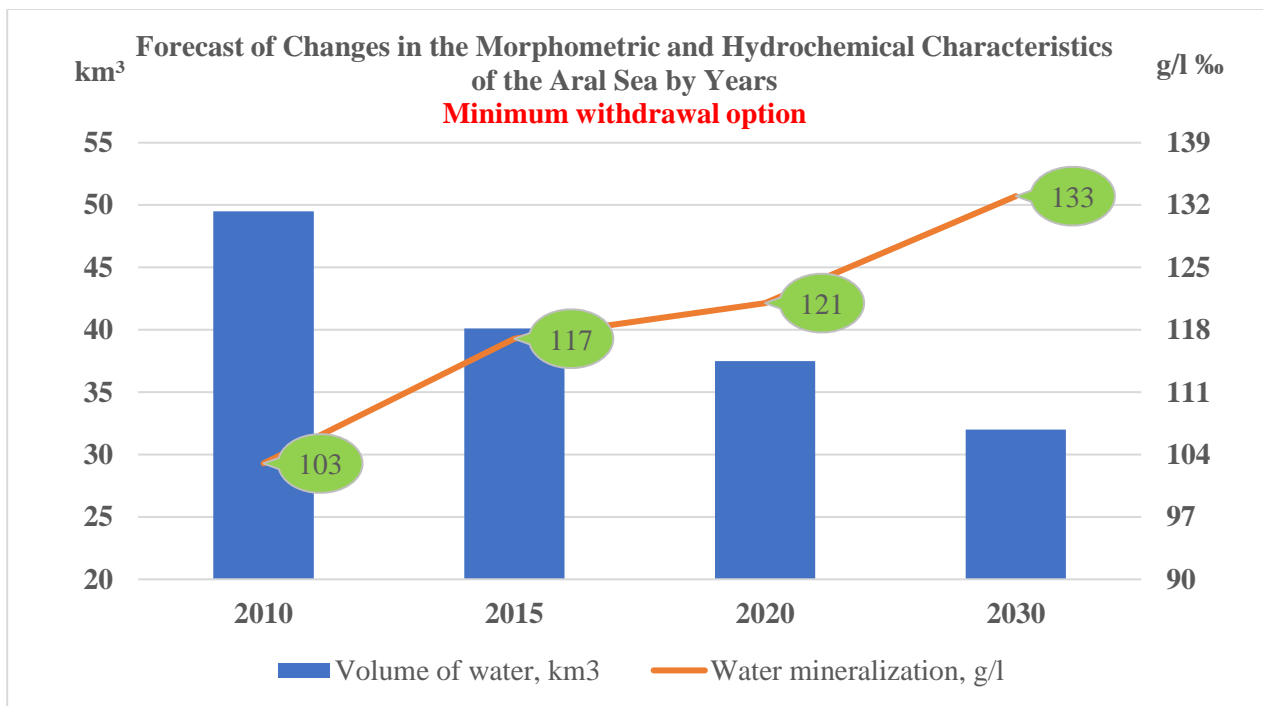
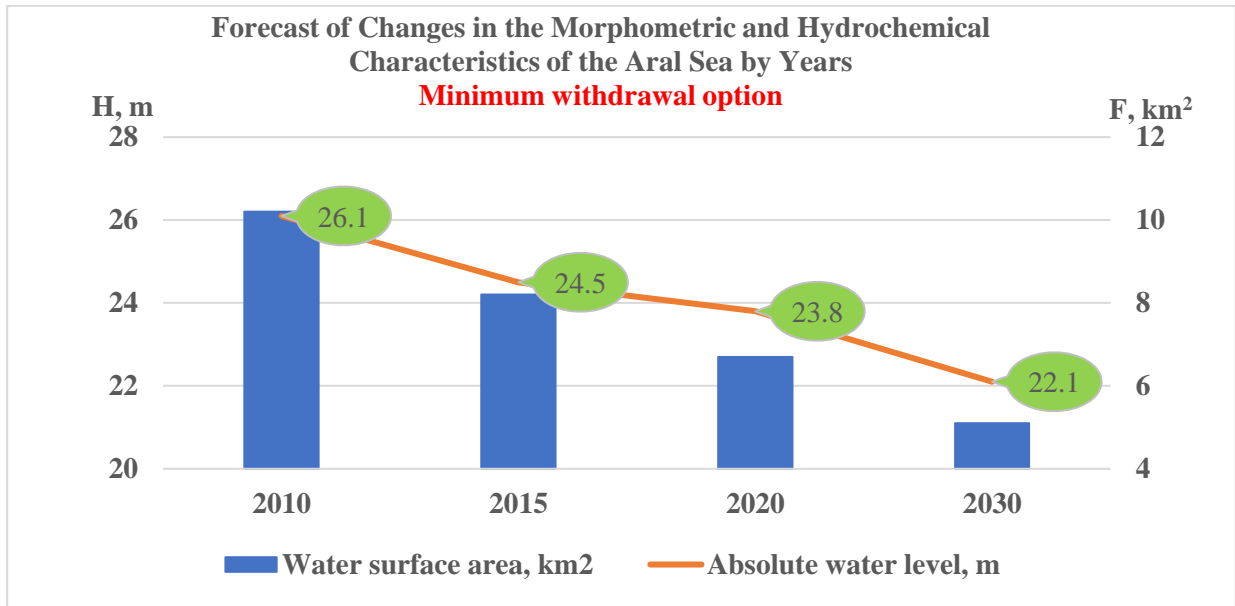
Table 2.

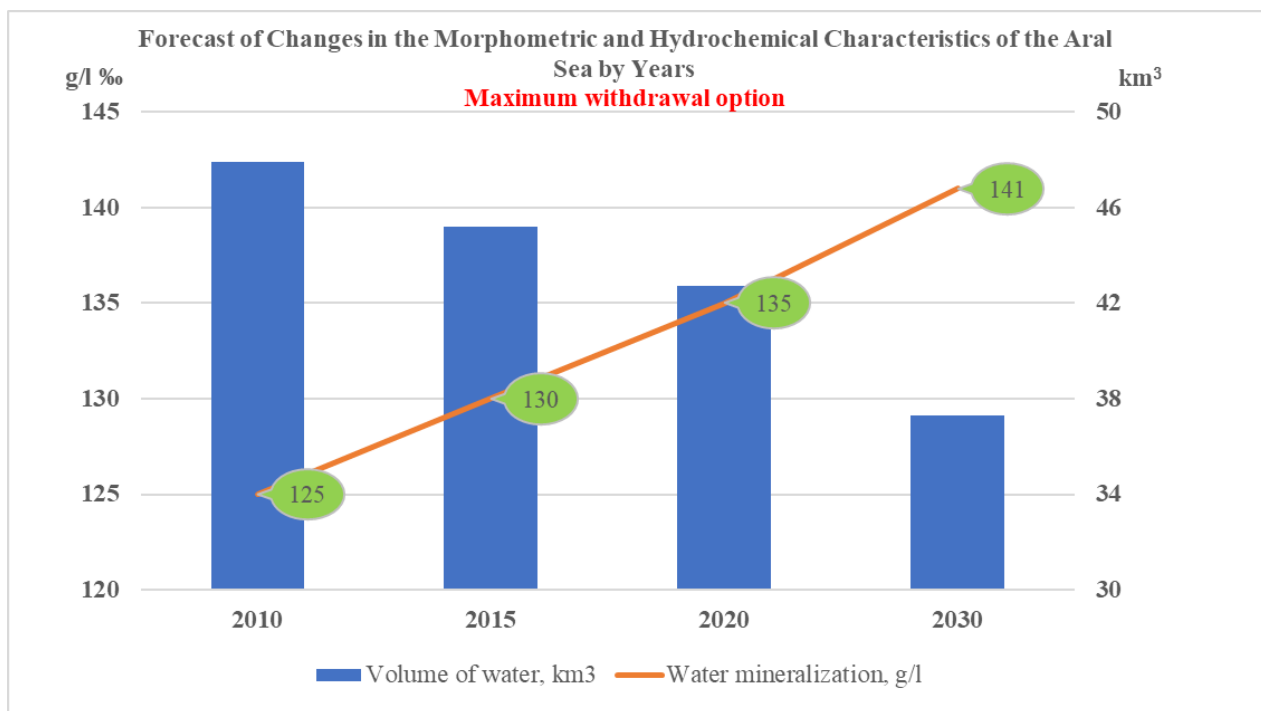
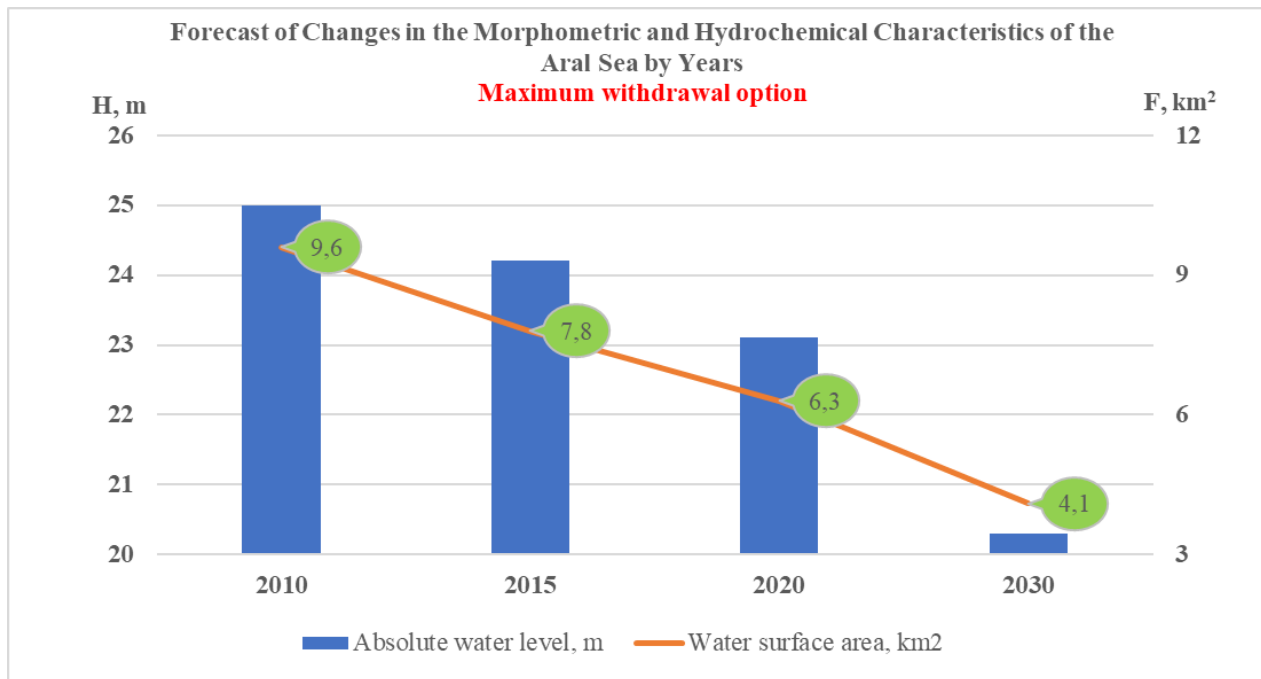
Forecast of Changes in the Morphometric and Hydrochemical Characteristics of the Aral Sea by Years

Years	Absolute water level, m	Water surface area, km²	Volume of water, km³	Water mineralization, g/l
Minimum withdrawal option				
2010	26,1	10,2	49,5	103
2015	24,5	8,2	40,1	117
2020	23,8	6,7	37,5	121
2030	22,1	5,1	32,0	133

Maximum withdrawal option

2010	25,0	9,6	47,9	125
2015	24,2	7,8	45,2	130
2020	23,1	6,3	42,7	135
2030	20,3	4,1	37,3	141





DISCUSSION

As the salinity of the sea water increases, a metamorphosis of its salt composition will occur, associated with the precipitation of certain poorly soluble salts. According to conducted assessments, the joint precipitation of only these salts will continue for a long period—until seasonal deposition of

mirabilite (in the colder part of the year) begins. By that time, the Aral Sea, having drastically reduced in volume and area, will become hydrochemically similar to the Kara-Bogaz-Gol in the stage when the Karabogaz brine had not yet reached NaCl saturation.

Salt precipitation in the Aral Sea brine will follow a pattern similar to the Kara-Bogaz-Gol's salt deposition during that

stage: in winter, with brine cooling, mirabilite ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$) and calcium salts will precipitate; in summer, while the deposition of the latter continues, mirabilite will re-dissolve. However, since the water body will have a relatively great depth and its water mass will warm up very slowly, it is likely that not all of the mirabilite precipitated in winter will dissolve. A portion of the mirabilite formed during the winter may be thrown ashore by storm winds, similar to what happened at Kara-Bogaz-Gol.

By analogy, the mirabilite thrown ashore may represent only a negligible fraction of the total amount precipitated from the Aral Sea brine. As the concentration of the Aral brine further increases, it will eventually reach NaCl saturation. Unlike mirabilite, the precipitation of NaCl will not be seasonal, since NaCl's solubility is minimally affected by water temperature. In the early stage of NaCl saturation of Aral brine, its precipitation during winter may temporarily stop, as the overall salinity of the brine will decrease due to mirabilite deposition. However, with the complete cessation of river water inflow into the Aral Sea, this stage will last only a few years. As the brine concentration continues to rise, NaCl will gradually cover the sulfate salts that have settled on the bottom of the water body. Initially, this will hinder their dissolution, and eventually, it will completely prevent it during the warm season.

The process of transformation into a chloride brine lake. This transformation will likely occur rapidly, since the precipitation of sulfates will begin while the Aral Sea still maintains considerable depth, and, as previously noted, the warming of bottom waters during the warm season will be insufficient for their complete dissolution. Such a phenomenon has been observed repeatedly in the shallower Kara-Bogaz-Gol; it is primarily due to this that the concentration of the sulfate ion in the Karabogaz brine is relatively lower than in Caspian water.

With the Aral Sea turning into a chloride brine lake, practically only NaCl will precipitate, accounting for over 99% of the total mass of deposited salts. Calcium salts will make up only fractions of a percent. Ultimately, a brine lake will form, with the upper part of its bottom represented by a layer of nearly pure table salt (halite), and the lower part consisting of various sulfates: mirabilite ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$), glauberite ($\text{CaSO}_4 \cdot \text{Na}_2\text{SO}_4$), astrakhanite ($\text{Na}_2\text{SO}_4 \cdot \text{MgSO}_4 \cdot 4\text{H}_2\text{O}$), and others.

The average thickness of the salt layer will be no less than 2.5–3 meters, even if we assume an overestimated area of the Aral Sea at the start of NaCl precipitation—1,500 km². Roughly half of this thickness will consist of the halite layer. Numerous observations from Russian salt lakes—such as Lake Kulunda (Altai Krai), Baskunchak (Astrakhan Oblast), Elton (Volgograd Oblast), and others—show that halite layers form very dense deposits, practically immune to wind erosion. No deflation (wind erosion) of this layer is expected, and therefore, salt removal by wind cannot occur. In contrast to halite, anhydrous sodium sulfate (Na_2SO_4) is a wind-sensitive powder. However, under the described conditions, all sulfate salts will be protected from deflation by the dense halite crust.

CONCLUSIONS

These assessments indicate that in the coming decade, the decline in the Aral Sea's water level will continue. Its rate will be determined mainly by anthropogenic factors—specifically, the volume of irreversible water withdrawals, which depend on various water management strategies in the sea's basin. Changes in the salinity of the Aral Sea during the current and future periods will primarily be caused by the concentration of sea water as the sea's volume decreases. At the same time, the influence of ion runoff and other components of the salt balance will be extremely minimal due to the sharp reduction in river inflow and sea surface area. Moreover, a significant portion of salts brought by rivers (carbonates and some sulfates) will precipitate during the mixing of river and sea waters as a result of the sea water being supersaturated with these salts.

Hydrological and hydrochemical characteristics of the Aral Sea will continue to degrade under destructive conditions. The sea, as such, will transform into a brine lake. It may acquire balneological significance (for therapeutic use) or become suitable for salt extraction. Thus, due to anthropogenic impact and natural processes, the Aral Sea is losing its original features—necessitating new approaches to crisis management and mitigation of its consequences.

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