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Diversity of Fauna in Crimean Hypersaline Water Bodies

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On the Crimean peninsula, there are more than 50 hypersaline water bodies, including the Sivash (the Sea of Azov), the largest hypersaline lagoon in the world. Based on the literature and our own long-term research data (2000–2017), a review of the fauna of the hypersaline waters in the Crimea is presented, including 298 species of animals belonging to 8 phyla, 14 classes and 27 orders. The variety of phyla and classes within a particular range of salinity was shown to decrease significantly with an increase in salinity; 8 classes in 3 phyla can withstand salinities above 100 g/L, and only 4 classes (Branchiopoda, Hexanauplia, Ostracoda and Insecta) within 1 phylum (Arthropoda) occur at salinities above 200 g/L. The number of species found in a single sample also decreased with increasing salinity. However, in the range of 50–120 g/L, the number of species was mainly determined by a different set of factors. The abundance of animals in the hypersaline waters of the Crimea can be very high: e.g., Nematoda – up to $1.4 \cdot 10^7$ ind./m^2, Harpacticoida – up to $3.5 \cdot 10^6$ ind./m^2, Ostracoda – up to $5.8 \cdot 10^5$ ind./m^2, and Moina salina – up to $1.3 \cdot 10^6$ ind./m^3. A characteristic feature of hypersaline water ecosystems is the fact that increases in salinity cause increasing amounts of benthic animals (Chironomidae, Harpacticoida, Ostracoda) to change their habitats from the bottom to the water column. At salinities above 120–150 g/L, there is almost no animal life at the bottom. Most of the species found in shallow hypersaline waters have a resting stage in their life cycle, which ensures their survival in abruptly changing environments, even those in ephemeral water bodies.

Keywords: fauna, crustaceans, hypersaline waters, Crimea.

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Фаунистическое разнообразие в гиперсоленых водоемах Крыма

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На Крымском полуострове расположено более 50 гиперсоленых водоемов, включая залив Азовского моря Сиваш, крупнейшую гиперсоленую лагуну мира. С использованием литературных и собственных многолетних данных (2000–2017 гг.) нами дан обзор фауны гиперсоленых водоемов Крыма. Найдены представители 8 типов, 14 классов и 27 отрядов животных. Разнообразие типов и классов, существующих в определенном диапазоне солености, существенно уменьшается при росте солености: выше 100 г/л остаются представители 3 типов и 8 классов, выше 200 г/л – 1 типа (Arthropoda) и 4 классов (Branchiopoda, Hexanauplia, Ostracoda и Insecta). Общее количество видов, найденных в одной пробе, также убывает с ростом солености. В диапазоне 50–120 г/л не соленость, а другие факторы в большей степени определяют количество видов. Численность животных в гиперсоленых водоемах Крыма иногда достигает очень больших величин, например, Nematoda – до $1.4{\cdot}10^7$ экз/м^2, Harpacticoida – до $3.5{\cdot}10^6$ экз/м^2, Ostracoda – до $5.8{\cdot}10^5$ экз/м^2, Moina salina – до $1.3{\cdot}10^6$ экз/м^3. Особенностью экосистем гиперсоленых водоемов является то, что с увеличением солености все большая часть донных животных (Chironomidae, Harpacticoida, Ostracoda) переходит к жизни в водной толще. При солености выше 120–150 г/л на дне активных стадий животных практически не остается. Большинство видов, обитающих в гиперсоленых мелководных водоемах Крыма, имеют покоящиеся стадии, что обеспечивает их существование в озерах с резко флуктуирующей средой, нередко пересыхающих.

Ключевые слова: фауна, ракообразные, гиперсоленые водоемы, Крым.

Introduction

Hypersaline waters, common in arid and subarid regions, are among the planet's extreme biotopes (Wharton, 2002; Zheng, 2014). Alongside a high degree of salinity, other abiotic factors determine their extremity (Grant, 2004). Salinity affects other characteristics of the environment, thus shifting them into the extreme range (Shadrin, 2018). For example, an increase in salinity can alter the temperature regime significantly due to the decrease in heat capacity and heat conductivity of the solution. It causes a rise in the maximum and a fall in the minimum temperatures, thus increasing the diurnal temperature range of the water. High salinity reduces oxygen solubility in the water (Nishri, Ben-Yaakov, 1990; Debelius et al., 2009) and in this way generates anoxic zones in water bodies (Shadrin, Anufriieva, 2013a; Shadrin et al., 2016).

In recent decades, more species inhabiting hypersaline waters have been discovered (Lamprey, Armah, 2008; Sultana et al., 2011; Amarouayache et al., 2012; Belmonte et al., 2012;

Carrasco, Perissinotto, 2012). At least 28 species of Copepoda (Crustacea) have been found to occur in hypersaline waters (> 100 g/L) across the world, and among them, 12 species are able to survive at extreme salinity levels (> 200 g/L) (Anufriieva, 2015a; Anufriieva, 2016). Studying life in extreme environments allows for a more accurate assessment of the limits of adaptability, the variety of adaptations and how they developed. These assessments are essential for a better understanding of the evolution of life on Earth and for predicting possible changes in ecosystems caused by climate change and anthropogenic impacts.

On the Crimean Peninsula, there are more than 50 hypersaline (> 35 g/L) water bodies, including the Sivash (the Sea of Azov), the largest hypersaline lagoon in the world (Fig. 1) (Fedchenko, 1870; Balushkina et al., 2009; Shadrin et al., 2016). Among them are hypersaline lakes of marine and continental origin. The ion ratio in marine lakes is the same as that in sea water, whereas continental reservoirs are sulphate lakes. All the lakes are shallow and polymictic and differ only in their size, the range of fluctuations in abiotic factors and their biota. Research into the biodiversity of Crimean hypersaline waters has been ongoing since the mid-19th century (Fedchenko, 1870; Anufriieva et al., 2017). Since 1992, the diversity of their fauna has been studied systematically (Ivanova et al., 1994; Zagorodnyaya, Shadrin, 2004; Balushkina et al., 2009; Belmonte et al., 2012; Anufriieva et al., 2017; Shadrin et al., 2017); thus, hypersaline waters of this region are among the most thoroughly investigated worldwide. On the other hand, an analysis of the effects of salinity on biodiversity based on the entirety of the published data has never been performed.

This study aims to provide a review of the fauna in the hypersaline waters of the Crimea based on published data and the authors' own long-term observations (2000–2017) and to examine the influence of water salinity on the biodiversity of invertebrates and fishes.

Taxonomic diversity

Decades of research on the hypersaline lakes of the Crimea (Anufriieva et al., 2017) have revealed that the taxonomic diversity of invertebrates and fishes is fairly high (Table 1); species belonging to 8 phyla, 14 classes and 27 orders of animals have been discovered. The diversity of phyla and classes was shown

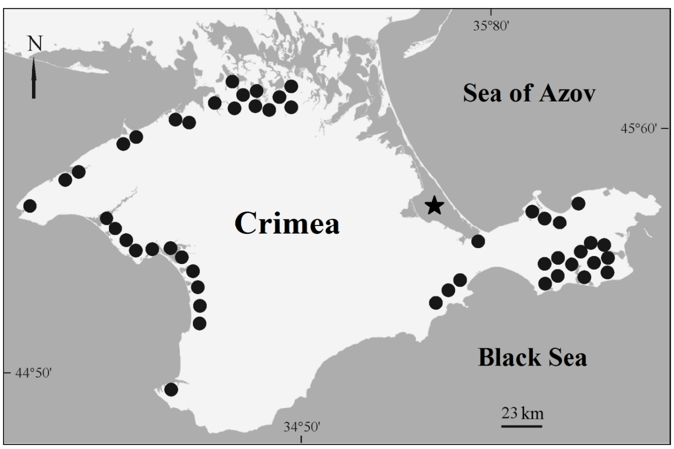

Fig. 1. Examined hypersaline water bodies in the Crimea

● – lakes ★ – the Sivash

Table 1. Animal taxa in the hypersaline waters of Crimea

Taxon	Max salinity, g/L	Number of species	Reference
1	2	3	4
Phylum Nematoda	190	4	Kolesnikova et al., 2008
Class Chromadorea	190	2	Kolesnikova et al., 2008
Order Monhysterida	190	2	Kolesnikova et al., 2008
Class Enoplea	190	2	Kolesnikova et al., 2008
Order Enoplida	190	2	Kolesnikova et al., 2008
Phylum Rotifera	190	4	Zagorodnyaya et al., 2008; Balushkina et al., 2009
Class Eurotatoria	190	4	Zagorodnyaya et al., 2008; Balushkina et al., 2009
Order Ploima	190	2	Zagorodnyaya et al., 2008; Balushkina et al., 2009
Order Flosculariaceae	100	2	Dagaeva, 1927; Balushkina et al., 2009
Phylum Platyhelminthes	100	2	Kulagin, 1888; Dagaeva, 1927
Class Turbellaria	100	2	Kulagin, 1888; Dagaeva, 1927
Order Macrostomorpha	100	1	Dagaeva, 1927
Order Proseriata	100	1	Dagaeva, 1927
Phylum Annelida	80–100	2	Shadrin et al., 2016
Class Polychaeta	80–100	2	Shadrin et al., 2016
Order Phyllodocida	80–100	2	Zagorodnyaya et al., 2008; Shadrin et al., 2016
Phylum Bryozoa	80	1	Kulagin, 1888
Class Gymnolaemata	80	1	Kulagin, 1888
Order Ctenostomata	80	1	Kulagin, 1888
Phylum Mollusca	100	3	Shadrin, 2014
Class Bivalvia	80–100	2	Shadrin, 2014
Order Mytilida	80	1	authors' unpublished data
Order Cardiida	80–100	1	Shadrin, 2014
Class Gastropoda	80	1	Kulagin, 1888; authors' unpublished data
Order Littorinimorpha	80–100	1	Kulagin, 1888; authors' unpublished data
Phylum Arthropoda	360	55	Anufriieva et al., 2017
Subphylum Crustacea	360	40	See Table 2
Class Branchiopoda	360	6	See Table 2
Order Anostraca	360	4	See Table 2
Order Cladocera	110	2	See Table 2
Class Hexanauplia	360	18	See Table 2
Subclass Copepoda	360	18	See Table 2
Order Calanoida	300	2	See Table 2
Order Cyclopoida	212	7	See Table 2
Order Harpacticoida	360	9	See Table 2
Class Ostracoda	300	5	See Table 2
Order Podocopida	300	5	See Table 2
Class Malacostraca	200	11	See Table 2
Order Amphipoda	200	4	See Table 2
Order Decapoda	85	3	See Table 2

Continuation Table 1

1	2	3	4
Order Isopoda	85	3	See Table 2
Order Mysida	120	1	See Table 2
Subphylum Hexapoda	300	15	Przhiboro, Shadrin, 2012; Shadrin et al., 2017
Class Insecta	300	15	Przhiboro, Shadrin, 2012; Shadrin et al., 2017
Order Coleoptera	200	3	authors' unpublished data
Order Diptera	300	10	Przhiboro, Shadrin, 2012
Order Hemiptera	120	2	Anufriieva, Shadrin, 2016
Phylum Chordata	100	3	Shadrin et al., 2016; Shadrin, Anufriieva, 2013a
Infraclass Teleostei	80–100	3	Shadrin et al., 2016; Shadrin, Anufriieva, 2013a
Class Actinopterygii	80–100	3	Shadrin et al., 2016; Shadrin, Anufriieva, 2013a
Order Mugiliformes	80–100	1	Shadrin, Anufriieva, 2013a
Order Atheriniformes	80–100	1	Shadrin et al., 2016
Order Perciformes	80–100	1	Shadrin et al., 2016

to drop significantly with increasing salinity; 3 phyla and 8 classes can withstand salinities above 100 g/L, and only 1 phylum (Arthropoda) and 4 classes (Branchiopoda, Hexanauplia, Ostracoda and Insecta) occur at salinities above 200 g/L. However, many of the species inhabiting hypersaline waters (Nematoda, Platyhelminthes, Rotifera, Bryozoa, etc.) have never been studied extensively.

Currently, crustaceans are the best studied group (Table 2). The number of species studied has grown significantly from 1870 (Fedchenko, 1870) to 2017, as shown in Fig. 2. Of all the species discovered within this period, 10 species (22%) were discovered from 2012–2016. It can be seen in Fig. 2 that the curve representing the number of species has not yet approached the stationary phase; therefore, the finding of more new species can be expected. Recently, based on the analysis of the dynamics of discovering new species, we concluded that 3 to 5 species of Cyclopoida may be discovered in the lakes of the Crimea (Anufriieva et al., 2014). It should be mentioned that in the well-studied hypersaline lakes of Australia, the taxonomic diversity of the fauna is also high (Williams et al., 1990; Timms, 1993, 2002; Kokkinn, Williams, 1988; Pinder et al., 2005).

Salinity and taxonomic diversity

An increase in salinity is associated with a decrease in the biodiversity of crustaceans in water bodies (Fig. 3). As species composition varies seasonally and yearly, the relationship between the number of species and salinity was investigated in samples of water collected at the same time in 14 different hypersaline lakes in August 2012 (Fig. 4). The number of species per sample decreased with increasing salinity. Other researchers observed a similar pattern, although the exact data could be different (Williams et al., 1990; Pinder et al., 2005; Balushkina et al., 2009; Belmonte et al., 2012). Fig. 4 shows that the number of species in the samples within the 50–120 g/L salinity interval does not correlate with salinity and is significantly more diverse than in the samples from the habitats with higher salinity. The variation coefficient of the number of species in the waters within the 50-150 g/L salinity interval equals 0.49, whereas

Table 2. Crustacean species in Crimean hypersaline water bodies

Species	Max salinity, g/L	Reference
1	2	3
Class Branchiopoda **Order Anostraca**		
Artemia salina Leach, 1819	340	Shadrin et al., 2012
A. urmiana Günther, 1899	360	Shadrin, Anufriieva, 2017
Parthenogenetic populations *Artemia*	360	Shadrin et al., 2012
Phallocryptus spinosa (Milne-Edwards, 1840)	85	Shadrin et al., 2009
Order Cladocera		
Moina salina Daday, 1888	110	Zagorodnyaya, Shadrin, 2004
Daphnia atkinsoni Baird, 1859	45	authors' unpublished data
Class Hexanauplia **Subclass Copepoda** **Order Calanoida**		
Acartia tonsa Dana, 1849	55	Shadrin, Anufriieva, 2013a
Arctodiaptomus salinus (Daday, 1885)	300	Anufriieva, 2015a
Order Harpacticoida		
Canuella perplexa Scott T. et al., 1893	100	Zagorodnyaya et al., 2008
Cletocamptus retrogressus Schmankevitsch, 1875	360	Anufriieva, 2015a
Harpacticus littoralis Sars G.O., 1910	70	Kolesnikova et al., 2017
Mesochra lilljeborgii Boeck, 1865	240	Tseeb, 1958
M. rapiens (Schmelin, 1894)	240	Tseeb, 1958
M. rostrata Gurney, 1927	240	Tseeb, 1958
Metis ignea ignea Philippi, 1843	260	Anufriieva, 2015a
Microarthridion littorale (Poppe, 1881)	70	Kolesnikova et al., 2017
Nitokra spinipes spinipes Boeck, 1865	240	Tseeb, 1958
Order Cyclopoida		
Acanthocyclops sp.	212	Anufriieva et al., 2014
A. americanus (Marsh, 1893)	80	Anufriieva, Shadrin, 2012
Cyclops furcifer Claus, 1857	150	Anufriieva et al., 2014
Diacyclops sp.	150	Anufriieva et al., 2014
D. bisetosus (Rehberg, 1880)	150	Anufriieva et al., 2014
Eucyclops sp.	150	Anufriieva et al., 2014
Thermocyclops crassus (Fischer, 1853)	120	authors' unpublished data
Class Ostracoda **Order Podocopida**		
Cyprideis torosa (Jones, 1850)	70	Drapun et al., 2017
Cytherois cepa Klie, 1937	70	Drapun et al., 2017
Eucypris mareotica (Fischer, 1855)	300	Jia et al., 2015
Loxoconcha aestuarii Marinov, 1963	70	Drapun et al., 2017
L. bulgarica Caraion, 1960	70	Drapun et al., 2017

Continuation Table 2

1	2	3
Class Malacostraca **Order Isopoda**		
Idotea balthica (Pallas, 1772)	85	Shadrin, Anufriieva, 2013a
Lekanesphaera hookeri (Leach, 1814)	58	authors' unpublished data
Sphaeroma serratum (Fabricius, 1787)	85	authors' unpublished data
Order Amphipoda		
Echinogammarus olivii (Milne-Edwards, 1830)	45	Anufriieva, Shadrin, 2012
Gammarus aequicauda (Martynov, 1931)	200	authors' unpublished data
Orchestia gammarellus Pallas, 1766	75	Anufriieva, Shadrin, 2012
Orchestia mediterranea Costa, 1853	75	Anufriieva, Shadrin, 2012
Order Mysida		
Mesopodopsis slabberi (Van Beneden, 1861)	120	Shadrin, Anufriieva, 2013a
Order Decapoda		
Carcinus maenas (Linnaeus, 1758)	85	Kulagin, 1888
Hippolyte leptocerus (Heller, 1863)	55	Shadrin, Anufriieva, 2013a
Palaemon elegans Rathke, 1837	40	authors' unpublished data

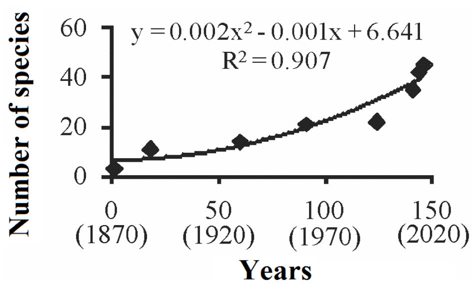

Fig. 2. The number of crustacean species found in Crimean hypersaline water bodies

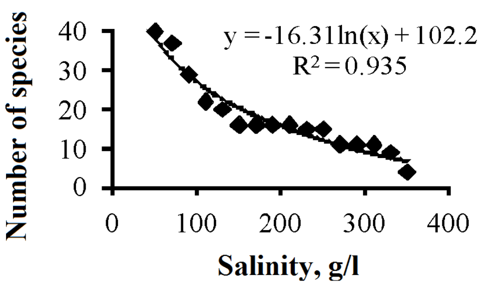

Fig. 3. The number of crustacean species occurring at different salinities in Crimean hypersaline waters

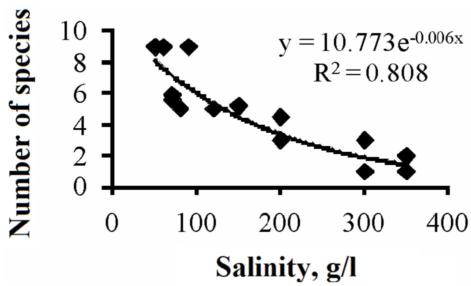

Fig. 4. Number of animal species per sample as a function of water salinity (August 2012)

that in the range of 200–300 g/L equals 0.28. This might be explained by the fact that many species demonstrate halotolerance within the high salinity interval and can survive in such environments. Within the lower salinity interval (from 50 to 120 g/L), different factors must determine the number of species, as was also shown in the lakes from other regions (Williams, 1998; Pinder et al., 2005). The survival of animals in hypersaline waters is permitted by two mechanisms: osmoregulation of salt concentrations in the body liquids and/or the accumulation of osmolytes inside the cells, similar to the case in single-cell organisms (Khlebovich, Aladin, 2010; Shadrin, Anufriieva, 2013b; Shadrin et al., 2017). The ability of some species to survive in hypersaline waters may depend on the concentration of algae accumulating high amounts of osmolytes in their cells (Shadrin, Anufriieva, 2013b; Anufriieva, 2015a; Shadrin et al., 2017). Among the many causes affecting biodiversity may be abiotic (oxygen concentration, temperature, etc.) as well as biotic factors (predators, competitors and the amount and quality of food) (Kokkinn, Williams, 1998; Wurtsbaugh, 1992; Shadrin et al., 2012). According to V.S. Ivlev, biotic factors are crucial for the survival of most animals, and only at critical values can abiotic factors be of the same significance (Ivlev, 1955). V.D. Williams came to a similar conclusion about the role of biotic and abiotic factors in saline lakes (Williams, 1998). Salinity is considered to be a critical factor when it reaches values above 120–150 g/L.

Animal abundance and possible applications

The animal abundance in the hypersaline lakes of the Crimea can be high (Table 3), which means that animal species play an important role in the trophic chains of these waters (Balushkina et al., 2009). In other regions, similar observations have been made (Kokkinn, Williams, 1988; Wurtsbaugh, 1992; Lamptey, Armah, 2008; Amarouayache et al., 2012; Carrasco, Perissinotto, 2012). Arthropoda species normally constitute 70 to 100% of the abundance and biomass.

The hypersaline waters of the Crimea are common habitats for many species of birds, such as wintering, nesting and feeding grounds, during their seasonal migrations. Invertebrates are a very important constituent of bird diets, especially for *Himantopus himantopus* (Linnaeus, 1758), *Tadorna tadorna* (Linnaeus, 1758), *Tringa totanus* (Linneaus, 1758), *Recurvirostra avosetta* (Linneaus, 1758), *Calidris ferruginea* Pontoppidan, (1763), etc. (Khomenko, 2003; Khomenko, Shadrin, 2009).

A characteristic feature of hypersaline water ecosystems is the fact that increases in salinity cause increasing amounts of benthic animals (Chironomidae, Harpacticoida, Ostracoda) to change their habitats from the bottom to the water column (Shadrin et al., 2016; Shadrin et al., 2017). At salinities above 120–150 g/L, there is almost no animal life at the bottom. Most of the species found in shallow hypersaline waters have a resting stage in their life cycle (Moscatello, Belmonte, 2009; Shadrin et al., 2015), which ensures their survival in abruptly changing environments of water bodies that are frequently ephemeral.

Many of the abundant species, such as the rotifer *Brachionus plicatilis* Müller, 1786, the crustaceans *Artemia* spp., *Moina salina*, *Daphnia atkinsoni*, *Cletocamptus retrogressus*, *Arctodiaptomus salinus*, and *Chironomidae* larvae, are prospective food sources in aquaculture (Anufriieva, 2015b) because they are tolerant to high temperatures and salinity, can resist oxygen deficiency, have resting stages in their life cycles and are easy to cultivate.

Table 3. Maximum abundance of different animal taxa in the hypersaline waters of Crimea

Animal taxon	Plankton, ind./m^3	Floating green algae mat, ind./m^2	Benthos, ind./m^2	Reference
Nematoda	–	$1.4 \cdot 10^7$	$6.0 \cdot 10^5$	Kolesnikova et al., 2008
Harpacticoida	$7.8 \cdot 10^5$	$2.5 \cdot 10^6$	$3.5 \cdot 10^6$	Zagorodnyaya et al., 2008; Kolesnikova et al., 2008; Kolesnikova et al., 2017
Artemia spp.	$5.6 \cdot 10^4$	–	–	Zagorodnyaya et al., 2008
Moina salina	$1.3 \cdot 10^6$	–	–	Zagorodnyaya, Shadrin, 2004; Zagorodnyaya et al., 2008
Arctodiaptomus salinus	$3.1 \cdot 10^5$	–	–	Anufriieva, Shadrin, 2015
Gammarus aequicauda	–	$1.8 \cdot 10^4$	–	Ivanova et al., 1994
Ostracoda	$2.0 \cdot 10^5$	$5.4 \cdot 10^5$	$5.8 \cdot 10^5$	Drapun et al., 2017
Chironomidae larvae	$8.0 \cdot 10^3$	$3.0 \cdot 10^3$	$9.0 \cdot 10^3$	Ivanova et al., 1994; Shadrin et al., 2017

Conclusion

In the hypersaline waters of the Crimea, similar to other regions, the fauna is diverse. The animal diversity decreases with increasing water salinity. However, in every case, there are other factors that influence the number of species. The animal abundance in the hypersaline waters of the Crimea can be high and serve as an important biological resource.

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