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# Impact of water salinity on long-term dynamics and spatial distribution of benthic invertebrates in the Small Aral Sea

by

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## Abstract

In 1996–2008, macrozoobenthos of the Small Aral Sea was investigated. A total of 320 macrozoobenthos samples were collected. Statistical analysis and statistical mapping were performed using Statistica and Photoshop software. Ten taxa of macrozoobenthos were identified, with an average water salinity of the Small Aral Sea ranging from 6.3 to 19.0 PSU. Average annual community abundance reached 1962 specimens $m^{-2}$, with biomass of 107.1 g $m^{-2}$. Quantitative variables of macrozoobenthos decreased by an order of magnitude by the end of the analyzed period. The polychaete *Hediste diversicolor* and mollusks *Abra ovata*, *Cerastoderma glaucum*, *Caspiohydrobia* sp. were the dominant taxa. Statistical mapping and correlation analysis revealed that the high biomass of *A. ovata* and *Caspiohydrobia* sp. occur in areas with high water salinity. Aggregations of the mollusk *C. glaucum* were observed in various areas of the sea. The polychaete *H. diversicolor* preferred areas with relatively low salinity. Analysis of the results showed that the optimum salinity gradient with Aral salt composition was 17–27 PSU for *A. ovata, Caspiohydrobia* sp. and *C. glaucum*, while 1–27 PSU for *H. diversicolor.* Along with changes in water salinity, the currently growing pressure from freshwater fish is an additional factor affecting the structure of benthic communities in the Small Aral Sea.

**Key words:** Small Aral Sea, benthic invertebrates, hydrological regime, optimum salinity limit, spatial distribution

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## Introduction

Salinity directly determines the quality of water resources and their use for human purposes (Abedin et al. 2014). Arid and semi-arid areas are characterized by general poverty of hydrographic networks and naturally high water salinity (Wu et al. 2014). Climate warming causes an even greater increase in water salinity in dry regions (Eimanifar & Mohebbi 2007; Meng et al. 2012). Irrational use of water resources exacerbates the existing problems with water availability in arid areas (Karthe et al. 2017).

The ecological disaster of the Aral Sea, the largest fishery water body in the arid zone of Central Asia, is a consequence of the cumulative negative impact of natural and anthropogenic factors. The irretrievable loss of water in the Aral Sea basin was caused both by anthropogenic changes in river runoff in the second half of the 20th century and by adverse weather conditions (Pokhrel et al. 2017). The progressive lowering of the water level led to an increase in salinity and division of the sea into northern (the Small Aral Sea) and southern parts (the Large Aral Sea) in 1988–1989 (Aladin et al. 1998). To maintain fish productivity in conditions of increasing salinity, flounder (*Platichthys flesus luscus* Pallas) was introduced into the Aral Sea in the 1980s (Karpevich 1975). It is an euryhaline marine species living in a wide range of salinity (Muus & Nielsen 1999; Güneş et al. 2011). By the end of the 1990s, the flounder became extinct in the Large Aral Sea along with other fish due to extremely high water salinity (Ermakhanov et al. 2012). The Large Aral Sea has been divided into several water bodies with mostly euryhaline fauna (Aladin & Plotnikov 2008). The Small Aral Sea has undergone smaller changes compared to the Large Aral Sea. The maximum average salinity (33.8 PSU) was recorded in the Small Aral Sea in 1991 (Krupa & Grishaeva 2011).

The rising water level in the following years created favorable conditions for the restoration of the Small Aral Sea. The expansion of the desalinated zone and the reduction of average salinity in the Small Aral Sea led to the return of freshwater fish species that migrated into the sea from the Syr Darya River and its delta lakes (Aladin et al. 2018). These changes in water salinity were unfavorable for flounder. Fishing for flounder decreased from 1050–1350 tons in 1999–2004 to 303–715 tons in 2005–2010 (Ermakhanov et al. 2012). The total number of fish caught in the same period increased from 685 to 2810 tons per year owing to freshwater species.

Further restoration of fish productivity of the Small Aral Sea will obviously depend not only on hydrochemical conditions (Plotnikov & Aladin 2014), but also on the status of food sources. Benthic invertebrates play an important role in fish nutrition in the Aral Sea (Grishaeva 2005; Balymbetov & Grishaeva 2005). During the period of the natural hydrological regime with an average water salinity of about 10 PSU, macrozoobenthos was represented by 40 species, including eight introduced species (Plotnikov et al. 2014). The polychaete *Hediste devirsicolor* Muller, the freshwater amphipod *Dikerogammarus aralychensis* (Birstein, 1932), Chironomidae larvae, mollusks of *Dreissena*, *Cerastoderma*, *Caspiohydrobia*, *Abra*, *Hypanis*, and *Theodoxus* dominated. Macrozoobenthos biomass reached 12.0–40.6 g m$^{-2}$ (Andreev 1999). In subsequent years of progressive salinization, a few euryhaline and marine species remained in the composition of benthic fauna (Aladin 1990; Andreev et al. 1992; Aladin et al. 2008; Sapozhnikov et al. 2010; Filippov 1996; 2001). The average biomass of macrozoobenthos increased to 125.3–372.5 g m$^{-2}$ (Grishaeva 2009). In regions with high salinity, the biomass of benthic invertebrates was even higher, up to 821.0–1896.0 g m$^{-2}$ (Filippov 2001).

With the average water salinity of the Small Aral Sea decreasing to 9.5–11.8 PSU in 2005–2008 (Krupa & Grishaeva 2011), the benthic community was represented by the same euryhaline and marine species (Aladin et al. 2005; 2008; 2009; 2018; Plotnikov 2013) as in 1991, with an average salinity of 33.8 PSU (Krupa & Grishaeva 2011). It is evident that desalination of the Small Aral Sea will result in further restructuring of macrozoobenthos represented by marine and euryhaline species. One of the signs of such changes is a linear decrease in the biomass of benthic invertebrates since the late 1990s (Krupa & Grishaeva 2011). In this regard, it is important to assess the effect of salinity on the modern fauna of benthic invertebrates in the Aral Sea based on statistical methods, which has not been done previously.

The purpose of this work was to study the long-term dynamics and spatial distribution of dominant species of benthic invertebrates during the period of salinity reduction in the Small Aral Sea based on the correlation analysis and statistical data mapping.

## Description of the study site

### Climate

The Aral Sea region occupies the northernmost location in the continental subtropical climate zone (Zhitomirskaya 1964). The area receives a large amount of solar heat, equal to an average of 5860 MJ m$^{-2}$ per year. The average annual precipitation is 100–115 mm. It is characterized by a pronounced intra-annual air temperature difference, ranging from +43°C in summer to –36°C in winter.

### Hydrography

The two largest rivers of Central Asia – the Amu Darya and the Syr Darya – flow into the Aral Sea. The length of the Amu Darya River is 1415 km. The area of its basin is 309 000 km$^2$ (Kosarev 1975). The Amu Darya River is formed by the confluence of the Panj and the Vakhsh rivers. It is fed by snow and ice. The river flows into the Large Aral Sea. In recent years, water from the Amu Darya River does not reach the sea for most of the year. The Syr Darya River flows into the southern part of the Small Aral Sea. It is predominantly fed by snow and, to a lesser extent, by glaciers and rainwater (Armstrong et al. 2018). The length of the Syr Darya River is 2212 km. It is formed by the confluence of the Naryn and the Kara Darya rivers in the eastern part of the Fergana Valley (Uzbekistan). The basin area is 219 000 km$^2$.

### River runoff

The total long-term average annual river runoff to the Aral Sea reached 56.0 km$^3$ in 1911–1960 (UNESCO 2017). In 1961–1980, it decreased to 30.00 km$^3$ and in 1981–1990, it reached a minimum of 3.45 km$^3$. The average runoff of the Amu Darya River for 1992–2014 amounted to 9.04 km$^3$, ranging from 0.40 km$^3$ in 2001 to 17.6 km$^3$ in 2005. The runoff volume of the Syr Darya River for the same period was on average 5.96 km$^3$, ranging from 10.3 km$^3$ during high-water years (2004–2005) up to 2.5 km$^3$ in dry 2000 (Gaybullaev et al. 2012).

### The Aral Sea

The Aral Sea is located in the Turan Lowland near the eastern edge of the Ustyurt Plateau in the territory of Uzbekistan and Kazakhstan. Its geological history is characterized by gradual isolation from the ocean, which resulted in desalination and changes in the chemical composition of water (Alekin & Lyakhin 1984). Until the second half of the 20th century, the Aral Sea was the largest brackish water body in Central Asia.

At the absolute level of 53.0 m, the Aral Sea water area reached 66 000 km$^2$, the maximum depth was 69.0 m and the average depth was 16.1 m (Bortnik & Chistyaevaya 1990; Micklin 2014). The coastline was 4430 km. The greatest length of the sea was 424 km, with a width of 292 km. The salinity of water varied insignificantly, with an average value of 10.2 PSU (Alekin & Lyakhin 1984). Chlorides, sulfates and sodium dominated in the chemical composition of water.

The complex of anthropogenic and natural factors caused a significant reduction in the water surface area and progressive salinization of the sea (Andreev 1999). By 1988–1989, the sea was divided into two isolated parts: the northern one, i.e. the Small Aral Sea, and the southern one, i.e. the Large Aral Sea (Aladin et al. 1998; Gaybullaev et al. 2012; Micklin 2014). Since 1988–1989, succession of the northern and southern parts of the sea has progressed independently of each other.

### The Large Aral Sea

At the level of 53.0 m BS (Baltic System), the area of the Large Aral Sea reached 60 090 km$^2$ and the volume of water was 984.00 km$^3$ (Bortnik & Chistyaevaya 1990). In the period from 1986 to 2004, the area of the Large Aral Sea decreased from 38 560 to 16 400 km$^2$, the volume of water was reduced from 380.63 to 93.46 km$^3$ (UNESCO 2017). By 2007, at the absolute level of 29.50 m, the Large Aral Sea was divided into western and eastern parts (Aladin et al. 2008). The area of the Western Aral Sea was 4450 km$^2$ and the volume of water was 19.76 km$^3$. The area of the Eastern Aral Sea was 7030 km$^2$ and the volume of water was 49.5 km$^3$ (UNESCO 2017). By the end of the 1990s, the salinity of the Large Aral Sea exceeded 130–150 PSU (Aladin & Plotnikov 2008).

### The Small Aral Sea

At the level of 53.0 m BS, the area of the northern part of the sea was 5990 km$^2$ and the volume of water was 79.7 km$^3$ (Bortnik & Chistyaevaya 1990). From 1986 to 2004, the area of the Small Aral Sea varied from 2090 to 3240 km$^2$, with the water volume of 12.03–27.03 km$^3$ (UNESCO 2017). To restore the Small Aral Sea, a sand dam was constructed in the Berg Strait in 1992 to prevent the runoff of the Syr Darya River into the Large Aral Sea (Aladin & Plotnikov 1995). After its destruction in 1993, another temporary dam was built in the spring of 1997. It existed for about two years (Aladin et al. 2005). In 2005, a permanent dam was built, designed to fill the northern part of the sea up to 42.2 m. By 2007, the area of the Small Aral Sea increased to 3280 km$^2$ and the water volume increased from 22.52 to 26.33 km$^3$ as a result of the accumulation of the Syr Darya River runoff. As the level of the Small Aral Sea increased to 42.0 m between 2006 and 2008, the average salinity of water dropped to 12.9 PSU (Krupa & Grishaeva 2011).

# Materials and methods

### Field sampling

Samples of macrozoobenthos were collected in the summer of 1996–1998 and 2001–2008. A standard grid of 20 locations covered the entire water surface area of the Small Aral Sea, except for the partially dry Saryshyganak Bay (Fig. 1). A small Petersen bottom grab with a sampling area of 0.025 m$^2$ was used to sample the macrozoobenthos. At each station, two samples of macrozoobenthos were collected. Samples were fixed with formaldehyde solution (10%) or solution of ethyl alcohol (70%). A total of 320 macrozoobenthos samples were collected and processed. Physicochemical properties of water at the sampling locations were measured simultaneously with macrozoobenthos sampling. Water temperature was measured at each location using a Hanna HI 98129 portable meter. Water transparency was determined by a Secchi disk. The dominant type of soil was determined by the ratio of fractions in bottom grab samples. To determine the chemical composition and salinity, water samples were collected in plastic containers with a volume of 1 l.

### Laboratory Processing

Conventional methods of chemical analysis of water were used (Semenova 1977). Water samples were analyzed in three to four replications. The error of estimate for main ions in water was 0.5–5.0%, depending on the analysis.

Macrozoobenthos samples were processed according to currently accepted methods (Barulin 1984). The taxonomic composition of benthic invertebrates was determined using MBS-10 and MS-300 microscopes according to Shilova (1976), Pankratova (1977), Tsalolikhin (1995), Bogutskaya et al. (2013). The number of individuals of each species was calculated in each sample. To determine the biomass, specimens were weighed on torsion (WT-1000, from 0 to 1000 mg) and electronic balances (OHAUS Adventurer TM AR5120, up to 510 g). Further, the abundance and biomass of each species and of the total macrozoobenthos were calculated per 1 m$^2$ of the seabed of the water body.

### Statistical analysis

Average values with a standard deviation were calculated for all variables in Excel. To analyze the biomass distribution of dominant species of benthic invertebrates in a salinity gradient, scatterplots were constructed. Long-term data were used for this purpose. Spearman correlation coefficients (R) between biological variables and salinity were calculated using the Statistica 12.0 software, with $p < 0.05$. With regard to the coordinates of the sampling locations, distribution maps of the analyzed variables were drawn using the same software. For this purpose, we used data from 1997, 2001, 2006, 2007 with different average salinity of water. Next, the outlines of the Small Aral Sea were drawn in Adobe Photoshop based on Google maps. For better visibility, statistical maps of the analyzed variables were combined with a contour map of the sea in the same software. All statistical maps show the gradient of the measured variables in color.

# Results

### Hydrophysical and hydrochemical characteristics of the Small Aral Sea

The Small Aral Sea has a highly dissected coastline that forms three large bays – Shevchenko in the west, Butakov in the north and Saryshyganak in the northeast (Fig. 1). During the study period, the average depth of the Small Aral Sea was 5.0 m, ranging from 2.6 to 11.5 m. The water transparency varied from 0.8 to 1.8 m. Water temperature ranged from 17.5 to 22.4°C. The western part of Shevchenko Bay as well as the central and northeastern parts of the water area were characterized by the greatest depths and transparency of water (Fig. 2). The minimum values of all variables were recorded in the impact zone of the Syr Darya River. The dominant types of soil were dark gray silt and sand.

The average salinity of water varied considerably over the years (Table 1). The maximum values of this variable were observed in the summer of 1996, 1997, 2001, while the minimum ones – in the spring of 2006–2007. In all the years, the minimum values of salinity were recorded in the impact zone of the Syr Darya River. Shevchenko and Butakov bays, located far from the impact of the river runoff and with a slow water exchange, were characterized by the highest content of total dissolved solids in water.

### Species composition of macrozoobenthos

Ten species of benthic invertebrates were identified over a period of 10 years. The polychaete *Hediste diversicolor* Muller as well as the mollusks *Abra ovata* Philippi, *Cerastoderma glaucum* (Bruguière) and *Caspiohydrobia* sp. were constant in the benthic


**Figure 1**

Map of macrozoobenthos sampling in the Small Aral Sea. Circles indicate macrozoobenthos sampling locations; blue arrows – the direction of water mass movement. The numbers indicate bays: 1 – Shevchenko, 2 – Saryshyganak, 3 – Butakova

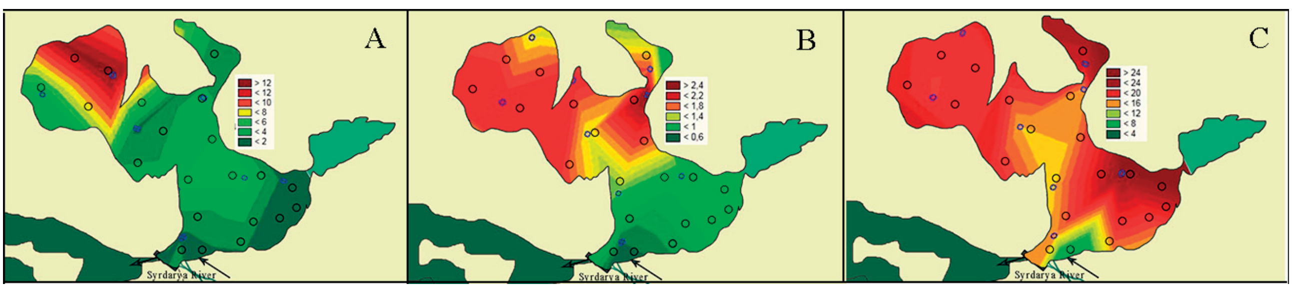


**Figure 2**

Distribution of depths (A), transparency (B) and water temperature (C) in the Small Aral Sea, 1997

community. Other species of benthic invertebrates [oligochaetes, chironomids *Procladius ferrugineus* Kieffer, *Chironomus behningi* Goetghebuer, mollusk *Theodoxus pallasi* Lindholm, shrimp *Palaemon elegans* Rathke, mysid *Paramysis (Mesomysis) lacustris* Czerniavsky] were rare and were recorded mainly in desalinated areas of the sea.

**Table 1**

Water salinity in the Small Aral Sea

| Month, year | Salinity, PSU | |
|---|---|---|
| | average | min.–max |
| June 1996 | 20.4 | – |
| June 1997 | 19.0 | 1.0–25.0 |
| June 1998 | 14.5 | 1.2–28.3 |
| June 2001 | 18.6 | 12.8–26.8 |
| June 2002 | 15.1 | 2.7–26.8 |
| August 2004 | 13.9 | 2.6–35.3 |
| May–June 2005 | 10.8 | 1.9–23.9 |
| May–June 2006 | 8.9 | 4.0–11.5 |
| July–September 2006 | 11.2 | 9.2–17.3 |
| May–June 2007 | 6.3 | 1.2–10.2 |
| August 2007 | 10.5 | – |
| June–July 2008 | 11.8 | 5.6–17.2 |

### Long-term dynamics and spatial distribution of macrozoobenthos

The long-term average annual abundance of macrozoobenthos was equal to 1962 ± 624 specimens $m^{-2}$, with the biomass of 107.1 ± 20.6 g $m^{-2}$. During the study period, the maximum quantitative variables of benthic invertebrates were observed in the western region of the sea – Shevchenko Bay (Table 2). In general, the desalinated southern part of the water area, which is affected by the Syr Darya River flow, was characterized by the minimum biomass of macrozoobenthos. The persistently low biomass of benthic invertebrates in this region (except for 2001) was due to the absence of large mollusks in the community. The eastern and central regions of the sea were characterized by intermediate values of the macrozoobenthos biomass. From 1996 to 2008, the quantitative variables of macrozoobenthos decreased by an order of magnitude for all surveyed areas of the sea. The correlation between the water salinity and the biomass of the benthic community was positive and statistically significant at $R = 0.75$ and $p < 0.05$.

**Table 2**

Long-term dynamics of quantitative variables of macrozoobenthos in different parts of the Small Aral Sea

| Year | Impact zone of the Syrdarya River | Shevchenko, Saryshyganak, and Butakov bays | Eastern part of the sea | Open sea | Mean |
|---|---|---|---|---|---|
| Abundance, specimens $m^{-2}$ | | | | | |
| 2001 | 33 080 ± 1366 | 3960 ± 1998 | 11 110 ± 6830 | 2670 ± 1542 | 4274 ± 1229 |
| 2002 | 1184 ± 315 | 5413 ± 1183 | 11 237 ± 4304 | 3040 ± 1280 | 4540 ± 1084 |
| 2003 | 1112 ± 127 | 2301 ± 839 | 9997 ± 7624 | 2010 ± 693 | 3321 ± 1600 |
| 2004 | 280 ± 79 | 1467 ± 109 | 1774 ± 627 | 1210 ± 601 | 1014 ± 307 |
| 2005 | 628 ± 171 | 400 ± 162 | 1774 ± 1107 | 400 ± 134 | 781 ± 210 |
| 2006 | 280 ± 133 | 720 ± 600 | 1907 ± 674 | 180 ± 115 | 681 ± 261 |
| 2007 | 528 ± 92 | 453 ± 150 | 610 ± 30 | 270 ± 134 | 442 ± 73 |
| 2008 | 224 ± 78 | 373 ± 58 | 1599 ± 492 | 470 ± 112 | 641 ± 140 |
| mean | 4664 ± 4061 | 1886 ± 668 | 5001 ± 1703 | 1281 ± 406 | 1962 ± 624 |
| Biomass, g $m^{-2}$ | | | | | |
| 1996 | 115.4 ± 30.7 | 390.9 ± 145.3 | 132.15 ± 75.4 | 95.5 ± 41.0 | 169.7 ± 43.9 |
| 1997 | 16.0 ± 3.8 | 148.7 ± 115.5 | 231.0 ± 89.5 | 130.7 ± 72.3 | 125.2 ± 40.7 |
| 1998 | 13.10 ± 3.9 | 116.1 ± 83.0 | 271.1 ± 99.2 | 157.4 ± 84.8 | 134.2 ± 40.0 |
| 2000 | 67.4 ± 35.37 | 323.5 ± 54.0 | 302.4 ± 105.5 | 144.0 ± 49.9 | 189.7 ± 41.9 |
| 2001 | 160.7 ± 75.0 | 214.9 ± 107.9 | 406.2 ± 237.4 | 182.5 ± 106.8 | 206.7 ± 48.7 |
| 2002 | 10.5 ± 2.6 | 109.4 ± 65.7 | 434.9 ± 89.2 | 249.6 ± 134.5 | 192.1 ± 53.8 |
| 2003 | 4.5 ± 1.0 | 37.5 ± 29.2 | 269.8 ± 207.8 | 147.9 ± 98.7 | 94.7 ± 50.2 |
| 2004 | 5.8 ± 2.7 | 0.6 ± 0.5 | 114.1 ± 10.3 | 68.3 ± 46.8 | 50.4 ± 18.6 |
| 2005 | 7.0 ± 0.7 | 23.7 ± 17.6 | 131.0 ± 43.0 | 21.6 ± 12.0 | 40.7 ± 17.0 |
| 2006 | 3.1 ± 1.9 | 68.5 ± 62.8 | 90.6 ± 8.9 | 18.0 ± 17.0 | 38.6 ± 15.0 |
| 2007 | 18.6 ± 5.8 | 8.2 ± 5.7 | 39.3 ± 2.7 | 26.2 ± 9.6 | 22.3 ± 5.1 |
| 2008 | 6.5 ± 2.4 | 10.9 ± 1.8 | 52.7 ± 12.9 | 15.8 ± 4.4 | 20.6 ± 4.9 |
| mean | 35.7 ± 14.9 | 121.1 ± 37.1 | 206.3 ± 38.4 | 104.8 ± 22.0 | 107.1 ± 20.6 |

## Long-term dynamics and spatial distribution of the dominant species of macrozoobenthos

The mollusk *Abra ovata* was the dominant taxon in the macrozoobenthos – on average 55.4% of the abundance and 64.1% of the biomass of the community. In terms of abundance, the polychaete *Hediste diversicolor* (24.6%) sub-dominated and was followed by the mollusk C. *glaucum* (20.4%). Relatively high abundance and biomass values of the mollusk *Caspiohydrobia* sp. were recorded in particular years. During the study period, the abundance and biomass of the dominant species of macrozoobenthos changed simultaneously (R = 0.89–0.92, $p < 0.05$). Therefore, only the biomass values of benthic invertebrates were used for further analysis.

The highest biomass values of the dominant invertebrates were recorded in the period before 2003 (Fig. 3). In the following years, the biomass of all species decreased by an order of magnitude. Since 2004, the mollusk *Caspiohydrobia* sp. has almost disappeared from the benthic community.

The spatial distribution of benthic invertebrates was analyzed for 4 years (1997, 2001, 2006 and 2007) characterized by different average salinity (Table 1). In 1997 and 2001, high values of salinity were recorded almost throughout the entire area of the Small Aral Sea, except for the southernmost part near the mouth of the Syr Darya River. As the water level increased in 2006 and 2007, the area of high salinity zones decreased.

Statistical mapping (Fig. 4) showed that the accumulation of the mollusk *Abra ovata* was recorded mainly in Butakov Bay. In 2007, in the conditions of strong desalination of the entire sea area, the *A. ovata* concentration was also recorded in the western part of Shevchenko Bay. The highest biomass of the mollusk *Caspiohydrobia* sp. was recorded in those areas of the sea, which were far from the impact of fresh river water. In 2007, these mollusks were found only in the western part of the sea, while in 2006 they were not found at all. The polychaete *Hediste diversicolor* preferred areas of the sea with relatively low salinity. In 1997, high biomass of polychaetes was recorded not only in the desalinated zone but also in the central part of the sea and in Butakov Bay, where water salinity reached its maximum. Aggregations of the bivalve mollusk *Cerastoderma glaucum* were recorded in various parts of the sea, including the southeastern freshened water area.

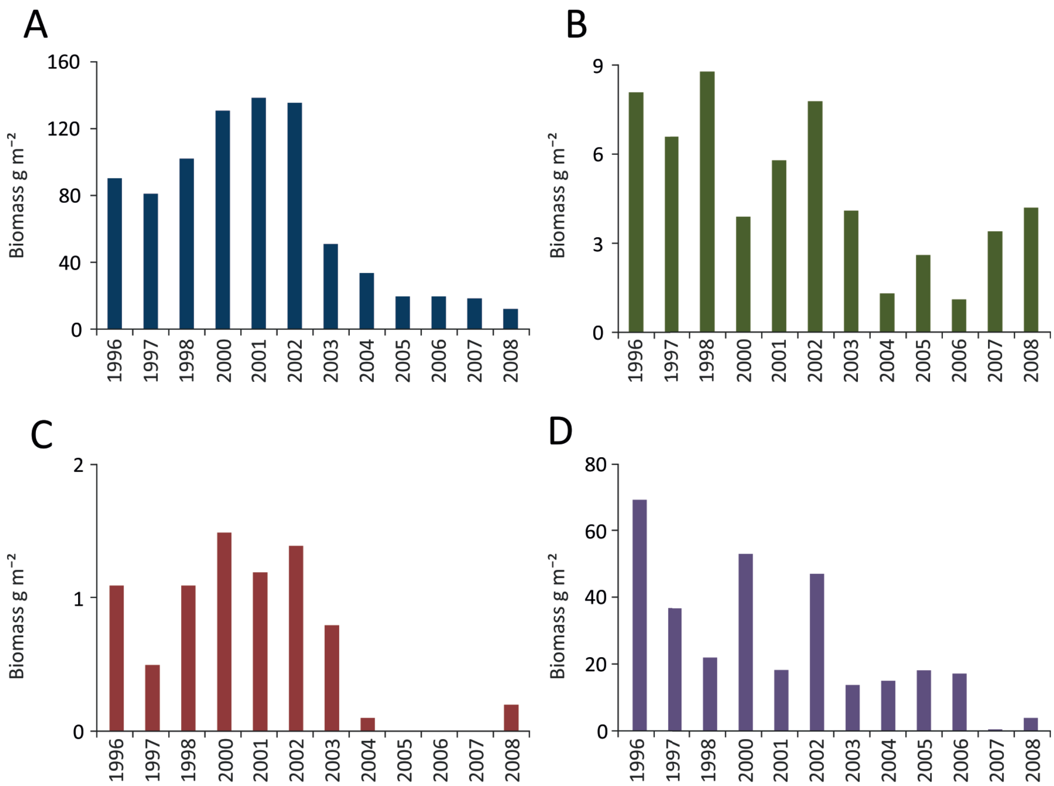


**Figure 3**

Long-term biomass dynamics of benthic invertebrates in the Small Aral Sea. A – *Abra ovata*, B – *Hediste diversicolor*, C – *Caspiohydrobia* sp., D – *Cerastoderma glaucum*

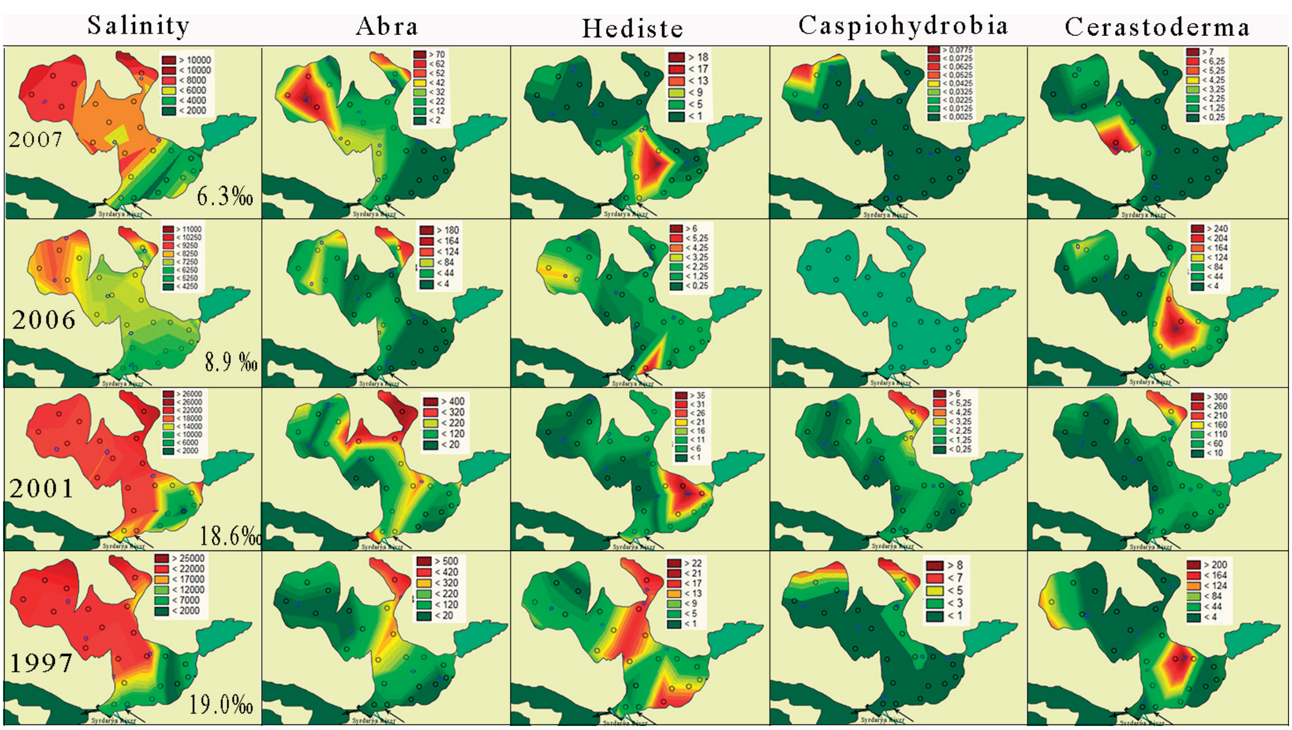


**Figure 4**

Biomass distribution of background species of benthic invertebrates and water salinity of the Small Aral Sea

The analysis of the correlation data showed that statistically significant positive correlations were most frequently observed between the water salinity and the biomass of mollusks A. *ovata* and C. *glaucum* (Table 3). Salinity had a significant positive impact on the polychaete *H. diversicolor* in 2006 and 2008, but in 2005 this relationship was negative. Positive and statistically significant moderate correlations between the biomass of the mollusk *Caspiohydrobia* sp. and water salinity were recorded in the period up to 2004. No correlation was recorded in the following years.

To further analyze the effect of water salinity on quantitative variables of the benthic invertebrates, we prepared scatterplots. Figure 5A demonstrates that the biomass of *A. ovata* increased almost linearly with the increase of salinity. In general, the distribution of biomass of *Caspiohydrobia* sp. and *C. glaucum* was characterized by a similar pattern of variability within the water salinity gradient (Figs 5C,D). Unlike other species, the distribution of *H. diversicolor* biomass within the water salinity gradient was even (Fig. 5B). High biomass of the polychaete was recorded both at low (about 1.0–1.5 PSU) and increased salinity (15.0–20.0 PSU).

**Table 3**

Spearman's rank correlation coefficients between the biomass of background species of benthic invertebrates and the water salinity of the Small Aral Sea, at $p < 0.05$

| Month, year | Salinity, PSU | Spearman's rank correlation coefficients | | | |
|---|---|---|---|---|---|
| | | *A. ovata* | *H. diversicolor* | *Caspiohydrobia* sp. | *C. glaucum* |
| June 1997 | 19.0 | 0.720 | – | 0.615 | – |
| June 1998 | 14.5 | 0.728 | – | 0.615 | – |
| June 2001 | 18.6 | – | – | – | 0.488 |
| June 2002 | 15.1 | 0.604 | – | 0.595 | 0.669 |
| August 2004 | 13.9 | 0.674 | – | 0.524 | 0.793 |
| May–June 2005 | 10.8 | 0.575 | −0.619 | – | 0.704 |
| May–June 2006 | 8.9 | – | – | – | – |
| July–September 2006 | 11.2 | 0.748 | 0.656 | – | 0.665 |
| May–June 2007 | 6.3 | 0.796 | – | – | – |
| August 2007 | 11.8 | 0.748 | 0.656 | – | 0.666 |
| June–July 2008 | – | – | – | – | – |

A dash (–) means that the correlation between variables was not statistically significant.

## Discussion

Our studies of macrozoobenthos in the Small Aral Sea cover two periods with different hydrological and hydrochemical conditions. In 1996–2004, the average water salinity was higher and the range of fluctuations of this variable over the sea was more pronounced than in 2005–2008 (Table 1). The sharp interannual fluctuations of the average water salinity (from 14.5 to 20.5 PSU) at the beginning of the observation period (1996–2004) were due to the instability of the hydrological regime of the Small Aral Sea (UNESCO 2017). Depending on the amount of precipitation, the sea level changed in these years from 36.8 to 42.5 m BS. In addition, sharp fluctuations in the level and salinity of the sea were associated with the construction of two temporary dams in the Berg Strait and their subsequent destruction (Aladin & Plotnikov 1995). The second period, which began in 2005 after the construction of the permanent dam (Aladin et al. 2005), was characterized by more stable conditions. The water level varied to a smaller extent from 39.62 to 41.05 m BS and the average water salinity decreased to 6.3–12.1 PSU (Table 1).

The correlation analysis showed a pronounced positive effect of water salinity on the interannual dynamics of quantitative variables of macrozoobenthos (R = 0.75, with $p < 0.05$), represented mainly by halophilic species. Desalination of the Small Aral Sea caused a decrease in the biomass of benthic invertebrates throughout the study period (Table 2), but the composition of the dominant species of macrozoobenthos was constant. It included the polychaete *Hediste diversicolor* and the mollusk *Abra ovata*, which acclimatized to the Aral Sea in the 1960s (Plotnikov 2013), and two native mollusks *Cerastoderma glaucum* and *Caspiohydrobia* sp. These marine and euryhaline species did not play a major role in macrozoobenthos (Sapozhnikov et al. 2010) until the level of the Aral Sea began to drop and average water salinity was about 10 PSU. The progressive increase in salinity in the second half of the last century caused the gradual disappearance of freshwater and brackish water species (Andreev et al. 1992) and the increase in

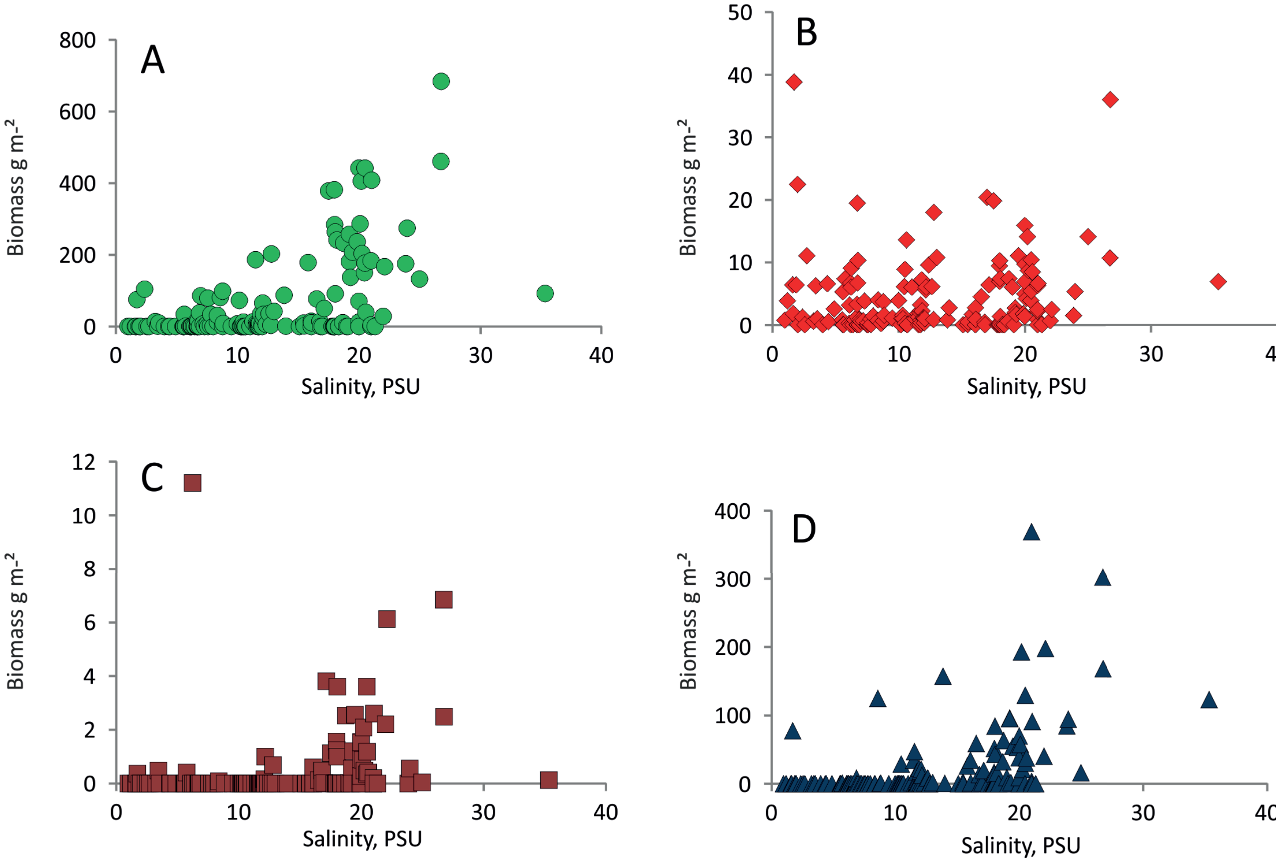


**Figure 5**

Distribution of biomass of background species of benthic invertebrates within the salinity gradient of water in the Small Aral Sea. A – *Abra ovata*, B – *Hediste diversicolor*, C – *Caspiohydrobia* sp., D – *Cerastoderma glaucum*

biomass of the above-mentioned euryhaline species of benthic invertebrates (Andreev 1999).

The decrease in water salinity affected the abundance of benthic invertebrates in a number of ways. The correlation analysis (Table 2) and statistical mapping of selected data (Fig. 4) showed a pronounced effect of salinity on the mollusks *A. ovata* and *C. glaucum*. Statistically significant positive correlations between water salinity and *Caspiohydrobia* sp. biomass were recorded during the unstable hydrological regime, up to 2004. Despite the absence of a statistically significant correlation between *Caspiohydrobia* and water salinity after 2004, salinity was clearly more important to this mollusk than to *A. ovata* and *C. glaucum*. This was evidenced by a sharp decrease in the average biomass of *Caspiohydrobia* with a steady decrease in water salinity after 2005 (Fig. 3). In the case of the polychaete *H. diversicolor*, statistically significant correlations with salinity were recorded only in certain years.

It is known that the ability of organisms to live at certain salinity is not only due to their physiological characteristics but also due to the chemical composition of water (Khlebovich & Aladin 2010). The chemical composition of the Aral Sea was closer to freshwater rather than the ocean water (Alekin & Lyakhin 1984).

The analysis of scatterplots (Fig. 5) allowed us to select the optimal salinity ranges for the dominant species of benthic invertebrates in the conditions of the Aral Sea. During our studies, *Abra ovata* was found within the entire range of water salinity, but the population of this species formed the maximum biomass at 17–27 PSU (Table 4). The literature indicates different salinity limits for *A. ovata*. According to V.V. Khlebovich and N.V. Aladin (2010), these largely euryhaline marine mollusks can withstand a salinity from 5 to 42 PSU in the conditions of the Aral Sea. According to field observations, the optimum salinity limit for *A. ovata* in the Sea of Azov is in the range of 9–12 PSU (Vorobiev 1949), while according to experimental data, it is 10–25 PSU (Karpevich 1975).

**Table 4**

Salinity limits and optimum salinity for dominant species of macrozoobenthos in the Aral Sea

| Species name | Salinity limits, PSU | | Optimum salinity, PSU | |
|---|---|---|---|---|
| | [1–5]literature data | our data | experimental data | our data |
| *A. ovata* | 5.0–42.0 | 1.0–35.3 | [6]10.0–25.0 | 17.0–27.0 |
| *Caspiohydrobia* sp. | 6.0–42.0 | 10.0–35.3 | no data | 17.0–27.0 |
| *C. glaucum* | 7.0–36.0 | 10.0–35.3 | [3]8.1–27.3 | 17.0–27.0 |
| *H. diversicolor* | 0.5–40.0 | 1.0–35.3 | no data | 1.0–27.0 |

According to: [1]Andreev (1999), [2]Andreev & Andreeva (1983), [3]Andreev & Andreeva (1990a), [4]Andreev & Andreeva (1990b), [5]Khlebovich & Aladin 2010, [6]Karpevich 1975

Experimental studies of the resistance of *A. ovata* from the Aral Sea showed that the lower salinity limit for this species is 12–14 PSU (Andreev & Andreeva 1983). At lower salinity, the survival rate of *A. ovata* specimens and sperm lifespan decreased.

According to theoretical premises (Khlebovich & Aladin 2010), the mollusks *Caspiohydrobia* and *Cerastoderma glaucum* withstand salinity up to 42 PSU in the conditions of the Aral Sea. In hyperhaline water bodies formed in place of the Large Aral Sea, *C. glaucum* was absent at the salinity of 67 PSU (Aladin & Plotnikov 2008). According to N.I. Andreev and S.I. Andreeva (1990b), the abundance of *C. glaucum* in the Aral Sea decreased at salinity over 32 PSU, and no live mollusks were found at the salinity of 36 PSU. In the Small Aral Sea with salinity below 10 PSU, *Caspiohydrobia* and *C. glaucum* were found occasionally (Fig. 4). Obviously, the salinity of 10 PSU is the lower limit for these mollusks in the Aral Sea. For both mollusks, salinity below 10 PSU (Table 4) was established as a lower limit under experimental conditions only (Andreev & Andreeva 1990b). According to our results, the maximum biomass of *Caspiohydrobia* and *C. glaucum* was recorded at salinity ranging from 17 to 27 PSU. Obviously, these values of salinity are the optimal limits for both mollusks in the Aral Sea.

The polychaete *Hediste diversicolor* tolerates salinity from 0.5 to 40 PSU in the conditions of the Aral Sea (Andreev, Andreeva 1990b; Khlebovich & Aladin 2010). According to the results of experiments (Neuhoff 1979) and field observations of *H. diversicolor* in the Caspian Sea (Malinovskaya & Zinchenko 2011) and the Sea of Azov (Semin 2011), salinity had a positive effect on the species. The death of the polychaete was observed when water salinity of the Large Aral Sea exceeded 67 PSU (Aladin & Plotnikov 2008). During our studies, the distribution of *H. diversicolor* in the Small Aral Sea did not depend on water salinity (Fig. 5), which was confirmed by the correlation analysis (Table 2) and statistical mapping (Fig. 4). Our results indicate euryhalinity of the polychaete. Apparently, its favorable salinity in the conditions of the Aral Sea ranges from 1.0 to 27.0 PSU.

The diagrams (Fig. 5) illustrate that benthic invertebrates were either absent or formed low biomass even in the conditions of favorable salinity of the Small Aral Sea. This indicates that water salinity was the main but not the only factor affecting their biology. It is known that for benthic animals, the type of soil (Semin 2011), the content of organic matter (Kocheshkova et al. 2012) and the amount of oxygen in the bottom water layers are important in addition to salinity. In the fall of 1997 and 1999, the absence of benthic animals in the central part of the Small Aral Sea, with a depth of more than 8.0 m, was associated with the presence of hydrogen sulfide in these zones (Filippov 2001). According to our data, water salinity in these areas reached 20.5–28.3 PSU during this period, i.e. it was in the optimal range for euryhaline species of benthic invertebrates. The return of breeding freshwater fish fauna (Ermakhanov et al. 2012; Aladin et al. 2018) will be another significant factor affecting the species composition and quantitative variables of macrozoobenthos in modern desalination conditions of the Small Aral Sea.

## Conclusion

In 1996–2008, with the average water salinity of the Small Aral Sea at 6.3–19.0 PSU, 10 taxa of the macrozoobenthos were identified. The long-term average annual abundance of benthic invertebrates was 1962 specimens $m^{-2}$, with the biomass of 107.1 g $m^{-2}$. With the decrease in the average water salinity from 14.5–20.5 PSU to 6.3–12.1 PSU from the beginning to the end of the analyzed period, the biomass of benthic invertebrates statistically significantly decreased from 125.5–206.7 g $m^{-2}$ to 20.6–94.7 g $m^{-2}$. Despite the decrease in the average salinity of water during the study period, the main part of quantitative variables of macrozoobenthos was formed by euryhaline and marine species – the polychaete *Hediste diversicolor* and the mollusks *Abra ovata*, *Cerastoderma glaucum*, *Caspiohydrobia* sp. Aggregations of mollusks *A. ovata* and *Caspiohydrobia* sp. were recorded in areas of the sea with high salinity.

The mollusk *C. glaucum* inhabited various parts of the Small Aral Sea. The polychaete *H. diversicolor* preferred regions with relatively low salinity. The statistically significant positive correlation with salinity was found for the mollusks *A. ovata* and *C. glaucum*, less frequently – for *H. diversicolor* and *Caspiohydrobia* sp. On the basis of the obtained results, we have determined for the first time the optimum salinity limits for the dominant species of benthic invertebrates in the conditions of the Aral Sea. For the mollusks *A. ovata*, *Caspiohydrobia* sp. and *C. glaucum*, the optimum salinity ranged from 17 to 27 PSU and for the polychaete *H. diversicolor* from 1 to 27 PSU. It is clear that a steady decrease in the average water salinity of the Small Aral Sea will lead to a change in the macrozoobenthos species composition due to the inhibition of marine species and occurrence of freshwater and brackish water species. The mollusks *A. ovata*, *Caspiohydrobia* sp. and *C. glaucum* will be able to survive only in the western and northern bays of the sea, far from the impact of freshwater of the Syr Darya River. The growing pressure from freshwater and brackish water fish species will be an additional factor determining the specific features of the structure of benthic communities in various areas of the Small Aral Sea.

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