

The Crimean hypersaline lakes: towards development of scientific basis of integrated sustainable management

N.V. SHADRIN

Institute of biology of the Southern seas, Sevastopol, Ukraine 99011
(snickolai@yandex.ru)

Abstract: There are a lot of saline/hypersaline lakes of marine and continental origin in the Crimea (Ukraine). Both types of lakes were studied during 9 years. This paper presents main results of that study showing general abiotic and biotic peculiarity of two types of lakes. In paper also there are conclusions, which are important for their sustainable use of these lakes under climatic changes.

Keywords: saline/hypersaline lake, limnology, Crimea, Ukraine.

1. Introduction

Hypersaline lakes and lagoons of marine and continental origin are found on all continents, being most numerous in arid and semi-arid zones, which make up about one-third of the world land. They are an essential, integral and dynamic part of the biosphere while the biogeochemical processes occurring in their unique ecosystems have considerable environmental, social and economic value. Owing to extremely high rates of organic matter production and sedimentation, and the deposition of calcium carbonate [9, 14, 24], they can be regarded as efficient carbon sinks and natural mechanisms to retard the human-related greenhouse effect. They are also natural resting and wintering grounds for migrating birds, and biotopes for many unique micro- and macroorganisms [27 - 29], for which there is as yet no description. A large number of these lakes are exploited for raw materials used in industry, agriculture and medicine, e.g. the minerals halite, mirabilite and zeolite, and the elements lithium, magnesium, boron and tungsten [18, 30]. They also contain considerable amounts of biological resources such as halophilic cyanobacteria and algae (e.g. *Spirulina* spp., *Dunaliella salina*, *Chlorella vulgaris*), and animals (*Artemia* spp., Chironomidae larvae) of economic and scientific value [21, 27]. Another valuable product is the widely used medicinal mud, the result of biota function in the lakes generally [18] and as exploited locally in the Crimea [5]. A further important aspect to these unique lakes is their potential in the tourism industry. Although this can be a double-edged sword, with care profit can be made to build on the current exploitation in for instance the Dead Sea (Israel/Jordan/Palestine), the hypersaline lakes of Khakasia (Russia), Solar Lake (Egypt), and

Mono Lake (USA). Unfortunately, the current, unregulated practice for exploiting hypersaline lakes disturbs the normal functioning of their ecosystems and their contribution to the biosphere, finally resulting in the exhaustion of their capacity to yield social and economical values [6, 30]. Moreover, there is no well-grounded scientific basis to develop sustainable management strategies and technology [30]. This paper is one of the first steps towards developing of scientific basis of sustainable management of the Crimean hypersaline lakes.

2. Saline lakes and climate

The climatic prerequisite of water body salinization and hypersalinity incorporates several geophysical factors. The hydrophysical and hydrochemical structure of saline lake forms under region-specific climatic conditions and directly depends upon the lake/ air interaction, i.e. the fluxes of warm air and moisture, and also upon the water exchange with the sea or a river; in their turn, the fluxes and the water exchange are influenced by regional hydrometeorological conditions. An important factor for marine lakes/closed lagoon is the storm winds that suddenly rise the sea level: huge waves are rolling up onto the shore land and the overflow drastically increases filtration rate of the lake/ lagoon and the received seawater influx.

It is noteworthy that under the hypersaline lake/air exchange evaporation exceeds precipitation; then the received water influx (underground drainage or terrestrial run-off) compensates the difference. Accumulating dissolved salts of the inflow increase salinity of the lake. To attain a quasi-stationary state, i.e. to cease further salinization, the total water balance, i.e. precipitation, evaporation and drainage balance should equal zero. Steady temperature balance requires zero thermal balance, i.e. the balanced solar irradiation, direct and hidden (the heat used for evaporation) heat exchange between the lake and the air; the heat exchange between the lake and the shore land may be ignored.

In assessing humidity not only the rainfall but also evaporation from the surface should be taken into account. The ratio between annual, monthly or seasonal total precipitation, P , and evaporation, E_e , (the local-specific evaporation possible under an unlimited ground water

reserve) determines the humidity coefficient. Under increasing salinity, humidity equilibrium (the relative pressure of saturated water vapour) decreases [28]. Evaporation from the surface of saline lakes is a changeable value that depends upon weather conditions and the salinity; given equal conditions, the higher salinity, the lower evaporation rate that has been proved for hypersaline water bodies in the Crimea [3] and Mono lake in the USA [28]. Exometabolic biofilms on water surface may also reduce evaporation from the lake surface by 30-50% [3].

Assuming that total annual land/air heat exchange performed through heat-conductivity is negligible and can be ignored, it can be deduced that the annual locality-specific evaporation would consume the amount of heat equal to the annual irradiation balance. Thereby the irradiation index of dryness for a year is determined as [10]:

$$K_d = \frac{B}{L} \cdot P, \quad (1)$$

where B is annual irradiation balance, P – total annual precipitation, and L – evaporation heat. Irradiation index of dryness indicates the portion of irradiation balance used for rainfall evaporation. It was assumed that under the values greater than the conventional limit of climate dryness, $K_d = 3$, the climate in the locality is dry that favours salt accumulation and hypersaline lake formation [4]. In the Mediterranean where the climate is arid hypersaline water bodies are usual all along the coastline of the Mediterranean and the Black seas. Considering the aforesaid it is clear that salty lakes are extremely sympathetic on climatic changes.

3. The Crimean hypersaline lake peculiarities

Our interest focuses on characteristic features of hypersaline lakes located in the Crimea (Ukraine); in their description we use the data of our long-term investigations [11, 15, 20, 23 - 26]. Methodology and methods are given in our earlier cited here papers. Situated in the northern Black Sea, the Crimea is the largest (nearly 26.5 thousands km²) Black Sea peninsula. Figure 1 and Table 1 show the Crimean hypersaline water bodies distribution and their general characteristics: 50 comparatively large and numerous small (from several to hundreds meters long) lakes. The exact count of small lakes is shaky for it is difficult to differentiate between a large puddle and a tiny lake. In the Crimea most of hypersaline lakes have marine origin and are the seawater localities that have once separated from the main sea. Sasyk-Sivash that has the surface of 75.3 km² is the largest [13]. At present all these lakes receive the infiltrated and storm inflows from the sea. For the majority of such lakes/enclosed lagoons the infiltration from the sea provides the basic supply in their water

balance. The age (probably not greater than 3-5 thousands years),

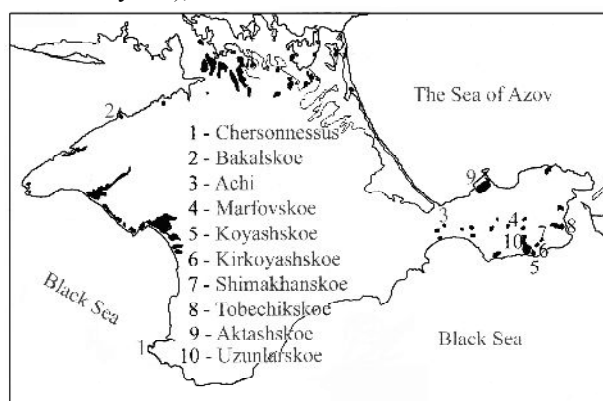


Fig. 1 The Crimean studied hypersaline lakes

size and other characteristics of marine lakes vary broadly. This makes the lakes remarkably diverse in physicochemical and biotic characteristics. For instance, the annual average salinity varies from 30 to 250‰; interannual differences are also considerable. All the lakes have a distinct annual salinity cycle; the variability range is different in each lake as Table 1.

With regard to chemical composition of the water the Crimean marine lakes divide into two types [13]. One type are lakes the brine of which contains calcium, magnesium or sodium sulphates; the major inflow into those lakes is from the sea. The other type are lakes with the brine having the concentration of sulphuric acid ions sufficient (or less) to generate sulphuric calcium salt; those lakes receive water supply from terrestrial and underground sources. In the first type sea water metamorphization is described with metamorphization coefficient as $K = MgSO_4 / MgCl_2$, and in the second type as $K = MgCl_2 / CaCl_2$ [13]. $K = MgSO_4 / MgCl_2$ evaluated for the first group of the Crimean marine lakes fluctuates from 0.20 to 5.3, and for different locations of the Black Sea from 0.64 to 0.71. In the second group the estimates of $K = MgCl_2 / CaCl_2$ vary from 0.11 to 0.34. On the Crimean peninsula marine hypersaline lakes concentrate along the western, northern and eastern coasts.

Notably less numerous is the group of continental hypersaline lakes, or *koli*, in the local dialect, that concentrate on the Kerch peninsula (Eastern Crimea) in the calderas of the Prehistoric mud volcanos. These are shallow and relatively small lakes, their water holds sulphate brine with $K = Na_2SO_4 / MgSO_4$ that varies from 0.32 to 2.48 [13, 25].

Chemical composition of the water, i.e. ion ratios, is different in the marine and in the continental lakes. Therefore it is sensible to use relative, not absolute values of ions, i.e. chlorine coefficients [13]. These coefficients computed in different years and seasons for the investigated lakes. The tabulated data are our own

and those taken from the relevant literature [13, 19]; this series of figures permits to assess how the chemical

Table 1. Main characteristics of the Crimean hypersaline lakes (2000 – 2006)

Lake	Surface, (km ²)	Catchment area, (km ²)	Average depth, (m)	Maximum depth, (m)	Temperature range, °C	Salinity range, ‰	pH	eH
Marine:								
Bakalskoye*	8,0	31,65	2000 – 0,4	2000 – 0,55	31,45- summer	30 – 110	7,85 – 9,0	-138 ÷
*			2004 – 0,8	2004 – 1,20	0,0 – winter			+153
Tobechik*	20,0	92,32		2004 – 1,20	28,0- summer	57 – 290	7,85 – 9,12	
					0,0 – winter			
Koyash*	7,0	17,40		2004 – 1,2	29,5 – summer	160 – 360	7,7 – 8,08	
Chersonessus	0,014	0,032	2000 – 0,4	2000 – 0,60	29,0 – summer	35 – 120	7,35	-334 ÷
**			2004 – 0,7	2004 – 1,00	0,0 – winter			+277
Continental:								
Marfovskoye	2,65	13,55			32 –summer	95 – 480	7,3 – 8,73	
*					0,0 – winter			
Kirkoyash*	1,25			2000 – 0,00	33,75 –summer	16 – 360	8,6 – 9,43	
				(summer);	0,0 – winter			
				2004 – 1,3				
Shimakhan*	2,64	5,70		2000 – 0,00	26,35 –summer	30 – 360	8,85 – 11,0	
				(summer);	0,0 – winter			
				2004 – 1,2				
Achi	3,2	7,1			28 – summer	116 – 158	7,6 – 8,32	+44
					0,0 – winter			

* solitary summer measurements;

** summer night-time measurements included

composition of lake water has been changing for more than 75 years. In some of the lakes chemical composition of the brine is comparatively invariable, seasonal and interannual variations are insignificant, while in other lakes it varies broadly. A number of seasonal variations in ion ratios, e.g., Ca and SO₂ ions in the water is related to biotic processes, such as calcification – the overabundance of calcium-shelled ostracods, anoxic photosynthesis, chemosynthesis.

The biodiversity evaluation is difficult in variable habitats: information regarding their biological composition should be conducted in different periods of the year, and even in distant years to obtain results as complete as possible. Species compositions vary with seasons, up to complete disappearing if abiotic conditions become extreme. This is the case of the Crimean hypersaline lakes, which suffer deep variation in salinity concentration at every intense rain episode, or that can even evolve toward a complete loss of the water by evaporation. In fact, the possibility to resist to adverse conditions could be extended for many years in the case of certain species. Those species, which are not active in certain conditions, these notwithstanding are present in the environment under the form of resting stages (cysts, resting embryos, lethargic individuals).

When species diversity is poor and partly in “sleeping” form, most of the active species yield high abundance and biomass, especially during warm season. Though subject to fluctuations, phytoplankton biomass estimates can be

greater than 60 g · m⁻³ [6, 8, 26]. Highly saline lakes may harbour only one species - nearly monoculture, *Dunaliella* sp., that colours the water opalescent pink. Lakes with high salinity are often coloured various shades of pink or red. The salts settled on the bottom get similarly coloured because of high concentrations of carotenes – beta-carotene produced by the green alga *Dunaliella*, or bacterioruberins of halobacteria. Under the water salinity of 80 – 170 ‰, *Dunaliella*, cyanobacteria, dinoflagellates and benthic diatoms produce the major portion of the biomass.

At the depth of 35-45 cm *Cladophora* biomass had been as large as 6 - 8 kg · m⁻² owing to the joint contribution (about 50 – 800 g · m⁻²) of diatoms and cyanobacteria settled primarily on the algal filaments close to the water surface. Exopolysaccharides, which contribute about 60% to the total carbon production, play a significant role in metabolism of *Cladophora* mats [20]. Growing mats decrease lake water evaporation and thereby slow down the summer salinity increase. This important function of *Cladophora* mats with all the fouling diatoms and cyanobacteria has been reported for hypersaline lake Saky in the Crimea [6]. In some years *Cladophora* mats with their epibionts and the biofilms that grow in the supralittoral and on the bottom may drive back phytoplankton and produce most of the phytomass in the lakes. Anoxic phototrophs (e.g., purple bacteria) are comparatively abundant on the lake bottom and on the underlying surface of *Cladophora* mats. Their

biomass can amount to $0.5 - 1 \text{ kg} \cdot \text{m}^{-2}$ bottom and even more. The role that purple bacteria play in biofilms of Crimean hypersaline lakes has been described [7]. Depended upon the water salinity, purple bacteria contribute from 10 to 60% of the total primary production of biofilms. Lake phytoplankton also depends upon anoxic photosynthesis that may account for 50% of total primary production [16]. For instance, a study conducted on lake Saky [6] has shown that in 1990 phytoplankton production per square metre was evaluated as less than 10% of the total primary production; in 1991 it only decreased. Doing these computations, the researchers did not take into account the primary production of biofilms, otherwise the portion of phytoplankton in the total primary production had been not larger than 1 – 5%. The biofilms yield as abundant primary production as $200 \text{ mg C} \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ and more [7]. The shallower is the lake, the greater is the collective share that macrophytes and periphyton (biofilms) contribute to the total production; the pertinent estimates vary from 0 to 51% [1]. Though beyond the limits acknowledged for freshwater lakes, as large portion as that is not rare in the Crimean shallow (less than 1m depths) lakes [22].

Sometimes the portion of zooplankton and benthos biomass in the plankton is greater than $65 \text{ g} \cdot \text{m}^{-3}$ (mostly owing to *Artemia* and *Moina*), but the usual average is not as large [15]. Larvae of Chironomidae prevail in the benthic biomass; water salinity increasing, their abundance on the bottom of the lakes decreases. Highest biomass estimates were measured in the floating mats of *Cladophora*, where not less than 90% of the total animal biomass concentrated [6, 11]; the basic contributors had been the larvae of Chironomidae, Harpacticoida, Ostracoda and Coleoptera. Total biomass of animals in the mats can reach $480 \text{ g} \cdot \text{m}^{-2}$, but usually the estimates are 3 – 5 times as less. Total biomass of zooplankton and benthos has never been greater than $500 \text{ g} \cdot \text{m}^{-2}$, making on the average about $100 \text{ g} \cdot \text{m}^{-2}$. This is nearly 100 times as less as the total biomass of photoautotrophs. Knowing the production potentiality of one and the other, it is reasonable to suggest that difference between the productions is even greater, and the animal organisms inhabiting Crimean hypersaline lakes usually consume less than 1% of the total primary production. This is in a sharp contrast with the ratios of primary producers/zooconsumers having been acknowledged for a large number of freshwater lakes [1]. The biomass estimates obtained for different heterotrophic bacteria and the microcalorimetric measurements of heat flows produced by phototrophs and unicellular heterotrophs assess the organic substance destruction by unicellular organisms as 3 – 5% of the primary production [17]. Usually, about 60% of primary production in lakes is used in microbial plankton loop and never reaches the bottom [1]. In the lakes under our study the situation is quite

different, and the microbial loop in plankton is only of minor importance. As a rule, 15 – 70% of the primary production settles onto the bottom of lakes where detritivorous animals and microorganisms consume about 25% of it [1]. Destruction of the total organic matter by bottom bacteria is 2 – 8 times as large as by animal organisms. In the Crimean lakes animal life is so scarce that would hardly consume more than 0.1% of the settled organic substance. Assuming that the part aerobic and anaerobic bacteria take in the destruction is 10-20 times as large as that of animal organisms, the total organic substance consumption will be no more than 2% of the settled onto the lake bottom. The cited estimates suggest that heterotrophic organisms consume 3 – 7% of the total primary production. Thus, in hypersaline lakes more than 90% of primary production is deposited in bottom sediment that is significantly greater than in lakes of different types. To roughly evaluate sedimentation processes in lake Bakalskoe we used two approaches. A depth survey conducted in August 1932 had reported the 85-cm depth as maximum for Bakalskoe [13]. When in August 2000 and 2001 we made similar measurements, the registered maximums (52 and 60 cm, respectively) were considerably less than in 1932. Comparison of the earlier and recent data permits to estimate the average sedimentation rate as high as $4 - 5 \text{ mm} \cdot \text{yr}^{-1}$. Organic substance, gypsum and calcium carbonate in the form of calcite with the admixture of aragonite compose the bottom sediment. The algal floating mats and the cast-out are encrusted with a solid mineral (mostly calcite-gypsum) layer. In the depth of floating or on-shore mats small gypsum, calcite and aragonite crystals are also abundant. In 2001 ring-like traps equipped with the sieve were placed in the water at the edge of the lake where they stayed from March to August. For the months passed a 5 – 7 mm thick stratified membrane had formed on the sieve in which calcium carbonate and gypsum made up about 65-70% of the total dry mass. This fact also proves high deposition rate characteristic of the lake.

High rates of calcite and aragonite formation in the biofilms of Crimean hypersaline lakes have already been reported [7]. In those lakes the origin of these minerals is biological rather than chemical: exopolysaccharides that green algae, cyanobacteria and diatoms excrete play the key role [2, 12]. Other influential factors are the ambient pH, Eh and temperature. Phototrophs affect these factors so that calcification rate increases.

Carbon (CO_2) intensively removed through organic matter and calcium carbonate from the biotic cycle and air makes the Crimean shallow hypersaline and highly eutrophic lakes unique natural machines that impede the greenhouse effect. Probably, today this is their mission of top importance for the humanity.

Saline Lakes of Crimea play a crucial role in supporting large number of water birds both during seasonal migrations and wintering period. Introduction of

non-native *Artemia urmiana* by birds to the Black Sea area from Iran (Shadrin et al, 2007) is particularly interesting given its cross-road position the Afro-Eurasian waterbird flyway system. This issue with its potentially far-going ecological and conservation consequences becomes increasingly important under the conditions of global climate change.

4. Conclusions

From the above-stated the principal characteristics of the Crimean hypersaline lakes as unique ecosystems can be defined as: (1) these are heavily eutrophicated water bodies in which the floating mats (*Cladophora* and epibionts) and/or the biofilms (diatoms and cyanobacteria) under the assistance of anoxic photoautotrophs can yield most of the primary production; (2) heterotrophic organisms uptake only a negligible portion of the primary production in the lakes, the rest (about 90%) settles down onto the bottom sediment; (3) biogenic calcium carbonate (calcite and aragonite) and gypsum intensively form and accumulate in the lakes, that leads to (4) rapid ($4 - 5 \text{ mm} \cdot \text{yr}^{-1}$) bottom sediment accumulation; (5) circadian rhythms of the biota-influenced physicochemical parameters (environmental temperature, pH and Eh) are clearly manifested; though poorly understood as yet, this may be of considerable environmental importance; (6) phototrophs significantly influence temperature fields by adding to their mosaic distribution pattern and generating positive anomalies which accelerate production and calcification rates; (7) bacterial plankton loop is of minor importance in ecosystems of the lakes; and (8) considerable year-to-year differences in the structure and function of ecosystems are owing to the changeable climate; (9) they play a crucial role in supporting large number of waterbirds both during seasonal migrations and wintering period.

The most important challenge in the management of the Crimean hypersaline lakes is *to integrate and balance the interests of the environment (biosphere), society (different groups of people), and profit (economy)*. It is a principal, practical goal of needed new investigation *to provide the sound, scientific basis on which to engineer this balance in long-term climatic changes*.

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