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Assessing Climate and Human Activity Effects on Hypersaline Lake Ecosystem: Case Study of Saki Lake, Crimea

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Abstract: In the Crimean Peninsula, there are several hypersaline lakes that have hydromineral and biological resources. However, they are under a significant anthropogenic load, which together with the climate change leads to negative consequences for the ecosystems. The aim of the work was to study the seasonal changes of physicochemical parameters of water (temperature, pH, oxygen content, salinity, redox potential Eh, optical density and transparency) and *Artemia* population in Saki Lake in 2022. For the daily fluctuations of temperature, O_2, CH_4 and CO_2, a vertical temperature profile measuring system was installed at the boundaries of the air, water and bottom at a depth of 4 m and with a spatial discreteness of 0.2 m. The drive sensors for the content of gases assay in the air were installed. The increase in salinity and Eh in summer was accompanied by an increase in air and water temperature. Simultaneously, decreases in oxygen content and pH in brine have been observed. *Artemia* cysts were found throughout the year, nauplii were mostly available during spring and autumn, and the adults were shown in summer. The obtained results demonstrated the seasonal fluctuations in the hypersaline ecosystem within the ongoing climate change, and they can be used for the development of the optimal management of the mineral and biological resources of such water bodies.

Keywords: salt lake; seasonal and daily fluctuations; *Artemia*; salinity; oxygen content; temperature; pH; Eh; CH_4; CO_2

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1. Introduction

Hypersaline lakes are drainless water bodies containing over 44% water and occupying 23% of all planet's lakes area [1,2]. They are small and shallow ecosystems characterized by changing water parameters and frequent drying. They are widespread around the world, especially in arid and desert areas, where people have used wells for water supply.

Since ancient times, salt lakes were used for salt production, as a source for water supply especially in regions of arid climate and low groundwater level, food provision, climate regulation, avifauna support, tourism and landscape aesthetics [3]. Resources of hypersaline lakes are actively used in the economy of various countries. Minerals of the brine and sediments are utilized in the chemical industry, in balneology and for producing cosmetics, pharmaceuticals, and spa materials. Sediments are very effective for the treatment of many diseases, especially of bone and skin pathologies. A highly distributed invertebrate species is a brine shrimp, *Artemia salina*, which is the main and the most effective starting food for many aquacultural organisms [4,5]. *Artemia* plays an important role in the regulation of hydromineral regime of salt lakes. As a filter-feeding crustacean, it takes part in the transformation and utilization of diverse mineral and organic matters supplying in these basins. It is the key link in the food chain and in the biogenic migration of elements, including xenobiotis. This concern makes salt lakes valuable for humans.

Many hypersaline lakes are located in the areas of high people activity, such as operations of the agriculture, sand mining, production and processing of minerals and salt, recreation, and tourism. Anthropogenic activity impacted salt lakes by many ways, firstly chemical contamination of the water bodies, damage of their hydrological regime accompanied with the constructions of the buildings on the shores, etc. This activity variably affects these unique ecosystems and together with climate change leads to their salination, desalination and degradation. Changes of hydromineral regime and ions composition of the brine and sediments disturb the living conditions and relationships between aquatic organisms, thus decreasing already low biodiversity [6]. In addition, various xenobiotics, such as heavy metals, pesticides, synthetic surfactants, crude oil, PAH, etc., cause changes in the concentrations of natural native chemical composition, including biogens and minerals. Salt lakes play a role in global biogeochemical cycles, because they accumulate and recycle nutrients better than freshwater lakes [3,7]. Therefore, they can utilize great storage of nitrogen, phosphorus and carbon, which migrate in biogenic cycles, where birds and invertebrates take part. In this case, the anthropogenic activity notably modifies the ecological states of the lakes, including physicochemical properties of their brine and sediments. It affects the state of their biota, especially the microbial communities, phyto- and zooplankton. The microbial consortium is the key component of the nutrients recycling, and its modification disturbs the balance between different groups of microorganisms, including those involved in the transformation of organic and inorganic matters, in particular, nitrogen, phosphorus and carbon in biogeochemical cycles [8–10]. These processes together with climatic changes result in extremely negative consequences for salt lakes, which have been already observed worldwide, namely: their drying out, desalination and complete degradation [11]. In this case, they cannot provide their ecosystem services, such as groundwater recharge, nutrient recycling and biodiversity maintenance [12].

At present, anthropogenic processes influence natural biogeochemical cycles, because often, nitrogen- phosphorus- and carbon-bearing chemicals are introduced into the environments. Sometimes, they contain the compounds disturbing the natural migration and transformation of these elements in water bodies [10,13]. Climate change and the modification of the key biogen elements cycles can adversely affect ecosystems and their biota, resulting in changes in the concentrations of these compounds in aquatic ecosystems, the physicochemical properties of the water and bottom sediments, and the structure and composition of the aquatic life [14]. The consequences of these processes affect the water quality and stimulate eutrophication, hypoxia and anoxia [15–17]. Because CO_2 emissions from fossil fuels and industry comprise ~90% of all CO_2 emissions from anthropogenic activities, these changes are widely accompanied to increased CO_2, which contributes up to 70% to the cause of global warming [18]. Methane CH_4 is the other important greenhouse gas, and its 100-year global warming potential is estimated as 28–34 times that of CO_2 [19,20]. It is responsible for a 0.5 °C of increase in the global average temperature during 2010–2019 compared to 1850–1900, contributing to 16% of global warming [21]. Therefore, monitoring and controlling CO_2 and CH_4 emissions are the key to analyzing and predicting the global greenhouse effect and global warming

In the environment, the peculiarities of the intensity of the processes of biogen migration and gas emission depend on season. In salt lakes, the variables of the brine parameters are observed daily, which depend on temperature fluctuations, wind velocity and precipitation. For the understanding the interactions between the lakes genesis and the dependence of their hydromineral regime on meteorological and climatic conditions, it is important to analyze the mechanisms and factors for the seasonal and daily changes of several hydrochemical characteristics and carbon-bearing gases in the lakes. For these purposes, the usual hydrochemical methods are used. However, at present, the novel technique for monitoring is developing, including the telemetric autonomous systems, which allows obtaining information in the online regime [22,23].

There are 45 hypersaline lakes in Crimea peninsula [6,24]; their total surface area is estimated as 52,000 ha. The depths of them do not exceed 3 m. Hypersaline lakes in Crimea were formed about 6500–7000 years ago, and many of them in ancient time were formerly marine lagoons and estuaries. Their salinity and other physicochemical parameters vary widely and depend on the genesis, hydrometeorological (climatic) factors, seasonal and diurnal temperature fluctuations. The state of air, water, and bottom sediments at different depths, the level of atmospheric precipitation, the velocity and direction of wind, etc., are determined by the geographical position, global climatic changes and anthropogenic activities influence on the ecological status of these water bodies. Therefore, the study of general and specific characteristics of salt lakes in different geographical regions provides insight into effects of land–lake–sea interactions and offers an opportunity to predict further transformation of these aquatic ecosystems as a result of these interactions [25].

The major aims of this study are the following:

1. To analyze the seasonal climate changes in the area of Saki Lake (Easter basin) in 2022;
2. To reveal the seasonal fluctuations of physicochemical parameters of brine;
3. To determine daily fluctuations of temperature and carbon-bearing gases in the different layers of the lake water column;
4. To analyze seasonal dynamics of *Artemia* population.

2. Materials and Methods

2.1. Sampling Site

Saki Lake is one of the largest salt lakes in Crimea (Figures 1 and 2). It is well studied due to its medical and economic significance. In ancient times, it was a bed of the draws flooded by the sea waters. Its bottom sediments, which are the main balneological resources of this water body, have formed for thousands of years under the influence of complex factors: namely, hydrometeorological, hydrogeological, hydrochemical, and biological. According the present data, the mineral resources of Saki Lake are estimated as several billions tons.

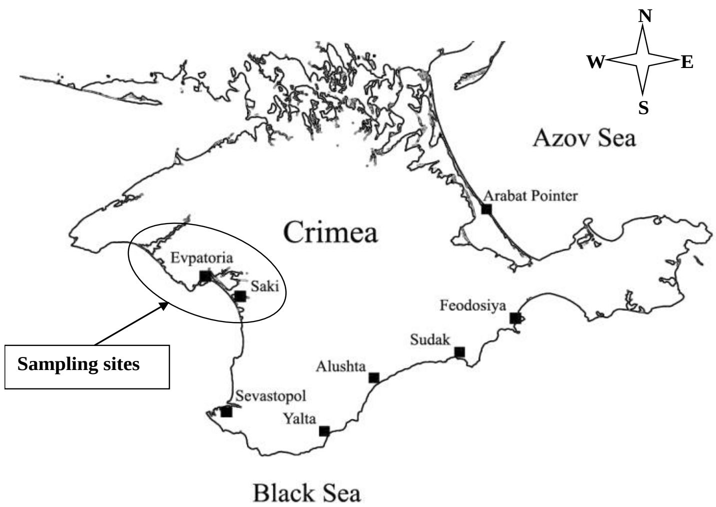

Figure 1. Location of Saki Lake.

The lake is 5.5 km long, its average width is 1.6 km, and the greatest one is 3 km; the average depth is 0.6 m, and the greatest one is 1.52 m. Its elevation is 0.7 m a.s.l. The quality of sediments in the bottom of the saline basin is differed: an upper layer contains the black mud, gray, steel-gray, occasionally bluish silt, which is used for balneological methods in therapy. Higher aquatic plants are found in the desalinated part of the lake, in which ground waters enter and feed it together with atmospheric precipitation. The annual average atmospheric precipitation is estimated as approximately 400 mm.

Figure 2. Saki Lake.

Over two hundred years, the lake's balneological resources and brine were used very intensively by humans. The formation of peloids (medicinal sulfide-silt mud) in Saki Lake occurs as a result of the deposition of organic matter with subsequent transformation by its aquatic organisms, including the filter-feeding crustacean *Artemia* and microbial consortium. Therefore, to protect the water body and keep its ecological regime, it was subdivided into seven basins by artificial dams (Figure 3). Two of these bodies (Eastern basin and Western basin) are used for medicinal sulfide-silt mud (peloids) and brine processing for medical purposes, and the other five protect them by a special hydrotechnical system (FPHTS). The Eastern basin with coordinates 45°07′25.8″ N, 33°35′09.8″ E is now exploited intensively; for its stable functioning and ecosystem protection under intensive economical activities, the FPHTS is used successfully. It contains the diversion dams, channels, pumping stations, and division gates, which regulate the water flux from the sea and block the income of the excess fresh water. FPHTS helps to regulate the salinity in the Eastern basin and compensates the intense evaporation of water from brine in the hot season. For this, sea water is supplied from the Kalamitsky Bay of the Black Sea by means of hydraulic structures, resulting in the decrease in salt concentration in the brine. It was estimated that to obtain the optimal salinity (150 g/L) in the Eastern basin, it needs to pump 500,000 m^3 of marine water per year and remove 50,000 m^3 of brine during the period of 3–4 years. Because the marine barrier was under anthropogenic impact for a long time, at present, it does not provide the natural process of water filtration from the sea to Saki Lake. In addition, many buildings constructed on the shore of the lake, roads and new embankment limit the natural inflow of marine water in the basins. Thus, the artificial regulation of the hydrochemical regime with the FPHTS is performed successfully, which provides optimal conditions for the development of biota. On the other hand, the geochemical function of the lithosphere has little effect on the formation of bottom sediments. As a result, the natural processes of peloids formation have reduced significantly in recent years [26].

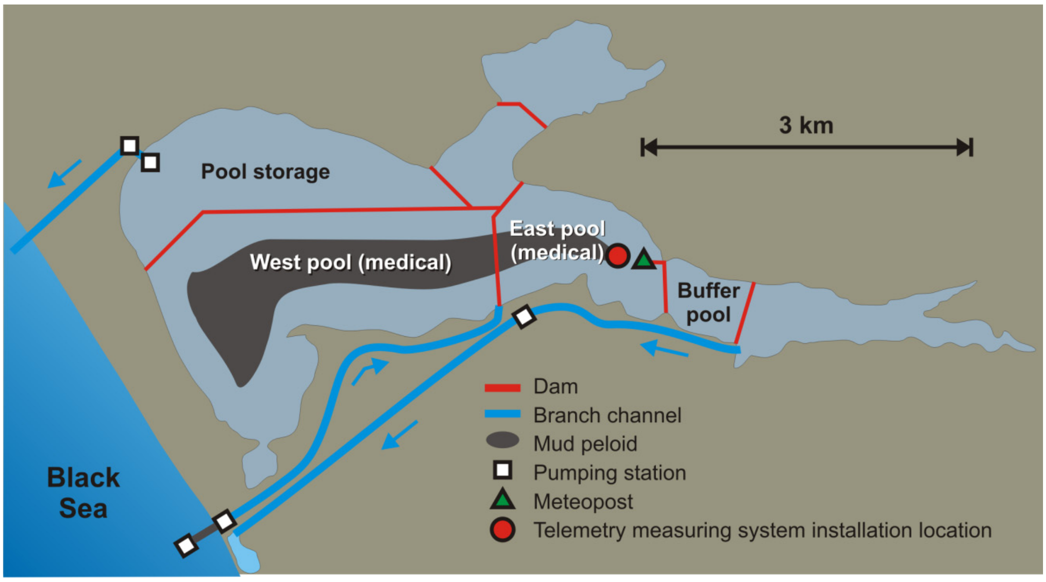

Figure 3. The pools of Saki Lake.

Therefore, Saki Lake is undergoing an intense anthropogenic impact, and there is a need to evaluate the changes and influence of different factors, taking place there for the purpose of development of the protection measures and the optimization of the management of its resources.

2.2. Methods

2.2.1. Meteorological Characteristics

Internet resources [27] were used for the analysis of the meteorological characteristics of the studied area near Saki Lake in 2022. The presence of precipitation, the average monthly air temperature, the number of sunny days and days with precipitation, and the quantity of the precipitation were analyzed. Irradiance was measured by a luxmeter TKA-LUX (Russia), and the obtained results were converted to the fc. The air temperature and humidity of each sampling day were assayed by a Temperature and Humidity Meter CEM DT-321 (Russia).

Selayninov's hydrothermic coefficient of humidification (HCH), characterizing the level of humidity of the area, is widely used in agriculture for climate status and the determination of the zones with different humidity [28]. It is estimated according to the equation:

$$K = R * 10/\Sigma t$$

where R is the sum of the precipitation in mm at the period with the air temperature > + 10 °C, and Σt is the sum of the temperature values in °C at the same period.

According to the classification, which used the HCH, the areas are grouped as following:

High humidity zones (HCH > 1.3);

Medium humidity zones (1.0–1.3);

Arid (0.7–1.0);

Dry agriculture (0.5–0.7); and

Irrigation (<0.5) [2].

2.2.2. Hydrochemical Parameters

The seasonal hydrochemical parameters of the lake brine were analyzed with the methods described previously [29]. Water samples with a volume of 2 L each were taken monthly during 2022 and examined (each in duplicate from sampling sites). The temperature of the water in the lake was measured with an HANNA Instruments Check Temp-1 electronic thermometer directly in the water body. The brine salinity was assayed with a PAL-06S

LTA GO refractometer (Japan) and expressed in %. The pH value, the redox potential Eh, and the concentration of dissolved oxygen in the brine were analyzed in the laboratory with an Expert-001 analyzer (Econix-Expert Moexa Co., Ltd., Moscow, Russia). The optical density at 525 nm (OD_{525}) and transparency of the water at the same wavelength were assayed in a photometer Expert-003 analyzer (Econix-Expert Moexa Co., Ltd., Russia).

2.2.3. Telemetry Measuring System

Based on the author's technical developments of spatial distributed temperature sensors [30], a telemetric autonomous system for monitoring of the vertical five-meter temperature profile in air, water and soil environments with a spatial resolution of 20 cm was created. To simultaneously monitor gas emissions near the water surface, methane and carbon dioxide concentration sensors were installed in the system. In addition to recording measuring information with a period of 10 s to the built-in memory module, telemetry relay of data over the mobile Internet was provided.

The telemetry measuring system installed at the boundary of the mud peloid includes a distributed temperature sensor (thermoprofilemeter), which is a sealed temperature-sensitive cable with a diameter of 4 mm and a length of 4.8 m in a stainless steel protective tube with a diameter of 8 mm. The thermoprofilemeter is installed vertically at the boundaries of the air–rap–soil sections to a depth of 3 m in mud deposits. The sensor consists of 24 sections with a length of 20 cm each. The temperature measurement error in each section is less than 0.1 °C. Changes of depth and border of level of the water surface have a seasonal nature and fluctuate in the range of 0.5–1 m. As primary measuring instruments of concentration of CO_2 and methane in air, Winsen sensors were used: MH410D (0 ÷ 5%) and MH440D (0 ÷ 5%). Telemetry registration and the display of data is provided using a tablet computer, and measuring data are relayed via mobile communication. At the same time, data are accumulated in a removable replaceable flash memory module that operates independently of the computer system.

The primary installation location of the system was determined based on the technical and organizational capabilities of the control system. A sampling site was chosen according to the characteristic features of the composition and depth of bottom sediments on the bridge near the standard hydrometeosite at the border of the mud peloid (Figure 4).

Figure 4. View of telemetry measuring system installation.

2.2.4. Determination of Brine Shrimp *Artemia* and Its Population Dynamics

Samples for hydrobiological analysis were collected at the lake by a special planktonic net with a working volume of 5 L. In the samples, various life stages of *Artemia* were determined, and their numbers were counted under an MBS-10 binocular microscope (indicators were expressed as spec./L).

Artemia cysts were collected monthly at the lake shore (Figure 5). Cysts were processed according the general recommendations [29,31]; then, cysts were incubated in salinity of

35‰ and temperature +25 °C for 48 h with periodic stirring. The cyst-hatching rate was calculated as the ratio of the number of larvae hatched after 24 and 48 h to the total number of cysts used for the incubation.

Figure 5. *Artemia* cysts on the shore of Eastern basin of Saki Lake.

2.3. Statistical Analysis

All measurements were conducted in triplicates, and their averages were calculated and analyzed. Cyst hatching rate measurements were detected in triplicate for each sample, and the results were presented as Mean ± SD. The graphs were made using the computer program EXELL. Statistical correlations between studied hydrological parameters were calculated by the least-squares method using software CURVFIT (Version 2.10-L).

3. Results

3.1. Seasonal Dynamics of Weather Characteristics near Saki Lake

The meteorological parameters near Saki Lake are shown in Figures 6 and 7 and in Table 1, which demonstrate the analysis of studying characteristics during the period of water and brine shrimp sampling in the lake. The weather conditions in the days of sampling corresponded to the average ones for the test month (Table 1).

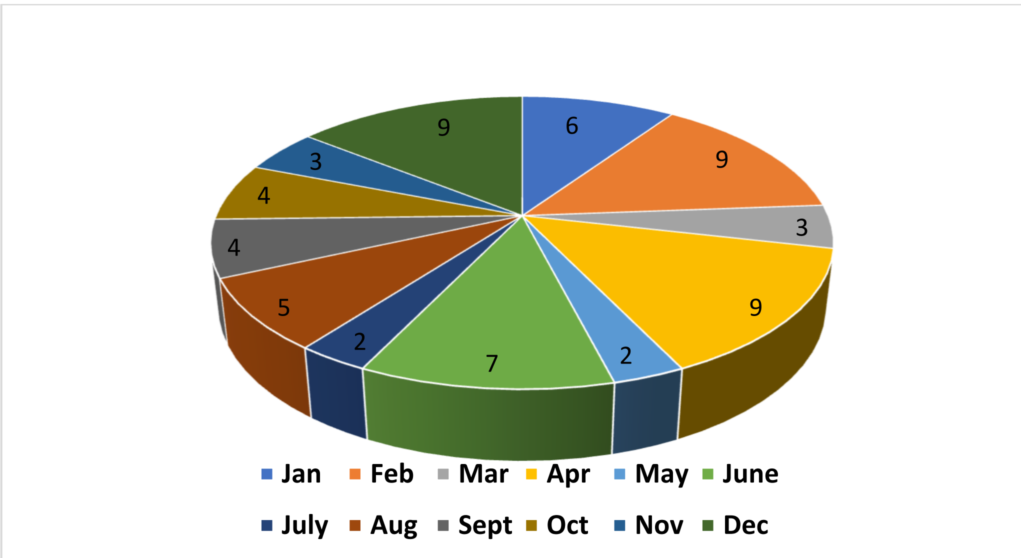

Figure 6. Number of the days with precipitation.

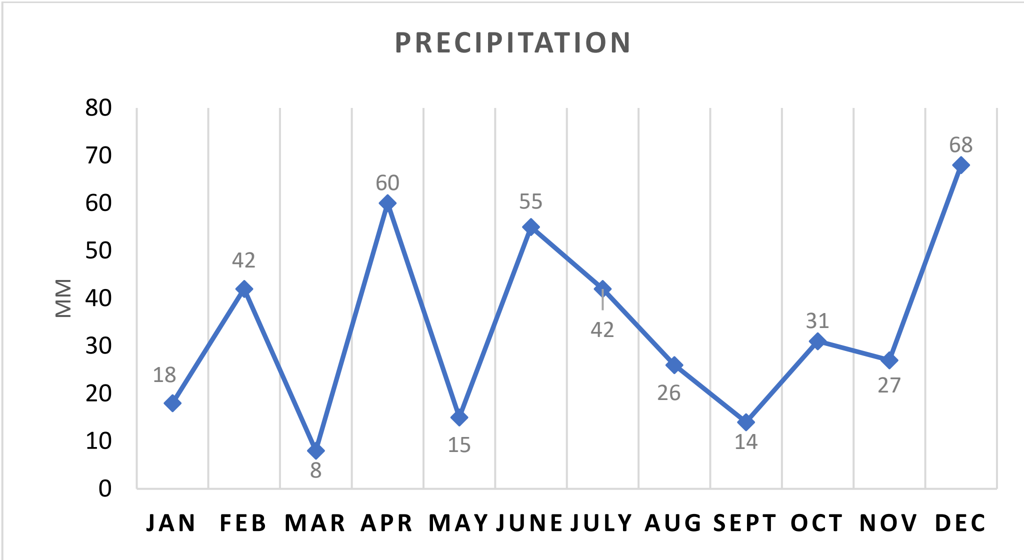

Figure 7. The level of precipitation at the studying area in 2022.

Table 1. Characteristics of the meteorological parameters in the sampling period near Saki Lake in 2022.

Date	Air Temperature, °C			Sunrise Intensity, fc	Humidity, %
	At the Day of Sampling	The Average of the Month (Total/Day)	The Range in the Month (min/max)		
January, 15	**+1.3**	+0.9/+1.1	−9/+12		
February, 19	+6.2	+5.2/+8.3	−4/+3	2044.6	56.9
March, 19	+0.4	+2.6/+6.3	−9/+16	1171.0	59.4
April, 16	+12.2	+11.4/+15.6	+3/+26	4656.1	60.5
May, 17	+16.4	+14.9/+19.0	+5/+30	1356.9	64.5
June, 21	+26.6	+22.1/+28.2	+14/+35	5817.8	49.9
July, 20	+23.2	+21.6/+27.8	+15/+36	5288.1	60.6
August, 16	+26.4	+26.5/+32.5	+18/+37	938.7	68.2
September, 20	+23.6	+19.2/+24.0	+7/+32	4674.7	45.2
October, 18	+15.8	+13.7/+18.4	+3/+26	2193.3	67.6
November	+18.1	+9.3/+13.4	+1/+20	250.9	63.5
December	+7.6	+2.0/+9.5	0/+17	237.5	51.4

As can be seen from Table 1, the average monthly air temperature was increasing progressively during the warm season to reach its maximum in August (+32.5 °C). Generally, the air temperature in the sampling days corresponded with the average values of the month. Since September, it dropped. Air temperature varied significantly during the day and night and each month; in some cases, it ranged from the negative to positive values. There were several days with subzero air temperature in the winter period and in March, and then, the average monthly air temperature became positive throughout 2022.

The highest sunrise intensity was observed in June and July; in other months, it varied less, and the minimum was noted in December. The humidity ranged less also compared with air temperature, and the low values were observed in June and September.

The number of days with precipitation was maximal in February, April and December (9 days) (Figure 6), while in other months of 2022, they were estimated as 3–6, thus demonstrating a tendency toward the formation of sub-arid climate in the region, because the level of the precipitation was very low (Figure 7). The highest value was observed in April and December and the lowest one was determined in September. The total volume of the precipitation at 2022 was estimated as 406 mm, which corresponds with the characteristic feature of sub-arid zones. Additionally, the HCH was 0.75, which characterizes the humidity in dry climate.

3.2. Seasonal Dynamics of Some Hydrochemical Characteristics of Water in Saki Lake in 2022

The highest water temperature was observed in summer months, with the maximum in June (Figure 8), and the lowest one was fixed in March (–0.5 °C). High correlation was found between air temperature and water temperature in the lake (r = 0.93, $p < 0.05$). Water salinity in the lake in 2022 varied from 204% to 273% (Figure 8).

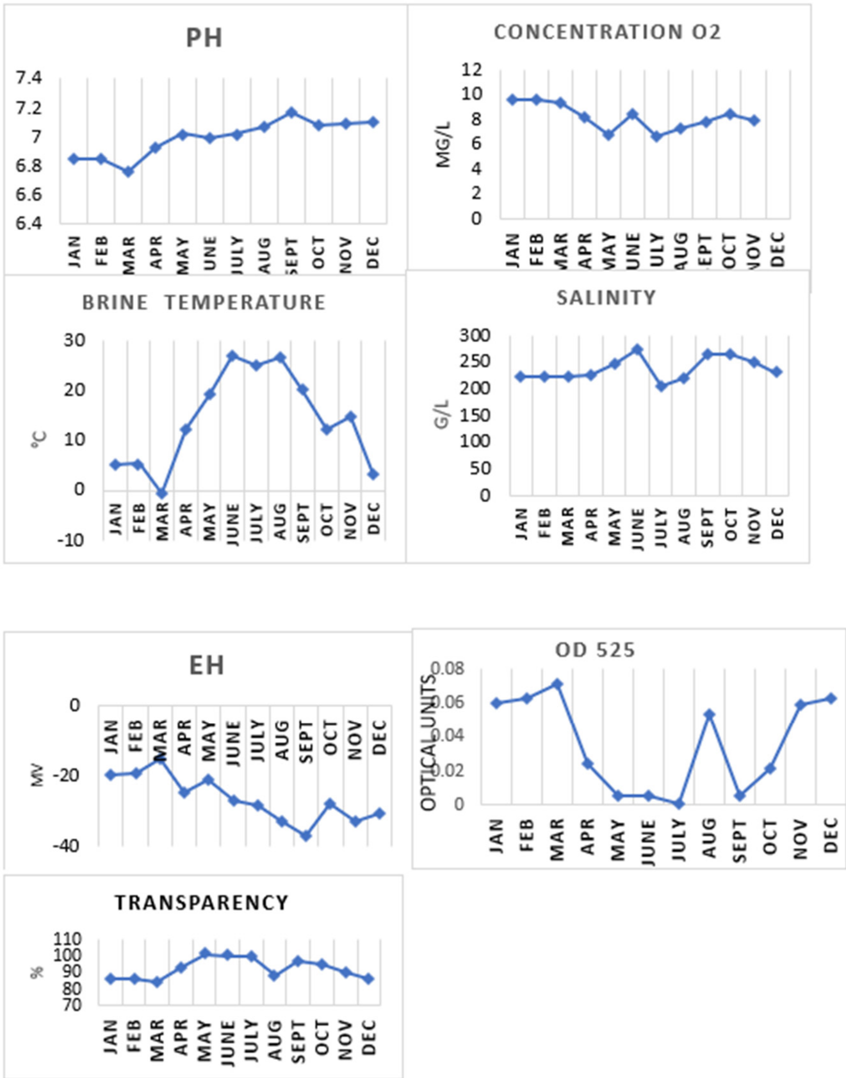

Figure 8. Seasonal dynamics of water physicochemical characteristics.

The oxygen content of the water also ranged from 6.68 mg/L in July to 9.65 mg/L in February. No correlation was observed between salinity and oxygen concentration.

The values of pH and Eh varied to a lesser extent; the least Eh value (–37.1 mV) was recorded in September, and the largest (–15.1 mV) was recorded in March. pH ranged between 6.76 in March and 7.17 in September. High correlation was shown between these parameters (r = 0.89, $p < 0.05$).

The OD_{525} dropped progressively from March to July; then it experienced a peak in August, decreased again in September and elevated in October and November. The values of transparency varied from 100.0% in June to 84.8% in March. The correlation between them was r = 0.95 ($p < 0.01$). Therefore, hydrochemical characteristics in the water varied during the studying period generally related to season.

3.3. Telemetry Measurement Results in 2022

During semi-annual continuous measurements with a period of 1 times per 10 s, a series of data was obtained, reflecting the dynamics of temperature changes in the vertical mud layer up to 3 m as well as on the upper section of 1.8 m at the air–rap interfaces, taking into account the variability of the level due to seasonal and weather fluctuations. A typical three-day pattern of temperature distribution in isolines for the winter period is shown in Figure 9.

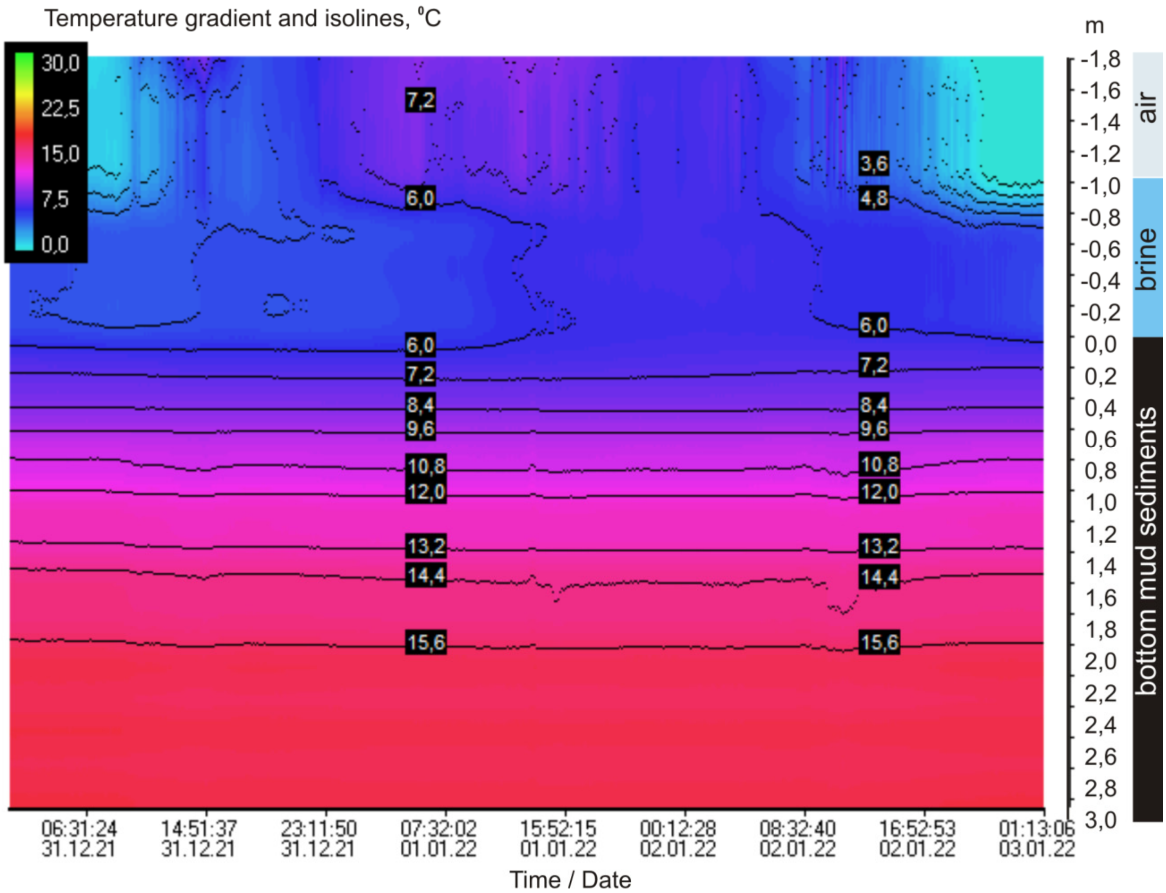

Figure 9. Typical pattern of vertical temperature distribution in isolines for winter period.

The overall picture of seasonal dynamics over 200 days is shown in Figure 10. It is obvious that already at a depth of 1 m, an exceptional thermostatic environment was formed in mud deposits in a year-round temperature variation in the range from 12 to 16 °C. This is a clear sign of the presence of internal continuous chemical processes and indicates the need to study the biological composition of deep mud deposits.

The results of measurements of near-surface carbon dioxide and methane gas emissions showed slight changes in the concentration and fluctuations of the first from 0.03 to 0.09% and the presence of emissions with increasing seasonal symptoms of the second from 0.0002 to 1% (Figures 11 and 12). Methane emission changed seasonally. CO_2 concentration fluctuated less, and both parameters were not correlated with the weather changes.

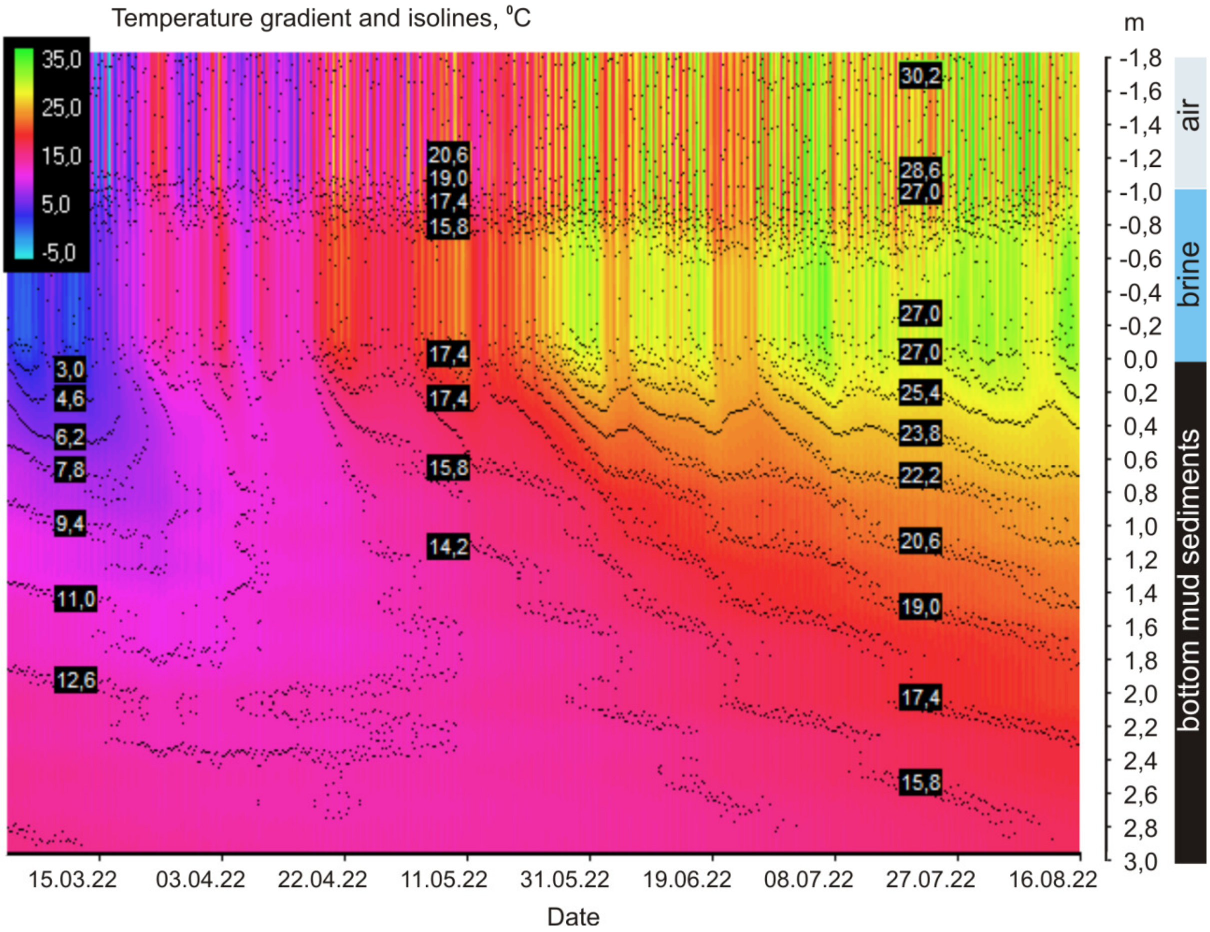

Figure 10. Seasonal dynamics of the measured vertical temperature profile during 200 days.

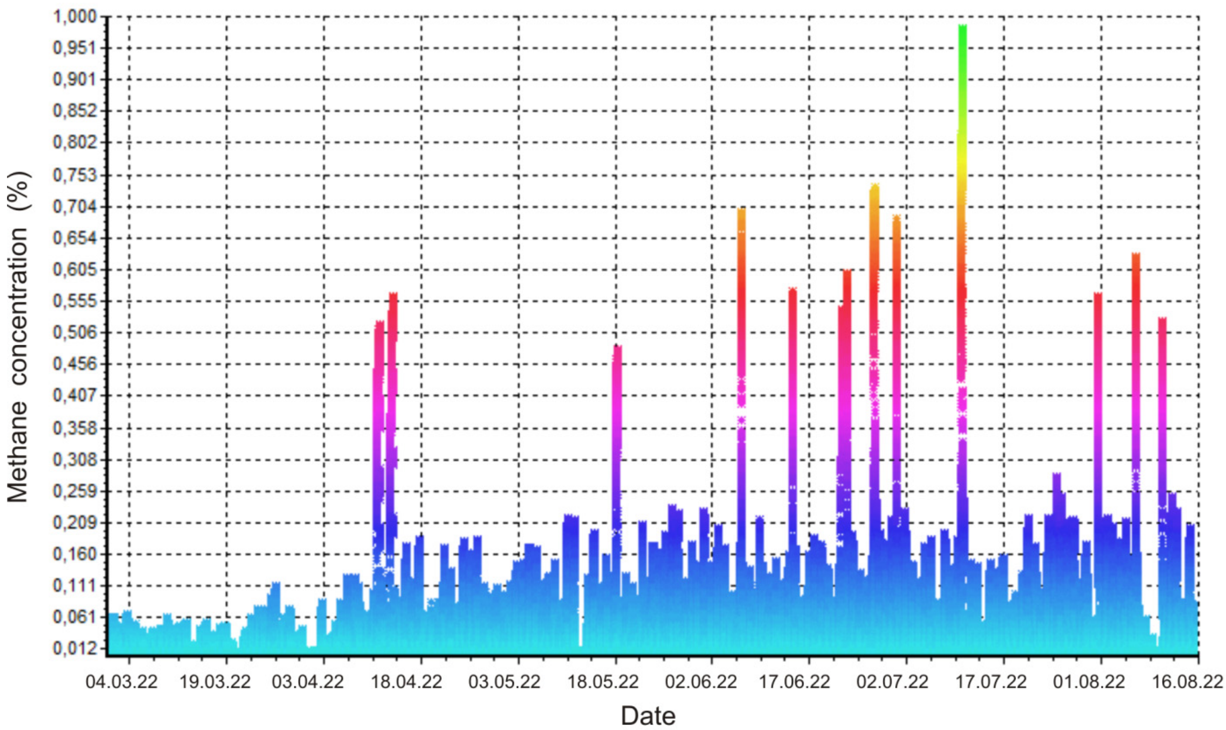

Figure 11. Seasonal dynamics of measured methane (CH_4) concentration in near-surface air.

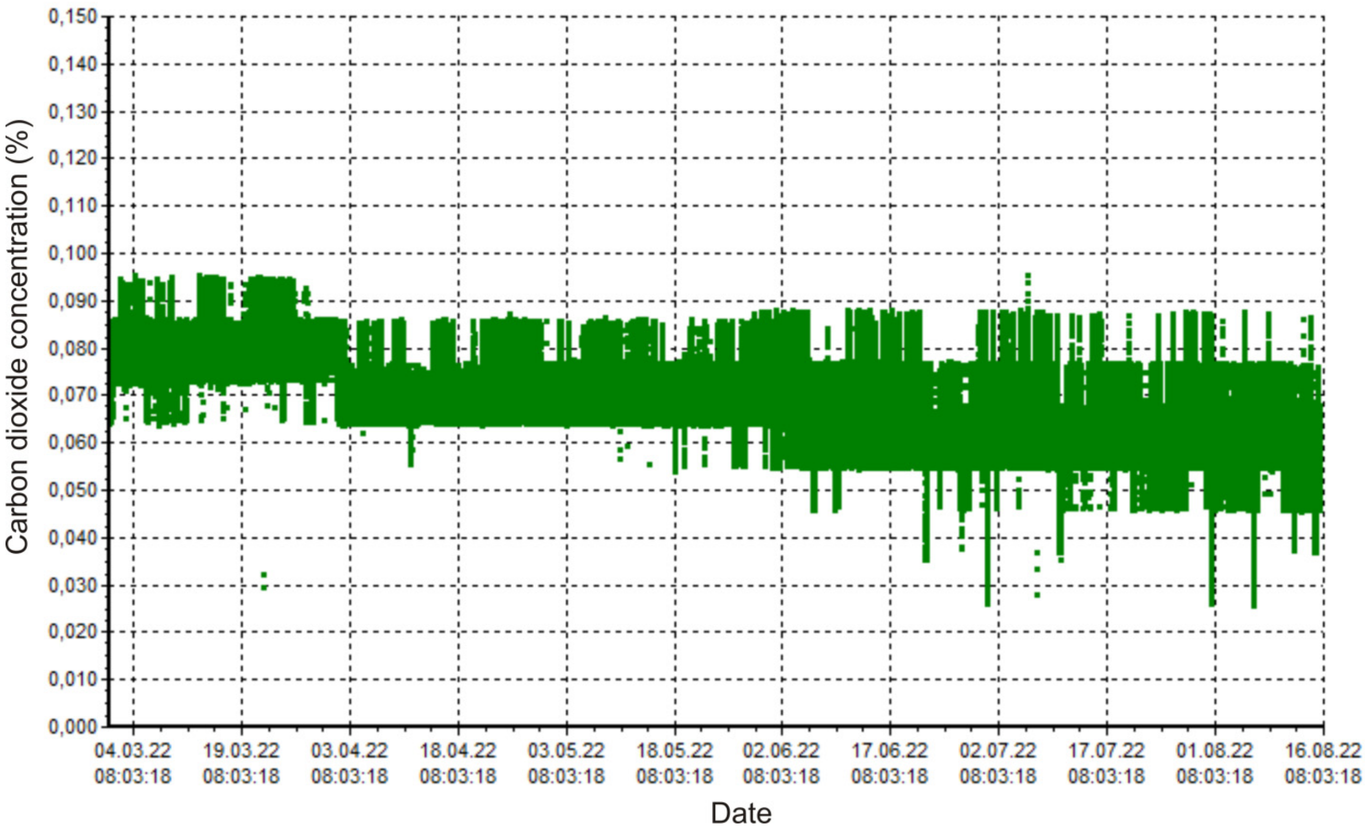

Figure 12. Seasonal dynamics of measured carbon dioxide (CO_2) concentration in near-surface air.

3.4. Seasonal Variations of Brine Shrimp Artemia Population

In January and February, cysts were found in the water in high concentration and in some places of the shore (Table 2). In March, the number of eggs was decreased progressively; however, in April, it was higher as compared with March. The lowest amount of eggs was observed in May, June and July. In September, the number of cysts increased again and then decreased in October and November. The number of nauplia fluctuated less, and they were not found in February, March, June, October, November and December, as well as juveniles, which were shown in May, June and September in low concentrations. The adults (female) were found since June to October at the concentration 1–2 specimen per l. Therefore, in the period from April to September, all ontogenetic stages of the brine shrimp were observed, and cysts were present in large amounts, while nauplia, juveniles and adults were present in small one. Dead crustaceans were found in July and August, and their number increased considerably in September. In October and November, no early developmental stages of brine shrimp were shown in the water, while the inshore was found to contain many dead organisms.

The samples of cysts which were collected on the shore were analyzed to determine the hatching rate of nauplii (Figure 13). The highest hatching rate was indicated in January and August (43.3% and 44.7%, respectively). In February–May, it varied between 18.3 and 22.8%; then, it decreased in the summer months: June and July (13.6% and 10.7%). In August, the parameter elevated 4-folds; then, it progressively dropped in September and October, and in November, it increased again. The obtained data demonstrate the different quality of brine shrimp cysts in different periods of the annual cycle; this should be taken into account when collecting them for aquaculture purposes.

Table 2. Seasonal dynamics of the distribution and abundance of various ontogenetic stages of brine shrimp in the water of Saki Lake (spec./L, given in parentheses are averages ± SD of three to five determinations).

Month	Cysts	Nauplia	Juveniles	Adults (Female)
January	294–5000 (2200 ± 714)	1–7 (4 ± 3)	0	0
February	500–1200 (867 ± 242)	0	0	0
March	45–157 (101 ± 67)	0	0	0
April	480–4000 (1525 ± 1261)	0–40 (20 ± 14)	0	0
May	1–4 (3 ± 2)	2–4 (3 ± 1)	1–3 (2 ± 0.6)	0
June	370–10,400 (5385 ± 193)	0	1 (1 ± 0)	1 (1 ± 0)
July	18–38 (28 ± 12)	1 (1 ± 0)	0	1–2 (2 ± 1)
August	2–40 (21 ± 18)	1–2 (2 ± 1)	0	0–1 (1 ± 0)
September	142–11,000 (5380 ± 3058)	1–20 (7 ± 4)	1 (1 ± 0)	0–2 (1± 0)
October	29–80 (54 ± 15)	0	0	1–2 (2 ± 1)
November	3–29 (13 ± 3)	0	0	0
December	120–460 (243 ± 157)	0	0	0

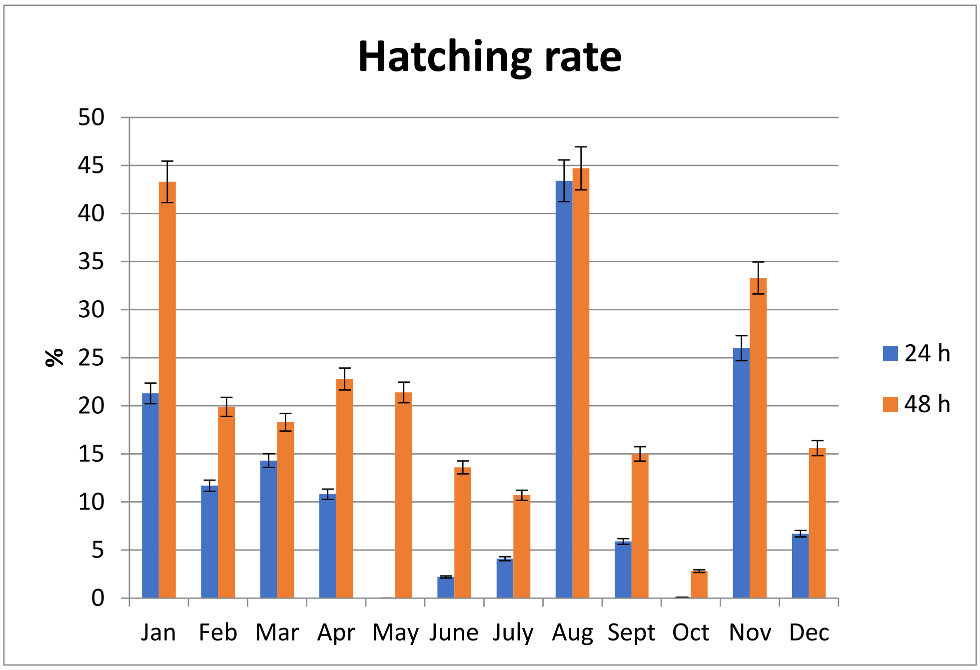

Figure 13. Seasonal dynamics of *Artemia* nauplia hatching rate, % (mean ± SD of three to five determinations).

4. Discussion

Salt lakes are unique and unusual water bodies, because many abiotic and biotic parameters in the ecosystem can be changed due to environmental factors, namely air and water temperature, concentration of oxygen, pH, Eh, and chemical composition, both annually and daily. Climate change accompanied with global warming and unsustainable anthropogenic activities can affect salt lakes ecosystems [32–34] and disturb these water bodies, especially at the case of drying [35–37]. At a global scale, the warming that resulted from climate change influenced primary production, reducing the input of nutrients into surface waters from mixing [38,39]. Therefore, it is able to indirectly impact the physical, chemical and biological processes in the ecosystem and can decline or lose ecosystem services, namely food provision, climate regulation, avifauna support, education and landscape aesthetics [3]. These dramatic consequences are well known for the Aral Sea [40], Lake Urmia [36] and some others [11]. Therefore, to understand the functioning mechanisms of aquatic ecosystems and their adaptation to the extreme conditions in zones with arid and semi-arid climate, the factors that govern the dynamics of water body parameters are important for their protection and the management optimization of their resources exploitation.

Salt lakes on the western coast of the Crimea peninsula are located in a sub-arid climate zone, and their hydromineral regime is very changeable seasonally and daily, because it depends on both climatic and anthropogenic factors. They provide important ecosystem services such as groundwater recharge, nutrient recycling, biodiversity maintenance, and food for birds, because invertebrates such as *Artemia* and *Chironomidae* larvae are favorable diet for them. Many of the migratory shorebirds use Crimean salt lakes for nesting. Salt lakes in the Crimean peninsula play a role in medical purposes because they are rich in balneological resources. They perform important social functions: namely, aesthetic, touristic, educational, visual, and water supply. Considering the fact that Crimean hypersaline lakes are located in the zone of high human activity, the data of the peculiarities of physical, chemical and biological processes in them can have practical applications and can be taken into account in the elaboration of the programs of the optimal management of their resources, either mineral or biological.

To understand the annual cycle, the trends of the ecosystem functioning and the state of its resources, we studied the relationships between the annual and daily dynamics of meteorological characteristics near Saki Lake and the seasonal fluctuations of its hydrochemical and hydrobiological parameters in 2022. Moreover, taking into account that the lake ecosystem takes part in the biogen migration of the carbon, we analyzed daily fluctuations of the temperature in the water column and concentration of carbon gases such as CO_2 and CH_4, which play an important role in climate warming and aquatic ecosystems [41,42].

We found that a progressive rise in air temperature began near Saki Lake in April–May with temperature reaching maximal values in the summer months (>+26 °C), after which the temperature gradually decreased. Generally, the days of sampling demonstrated the similar air temperature as average value in the month. We could note the wide range between the temperature in the day and in night, which in some summer months and in September differed by more than 20 °C. These fluctuations influenced the daily temperature of the lake water. As compared with our previous data [43], the seasonal trends, characterizing the increasing of the temperature in the spring–summer period and decreasing in the autumn, were similar in 2017–2018 and in 2022. The lowest and the highest temperature were recorded in January 2017 (−13.0 °C in January and +39.0 °C in August, correspondingly). The annual precipitation in 2018 was 169.6 mm, which was less compared with the data in 2017 and in 2022. The precipitation was completely absent only in October 2017, while the dry months in 2018 were May, July, and September. In 2022, we did not have complete dry months at the area near Saki Lake.

The sunrise intensity fluctuated independently; however, the highest values were shown in June and July, in clear weather. The humidity varied lower between 45.2% and 68.6%, and the data were independent of season. The number of days with precipitation depended on the season: the lowest value of precipitation was in May and July (2 days), while 3–7 days per month were in other months with the exception of February, April and December, where they were estimated as 9 days. This situation correlated with the HCH = 0.75 and the total level of precipitation (415 mm in the year), which corresponds with the meteorological parameters of the sub-arid areas [3,44].

Saki Lake belongs to the group of coastal marine lakes; therefore, the fluctuations in the meteorological parameters influence significantly on its hydrochemical characteristics. The temperature of brine in the lake in 2022 progressively increased in the spring, reaching maximum values in June–August (exceeding +25 °C). It was lower compared with the data of 2017–2018 [43]. In autumn and winter, the temperature of brine decreased, and the values were the similar to those in 2017–2018. The wind is another important hydrometeorological factor affecting the state of the brine and biota, because it promotes the mixing of the waters and their vertical stratification, the overflow of marine water through the sand barrier into the lake [45].

Additionally, the hydrometeorological situation in the lake area has also significantly affected the hydrochemical parameters of its water. In winter and spring, the salinity range varied insignificantly as 223–226%, increasing up to 248–273% in May–June and then dropping to 204%. The decrease in the water salinity in the Eastern basin of Saki Lake in June and July may be due to both atmospheric precipitation and flood. The seasonal dependence of salinity fluctuations on precipitation was also observed in other hypersaline lakes [46,47]. The interannual fluctuations of the brine salinity of the Saki Lake was shown in 2017 and 2018 [43], when the precipitation was higher in 2018 than in 2017, which influenced the lake salinity. On the other hand, salinity in the tested water body in 2022 was greater compared with the previous years, and we could note the clear trend of salination of the lake. There is a strong evaporation of water, which causes the decrease in water level. This is the common tendency, which was noted for many salt lakes all over the world: namely, Urmia Lake, Owens Lake, Aral Sea, and the Great Salt Lake in Utah, which have been decreasing, breaking the balance, and resulting in the reduction in each lake's water level [2,11,36,37]. However, there is no correlation between water temperature and salinity. The explanations of this can be connected with the fact that the lake is fed by ground waters, which maintains the salinity at a certain level and feeds the water body even at a critically high temperature, preventing it from fully drying up. The next reason is accompanied with the entering of the marine water through the artificial channel (see Figure 3) for regulating the salinity level in the Eastern basin of Saki Lake.

One of the most important elements in aquatic ecosystems is oxygen, because it is necessary for biota, it takes part in many chemical reactions through oxidation, and reflects a health of aquatic ecosystems [32]. The oxygen content in the brine also depended on seasonal changes, when it decreased from March to May. In June, the oxygen concentration increased again, which was connected with the precipitation and mixing of the water layers; then, it decreased in July and progressively increased in autumn months. However, the range of variability was very pronounced in 2017–2018 [43] as compared with 2022. Hypersaline water bodies are characterized by vertical salinity and oxygen-concentration gradients [48], and the decrease in O_2 concentration in low water layers can provoke anoxia and hypoxia. Therefore, a sharp decrease in the oxygen content in May both in 2022 and 2017–2018 may be associated with a decrease in the precipitation and low level of water mixing as well as with the formation of stagnant water zones, where the processes of decomposition of organic matter (dead organisms, microalgae, terrestrial plants, and etc.) are actively occurring, which requires a large amount of oxygen. The oxygen concentration in hot months was significantly lower than that in cold seasons, because the eutrophication processes develop in the water body in the hottest summer months (June–August), after which its concentration increased appreciably. Additionally, it was found that the dissolved oxygen in the lake depends on the total dissolved solids and therefore, 90–73% of the variance in dissolved O_2 can be expressed by total dissolved solids [32].

Water pH and Eh are also important characteristics of the ecological state of aquatic ecosystems, because they can significantly affect the vital processes in the lake and determine the living conditions for biota. The value of photosynthesis, respiration, and redox processes in the aquatic ecosystem depend on Eh [49]. Eh is determined on the complex of all oxidation and reduction reactions taking place in the water ecosystems. Water salinity, Eh and pH in hypersaline lakes vary widely within days and within seasons, and they are determined by either the concentrations of individual ions or the dominating buffer systems. The proportions of ions composition can vary in the course of evaporation, resulting in a shift in pH [50–52]. Water steadily decreased in 2022 from –19.4 mV in January to –37.5 mV in September, after which it again increased. A stable decrease in pH in January–March and then progressive increase in the summer–autumn season was consistent with a decrease in the redox potential during the same period. Since the value of pH varied within a day, the value of Eh also varied, depending on temperature as well. In this study, pH and Eh correlated (r = 0.89, $p < 0.05$). The main reason of this can be connected with the rapid phytoplankton development in lake water, and in the latter case, it is caused by an increase in the amount of organic matter, because of the death of the brine shrimp and the cessation of microalgae vegetation, which is in agreement with the data on the population dynamics of the crustacean. Therefore, there was an increased destruction of organic substances, which accumulated during this season due to dead organisms, microalgae, plants, etc.; we noted such a tendency in our previous study in the Eastern basin of Saki Lake in 2017–2018 [43].

We found a high correlation (r = 0.95, $p < 0.01$) between OD_{525} and the transparency of the water. The greatest OD_{525} was shown in March; then, the values were progressively dropped to the minimum in July, increased in August and decreased in the autumn period again. These dynamics were attributed to the high concentration of organic matter, which in spring and summer months is utilized by microalgae and *Artemia.* However, upon increasing the temperature to extreme levels in July and August, which is not suitable for *Artemia* and microalgae, they died, and the concentration of the organic matter elevated. In addition, human activities in coastal areas and water bodies have greatly impacted the sources and biogeochemical behaviors of organic matter, including particulate and dissolved ones. The changes of the organic matter flux influence the physical, chemical, and biological processes in the lake, including their optical properties [53]. Therefore, the parameters of OD_{525} and transparency are correlated each with other, with the biota state and organic matter fluxes. Additionally, optical properties of the brine are an effective tool for studying the source and dynamics of the organic matter in salt lakes in the year cycle.

Hydrogen sulfide, CO_2, and CH_4 are formed on the bottom due to the processes of the decay and subsequent mineralization of microalgae, aquatic invertebrates and plants residues, including those brought from land [32], and it requires monitoring these gases in salt lakes statistically. Therefore, it is an important problem to create and develop the methods for real-time monitoring of water quality. Monitoring systems which allow evaluating water quality in lakes in real time are required [23,54,55]. In addition, these monitoring systems in salt lakes can obtain information of the peculiarities of peloids formation and the factors that influence on these processes, as well as the carbon storage potential above and below bottom, dead organisms, microbial activity, sources and fluctuations of organic matter fluxes.

It is obvious that already at a depth of 1 m, an exceptional thermostatic environment was formed in mud deposits in a year-round temperature variation in the range from 12° to 16 °C. This is a clear sign of the presence of internal continuous chemical processes and indicates the need to study the biological composition of deep mud deposits. We can propose that the fluctuations of the temperature depended on the microbial communities activity, which was agreed with the data of the other authors [20,56,57], who postulated the seasonal changes in microbial activity and organic matter concentration in the various water bodies.

The initial analysis showed that methane and carbon dioxide emission activity increased seasonally against the summer period, and there was no association with current short-term weather conditions (temperature, illumination, precipitation and winds velocity). We could propose that these dynamics were accompanied with the fluctuations of production and degradation of organic matter both due to chemical reactions and microbial processes [58]. Taking into account that the inventories of organic matter are the most important organic carbon pools in the ocean, which play a crucial role in the global carbon cycle, thereby affecting climate change [59,60], it is interesting to know the role of coastal waters, including bays, estuaries and coastal salt lakes in this process. In addition, it is well known that inland waters are significant sites of global carbon cycling on the planet, because they emit high quantities of the greenhouse gases, especially carbon dioxide (CO_2) and methane (CH_4), to the atmosphere [61]. Therefore, to determine the possible localization or distribution of methane and carbon dioxide concentration on the surface of the estuary, additional studies are needed with the installation of a spatially distributed grid of stations.

Therefore, the obtained results have shown the common tendencies of seasonal fluctuation in salt lake ecosystem function. The researchers from various geographical regions also demonstrated the interannual and seasonal fluctuations of salt water bodies and their influence on both natural and anthropogenic factors. It was shown that salt lakes in specific environment of the Tibetan Plateau are more inclined to geological factors. The geological process is manifested by a series of extensional faults at the bottom of the lake basin generated from tectonic activities, providing fluid infiltration channels and inducing the eventual leakage of lake water to the lower strata [62]. A seasonal variability of organic matter was observed regarding distributions of microphytoplankton and photosynthetic pigments as well as oxygen and salinity changes along the depth profile in Rogonoiza Salt lake (Croatia). The dissolved oxygen saturation reached up to 300% in May and June, which was correlated with enhanced concentrations of phytoplankton biomass (reflected as chl a and b, fucoxanthin, peridinin, zeaxanthin) and increased concentrations of organic matter [63], which agree with our data. The researchers demonstrated that the total area of the four lakes in China had increased by 18% in the past 30 years due to climate change, using the meteorological data from 28 meteorological stations in the basin. They noted the fluctuations of lake annual evaporation level: it slightly increased from 1989 to 1995, which was followed by a sharp decrease from 1995 to 2018. From 1989 to 2018, the annual evaporation in the basin ranged between 615.37 and 921.66 mm, with a mean of 769.73 mm. The increase in precipitation and the decrease in the annual lake evaporation promote the expansion of the four lakes, and they postulated that lake evaporation is the main factor inducing changes in the lake areas [64]. For the analysis of drought spells of Urmia lake, the authors used mean monthly temperature and precipitation data for analysis for the period 1964–2005, and they found how fluctuations in the lake level are attributable to natural drought. The results indicated that mean precipitation has decreased by 9.2%, and the average maximum temperature has increased by 0.8 °C over these four decades. The seasonal changes are particularly visible in winter and spring [65], which also agree with our data. The seasonal abundance of 78 other aquatic species was investigated in Turkey, and it was observed that spring and fall seasonal eutrophication, as a consequence of canal construction and suspected warming due to climate change, has caused changes in Chlorophyll-a, dissolved oxygen, biological oxygen demand levels and the grazing habits of aquatic species [66]. Therefore, the comparative study of the seasonal and interannual fluctuations of various salt lakes all over the world demonstrated the similar mechanisms of the influence of both the warming climate and anthropogenic impact on the lake's chemical regimes [67].

At present, the influence of climate change is having short and long-term impacts on surface and groundwater all over the world, resulting in the range of their salinity in different parts of the geographical regions. For instance, a geochemical analysis of water resources in several areas of Africa showed the differences between the northern part, which was characterized by low mineralized groundwater (salinity ranging 0.4–3 g/L) and the southern area where the salinity ranges from 2.5 to 90 g/L. [68,69]. The researchers demonstrated a multitude of immediate and long-term climate changes impacts on water resources in Arab countries, such as flooding, drought, sea-level rise in estuaries, drying up of rivers, poor water quality in surface and groundwater systems, precipitation and water vapor pattern distortions, and snow and land ice bad distribution. These events and their combination have devastating impacts on aquatic ecosystems and organisms, ranging from economic and social impacts to health and food insecurity, all of which threaten the existence of many regions in Arab countries [70]. Because the salinity hazard of water bodies and agricultural land especially in semi-arid and arid regions remains one of the most serious environmental problems, further studies of it are required using the new methods of monitoring [71].

The biota of salt lakes, in spite of its poor biodiversity, have an active part in the transformation of organic matter in the ecosystem. Branchiopod *Artemia* sp., benthic larvae of *Chironomidae* mosquitoes, halophilic microorganisms, namely microalgae diatoms, and halobacteria form a powerful consortium on the bottom, which takes part in the biogenic transformation of organic matter and minerals. The community structure, the abundance and the functioning of these organisms determine the balance of production/destruction processes of organic matter and biotransformation elements in the ecosystem. The filter-feeding brine shrimp *Artemia* is the dominant species in hypersaline lakes. The changes in its population reflect the dynamics of processes in the ecosystem together with the hydrometeorological factors [72]. Therefore, studying the seasonal fluctuations of the number and composition of *Artemia* population in salt lakes is of importance for understanding ecosystem health, functioning, in particular, under environmental changes, climate warming and anthropogenic impact. Changes in the lake conditions influenced the dynamics of *Artemia* population, which significantly varied during the year. Other authors have postulated that interannual natural fluctuations in the population of crustaceans depend on the water mineral composition of the lake [28], climate changes and other physical and chemical conditions [73].

Seasonal fluctuations in the water are the main factors impacting the life cycle of *Artemia* in Saki Lake. The dominant factor is brine temperature, depending on the season, which determines the abundance dynamics of different life stages of brine shrimp. The first nauplii appeared in February–March, when the brine temperature was approaching +6 °C. The most intensive development of the brine shrimp population, including all life stages, was shown in May—September, when the water in the lake was estimated as +18° ... +28 °C. At this period, in the ecosystem, favorable feeding conditions were formed for *Artemia* as a result of the intensive development of phytoplankton and the high concentration of suspended and dissolved organic matter. In Saki Lake, *Artemia* produces from two to four generations per year. However, changes in the ionic composition of brine, accompanied by an increase in mineralization up to 200 g/L and higher, may also be limiting factors for its reproduction and further development. A decrease in oxygen concentration, the resulting eutrophication, and the formation of the hypoxic and even anoxic zones in the lake contribute to the death of brine shrimp. In hot summer months and at the beginning of the autumn, when the air and water temperature is very high, we observed a large number of dead organisms at different life stages in the shore of the water body as a result of this unfavorable situation in the lake. However, before the death, *Artemia* produces cysts, whose number increases significantly during this period both in the water column and along the shores of the lake. The cyst deposits along the shore depend on the movement of the wind, its velocity and speed.

The hatching rate of cysts, which were collected along the shores, may vary significantly in different seasons and years. Our data demonstrated that the hatching rate was higher for cysts collected in January 2022; however, it decreased gradually in late spring and summer until July. In August, the hatching rate increased, and in autumn, this parameter dropped and then elevated in November again. A decrease in the water salinity in spring caused snow melting and precipitation, which leads to the irreversible hydration of cysts and stimulates embryogenesis, but the subsequent development of larvae is impossible at unfavorable conditions, namely low temperatures and lack of sufficient food supply [74–76]. This is the main reason for the sharp decrease in the hatching rate of cysts collected in February–July. Further development of nauplii hatched from such cysts occurred when a sufficient fodder base and the favorable hydrochemical conditions (oxygen content, pH, temperature, and salinity) were formed [31,43]. These conditions were settled in the ecosystem of the Eastern basin of Saki Lake in the autumn of 2022, and we observed all living stages of *Artemia*. These data may be useful for optimizing the period of commercial collection of *Artemia* cysts in Saki Lake for aquaculture purposes.

Therefore, in our study, we evidenced that the increase in air temperature in summer, low level or complete absence of precipitation and strong evaporation are the most important factors which determine the ecological state and health of Saki Lake. Climate and weather changes lead to an increase in water temperature, salinity, a decrease in its oxygen content, and a change in water pH, Eh, optical density, transparency, and CO_2 and CH_4 production. The combination of these parameters influences biota functioning as well as physical and chemical processes in the lake, which should be taken into account in the case of artificial regulation of the hydromineral regime of the lake ecosystem. Therefore, the obtained results demonstrated the dynamics of changes in the ecological status of the hypersaline Saki Lake, which reflect the ecosystem transformation under fluctuations of climatic conditions and possibilities of its restoration to normal functioning under sustainable management.

5. Conclusions

The present study shows clear seasonal fluctuations of the ecological situation of hypersaline Saki Lake, which resulted in changes in the hydrochemical and hydrobiological characteristics of the water. During the hot period, the decrease in the water level caused strong evaporation and increased salinity to more than 200 g/L: the living conditions for biota and peloids formation are not favorable. In this case, the natural processes of microbial activity, destruction of organic matter, biogenic migration and transformation of minerals and nutrients, production of carbon gases CO_2 and CH_4, carbon utilization and deposit in the peloids are disturbed. The reproduction and development of the main component of biota filter-feeding crustacean *Artemia* is stopped, and the majority of brine shrimps are dead. All these processes have a negative influence on the functioning of the ecosystem, and in this extreme situation, it cannot perform its functions, including the ecosystem services for human activity. Therefore, it is necessary to maintain the lake's mineralization of about 150 g/L in order to prevent inhibition of the *Artemia* populations and the consortium of other aquatic organisms and peloids formation. For this purpose, the special hydrotechnical system (FPHTS) is successfully used in Saki Lake, which regulates the hydrochemical and hydrological regime of Saki Lake and prevents its ecosystem and especially biota against the influence of extreme natural factors. Thus, the artificial regulation of the hydromineral balance of the Eastern basin of Saki Lake, bearing in mind the effect of meteorological factors, provides favorable living conditions for biota, including *Artemia* population. This is a good example of the positive effect of anthropogenic activity for the protection of the salt water body against extreme natural climatic impact, especially in arid and sub-arid areas.

The results obtained in this study may be helpful for developing the further optimization of Saki Lake and its resources management as well as other saline lakes. However, to understand the processes in Saki Lake and improve the management of its resources, the following data are required:

- To obtain continuous time series for the water quality parameters (historical data), inflows, outflows, ground waters, and meteorological parameters during the long time period in order to develop a water quality model;
- To provide a statistically proven and robust technique capable of selecting the environmental variables that most impact greenhouse gases in salt lakes;
- To receive information on the variability of salt concentrations with different kinds of ions, which are changed annually, seasonally and even daily. For this purpose, the monitoring systems in real time are required.

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