



# Recent changes in physical and biogeochemical state in residual basins of the Aral Sea

Natalia Yu. Andrulionis<sup>1</sup> · Alexander S. Izhitskiy<sup>1</sup> · Alexander S. Savvichev<sup>2</sup> · Peter O. Zavialov<sup>1</sup>

Received: 22 October 2024 / Accepted: 9 December 2024  
© The Author(s), under exclusive licence to Springer Nature B.V. 2024

## Abstract

The Aral Sea is well known throughout the World as an inland lake disappearing due to unsustainable use of natural water resources for economic purposes. The degradation of the sea led to irreversible transformations of the ecosystem in the region and other destructive consequences. It has become a natural laboratory, allowing the study of the morphometric transformation of the properties of its waters under the influence of environmental conditions. This article is devoted to the study of temporal variability in the biogeochemical and physical characteristics with an emphasis on the metamorphosis of the ionic composition of the Aral waters and its individual water bodies (i.e., the Large and Small Aral Seas, Lakes Chernyshev and Tshchebas) in the period 1873–2022 based on newly obtained (2021 and 2022) and literature data. Periods of hydrochemical evolution are identified reflecting the order of salt deposition lasting for several years. The latest of these periods lasted from 2014 to 2022 waters in the salinity range of 126–244 ‰. It was characterized by the  $\text{SO}_4^{2-}/\text{Cl}^-$  ratio of 0.31, while  $\text{Mg}^{2+}/\text{Na}^+$  0.34 and  $\text{Ca}^{2+}/\text{Na}^+$  0.02. Migration curves for the Aral Sea's water reflect the influence of a number of regional features on the formation of the ion-salt composition of waters was constructed. The biogeochemical features of the final stage of the Aral Sea are discussed using the example of the former bay and now lake Chernyshev. Its salinity of ~243 ‰ and the microbial community inhabiting it, along with the ionic composition, determines the properties of its waters.

**Keywords** Large Aral Sea · Small Aral Sea · Hypersaline lake · Meromictic basin · Major ionic composition · Microbial communities

---

✉ Natalia Yu. Andrulionis  
natalya@ocean.ru

<sup>1</sup> Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia

<sup>2</sup> Winogradsky Institute of Microbiology, Research Center of Biotechnology of the Russian Academy of Sciences, Moscow, Russia

## 1 Introduction

The Aral Sea's disaster well known throughout the world and more than a thousand works are devoted to a comprehensive study of the Aral problem (Kostyanoy and Kosarev 2010). Since the 1960s, economic activity has intensified in the Aral Sea Basin (ASB) and the area of irrigated lands and water intake from rivers filling the sea have doubled. As a result of land management in ASB during the period between 1982 and 2015, the area of arable land expanded by ~3% and ~67% of the water area turned into barren land (Berdimbetov et al. 2021). Along with climate change resulting in a loss of ~90% of the water volume (Yang et al 2020) and an increase in the region's climatic continentality (Breckle et al. 2012). It have caused increased aridization, rising groundwater levels, soil salinization, degrading 54.5% of the region's land area from 1982 to 2015 (Jiang et al. 2019). The mean air temperature and potential evapotranspiration rate revealed significant increases from in ASB (Berdimbetov et al. 2021). Precipitation in most of the region has not changed significantly over the past 50–60 years but has decreased slightly in the western part of the region and increased more significantly in the irrigated areas (Lioubimtseva and Henebry 2009). Desertification of the territories around the Aral Sea has led to the formation of a new desert, Aralkum (Breckle et al. 2012), which contributes to the occurrence and intensification of dust storms polluted with salts and pesticides (White 2014; Indoitu et al. 2015; Wang et al. 2022). These changes have caused devastating ecological, economic and social consequences in the region (Kostyanoy and Kosarev 2010; Aladin et al. 2017) and also significantly changed the morphometric characteristics of the water bodies (Zavialov, 2009).

The shrinking surface area of the Aral Sea has changed the natural landscape in the ASB. Since 1989, the sea has been successively divided into five separate water bodies: four permanent (the western basin of the southern (Large) Aral Sea, the northern (Small) Aral Sea, Chernyshev and Tshchebas lakes) and one temporarily (the eastern basin). These water bodies differ in their hydrological and physicochemical properties (Roget et al. 2009). Mineralization, total alkalinity, and ion concentrations have increased, while pH value has decreased and relative ionic composition has transformed across all remaining water bodies. The ecosystem of the water body largely depends on the mineralization and ionic composition of its water, and changes in these factors have a detrimental effect on the water bodies ecosystem (Oberhänsli et al. 2007). The irreversible changes to the salt composition of the Aral waters resulted a loss of biological diversity (Sapozhnikov and Kalinina 2018; Plotnikov et al. 2021).

A number of works early have been devoted to the study of the hydrochemistry of the Aral Sea and, in particular, the major ion composition, since the end of the nineteenth century (Table 1). Studies of the entire water area of the sea in order to calculate possible changes in hydrochemical conditions when taking water from rivers in the 1950s give an idea of the hydrochemistry of the sea in its conditionally natural period (Blinov 1956). All subsequent studies recorded irreversible changes in the hydrochemical regime of the sea and its ecosystem. After 1985, there was a 10-year break in the studies of the Aral Sea, and since the 2000s by Shirshov Institute of Oceanology of Russian Academy of Sciences (IO RAS).

Historically, the chemical composition of the Aral Sea's waters differed significantly from that of the seawater and is classified as lake water. It was formed by the runoff of the Amu Darya and Syr Darya rivers under the control of evaporation and infiltration processes. Professor K. Schmidt was the first to note the unique composition of the Aral Sea's water in 1874, and the first chemical analysis was conducted by A. Neschel and published

**Table 1** Summary data from previous studies

| Location of the sampling area | Date of sampling | Number of samples  | Sampling depth (m) | Lake depth (m) | Average sample salinity (‰) | Reference                      |
|-------------------------------|------------------|--------------------|--------------------|----------------|-----------------------------|--------------------------------|
| Large Aral Sea                | Central part     | August, 1873       | 5                  | 0              | 68                          | Berg (1908), Blinov (1956)     |
|                               | No data          | 1925               | 8                  | 0              | 63                          | Blinov (1956)                  |
|                               |                  | 1946               | 8                  | 0              | No data                     |                                |
|                               | East Coast       | 1950               | 1                  | 0              | 62                          |                                |
|                               | All Sea          | 1952               | 8                  | 0              | 68                          | Bortnik and Chistyayeva (1990) |
|                               |                  | 1977               | 17                 | 0.2–0.4        | No data                     |                                |
|                               | Large Sea        | 1979               | 10                 | No data        | 15.27                       |                                |
|                               |                  | 1981               | 7                  | No data        | 16.22                       |                                |
|                               |                  | 1982               | 9                  | 63             | 17.75                       |                                |
|                               |                  | 1983               | 14                 | No data        | 20                          |                                |
|                               |                  | 1984               | 18                 | No data        | 20.15                       |                                |
|                               |                  | 1985               | 7                  | No data        | 21.64                       |                                |
|                               |                  | July, 2002         | No data            | 55             | 22.72                       |                                |
|                               | A2               | April, August 2004 |                    | 43             | 72.1                        | Zavialov et al. (2012)         |
|                               |                  | September, 2005    | 4                  | 43             | 86.7                        |                                |
|                               |                  |                    | 0–39               | 43             | 95.05                       |                                |
|                               |                  | September, 2006    | No data            | 43             | 97.7                        |                                |
|                               |                  | June, 2008         |                    | 42             | 102.4                       |                                |

**Table 1** (continued)

| Location of the sampling area | Date of sampling | Number of samples | Sampling depth (m) | Lake depth (m) | Average sample salinity (‰) | Reference                       |
|-------------------------------|------------------|-------------------|--------------------|----------------|-----------------------------|---------------------------------|
| Chernyshev Bay/<br>Lake       | A2               | August, 2009      | 0                  | 41             | 115.4                       | Andrulionis et al. (2021)       |
|                               |                  | October, 2014     | 1                  | 0              | 126.3                       |                                 |
|                               |                  | May, 2019         | 2                  | 0–15           | 136.49                      | Andrulionis et al. (2021)       |
|                               |                  |                   | 2                  | 25–30          | 139.17                      | Andrulionis and Zavialov (2019) |
|                               |                  | March, 2016       | 1                  | 0              | 127.63                      |                                 |
|                               | A2               | October, 2017     | 2                  | 0–29           | 140.34                      | Andrulionis et al. (2021)       |
|                               |                  | May, 2019         | 2                  | 0–15           | 136.49                      |                                 |
|                               |                  |                   | 2                  | 25–30          | 139.17                      | Friedrich and Oberhansli (2004) |
|                               | Northern part    | August, 2002      | No data            | 0              | 82.28                       |                                 |
|                               |                  |                   |                    | 22             | 109.24                      | Andrulionis et al. (2022)       |
|                               | Central part     | October, 2015     | 3                  | 0–5            | 142.31                      |                                 |
|                               |                  |                   | 2                  | 7–13           | 235.93                      | Andrulionis et al. (2022)       |
|                               |                  | October, 2016     | 1                  | 0              | 81.94                       |                                 |
|                               |                  |                   | 1                  | 12             | 242.74                      | Andrulionis et al. (2022)       |
|                               |                  | October, 2018     | 1                  | 0              | 71.61                       |                                 |
|                               |                  |                   | 1                  | 0–13           | 234.87                      | Andrulionis et al. (2022)       |
|                               |                  | September, 2019   | 3                  | 0–5            | 159.77                      |                                 |
|                               |                  |                   | 2                  | 7–12           | 235.43                      |                                 |

in 1870. Doctor L. S. Berg noted in 1907 that the Aral water was similar in composition to the Caspian Sea water, but contained more gypsum and less NaCl. It differed from sea's waters by a significantly higher sulfate-chlorine ratio (Blinov 1956). They has represented an intermediate type between sodium chloride oceanic and hydrocarbonate-calcium fluvial, belonging to the sodium group of the chloride class with a mass fraction of  $\text{Cl}^-$  of 35%,  $\text{SO}_4^{2-}$  of 32%,  $\text{Na}^+$  of 20%,  $\text{Mg}^{2+}$  of 7%, of 1%, and  $\text{Ca}^{2+}$  of 4% (Amirgaev, 2007). The salinity of the water in the open part of the sea fluctuated between 9.6–10.3 ‰ before 1960 (Bortnik and Chistyayeva, 1990).

Currently, in the hyperhaline water bodies, the concentration of sulfates, bicarbonates, and calcium ions has significantly decreased, whereas the concentration of chlorides and magnesium ions has increased. The sulfate-to-chloride ratio, which previously averaged 0.9 for the entire sea (Bortnik and Chistyayeva, 1990), had reduced threefold in the Large Aral by 2019, by 1.4 times in Tshchebas Lake, and by twofold on the surface and 1.4 times at the bottom of Chernyshev Lake. The metamorphosis of the waters in individual water bodies of the Aral Sea continues and salinity increases. With the exception of the slightly saline Small Aral, other individual bodies of water in the Aral Sea are hypersaline lakes with salinity levels reaching 140 ‰ in the western basin, 60 ‰ in Lake Tshchebas, and 160–242 ‰ in Lake Chernyshev. The construction of the Kokaral Dam in 2005 allowed for the regulation of water flow from the Small Sea through the Berg Strait, facilitating the partial restoration of the lake's ecosystem to conditions akin to those before 1960, with a salinity of 10–11‰ but whit change ionic composition and the sulfate-to-chloride ratio is more then 1 (Andrulionis et al. 2021, 2022). It should be noted that individual reservoirs of the Aral Sea, being currently hyperhaline, differ in their composition and properties from a number of other known hyperhaline lakes such as the Dead Sea and Lake Urmia (Andrulionis et al. 2023).

The most important physical characteristics, such as salinity and density, as well as their determination accuracy by indirect methods, depend on ionic variations. The study of the physical properties of hyperhaline lakes is complicated by the unique chemical composition of their waters. Typically, in seawater, the relationship between density, temperature, salinity, and pressure is determined by the EOS-80 equation of state, with salinity calculated based on electrical conductivity. Accurate salinity calculation on electrical conductivity is impossible in Aral Sea due to differences its relative ion-salt composition from the composition of standard seawater. However, variations in the electrical conductivity-salinity-density relationship introduce errors when determining the thermodynamic properties of seawater using electrical conductivity, as it largely depends on the concentration of the major ions (Pawlowicz 2013). Determining salinity and density using standard hydrophysical measurement methods with an STD probe does not yield reliable results, with potential density calculation errors reaching up to 10 kg/m<sup>3</sup> and more (Andrulionis et al. 2016). This work analyzes data obtained by the most accurate methods. Salinity was calculated based on the sum of the major ions, while density was measured using a laboratory densitometer and the evolution of the Aral sea's water density in period 2014–2022 was presented in this paper.

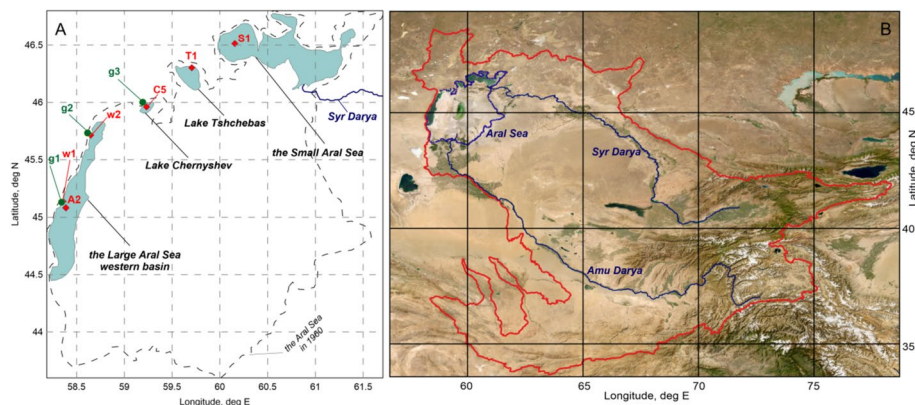
The purpose of this work is to trace the evolution of its physical and biogeochemical properties from the time of the first explorations of the slightly saline sea-lake to its hyper-saline state and note the features of metamorphosis of the main properties of lake waters. Discuss the relationship between the detected changes and environmental conditions and to assess the current state of the disappearing Aral Sea. For this purpose, data for the entire period of study of the ionic composition of Aral waters from 1873 to 2022 were analyzed using historical data from Table 1 and new data from Table 2. The results are presented

**Table 2** Hydrochemical characteristics of water samples from individual waterbodies of Aral Sea and coastal groundwater sources collected in 2021–2022. Concentration values of the major ions. N - Station name, D - Sampling depth (m), S – sum of ions (%), S – sum of ions (%), AT – total alkalinity (mmol/kg),  $\sigma_t$  – density (kg/m<sup>3</sup>), g1, g2 and g3 - groundwater sources (springs)

| N                                   | D    | S      | t °C in situ | σ <sub>t</sub> | pH   | AT     | Anions          |                               | Cations                       |                 |                |                  |                  |  |
|-------------------------------------|------|--------|--------------|----------------|------|--------|-----------------|-------------------------------|-------------------------------|-----------------|----------------|------------------|------------------|--|
|                                     |      |        |              |                |      |        | Cl <sup>-</sup> | SO <sub>4</sub> <sup>2-</sup> | HCO <sub>3</sub> <sup>-</sup> | Na <sup>+</sup> | K <sup>+</sup> | Ca <sup>2+</sup> | Mg <sup>2+</sup> |  |
| October 2021                        |      |        |              |                |      |        |                 |                               |                               |                 |                |                  |                  |  |
| Western basin of the Large Aral Sea |      |        |              |                |      |        |                 |                               |                               |                 |                |                  |                  |  |
| A2                                  | 0    | 161.02 | 25.0         | 125.16         | 8.12 | 14.31  | 82.99           | 22.87                         | 0.52                          | 37.99           | 3.08           | 0.66             | 12.90            |  |
|                                     | 26   | 160.61 | 3.0          | 136.23         | 8.10 | 14.41  | 80.83           | 24.87                         | 0.51                          | 38.37           | 2.88           | 0.58             | 12.58            |  |
| w1                                  | 0    | 161.71 | 25.0         | 126.47         | 8.05 | 13.09  | 82.83           | 23.49                         | 0.52                          | 38.70           | 2.85           | 0.57             | 12.76            |  |
| Spring                              |      |        |              |                |      |        |                 |                               |                               |                 |                |                  |                  |  |
| g1                                  | s    | 51.47  | 21           | 40.56          | 7.60 | 12.817 | 21.04           | 12.54                         | 0.82                          | 12.28           | 0.67           | 0.72             | 3.41             |  |
|                                     | e    | 53.15  | 21           | 42.84          | 8.15 | 9.559  | 21.79           | 13.10                         | 0.54                          | 13.02           | 0.62           | 0.66             | 3.42             |  |
| June 2022                           |      |        |              |                |      |        |                 |                               |                               |                 |                |                  |                  |  |
| A2                                  | 0    | 157.28 | 25.49        | 129.92         | 7.88 | 14.48  | 81.53           | 22.37                         | 0.51                          | 36.18           | 2.72           | 0.57             | 13.40            |  |
|                                     | 5    | 155.50 | 23.78        | 128.92         | 7.91 | 13.61  | 80.14           | 22.56                         | 0.52                          | 35.59           | 2.89           | 0.57             | 13.23            |  |
|                                     | 10   | 156.00 | 13.82        | 133.32         | 7.88 | 14.56  | 80.53           | 22.56                         | 0.52                          | 35.59           | 2.85           | 0.58             | 13.37            |  |
|                                     | 15   | 156.06 | 5.00         | 134.82         | 7.89 | 14.52  | 80.06           | 23.05                         | 0.52                          | 35.62           | 2.95           | 0.57             | 13.29            |  |
|                                     | 20   | 155.06 | 4.00         | 135.33         | 7.87 | 14.40  | 78.99           | 23.49                         | 0.52                          | 35.50           | 2.87           | 0.55             | 13.14            |  |
|                                     | 25   | 156.39 | 2.70         | 136.83         | 7.87 | 14.41  | 79.25           | 24.11                         | 0.52                          | 35.83           | 2.95           | 0.53             | 13.20            |  |
|                                     | 26   | 160.18 | 2.70         | 136.85         | 7.87 | 14.26  | 81.66           | 23.94                         | 0.53                          | 37.44           | 2.96           | 0.53             | 13.13            |  |
| October 2022                        |      |        |              |                |      |        |                 |                               |                               |                 |                |                  |                  |  |
| Western basin of the Large Aral Sea |      |        |              |                |      |        |                 |                               |                               |                 |                |                  |                  |  |
| w2                                  | 0    | 161.66 | 26.00        | 134.31         | 7.86 | 15.28  | 82.78           | 24.05                         | 0.53                          | 37.02           | 2.93           | 0.64             | 13.70            |  |
| Small Aral Sea                      |      |        |              |                |      |        |                 |                               |                               |                 |                |                  |                  |  |
| S1                                  | 0    | 11.15  | 25.23        | 6.42           | 8.13 | 2.81   | 3.09            | 3.95                          | 0.16                          | 2.61            | 0.14           | 0.60             | 0.61             |  |
|                                     | 13.7 | 10.98  | 22.12        | 7.14           | 7.92 | 2.59   | 3.10            | 3.82                          | 0.16                          | 2.54            | 0.15           | 0.60             | 0.61             |  |

**Table 2** (continued)

| N               | D    | S      | t °C in situ | σ <sub>t</sub> | pH   | AT    | Anions          |                               |                               | Cations         |                |                  |                  |  |
|-----------------|------|--------|--------------|----------------|------|-------|-----------------|-------------------------------|-------------------------------|-----------------|----------------|------------------|------------------|--|
|                 |      |        |              |                |      |       | Cl <sup>-</sup> | SO <sub>4</sub> <sup>2-</sup> | HCO <sub>3</sub> <sup>-</sup> | Na <sup>+</sup> | K <sup>+</sup> | Ca <sup>2+</sup> | Mg <sup>2+</sup> |  |
| Lake Tshchebas  |      |        |              |                |      |       |                 |                               |                               |                 |                |                  |                  |  |
| T1              | 0.15 | 114.38 | 26.75        | 93.86          | 8.21 | 7.15  | 44.08           | 32.13                         | 0.28                          | 28.21           | 1.52           | 0.61             | 7.55             |  |
|                 | 3    | 114.26 | 26.82        | 93.62          | 8.22 | 7.12  | 44.38           | 31.70                         | 0.30                          | 28.11           | 1.61           | 0.58             | 7.58             |  |
| Lake Chernyshev |      |        |              |                |      |       |                 |                               |                               |                 |                |                  |                  |  |
| C5              | 0    | 244.8  | 27           | 202.21         | 7.48 | 16.66 | 124.18          | 37.42                         | 0.62                          | 58.42           | 3.91           | 0.49             | 19.76            |  |
|                 | 2    | 243.63 | 24.7         | 202.27         | 7.48 | 16.29 | 124.49          | 36.32                         | 0.62                          | 58.02           | 3.86           | 0.52             | 19.8             |  |
|                 | 4    | 242.89 | 23.7         | 201.71         | 7.49 | 14.86 | 124.18          | 36.48                         | 0.62                          | 57.96           | 3.87           | 0.55             | 19.75            |  |
|                 | 6    | 243.41 | 23.2         | 205.38         | 7.44 | 13.45 | 116.71          | 43.72                         | 0.65                          | 59.29           | 3.59           | 0.49             | 18.44            |  |
| Springs         |      |        |              |                |      |       |                 |                               |                               |                 |                |                  |                  |  |
| g2              | 0    | 18.99  | 26.0         | 10.24          | 7.46 | 4.46  | 10.03           | 1.57                          | 0.30                          | 6.30            | 0.11           | 0.35             | 0.32             |  |
| g3              | 0    | 107.92 | 26.0         | 97.35          | 7.24 | 15.17 | 13.57           | 57.99                         | 0.97                          | 32.05           | 0.81           | 0.50             | 2.03             |  |



**Fig. 1** Study area and location of sampling sites during field campaigns of 2021 and 2022 (A): red points show off-shore sampling stations, green points show sampling from groundwater sources. The Aral Sea drainage basin (red line) and main tributary rivers (B)

graphically. Early observations of the evolution of the ionic composition of the Aral waters before 2019 were presented in the works (Andrulionis et al. 2021, 2022) and salinity before 2015 in (Plotnikov et al. 2023). The hydrochemical evolution of the Aral Sea water composition is determined by the migration of its components over time. It is reflected in this work in the form of migration curves determining the influence of a number of regional features on the formation of the chemical composition of the waters (Samarina 1977). Understanding the metamorphosis of the ionic composition as salinity increases is of particular relevance, especially in the context of a sharply continental climate. It can be compared with theories presented in scientific studies based on laboratory experiments, for example, in (Valyashko 1962; Sanford and Wood 1991). We have determined the microbiome composition of deep waters in the former bay, and now the most hypersaline part of the Aral Sea - Lake Chernyshev. This expands our understanding of the processes that form the composition of the lake waters and the life forms that exist in extreme conditions of salinity over 240 ‰ and anoxia.

This study provides a foundational understanding of the Aral sea's water composition behavior. It is important for predicting this lake's future and similar lakes under changing climatic conditions. It can help in the development of technologies for modeling biogeochemical processes of water and bottom sediment formation, as well as their dynamics in inland water bodies (Izhitskiy et al. 2014; Földváry et al. 2023).

## 2 Geographical location of the study area

The Aral Sea is located in Central Asia, spanning the territories of Uzbekistan and Kazakhstan. Prior to its desiccation, the sea level stood at 53 m above sea level (m.a.s.l.) with a surface of approximately 66,000 km<sup>2</sup>, a volume of 1064 km<sup>3</sup>, and a maximum depth of 66–69 m in the western part and 29 m in the northern part (Blinov 1956; Kosarev 1975). Today, it consists of five distinct water bodies—four permanent and one temporarily filled (Fig. 1). The dates of the field study locations and sampling stations are presented in Table 3. The deepest part of the lake remains in the western basin of the Large Aral

**Table 3** Information about water sampling stations in residual reservoirs of the Aral Sea and in groundwater sources in the drying zone in 2021 – 2022, considered in this work

| Site                          | Season          | Station (type)  | Depth (m) | N (°) | E (°) |
|-------------------------------|-----------------|-----------------|-----------|-------|-------|
| Large Aral Sea, western basin | October, 2021   | A2 (lake)       | 28        | 45.08 | 58.39 |
|                               |                 | w1 (lake shore) | 0.5       | 45.09 | 58.34 |
|                               |                 | g1 (spring)     | –         | –     | –     |
|                               | June, 2022      | A2 (lake)       | 26        | 45.08 | 58.39 |
|                               | September, 2022 | w2 (lake shore) | 0.5       | 45.71 | 58.65 |
|                               |                 | g2 (spring)     | –         | –     | –     |
| Lake Chernyshev               | September, 2022 | C5 (lake)       | 6         | 45.96 | 59.23 |
|                               |                 | g3 (spring)     | –         | 45.99 | 59.22 |
| Lake Tshchebas                |                 | T1              | 4.5       | 46.30 | 59.71 |
| Small Aral Sea                |                 | S1              | 14        | 46.51 | 60.16 |

Sea, with an area of approximately 2,300 km<sup>2</sup> by 2021, a volume of 32.59 km<sup>3</sup> (Ginzburg et al. 2022), and a depth of around 27 m. The sea depth had decreased by 39 m and the sea level probably is now ~ 14 m.a.s.l. Chernyshev Lake until the 1960s had a depth of 40 m and Tshchebas Lake – 30 m, (Blinov 1956), but now they are ~ 6 and ~ 4 m, respectively. The Small Aral Sea, previously the northern section of the Aral Sea with a depth of 29 m, saw its depth more than halve to ~ 14 m. The Small Aral is connected to the Large Aral by the Syr Darya River, whose flow toward the Large Aral has been regulated by the Kokaral Dam, constructed across the Berg Strait in 2005. Presently, the Syr Darya River is the primary water supplier to the Large Aral, as the waters of the Amu Darya River are largely consumed by the economic demands of the population before they can reach the sea. The long-term average annual freshwater volume, previously 56 m<sup>3</sup>, has dropped to 5.9 m<sup>3</sup> (Aladin et al. 2017). The increase in water intake caused its deficit (Lyubimtseva, 2014; Jiang et al. 2019).

### 3 Materials and methods

Water samples from the residual reservoirs of the Aral Sea and three groundwater sources on the dried seabed were collected by the staff of the Shirshov Institute of Oceanology, during three field studies conducted in Kazakhstan and Uzbekistan in October 2021, June 2022, and September 2022. These samples were taken from various reservoirs of the Aral Sea and from three underground sources located along the western coast of the Large Aral Sea and Lake Chernyshev (Fig. 1). The water samples were collected using a 5-L Niskin bottle at the locations specified in Table 3. One 5-L water bottle was taken from each water horizon. One sample was obtained from each bottle. The concentrations of seven major ions were determined from each sample. The analysis for each ion was carried out at least five times, from which the average value was calculated and taken as the result. A total of 23 samples were analyzed based on the results of two expeditions in 2021 and 2022. Water samples were filtered through a 0.7 µm GF/F Whatman membrane filter to remove suspended matter and organic matter and placed in 100–250 ml glass containers. The major ion content of the Aral Sea waters was analyzed in accordance with methods adapted for hypersaline waters, following analytical standards and state standard reference materials

(Andrulionis and Zavialov 2019; Andrulionis et al. 2023). Concentrations of chlorides, sulfates, calcium, magnesium, total inorganic carbon, and total alkalinity were measured using potentiometric titration on a Metrohm 905 Titrando automatic titrator, with indicator electrodes selected based on the reaction type and ion under analysis. Total dissolved inorganic carbon was determined in mmol/kg and converted to g/kg as  $\text{HCO}_3^-$ . The concentration of potassium ions was determined gravimetrically. Sodium was determined by the difference between the total anions and cations in molar equivalent, and then recalculated to g/kg. The salinity of the Aral Sea water samples being studied was determined by summing up the concentrations of the major ions.

Measurements of water density for the studied samples were conducted in the laboratory at in situ temperatures and atmospheric pressure. The density measurements were performed using a precision Anton Paar DMA 5000 M densitometer (Austria), with a measurement error of  $\pm 10^{-5}$  g/cm<sup>3</sup> (Instruction Manual DMA 2010). The density values, initially obtained in g/cm<sup>3</sup>, were recalculated and expressed in conventional density units  $\sigma_t$  in kg/m<sup>3</sup> using the formula:

$$\sigma_t = \rho - 1000 \quad (1)$$

where  $\rho$  is the density of water in kg/cm<sup>3</sup>.

The standard deviation when measuring  $\sigma_t$  in the studied hyperhaline water samples did not exceed 0.05 kg/m<sup>3</sup>.

The study of the microbial community of Lake Chernyshev water sample was carried out using methods of metagenomic DNA isolation, PCR amplification, and high-throughput sequencing of 16S rRNA gene fragments (Benlloch et al. 2002). The filter was homogenized by grinding with liquid nitrogen, and the metagenomic DNA preparation was isolated using a Power Soil DNA Isolation Kit (MO BIO Laboratories Inc., Carlsbad, USA). The detailed methodology has been previously described by Kadnikov et al. (2023) and Savvichev et al. (2023). The studies were carried out using an Illumina MiSeq sequencer. The total number of identified 16S rRNA fragments used to identify microbial communities was 14,393. They were identified using the SILVA program and the GTDB database.

## 4 Results

### 4.1 Hydrochemical characteristics of the residual water bodies of the Aral Sea in 2021 and 2022

The main hydrochemical characteristics of water samples from individual waterbodies of the Aral Sea and coastal groundwater sources collected in 2021–2022 are presented in Table 2. The depth of individual parts of the lakes was in the range of 6–27 m, salinity 11–244 ‰, density 6.42–202.71 kg/m<sup>3</sup>, total alkalinity (AT) from 2.59–16.66 mmol/kg and pH from 7.5–8.5. All water bodies belong to the chloride class ( $\text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^-$ ) and the sodium group ( $\text{Na}^+ + \text{K}^+ > \text{Mg}^{2+} > \text{Ca}^{2+}$ ) but the waters of the slightly saline Small Aral Sea currently belong closer to the mixed class (the contribution to the total mineralization of  $\text{Cl}^-$  and was 50 and 48%), and the mass contents of  $\text{Mg}^{2+}$  and  $\text{Ca}^{2+}$  are almost equal ( $\text{Na}^+ + \text{K}^+ > \text{Mg}^{2+} = \text{Ca}^{2+}$ ).

The western basin of the Large Aral Sea remains the deepest of the separated parts of the sea. The salinity, density, and relative content of the major ions in the salt composition measured in October 2021 and June 2022 were very similar while the level dropped by 1 m

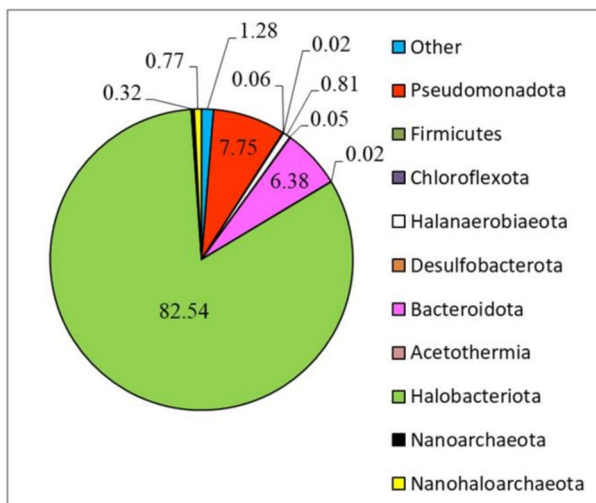
to 2022. Salinity ranged from 155 to 160 ‰, and  $\sigma_t$  ranged from 130 to 135 kg/m<sup>3</sup>. AT of the studied waters averaged ~14.32 mmol/kg. The water column of the lake exhibited thermohaline stratification in both 2021 and 2022. This is indicated by a decrease in temperature, an increase in salinity in the layer below 15 m. The presence of chemical stratification of the water column is indicated by a change in the relative content of ions to the bottom (starting from 20 m) toward an increase the  $\text{SO}_4^{2-}/\text{Cl}^-$  ratio by 11% in 2021 and by 7% in 2022 compared to the rest of the water column.

The waters of the Small Aral Sea had a salinity of about 11. This is the lowest value compared to other water bodies and corresponds to the salinity of the sea in the conditionally natural period. The total alkalinity was also the lowest and amounted to 2.81 and 2.59 mmol/kg on the surface and in the bottom layer, respectively. The pH value of the waters on the surface was 2.5% higher than at the bottom. The temperature of the bottom layer of water was lower by 12%. The salinity and the  $\text{SO}_4^{2-}/\text{Cl}^-$  value were slightly higher in the surface layer than at the bottom (by 1.5 and 3.6%, respectively), probably due to the increased water temperature on the surface, while the differences in the content of other ions were not significant.

A significant reduction in the bay's water level, halved over the past three years, led to its disconnection from the deeper parts of the Aral Sea, resulting in the formation of a separate lake (former Chernyshev Bay). The hydrochemical characteristics of the, as observed in September 2022, are presented in Table 2. The salinity was ~243 ‰, and the density was ~203 kg/m<sup>3</sup>. Chemical stratification was present in the lake, as evidenced by variations in the relative content of the major ions between the upper water layer at depths of 0.4 m and the lower (bottom) layer of ~6 m. Chemical stratification is critical for maintaining redox boundaries through anaerobic decomposition of organic matter. In stratified and near-neutral pH lake waters, sediment particles are entrained into dense bottom waters where maximum organic degradation and H<sub>2</sub>S formation occur. These conditions influence the speciation of dissolved inorganic and organic matter, solid-state reactions, mineral transformation, and sedimentation (Jones and Deocampo 2003). The relative chloride content was lower in the bottom layer, while sulfate levels were higher by ~3% in the lake waters. The increased content of sulfates is attributed to their release during the decomposition of organic matter and the dissolution of mineral compounds (Friedrich and Oberhänsli 2004). The  $\text{Mg}^{2+}/\text{Na}^{2+}$  ratio was 0.34 and 0.31 in the upper and lower layers, respectively. The content of  $\text{Ca}^{2+}$  and remained in trace amounts. The decrease in the content of  $\text{K}^+$  at the bottom was negligible, at just 0.1 ‰. As is well known, potassium ions precipitate last when water reaches a brine state (Sonnenfeld 1984). Lake Chernyshev has the highest salinity of all the individual water bodies > 243 ‰. The decrease in the relative content of  $\text{Na}^{2+}$ ,  $\text{K}^+$  and  $\text{Mg}^{2+}$  indicates oversaturation of the bottom brine with these ions. This evidence suggests that Lake Chernyshev represents the final stage of the hydrochemical degradation of the Aral Sea.

Lake (former bay) Tshchebas has a depth of about 3 m in 2022. It is well mixed to the bottom, and its physical and chemical characteristics are almost identical. It occupies an intermediate position in its properties between the Large Aral Sea and Lake Chernyshev. The salinity of its waters was about 114 ‰, the density was about 94 kg/m<sup>3</sup>, AT was about 7 mmol/kg, the  $\text{SO}_4^{2-}/\text{Cl}^-$  ratio was about 0.7 both on the surface and at the bottom.

**Fig. 2** The share of the main taxonomic groups of archaea and bacteria in the microbial community in the bottom water of the Chernyshev Lake



#### 4.2 Microbial community of deep waters of Lake Chernyshev

The taxonomic composition of microorganisms in the bottom layer of Lake Chernyshev of properties its water was studied. The studies showed that 84.44% of all 16S rRNA sequences were archaea (Fig. 2). They were represented by 3 phyla: *Halobacteriota*, *Nanohaloarchaeota* and *Nanoarchaeota*, with representatives of *Halobacteriota* clearly dominating. It was found that uncultured archaea of the genus *Halorubrum* (phylum *Halobacterota*), constitute 41.85% of the OTU (operational taxonomic units) of the entire community detected. They are the main representatives of archaea in red, salty brines across most continents of the Earth (Gómez-Villegas et al. 2018) and the largest genus of archaea in the class *Halobacteria*, whose representatives are obligate anaerobes. Most species have a bright red color due to the carotenoid bacterioruberin and may also contain bacteriorhodopsin. They caused the pink color of the waters of Lake Chernyshev. Uncultured archaea of the genus *Woesearchaeales* (phylum *Nanoarchaeota*) (OTU 0.32%) leading to anaerobic heterotrophic lifestyle with a pronounced deficiency in metabolic capabilities and the need for mandatory trophic interactions with other microorganisms, in particular with methanogenic archaea (Liu et al. 2018). Their presence indicates the existence of methanogenesis processes and the presence of methane in the lake waters.

The bacterial community of the bottom waters of Lake Chernyshev is inferior in number to the archaeal community (OTU 15.08%) (Fig. 2). Bacteria were represented by 7 phyla: *Acetothermia*, *Bacteroidota*, *Chloroflexota*, *Desulfobacterota*, *Bacteroidetes* (*Firmicutes*), *Halanaerobiaeota*, *Pseudomonadota* (*Proteobacteria*). The community includes *Salinibacter* (phylum *Bacteroidota*) (OTU 6.38%). The type species, *Salinibacter ruber*, is an extreme halophile found in natural and artificial brines worldwide and thrives in salt concentrations of 20–30% (Oren 2013) and shares many features with archaea of the family *Halobacteriaceae* in the same habitats. The second most abundant bacteria were the genus *Halopectonella* (phylum *Pseudomonadota*) (OTU 5.93%). The type culture of *Halopectonella vilamensis* found in the lake is strictly aerobic and typically forms pink to purple colonies. It grows at NaCl concentrations of 7.5–25%

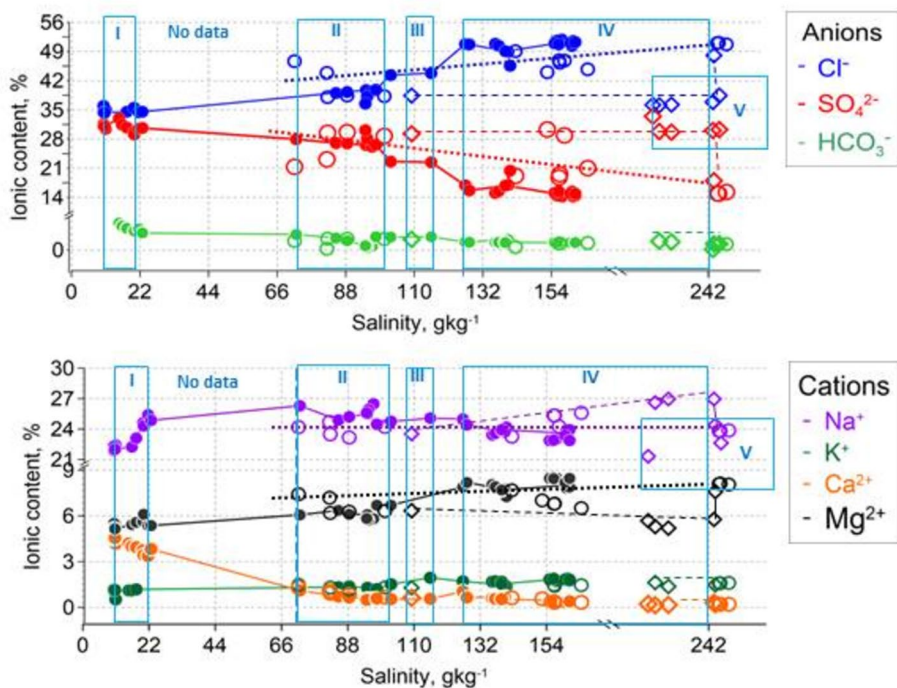
(Menes et al. 2016). Minor representatives of the microbiota included sulfate-reducing anaerobic halophilic bacteria of the genus *Desulfohalobium* (phylum *Desulfobacterota*) (OTU 0.05%), previously isolated from sediments of the pink hypersaline Lake Retba in Senegal (Ollivier et al. 1991), anaerobic halophilic bacteria of the genus *Halanaerobium* (phylum *Halanaerobiaeota*) (OTU 0.81%), previously isolated from groundwater sources as well as from oil field groundwater (Lipus et al. 2017), and bacteria of the genus *Izimaplasma* (phylum *Bacillota* (*Firmicutes*)) (OTU 0.06%), known to inhabit deep-sea methane seeps (Skenner et al. 2016).

### 4.3 Groundwater sources

On the western coast of the South Aral Sea, small groundwater seepage sources (g1, g2, and g3) were discovered on the dried-out bottom in October 2021 and September 2022 (Table 2). Two of them (g1 and g2) had a salinity of ~50 and 19 ‰, respectively, and flowed into the main part of the lake, and g3 had a salinity of 108 ‰ and flowed into Lake Chernyshev. The water samples from these sources differed in mineralization and the ratio of major ions, both from each other and the waters of the Large Aral Sea and Lake Chernyshev. The  $\text{SO}_4^{2-}/\text{Cl}^-$  ratio in source g1 was 0.60, in g2 – 0.16, in g3 – 4.27. The compositions of sources g1 and g2 were dominated by chlorides and sodium ions, but contained significant amounts of bicarbonates (~1.5%). Source g3 was distinct from the other water samples due to its higher concentrations of sulfates and bicarbonates, which exceeded the levels found in the lakes, with  $\text{Na}^+$  being the predominant cation.

### 4.4 Evolution of the major ion composition of the waters of the Aral Sea in the period 1873–2022

The five stages of ionic composition metamorphism of the Aral Sea's waters lasting several years reflect the order of precipitation of salts from the brine (Fig. 3). At the first stage, in the salinity range of 11–23 ‰ in period 1960–1985, the  $\text{SO}_4^{2-}/\text{Cl}^-$  ratio was 0.88, the  $\text{Mg}^{2+}/\text{Na}^+$  ratio was 0.24, and the  $\text{Ca}^{2+}/\text{Na}^+$  ratio was 0.18. Until the 1990s, minerals such as calcium and sodium carbonates, sulfates (gypsum, mirabilite, glauberite), chlorides (halite), etc., precipitated (Bortnik and Chistyeva 1990). Then there was a 10-year break in the studies of the Aral Sea, which were resumed in the early 2000s (Zavialov et al. 2009). At the next stage (2002–2006) with salinity of 72–98 ‰ the  $\text{SO}_4^{2-}/\text{Cl}^-$  ratio was 0.73, the  $\text{Mg}^{2+}/\text{Na}^+$  ratio was 0.24, and the  $\text{Ca}^{2+}/\text{Na}^+$  ratio was 0.03. The notable decrease in the calcium and sulfates indicates massive precipitation of as gypsum. The third stage (2008–2009) was characterized by a salinity range of 100–115 ‰ and the  $\text{SO}_4^{2-}/\text{Cl}^-$  ratio of 0.52, the  $\text{Mg}^{2+}/\text{Na}^+$  ratio of 0.27 and the  $\text{Ca}^{2+}/\text{Na}^+$  ratio of 0.02. By this stage, the content of  $\text{SO}_4^{2-}$ ,  $\text{Ca}^{2+}$ , and  $\text{Na}^+$  had further decreased. The fourth stage was documented during our research period 2014–2022 and applies to both the Large Aral Sea and Chernyshev Lake. It corresponds to a salinity of 126–244 ‰ and the  $\text{SO}_4^{2-}/\text{Cl}^-$  ratio was 0.31, while  $\text{Mg}^{2+}/\text{Na}^+$  was 0.34, and  $\text{Ca}^{2+}/\text{Na}^+$  was 0.02. By this time, the sulfate content had decreased, probably due to the precipitation of sodium sulfate. The fifth stage is characteristic of the lower layer of the chemically stratified Chernyshev Lake at a salinity of 243 ‰. The  $\text{SO}_4^{2-}/\text{Cl}^-$  ratio was 0.37, the  $\text{Mg}^{2+}/\text{Na}^+$  ratio was 0.31, and the  $\text{Ca}^{2+}/\text{Na}^+$  ratio was 0.01. The observed stages of the Large Aral Sea's waters can be associated with fluctuations (periods of increase and decrease) in the lake volume. Fluctuations, despite



**Fig. 3** Evolution of the major ionic composition of the waters of the deep-water part of the Aral Sea from 1873 to 2022, and from former Chernyshev Bay from 2002 to 2022. Fully filled circles indicate the values of the relative content of elements in the composition belonging to the deep-sea part of the sea, white circles with colored contours—to the upper layer of the Chernyshev Bay, white diamonds with a colored contour—in the lower layer. The solid line indicates trends in changes in ion content in the deep-sea part of the Aral Sea, dotted lines—in the Chernyshev Bay: frequent dotted lines—in the surface layer, rare—in the bottom layer. The blue frames highlight the stages of the evolution of the composition, and the Roman numerals indicate the stage number, which corresponds to the salinity interval: 1 in the range 10–23 ‰ (1873–1985); 2 in the range 72–98 ‰ (2002–2006); 3 in the range 100–115 ‰ (2008–2009); 4 in the range 126–244 ‰ (2014–2022) and the 5 stage is typical only for the bottom waters of part of Lake Chernyshev

the general trend toward a decrease in the volume and area of the lake during its degradation, were caused by alternating processes of continental runoff and evaporation (Wu et al 2022). Also, the concentrations of dissolved ions in salt lakes are controlled by the lithology of parent rocks, evaporation, loss of dissolved substances by minerals and biota (Jones and Deocampo 2003).

Figure 3 reflects the features of the formation of the modern chemical composition of the Aral Sea waters. The migration curves of the components of the main composition of the Aral Sea waters on the graph reflect the patterns of behavior of the components associated with their chemical properties. These curves reflect the influence of a number of regional features (geological, climatic, geomorphological and hydrogeological conditions) (Samarina 1977). The figure shows that the migration intensity of ions varies. In the main part of the Aral Sea,  $\text{Cl}^-$  migrates better than  $\text{SO}_4^{2-}$  and its concentration increases, while the concentration of  $\text{SO}_4^{2-}$  decreases. Among the cations,  $\text{Na}^+$  migrates better. In the deep

waters of Chernyshev Lake in 2022, the situation changes dramatically: the concentration of  $\text{SO}_4^{2-}$  and  $\text{Na}^+$  decreases.

The precipitation of components from the Aral Sea's waters in the form of an insoluble sediment occurs gradually upon reaching the saturation limit (individual for each ion). The maximum relative content of chloride ion in the water was 51% on average, while the salinity of the water was in the range of 157–243 ‰, and the minimum was ~35‰ at a salinity of 10 (the conditionally natural state of the lake). The maximum content of sulfates (~31%) was observed at a salinity of 10–18 ‰, and the minimum ~15% at a salinity of ~243 ‰. The highest content of hydrocarbonates was in conditionally natural conditions at a salinity of lake waters of ~10 ‰ and amounted to ~1.6%, they began to fall out of the composition first and their content in trace amounts (about 0.3%) is found in lake waters starting from a salinity of 90 to 243 ‰. Sodium cations content was on average ~26% at a average salinity of ~95 ‰ in the Large Aral and on average 27% at a salinity of ~235 ‰ in Lake Chernyshev, and their minimum of ~22% corresponds to the conditionally natural conditions of the lake at a salinity of ~10 ‰. The maximum calcium (4.5% on average) was observed in the composition at salinity of 10‰, and its minimum (~0.2%) at salinity of ~243 ‰. The maximum content of potassium (2%) and magnesium (8.5%) was at a salinity of 156–162 ‰, and the minimum was ~1% and ~5.5%, respectively, in the conditionally natural period of the lake.

The conditions that developed in the bottom layer of Chernyshev Bay during biogeochemical reactions force us to consider this layer separately from the rest of the water mass of the Aral Sea. These processes, contributing to the formation of chemical stratification, make adjustments to the order of precipitation-inflow of ions. As can be seen in Fig. 3, a tendency toward a decrease in  $\text{SO}_4^{2-}/\text{Cl}^-$  in the surface layer and its increase in the bottom layer was observed for several years. The situation on the surface in 2022 remained unchanged, while in the bottom layer a decrease in the sulfate-chlorine ratio by about 50% was compared to previous values. The trend toward a decrease in the  $\text{Mg}^+/\text{Na}^+$  ratio in the bottom layer over several years showed an increase 2022, while on the surface, weak growth continues to be observed.

## 5 Discussion

Salt lakes are widespread throughout the world. They constitute a significant portion of the planet's inland aquatic ecosystems and have significant aesthetic, cultural, economic, recreational, scientific, conservation and ecological functions. Global trends of increasing anthropogenic impact and climate change are currently leading to the degradation of a number of lakes on the planet's arid zones (O'Reilly et al. 2015; Yakushev et al. 2021). The fate of the Aral Sea may soon befall such endorheic lakes as, for example, the Dead Sea in Israel (Khlaifat et al. 2010), Lake Urmia in Iran (Karbassi et al. 2010), the Caspian Sea, located at the junction of Europe and Asia (Lahijani et al. 2024), the Great Salt Lake in northern Utah (Baxter 2018), etc. These lakes are experiencing heightened anthropogenic pressures and climate change which, along with hydrology are interconnected through complex processes, where changes in one system induce changes in the others. Understanding the fundamental biogeochemical processes is necessary for predicting the lake's future under changing climatic conditions as well as to manage water use and maintain favorable conditions in these lake basins.

The degradation of the lake's aquatic ecosystem had the following sequence: excessive intake of river water - decrease in lake level—increase in salinity and metamorphosis of water composition—reduction in the biodiversity of hydrobionts. The morphometric lakes characteristics since the intensive water withdrawal in the early 1960s significantly changes in have occurred. During this period of desiccation for 62 years, the lake's maximum depth decreased by ~59%, while water salinity increased up to 24-fold. The content of  $\text{HCO}_3^-$  and  $\text{Ca}^{2+}$  decreased more than by 1.4 and 4%, respectively and they have been present now only in trace amounts in the lake's waters. While the relative content of  $\text{Na}^+$ ,  $\text{K}^+$  and  $\text{Mg}^{2+}$  increased over the entire period of the sea's desiccation by 1, 0.6, and 3.4%, respectively. The rate of decline in lake water levels now is ~1 m per year. The rate of metamorphosis of the Aral Sea's water composition in the western basin has slowed in the range 2014 to 2022, while the lake level and volume continue to decrease (Yang et al. 2020).

The pH values tend to decrease over time in all water bodies of the Aral Sea. In October 1953, pH was typically between 8.3 and 8.4 (Blinov 1956), in September 2012 and October 2013 in the Large Aral it averaged to 8.1 (Makkaveev et al. 2018), in September 2022, according to our data, it was also 8.1 in the Large Aral Sea, 8.0 in the Small Aral Sea, and 7.5 and 8.2 in the hyperhaline lakes Chernyshev and Tshchebas, respectively. Usually, Salt lakes are characterized by a mildly basic reaction  $\text{pH}=7.5\text{--}8.5$ , associated with Ca–Mg carbonates (Jones and Deocampo 2003). A downward trend in pH values is observed.

Processes are currently underway in Lake Chernyshev differ from ones to the west basin of the Large Aral Sea. The lake level is rapidly declining, leading to significant transformations in the water column and its composition. Over the past decade, the depth of the lake has decreased from 22 to 6 m, and the  $\text{SO}_4^{2-}/\text{Cl}^-$  ratio at the surface and bottom has dropped by 2.5-fold probably due to the consumption of  $\text{SO}_4^{2-}$  in the sedimentation process with the formation of the minerals eugsterite, bloedite, konyaite, and thenardite and other (Reykhard et al. 2019) and a some part is consumed in the process of life by sulfate-reducing bacteria (Skrzypek 2024). The irregular migration of the major ions in the upper layer of Lake Chernyshev which can be seen in the Fig. 3 due to periodic desalination by continental runoff. But there are overall trends indicating an increase in the  $\text{SO}_4^{2-}/\text{Cl}^-$  and  $\text{Mg}^{2+}/\text{Na}^+$  ratios both in Lake Chernyshev and in the western basin of the Large Aral Sea.

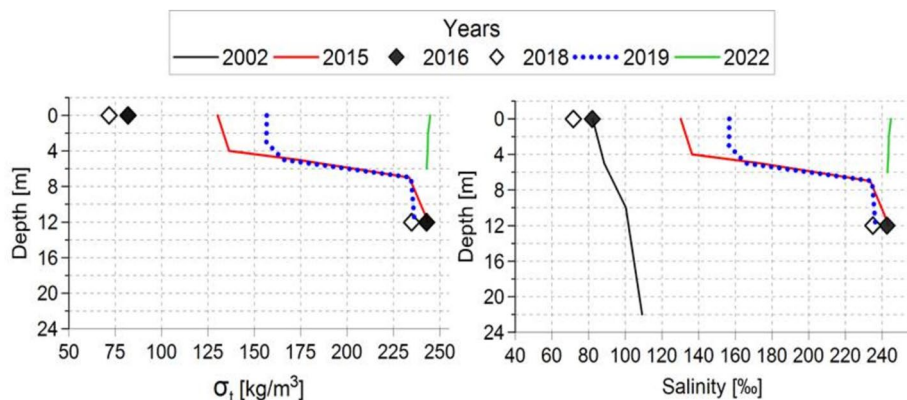
Historically, to around 20 species of fish and approximately 200 species of free-living invertebrates lived in the Aral Sea (Plotnikov et al. 2014). Since 2017, the Southern Aral Sea's macrofauna has been reduced to crustaceans, specifically *Artemia parthenogenetica*, while the microbial community has continuously adapted over the past 50 years (Shurygin et al. 2019). Several species of phyto- and bacterioplankton, benthic microphytes (diatoms and cyanoprokaryotes) were observed (Sapozhnikov and Kalinina 2018). Halophilic microbial communities in the lake are highly diverse and include both ubiquitous Proteobacteria and unique microbial populations representing new species or genera (Shurygin et al. 2019). Currently, clear distinctions are evident between surface and benthic communities in the four remaining water bodies of the Aral Sea and reflect the varying physicochemical conditions of the environment (Izhitsky et al. 2016). The microbiological composition of the waters and dried shores in certain parts of the Aral Sea includes bacteria, yeasts, and fungi (Mavloniy and Ruzieva 2020; Kondrasheva et al. 2022; Klimashik et al. 2022). Increased mineralization and changes in the ionic composition of the Aral Sea's waters have led to alterations in its microbial community. For example, elevated magnesium concentrations are likely contributing to changes in the composition of the halophilic archaeal microbial community (Podell et al. 2014) while the microbial community contributes to the metamorphism of the composition of the lake's waters, especially under anaerobic conditions. In Lake Chernyshev, microbial activity determines the physicochemical properties

of the waters: water color, chemical stratification and ion and gas composition of the waters. In October 2022 according to (Askerov et al. 2023), species-level differences in bacterioplankton were identified in the waters of the western part of the Large Aral Sea's western basin and in Lake Chernyshev. Aerobic bacteria from the genera *Spiribacter*, *Halo-peptonella*, and *Halanaerobacter* and species of *Salinibacter* were dominant in the surface waters of Lake Chernyshev in October 2022, aerobic bacteria of the genera *Spiribacter*, *Halo-peptonella* and *Halanaerobacter*, as well as *Salinibacter* species, dominated in the surface waters of Lake Chernyshev in October 2022. Due to their heterotrophic activity, they release monomers, including volatile fatty acids, which are consumed by halophilic sulfate-reducing bacteria and methanogenic archaea in the microbiome of deeper waters of Lake Chernyshev. The isolation and identification of microbial strains capable of surviving in hyperhaline water bodies are critical for identifying the most resilient species, understanding their mechanisms of adaptation to extreme conditions, and enriching the collection of microorganisms in Central Asia. These strains could potentially be utilized in breeding and genetic engineering to develop biological products for agricultural use (Podell et al. 2014; Davranov et al. 2023). The study of the colonization of the Aral Sea by extremophiles during its transition from a brackish to a hyperhaline reservoir provides insights into the regional and global distribution of microbes (Shurygin et al., 2019) which is regulated by changes in ionic composition.

Until 1960, the Aral Sea in the vicinity of the modern Small Aral Sea was characterized by a salinity of 10.0–10.5 g/kg. The trend of the general slowdown in the decline of the Small Aral Sea's water level has been observed since 2009 (Yang et al. 2020). The slightly saline Small Aral with today, it is of great importance for the economic use and well-being of the Aral region ecosystem (Savoskul et al. 2003; Izhitsky and Ayzel 2023; Izhitsky 2023), and is heavily dependent on the quality of river runoff (Abdimutalip et al. 2022). The increasing intensity of economic activity in the Central Asian countries within the river basin is deteriorating the quality of its waters and the waters of the Small Aral (Rzyski et al. 2019). Nevertheless, a reduction in pesticide use in recent years has had a positive effect (Amirgaliev et al. 2023). Presently, the Syr Darya River is the primary water supplier to the Large Aral, as the waters of the Amu Darya River are largely consumed by the economic demands of the population before they can reach the sea. Over subsequent decades, the salinity of the Small Aral Sea increased to ~34 g/kg by the early 2000s. But, after construction of a dam restricting the flow of the Syr Darya River, salinity returned to the previous values of 10–11 g/kg, but with a significantly altered ion-salt composition. In 1950s the  $\text{SO}_4^{2-}/\text{Cl}^-$  ratio by mass was about 0.9 (as well as for the whole sea) and by 2019 it increased 1.5 times to 1.4 (Andrulionis et al. 2022). The  $\text{SO}_4^{2-}/\text{Cl}^-$  ratio was less in October 2022 and amounted to 1.27. Modern research indicates an overall improvement in the environmental situation in the Syr Darya river basin in recent years (Kurbaniyazov et al. 2022; Amirgaliev et al. 2023).

Tshehebas Lake was once one from deep a bay in the Aral Sea (up to 30 m). It and was separated from the main part and in 2004 formed an isolated lake and is now the smallest of the remaining water bodies. Its maximum depth now is less about 3 m. The lake is periodically filled by Small Aral Sea water through the Dike Kokaral, as well as from atmospheric precipitation and, probably, underground runoff. But the tendency for the lake to gradually dry up indicates a reduction in the flow of water from these sources and deepens and ionic composition of its water.

The significance of groundwater sources on the western coast of the South Aral Sea in the water and chemical balance of the lake remains unclear. No comparable data on the composition of these underground sources authors could be found. It is possible that these

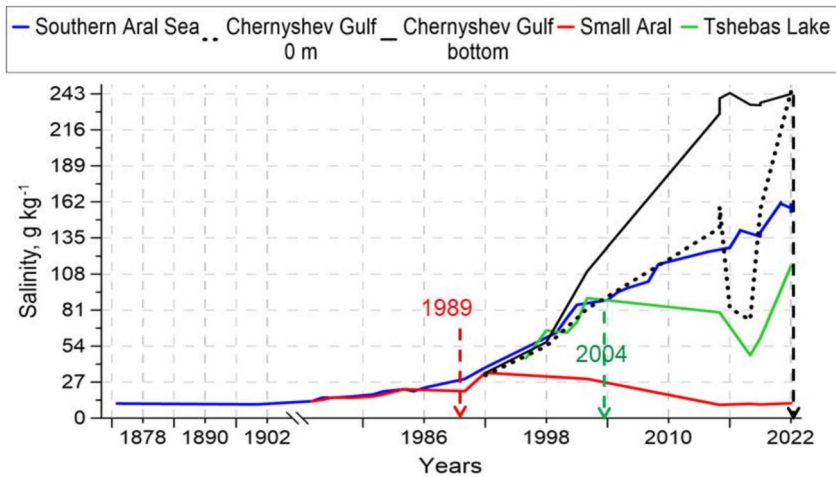


**Fig. 4** Haline and density stratifications evolution of Lake Chernyshov water column in the period from 2002-2022

waters, which are initially fresher, become salinized and change composition as they travel across the saline soil of the former seabed. These sources, along with others emerging on the dried bottom of the Aral Sea, may contribute to the water balance of the Aral Sea. Historical studies by Blinov (1950s) found no signs of groundwater release, such as noticeable decreases in salinity at the bottom of the main part of the sea during the sea's conditionally natural state. However, by 1998, it was established that the salinity of the former Chernyshev Bay was 15% lower (10 ‰) than that of the former Tshchebas Bay, indicating the presence of groundwater desalinating the sea's waters (Amirgaliev 2007). Today, due to the significant reduction in the sea's surface area, these sources are now found on the dried bottom of the northern part of the sea. Chemical composition of groundwater and surface water, the lake help understand how saline lakes function biochemically, hydrological and ecologically. Surface water and groundwater interactions in different ecosystem types remain poorly understood, particularly with regard to water flows, biogeochemical processes, groundwater ecology and geochemistry in inland wetland systems in drier regions. Geochemical modeling and quantitative assessment of the stable isotopic and chemical composition of ground and surface waters and sediments can explain their hydrological relationship with salt lakes and what hydrochemical and hydrological regimes are responsible for their formation (Skrzypek et al. 2013).

### 5.1 Evolution structure of the water column of former Chernyshev Bay in the period from 2002 to 2022

The former Chernyshev Bay of the Aral Sea became a stratified water body after 1991. Vertical heterogeneity of the water column was first recorded in 1992, when the halocline was located at a depth of 15 m. At that time, salinity was 1.5 g/kg higher than at the surface and 1.3 g/kg higher at the bottom (2–5 m) (Amirgaliev 2007). Over time, this stratification intensified. By 2002, a hydrogen sulfide pollution layer had formed beneath the halo- and pycnocline, starting at a depth of 10 m, and this layer continued to expand over the next decade. In October 2014, the halocline was located approximately 5 m below the surface mixed layer (Izhitsky et al. 2016). The evolution of the bay's water column structure between 2002 and 2022 is shown in Fig. 4, which illustrates the stages of its transformation as the bay

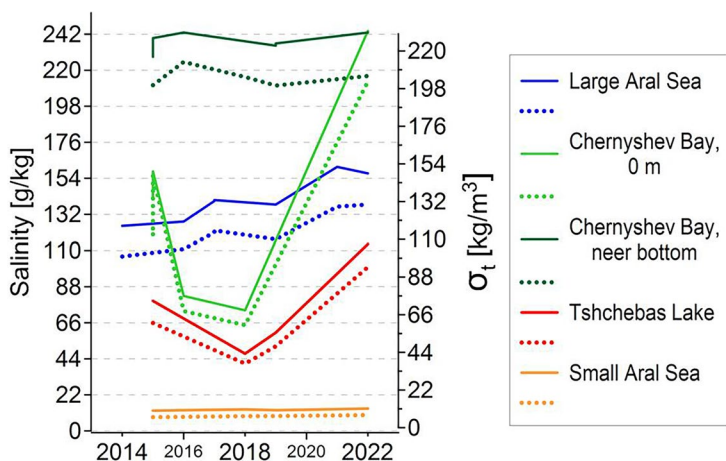


**Fig. 5** Evolution of the salinity in the Aral Sea's waters and its individual water bodies' waters during the period 1873–2022. The arrows indicate the years of separation of the reservoirs from the main part of the sea. The arrows indicate the years of separation of the reservoirs from the main part of the sea: the red arrow indicates the year of separation of the Small Aral, the green one - Lake Tshebas, the black one – Lake Chernyshev

continued to dry out over 10 years. In 2015–2016, the lake covered an area of 80 km<sup>2</sup>, and thermo-calcareous stratification was characterized by a lower layer from a depth of ~5 m. At this time, salinity in the bottom layer reached its highest values, and the lake developed heliothermal properties, with the lower layer being warmer (Izhitsky et al. 2021). Modern bedding conditions characterized by high biomass, have led to the formation of a hydrogen sulfide layer and anoxia in the lower layers of the lake (Zavialov 2005). Methanogenesis processes have also developed in these anoxic layers (Izhitskaya et al. 2019), affecting all chemical parameters of the water. Seasonal phases of active mixing generally did not impact the bottom anaerobic layer (Makkaveev et al. 2018; Izhitsky et al. 2018). As shown in Fig. 4, in 2002 the water column of the bay exhibited nearly uniform salinity, with average values of 90 ‰ in the upper layer and 109 ‰ in the lower layer. By 2015 thermohaline stratification has increased significantly and the salinity gradient has increased. In 2016 the salinity gradient has increased and reached its maximum. The reduced salinity of the surface waters in 2016 and 2018 may be attributed to the inflow of slightly saline waters from the Small Aral Sea, facilitated by discharges through the Kokaral Dam. In 2019, its values began to decrease with the increase in salinity of the upper layer of the lake waters and by 2022, thermohaline stratification has disappeared though chemical stratification persisted near the bottom. From 1960 to 2022 the Chernyshev Lake's water level has decreased by 85% and its depth dropped from 40 to 6 m.

## 5.2 Evolution of salinity in the waters of the Aral Sea from 1873 to 2022 and density from 2014 to 2022

Figure 5 illustrates how the salinity of the Aral Sea's waters changed during the period 1873 to 2022 of the lake. The most rapid increase in salinity began in the early 1990s,



**Fig. 6** Changes in the values of water salinity (solid lines) and density (dotted lines) in individual water bodies of the Aral Sea during the period 2014–2022

coinciding with the division of the sea, first into the Southern and Northern (Large and Small) sections, and then, as salinity exceeded 40 ‰, into Lake Tshchebas and Chernyshev Bay. Maximum salinity in the Small Sea in the early 2000s was ~34 ‰ (Amirgaliev 2007; Cawater-info), but since 2005 it has gradually returned to the pre-desiccation values of 10–11 ‰. The salinity values of other individual water bodies of the Aral Sea continued to grow, accompanied by metamorphism of the composition and an increase in the density of the waters. Figure 5 shows that salinity increases unevenly in water bodies depending on the various geomorphological features of each of them.

Instrumental measurements of the density of Aral Sea waters began in 2014, when the lake had already fragmented into several individual reservoirs. Figure 6 presents the results of a study on the density of these residual reservoirs compared to their salinity. The data align closely, confirming the reliability of the methods adapted for analyzing hypersaline waters.

This work does not account for seasonal variations in salinity and ionic composition in the Aral Sea's individual reservoirs, nor does it consider the changes caused by desalination from precipitation and continental runoff. The research was primarily conducted during the driest seasons (summer and autumn). Investigating seasonal changes in these characteristics will offer a more comprehensive understanding of the metamorphic processes affecting the composition and hydrophysical properties of salt lake's waters.

## 6 Conclusion

Results of this study indicate that the degradation of the Aral Sea, now represented by a set of residual separate lakes with salinity ranging from 11 ‰ to 243 ‰, is still ongoing. This degradation is manifested by decreasing water levels, reduced water volume, increased salinity and density, and metamorphosis of the ionic composition due to anthropogenic impact and climate warming. Metamorphization of the Aral Sea waters during the drying up of the sea in 1960–2022 was due to a successive decrease in the major ions from the composition during precipitation in the form of respective mineral compounds under the

influence of various factors such as evaporation, changes in water temperature, and activity of biota. Five stages of the hydrochemical evolution of the Aral Sea waters in the period from 1960 to 2022 are distinguishable. Metamorphism of the chemical water composition was reflected in a decrease in the  $\text{SO}_4^{2-}/\text{Cl}^-$  and  $\text{Ca}^{2+}/\text{Na}^+$  ratios, an increase in the  $\text{Mg}^{2+}/\text{Na}^+$  ratio by factors of 3, 1.6, and 10, respectively, as well as a decrease in pH values over time. It was found that since 2014, the intensity of ionic metamorphosis and the rate of salinity increase in the western basin of the Large Aral Sea have slowed down. It will probably remain so for a long time, since it almost corresponds to the composition of the upper layer of waters of Lake Chernyshev, which is in the final phase of degradation of the Aral Sea.

In contrast, Lake Chernyshev has experienced an intensification of changes, with its water level halving in just three years and the salinity of the upper layer increasing. For the first time since 2002, thermohaline stratification in the lake's water column was nearly neutral. By 2022, the maximum salinity ( $\sim 243$  ‰), previously confined to the lower layer, had reached the surface. This was accompanied by a decrease in the  $\text{SO}_4^{2-}/\text{Cl}^-$  ratio over time and an increase in the  $\text{Mg}^{2+}/\text{Na}^+$  ratio, the presence of dissolved hydrogen sulfide and methane in the bottom layer, which has also influenced the taxonomic structure of microorganisms. The microbiological community was dominated by anaerobic archaea. The archaeal community was led by uncultured *Halorubrum*, which gave to the lake waters their pink hue. Minor components included *Woesearchaeales* and bacteria of the genus *Izimaplasma*, both indicating ongoing methanogenesis in the lake's deep waters. Additionally, the presence of *Desulfohalobium* points to active sulfate reduction processes.

The current state of Lake Chernyshev represents the terminal stage of degradation of the Aral Sea, highlighting the physical and chemical transformations of its waters and their microbial composition.

**Acknowledgements** The research was carried out within the framework of the State assignment FMWE 2024-0015 and with partial support from Russian Foundation for Basic Research and DFG (project no. 20-55-12007). The authors are grateful to all participants of the Aral expeditions for the collection and delivery of water samples.

**Author Contribution** All authors have agreed to the contents of the manuscript and have given explicit consent for its submission to the journal. The authors have obtained consent from the responsible authorities at the institution where the work was performed before submitting this work. All authors whose names appear on the submission have made a substantial contribution to the conception of the work, to the acquisition, analysis, or interpretation of the data, revised it critically for important intellectual content, approved the version to be published, and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work will be appropriately investigated and resolved. Author contributions: N.Yu.A. participated in setting the aim and objectives of the research work, participated in the selection of methods for studying the ion-salt composition of waters, performed laboratory studies of the ion-salt composition, salinity and density of Aral Sea water samples, analyzed the obtained data, prepared graphic material and the main text of the article. A.S.I. carried out in-kind hydrophysical measurements and water sampling, participated in the discussion of the obtained result. A.S.I. carried out in-kind hydrophysical measurements and water sampling, participated in the discussion of the results obtained, prepared Fig. 1. A.S.S. analyzed the sample for the microbiome composition of the water of Lake Chernyshev, participated in writing the text of the article (Sect. 3.5) and prepared Fig. 2. P.O.Z. was the head of the research projects, participated in setting the goal and objectives of the research work, supervised the expeditionary research and carried out in-kind measurements,

**Funding** The research was carried out within the framework of the State assignment FMWE 2024-0015 and with partial support from Russian Foundation for Basic Research and DFG (project no. 20-55-12007). Author Savvichev A.S. has received research support from Winogradsky Institute of Microbiology, Research Center of Biotechnology of the Russian Academy of Sciences.

**Data Availability** No datasets were generated or analyzed during the current study.

## Declarations

**Competing Interests** The authors declare no competing interests.

## References

- Abdimutalip NA, Kurbaniyazov AK, Toychibekova G, Koishieva G, Shalabaeva G, Zholmagambetov N (2022) The effect of Syrdarya river runoff on the ecological state of waters the Small Sea. *NEWS of the Academy of Sciences of the Republic of Kazakhstan*. 4(448):6–14. <https://doi.org/10.32014/2022.2518-170X.206>
- Aladin NV, Chida T, Cretaux JF, Ermakhanov Z, Jollibekov B, Karimov B, Kawabata Y, Keyser D, Kubota J, Micklin P, Mingazova N, Plotnikov I, Toman M (2017) Current status of lake Aral – challenges and future opportunities. Conference Paper. In: Conference: Lake Ecosystem Health and Its Resilience: Diversity and Risks of Extinction. Proceedings of the 16th World Lake Conference, At Bali, Indonesia
- Amirgaliev NA (2007) Aral-Syr Darya basin: (hydrochemistry, problems of aquatic toxicology). Bastau Publishing House LLP, Almaty (in Russian)
- Amirgaliyev N, Opp C, Askarova M, Ismukhanova L, Madibekov A, Zhadi A (2023) Long-term dynamics of persistent organic pollutants in water bodies of the aral Sea-Syrdarya basin. *Appl Sci* 13(20):11453. <https://doi.org/10.3390/app132011453>
- Andrulionis NYu, Zavialov PO (2019) Laboratory studies of the main component composition of hyper-saline lakes. *Phys Oceanogr* 26(1):13–31. <https://doi.org/10.22449/1573-160X-2019-1-13-31>
- Andrulionis NY, Zavialov PO, Izhitskiy AS (2021) Current evolution of the salt composition of waters in the Western Basin of the South Aral Sea. *Oceanology* 61(6):899–908. <https://doi.org/10.1134/S0001437021060035>
- Andrulionis NYu, Zavialov PO, Izhitskiy AS (2022) Modern evolution of the salt composition of the residual basins of the aral sea. *Oceanology* 62(1):30–45. <https://doi.org/10.1134/S0001437022010027>
- Andrulionis N, Zavialov I, Kovaleva E, Zavialov P, Osadchiev A, Alukaeva A, Izhitskiy A (2016) Site-Specific Equations of State for Coastal Sea Areas and Inland Water Bodies. In: Materials of XXVI international coastal conference "Managinag risks to coastal regions and communities in a changing world". August 22–27. St Petersburg, Russia. Academus Publishing, 9. [https://doi.org/10.31519/conferencearticle\\_5b1b9452bebe47.34318019](https://doi.org/10.31519/conferencearticle_5b1b9452bebe47.34318019)
- Andrulionis NY, Yakushev EV, Jafari M, Zavialov PO, Lahijani HAK, Ghaffari P (2023) Comparative study of the major ion composition in Eurasian Salt Lakes: Lake Urmia, Lake Issyk-Kul, Aral Sea, and Dead Sea. In Ghaffari P, Yakushev EV (eds) Lake Urmia. A Hypersaline Waterbody in a Drying Climate. The Handbook of Environmental Chemistry. Springer, Berlin, Heidelberg, pp 203–222 [https://doi.org/10.1007/698\\_2023\\_978](https://doi.org/10.1007/698_2023_978)
- Askerov A (2023) Next-generation sequencing and imaging flow cytometry analysis of the microbial communities of aral sea remnant lakes. Dissertation, Nazarbayev University. [https://nur.nu.edu.kz/bitstream/handle/123456789/7168/AAskerov%20Master%20thesis\\_revised.pdf?sequence=1&isAllowed=y](https://nur.nu.edu.kz/bitstream/handle/123456789/7168/AAskerov%20Master%20thesis_revised.pdf?sequence=1&isAllowed=y)
- Baxter BK (2018) Great Salt Lake microbiology: A historical perspective. *Int Microbiol* 21(6):79–95. <https://doi.org/10.1007/s10123-018-0008-z>
- Benlloch S, Lopez-Lopez A, Casamayor EO, Ovreas L, Goddard V, Daae FL, Smerdon G, Massana R, Joint I, Thingstad F, Pedros-Alio C, Rodriguez-Valera F (2002) Prokaryotic genetic diversity throughout the salinity gradient of a coastal solar saltern. *Environ Microbiol* 4:349–360. <https://doi.org/10.1046/j.1462-2920.2002.00306.x>
- Berdimbetov T, Ma Z-G, Shelton S, Ilyas S, Nietullaeva S (2021) Identifying land degradation and its driving factors in the Aral sea basin from 1982 to 2015. *Front Earth Sci* 9:690000. <https://doi.org/10.3389/feart.2021.690000>
- Berg L (1908) Aral Sea. Experience in Physics and Geography. Stasyulevich MM Printing house, St. Petersburg (in Russian)
- Blinov LK (1956) Hydrochemistry of the Aral Sea. Gidrometeoizdat, Leningrad (in Russian)

- Bortnik VN, Chistyayeva SP (eds) (1990) Hydrometeorology and hydrochemistry of the seas of the USSR. 346 Vol. 7. The Aral Sea. Gidrometeoizdat, Leningrad (In Russian)
- Breckle SW, Wucherer W, Dimeyeva LA (2012) Vegetation of the Aralkum. In: Breckle SW, Wucherer W, Dimeyeva LA, Ogar NP (eds) Aralkum – a man-made desert. Springer, London, pp 127–159. [https://doi.org/10.1007/978-3-642-21117-1\\_4](https://doi.org/10.1007/978-3-642-21117-1_4)
- Cawater-info. Knowledge portal about water resources and ecology of Central Asia. <http://cawater-info.net/projects/peer-amudarya/index.htm>
- Davranov KD, Kulonov AI, Kondrasheva KV (2023) Assessment of enzymatic activity of halotolerant micro-organisms from natural samples of the Aral Sea Region. *Universum: Chemistry and Biology: Electron Scientific Journal* 7(109). <https://doi.org/10.32743/UNICHEM.2023.109.7.15738> (in Russian)
- Földváry L, Abdelmohsen K, Ambrus B (2023) Water density variations of the Aral Sea from GRACE and GRACE-FO monthly solutions. *Water* 15(9):1725. <https://doi.org/10.3390/w15091725>
- Friedrich J, Oberhansli H (2004) Hydrochemical properties of the Aral Sea water in summer 2002. *J Mar Syst* 47(1–7):77–88. <https://doi.org/10.1016/j.jmarsys.2003.12.010>
- Ginzburg AI, Kostianoy AG, Sheremet NA, Soloviev DM (2022) The drying dynamics of the Western Large Aral Sea from satellite data (2002–2021). *Modern Prob Remote Sens Earth Space* 19(5):246–263. <https://doi.org/10.21046/2070-7401-2022-19-5-246-263> (in Russian)
- Gómez-Villegas P, Vígara J, León R (2018) Characterization of the microbial population inhabiting a Solar Saltern Pond of the Odiel Marshlands (SW Spain). *Mar Drugs* 16(9):332. <https://doi.org/10.3390/md16090332>
- Indoitu R, Kozhoridze G, Batyrbaeva M, Vitkovskaya I, Orlovsky N, Blumberg D, Orlovsky L (2015) Dust emission and environmental changes in the dried bottom of the Aral Sea. *Aeol Res* 17:101–115. <https://doi.org/10.1016/j.aeolia.2015.02.004>
- Instruction Manual DMA 4100 M, DMA 4500 M, DMA, 5000 M, 2010. Firmware Version V1.70. Anton Paar. Graz
- Izhitskaya E, Egorov A, Zavialov P, Yakushev E, Izhitskiy A (2019) Dissolved methane in the residual basins of the Aral Sea. *Environ Res Lett* 14:065005. <https://doi.org/10.1088/1748-9326/ab0391>
- Izhitskiy A, Ayzel G (2023) Water balance of the regulated arid lake as an indicator of climate change and anthropogenic impact: The North (Small) Aral Sea Case Study. *Water* 15:1464. <https://doi.org/10.3390/w15081464>
- Izhitskiy AS, Zavialov PO, Roget E, Huang HP, Kurbaniyazov AK (2014) On thermohaline structure and circulation of the Western Large Aral Sea from 2009 to 2011: Observations and modeling. *J Mar Syst* 129:234–247. <https://doi.org/10.1016/j.jmarsys.2013.06.013>
- Izhitskiy AS, Zavialov PO, Sapozhnikov PV, Kirillin GB, Grossart HP, Kalinina OY, Zalota AK, Goncharenko IV, Kurbaniyazov AK (2016) Present state of the Aral Sea: diverging physical and biological characteristics of the residual basins. *Sci Rep* 6:23906. <https://doi.org/10.1038/srep23906>
- Izhitskiy A, Kirillin G, Goncharenko I, Kurbaniyazov A, Zavialov PO (2021) The world's largest heliothermal lake newly formed in the Aral Sea basin. *Environ Res Lett* 16:115009. <https://doi.org/10.1088/1748-9326/ac2d66>
- Izhitskiy AS (2023) Thermal regime of the Small Aral Sea in conditions of climate change. *J Oceanologic Res* 51(2):3–20. [https://doi.org/10.29006/1564-2291.JOR-2023.51\(2\).2](https://doi.org/10.29006/1564-2291.JOR-2023.51(2).2) (in Russian)
- Izhitskiy AS, Kirillin GB, Zavialov PO (2018) The Aral Sea as a natural “sun pond”: extreme conditions of temperature and mixing. In: Conference: The international symposium “Mesoscale and Submesoscale Processes in the Hydrosphere and Atmosphere”. <https://doi.org/10.29006/978-5-9901449-4-1-2018-45>. (in Russian)
- Jiang L, Jiapaer G, Bao A, Li Y, Guo H, Zheng G, Chen T, De Maeyer P (2019) Assessing land degradation and quantifying its drivers in the Amudarya River delta. *Ecol Ind* 107:105595. <https://doi.org/10.1016/j.ecolind.2019.105595>
- Jones BF, Deocampo DM (2003) Geochemistry of saline lakes, in *Treatise on geochemistry*. Elsevier, Amsterdam, pp 393–424
- Kadnikov VV, Mardanov AV, Beletsky AV, Karnachuk OV, Ravin NV (2023) Prokaryotic life associated with coal-fire gas vents revealed by metagenomics. *Biology* 12(5):723. <https://doi.org/10.3390/biology12050723>
- Karbassi A, Bidhendi GN, Pejman A, Bidhendi ME (2010) Environmental impacts of desalination on the ecology of Lake Urmia. *J Great Lakes Res* 36(3):419–424. <https://doi.org/10.1016/j.jglr.2010.06.004>
- Khlaifati A, Hogan M, Phillips G, Nawayseh K, Amira J, Talafeha E (2010) Long-term monitoring of the dead Sea level and brine physico-chemical parameters from 1987 to 2008. *J Mar Syst* 81:207–212
- Klimaszyk P, Kuczyńska-Kippen N, Szeląg-Wasielewska E, Marszelewski W, Borowiak D, Niedzielski P, Nowiński K, Kurmanbayev R, Baikenzheyeva A, Rzymyski P (2022) Spatial heterogeneity of

- chemistry of the Small Aral Sea and the Syr Darya River and its impact on plankton communities. *Chemosphere* 307:135788. <https://doi.org/10.1016/j.chemosphere.2022.135788>
- Kondrasheva KV, Egamberdiev FB, Kulonov AI, Lobanova PS (2022) Chemical and microbiological characteristics of water samples from the Aral Sea and soil from the Aral Sea region. Materials of the V international scientific and practical conference “Scientific Discussions in the World Crisis: New Challenges, Looking into the Future”. Rostov-on-Don, July 29. pp 262–265 (in Russian)
- Kosarev AN (1975) Hydrology of the Caspian and Aral Seas. Moscow University Publishing House, Moscow (in Russian)
- Kostianoy A, Kosarev N (eds.) (2010) The Aral Sea Environment. Springer-Verlag, Berlin, Heidelberg, New York, 332. <https://doi.org/10.1007/978-3-540-88277-0>. eBook ISBN 978-3-540-88277-0. Published: 10 March 2010
- Kurbaniyazov A, Barakbaev T, Sambaev N, Izhitskiy A, Kurbaniyazov N (2022) The effect of Syrdarya River runoff on the ecological state of waters the Small Aral Sea. *News Natl Acad Sci Repub Kazakhstan*, Ser Geol Tech Sci 4:136–151. <https://doi.org/10.32014/2022.2518-170X.206>
- Lahijani HAK, Ghaffari P, Leroy S, Beni AN, Yakushev EV, Abtahi B, Saleh A, Behraves MA (2024) A note on the silent decline of the Caspian environment. *Mar Pollut Bull* 205:116551. <https://doi.org/10.1016/j.marpolbul.2024.116551>
- Lioubimtseva E, Henebry, (2009) Climate and environmental change in Arid Central Asia: Impacts, vulnerability, and adaptations. *J Arid Environ* 73:963–977. <https://doi.org/10.1016/j.jaridenv.2009.04.022>
- Lioubimtseva E (2014) Impact of Climate Change on the Aral Sea and its Basin. In Micklin PP (ed) The Aral Sea. Springer-Verlag, Berlin, pp 405–427. [https://doi.org/10.1007/978-3-642-02356-9\\_17](https://doi.org/10.1007/978-3-642-02356-9_17)
- Lipus D, Vikram A, Ross D, Bain D, Gulliver D, Hammack R, Bibby K (2017) Predominance and Metabolic Potential of Halanaerobium spp. in Produced Water from Hydraulically Fractured Marcellus Shale Wells. *Appl Environm Microbio* 83(8):e02659-16. <https://doi.org/10.1128/AEM.02659-16>
- Liu X, Li M, Castelle CJ, Probst AJ, Zhou Z, Pan J, Liu Y, Banfield JF, Gu J-D (2018) Insights into the ecology, evolution, and metabolism of the widespread Woese archaeal lineages. *Microbiome* 6(1):102. <https://doi.org/10.1186/s40168-018-0488-2>
- Makkaveev PN, Gordeev VV, Zavialov PO, Polukhin AA, Khlebopashev PV, Kochenkova AI (2018) Hydrochemical characteristics of the Aral Sea in 2012–2013. *Water Resour* 45(2):188–198. <https://doi.org/10.1134/S0097807818020112>
- Mavloniy M, Ruzieva N (2020) Microbiocenosis of the Aral Sea Basin in the Conditions of the environmental crisis. *Biological Journal* 9(20). [https://elibrary.ru/download/elibrary\\_44099893\\_20329568.pdf](https://elibrary.ru/download/elibrary_44099893_20329568.pdf). (in Russian)
- Menes RJ, Viera CE, Farias ME, Seufferheld MJ (2016) Halopeptonella vilamensis gen. nov. sp. Nov., a halophilic strictly aerobic bacterium of the family Ectothiorhodospiraceae. *Extremop Life Under Extreme Cond* 20(1):19–25. <https://doi.org/10.1007/s00792-015-0793-7>
- O'Reilly CM, Sharma S, Gray DK, Hampton SE, Read JS, Rowley RJ et al (2015) Rapid and highly variable warming of lake surface waters around the globe. *Geophys Res Lett* 42:10773–10781. <https://doi.org/10.1002/2015GL066235>
- Oberhänsli H, Boroffka N, Sorrel P, Krivonogov S (2007) Climate variability during the past 2,000 years and past economic and irrigation activities in the Aral Sea Basin. *Irrig Drain Syst* 21:167–183. <https://doi.org/10.1007/s10795-007-903-5>
- Ollivier B, Hatchikian CE, Prensier G, Guezennec J, Garcia J-L (1991) Desulfohalobium retbaense gen. nov. sp. nov., a Halophilic Sulfate-Reducing Bacterium from Sediments of a Hypersaline Lake in Senegal. *Int J Systemat Bacteriol* 41(1):74–81. <https://doi.org/10.1099/00207713-41-1-74>
- Oren A (2002) Molecular ecology of extremely halophilic archaea and bacteria. *FEMS Microbiol Ecol* 39(1):1–7. <https://doi.org/10.1111/j.1574-6941.2002.tb00900.x>
- Oren A (2013) Salinibacter: an extremely halophilic bacterium with archaeal properties. *FEMS Microbiol Lett* 342(1):1–9. <https://doi.org/10.1111/1574-6968.12094>
- Pawlowicz R (2013) Key physical variables in the ocean: Temperature, salinity, and density. *Nat Edu Knowl* 4(4):13
- Plotnikov I, Aladin N, Ermakhanov Z, Zhakova L (2014) Biological dynamics of the Aral sea before its modern Decline (1900–1960). In: Micklin PP (ed) The Aral Sea the devastation and partial rehabilitation of a great lake. Springer, Heidelberg, pp 131–171. [https://doi.org/10.1007/978-3-642-02356-9\\_3](https://doi.org/10.1007/978-3-642-02356-9_3)
- Plotnikov IS, Aladin NV, Mossin J, Høeg JT (2021) Crustacean fauna of the Aral Sea and its relation to ichthyofauna during the modern regression crisis and efforts at restoration. *Zoologic Stud* 60:e25. <https://doi.org/10.6620/ZS.2021.60-25>

- Plotnikov IS, Aladin NV, Zhakova LV, Mossin J, Høeg JT (2023) Past, present and future of the Aral Sea -A review of its Fauna and Flora before and during the regression crisis. *Zool Stud.* 12(62):e19. <https://doi.org/10.6620/ZS.2023.62-19>
- Podell S, Emerson JB, Jones CM, Ugalde JA, Welch S, Heidelberg KB, Banfield JF, Allen EE (2014) Seasonal fluctuations in ionic concentrations drive microbial succession in a hypersaline lake community. *ISME J* 8(5):979–990. <https://doi.org/10.1038/ismej.2013.221>
- Prange M, Wilke T, Wesselingh FP (2020) The other side of sea level change. *Commun Earth Environ* 1(1):69. <https://doi.org/10.1038/s43247-020-00075-6>
- Reykhard L, Sapozhnikov P, Izhitskiy A, Dara O, Boev A, Andrulionis N, Kozina N, Kalinina O, Reikhard A (2019) Halogenesis and biomineralization in the residual basins of the Aral Sea. *Acta Crystallograph Sect Foundations Adv* 75(a2):e203–e203. <https://doi.org/10.1107/S2053273319093537>
- Roget E, Zavialov P, Khan V, Muniz MA (2009) Geodynamical processes in the channel connecting the two lobes of the Large Aral Sea. *Hydrol Earth Syst Sci* 6:5279–5301. <https://doi.org/10.5194/hess-13-2265-2009>
- Rzymiski P, Klimaszyn P, Niedzielski P, Marszelewski W, Borowiak D, Nowinski K, Baikenzheyeva A, Kurmanbayev R, Aladin N (2019) Pollution with trace elements and rare-earth metals in the lower course of Syr Darya River and Small Aral Sea, Kazakhstan. *Chemosphere* 234:81–88. <https://doi.org/10.1016/j.chemosphere.2019.06.036>
- Samarina VC (1977) In *Hydrogeochemistry*. Chapter 3. Some features of the structure of aqueous solutions. Intensity and contrast of migration. Geochemical barriers. Leningrad University Publishing House. 360. (in Russian)
- Sanford WE, Wood WW (1991) Brine evolution and mineral deposition in hydrologically open evaporite basins. *Am J Sci* 291:687–710. <https://doi.org/10.2475/ajs.291.7.687>
- Sapozhnikov P, Kalinina O (2018) Main results of observations of changes in bottom biota and ichthyofauna of the Large Aral Sea in the period 2002–2017. *Hydrosph Ecol* 1:2–14. [https://doi.org/10.33624/2587-9367-2018-1\(2\)-41-54](https://doi.org/10.33624/2587-9367-2018-1(2)-41-54)
- Savoskul OS, Chevina EV, Perziger FI, Vasilina LYu, Baburin VL, Danshin AI, Matyakubov B, Murakaev RR (2003) Water, Climate, Food, and Environment in the Syr Darya Basin. Contribution to the project ADAPT (Adaptation strategies to changing environments). <http://www.weap21.org/downloads/adaptsyrdarya.pdf>. Accessed July 2003
- Savvichev AS, Demidenko NA, Kadnikov V, Belenkova VV, Rusanov II, Gorlenko VM (2023) Microbial Community Composition as an Indicator of the State of Basins Located at the Sea Coast (Exemplified by the Kanda Bay, Kandalaksha Gulf, White Sea). *Microbiology* 92(6):819–830. <https://doi.org/10.31857/S0026365623600323.inRussian>
- Shurigin V, Hakobyan A, Panosyan H, Egamberdieva D, Davranov K, Birkeland N-K (2019) A glimpse of the prokaryotic diversity of the Large Aral Sea reveals novel extremophilic bacterial and archaeal groups. *MicrobiologyOpen* 8(2):e850. <https://doi.org/10.1002/mbo3.850>
- Skenneron C, Haroon M, Briegel A, Shi J, Jensen GJ, Tyson GW, Orphan VJ (2016) Phylogenomic analysis of Candidatus ‘Izimaplasma’ species: free-living representatives from a Tenericutes clade found in methane seeps. *ISME J* 10(11):2679–2692. <https://doi.org/10.1038/ismej.2016.55>
- Skrzypek G (2024) Stable sulfur and oxygen isotope compositions of sulfates to disentangle agrocontaminants from other sources of sulfur in agrosystems. In: Adu-Gyamfi J, Skrzypek, Grzegorz, Imfeld G, Heng L (eds) *Tracing the sources and fate of contaminants in agroecosystems applications of multi-stable isotopes*. Springer Nature, Switzerland, pp 99–125. [https://doi.org/10.1007/978-3-031-47265-7\\_6](https://doi.org/10.1007/978-3-031-47265-7_6)
- Skrzypek G, Dogramaci S, Grierson PF (2013) Geochemical and hydrological processes controlling groundwater salinity of a large inland wetland of northwest Australia. *Chem Geol* 357:164–177. <https://doi.org/10.1016/j.chemgeo.2013.08.035>
- Sonnenfeld P (1984) *Brines and Evaporites*. Academic Press, Orlando, Toronto
- Stiller M, Lensky N, Gavrieli I (2018) Recent evolution of the dead sea chemical composition: 2005–2015. Technical report book, Jerusalem, <https://doi.org/10.13140/RG.2.2.15272.62722> Accessed November 2018
- Valyashko MG (1962) The pattern of formation of deposits of potassium salts. Moscow State University, Moscow (**in Russian**)
- Wang W, Samat A, Abuduwaili J, Ge Y, De Maeyer P, Van de Voorde T (2022) Temporal characterization of sand and dust storm activity and its climatic and terrestrial drivers in the Aral Sea region. *Atmos Res* 275:106242. <https://doi.org/10.1016/j.atmosres.2022.106242>
- White K (2014) Nature and economy in the Aral Sea Basin. *The Aral Sea*. Springer-Verlag, Berlin, Heidelberg, pp 301–335

- Wu Q, Yue H, Liu Y, Hou E (2022) Geospatial quantitative analysis of the Aral Sea Shoreline changes using RS and GIS techniques. *Earth Sci Inf* 15:137–149. <https://doi.org/10.1007/s12145-021-00714-2>
- Yakushev EV, Andrulionis NYu, Jafari M, Lahijani HAK, Nooran PG (2021) How climate change and human interaction alter chemical regime in salt lakes, cases study: Lake Urmia, Issyk-Kull Lake, Aral Sea and Dead Sea. Lake Urmia: A Hypersaline Waterbody in a Drying Climate. In: Ghaffari P, Yakushev EV (eds) Lake Urmia. A hypersaline waterbody in a drying climate. The Handbook of Environmental Chemistry. Springer, Berlin, Heidelberg, pp 275–296. [https://doi.org/10.1007/698\\_2021\\_811](https://doi.org/10.1007/698_2021_811)
- Yang X, Wang N, Chen A, He J, Hua T, Qie Y (2020) Changes in area and water volume of the Aral Sea in the arid Central Asia over the period of 1960–2018 and their causes. *CATENA* 191:104566. <https://doi.org/10.1016/j.catena.2020.104566>
- Zavialov PO (2005) Physical Oceanography of the Dying Aral Sea. Springer-Verlag, Berlin, Heidelberg, p 0123415567816
- Zavialov PO, Ni AA, Kudyskin TV, Ishniyazov DP, Tomashevskaya IG, Mukhamedzhanova D (2009) Ongoing changes of ionic composition and dissolved gases in the Aral Sea. *Aquat Geochem* 15(1):263–275. <https://doi.org/10.1007/s10498-008-9057-9>
- Zavialov PO, Arashkevich EG, Bastida I et al (2012) Large Aral Sea in the Beginning of 21st Century: Physics, Biology, and Chemistry. Nauka, Moscow ((in Russian))

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.