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Chapter Title	How Climate Change and Human Interaction Alter Chemical Regime in Salt Lakes, Case Study: Lake Urmia, Aral Sea, the Dead Sea, and Lake Issyk-Kul
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Abstract	The components of the major chemical composition of waters of hypersaline lakes: Lake Urmia, the Aral Sea, the Dead Sea, and brackish Issyk Kul Lake are discussed concerning the recent decade changes. A comparative analysis of the investigated basins allowed to demonstrate a mechanism of the influence of both the warming climate and anthropogenic impact on the lake's chemical regimes.

Keywords (separated by '-')	Hydrochemistry - Hypersaline lake - Lake Urmia - Modelling - Sediment chemistry

How Climate Change and Human Interaction Alter Chemical Regime in Salt Lakes, Case Study: Lake Urmia, Aral Sea, the Dead Sea, and Lake Issyk-Kul

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Lake Urmia: A Hypersaline Waterbody in a Drying Climate,
Hdb Env Chem, DOI 10.1007/698_2021_811,

Abstract The components of the major chemical composition of waters of hypersaline lakes: Lake Urmia, the Aral Sea, the Dead Sea, and brackish Issyk Kul Lake are discussed concerning the recent decade changes. A comparative analysis of the investigated basins allowed to demonstrate a mechanism of the influence of both the warming climate and anthropogenic impact on the lake's chemical regimes.

Keywords Hydrochemistry, Hypersaline lake, Lake Urmia, Modelling, Sediment chemistry

Abbreviation

OM Organic matter

1 Introduction

An impact of global warming on continental drying results in falling water levels in enclosed seas and lake systems [1]. Climate change led to rapidly warming lakes around the world, threatening freshwater supplies and ecosystems. A study by O'Reilly et al. [2] using more than 25 years of satellite temperature data and ground measurements of 235 lakes found that lakes are warming an average of 0.34° each decade. This warming rate is greater than the warming rate of either oceans or the atmosphere, which in turn impacts local climates profoundly. In northern climates, lakes are losing their ice cover earlier in the spring. In tropical lakes, warming might have significant negative impacts on the ecosystem [2]. Endorheic lakes that do not have an outflow are particularly sensitive to climatic change since their volumes depend on a delicate balance between input water and evaporation [1]. Drastic volume decrease will lead to an increase in the content of salts, change of chemical compositions, formation of anoxia and hypersaline condition, and finally, disappearing those lakes. The most favorable conditions for the formation of salt lakes are niches in mountain ranges or high mountains, where there is no outflow, or it is strictly limited and there is a negative balance between evaporation and tributary. However, the inflow must be sufficient to maintain a relatively constant reservoir.

In this study, we will have a closer look at Eurasian salt lakes, i.e., Lake Urmia, Lake Issyk-Kul, the Aral Sea, and the Dead Sea (Fig. 1), which all are enclosed lakes

Fig. 1 Sampling area: The Issyk-Kul Lake, Aral Sea, Urmia Lake, and Dead Sea (http://mapas.owje.com/590_mapa-politico-del-suroeste-asiatico-2000.html) AU2

in an arid climate, and have different ion compositions compared with the oceanic ones. Except for Lake Issyk-Kul, all have a negative water balance and high salinity, which leads to massive brine release and minerals precipitation. This work aims to analyze the recent inter-annual changes of these lakes with specific emphasis on Lake Urmia. Here, we present the results of our research and literature data separately for each lake to trace the historical evolution of the salt composition of hypersaline Aral and Dead Seas, Lake Urmia, and the slightly salted Issyk-Kul Lake.

2 Data, Methods, and Equipment

The datasets for this work were received during field expeditions to Lake Urmia, the Lake Issyk-Kul, the Aral Sea, and the Dead Sea performed in 2013–2019. The collected samples of Lake Urmia, Lake Issyk-Kul, the Aral Sea, and the Dead Sea waters were analyzed at Shirshov Institute of Oceanology, and samples of Lake Urmia analyzed in Asarab Consulting Engineers Company. A detailed description of the methods is given in other chapters of this book [3]. We also used the published and achieved data for the interannual variability analyses.

3 Setting of Lake Urmia, Lake Issyk-Kul, the Aral Sea, and the Dead Sea

Figure 1 shows the location of the studied water bodies: Lake Urmia, Lake Issyk-Kul, the Aral Sea, and the Dead Sea. Lake Urmia is in Iran, the Dead Sea is in Israel, Lake Issyk-Kul is in Kyrgyzstan, and the Aral Sea is divided by Kazakhstan and Uzbekistan.

3.1 Lake Urmia

Lake Urmia is a shallow enclosed hypersaline lake located in the north-western part of Iran. It is known as one of the largest continental salt lakes in the world. Lake Urmia is an endorheic basin that retains water and does not allow any outflow. The primary water sources are precipitation and freshwater discharge from several rivers and springs and the principal water loss in Lake Urmia is evaporation. Recently, the surface area and volume of the lake have been shrinking significantly (Fig. 2). It has been shown that an increase in evaporation and decrease in rainfall and fluvial inflow have led to salinization and water level decline [4–8]. In the worst case, if Lake Urmia dries out, a vast salt desert will form, which is an undeniable threat to the local ecosystem and will trigger a chain of drastic alterations in the regional ecosystem, resulting in an ecological, agricultural, and social catastrophe, not only in the Azerbaijan of Iran but also in neighboring countries such as Turkey, Azerbaijan, Armenia, Georgia, and northern part of Iraq. It will force many people to abandon their villages and towns around the lake and a vast majority of the flora and fauna will be lost permanently [9].

Fluctuations in the lake level are usually controlled by the flow of surface and groundwater, which recently practically does not reach the lake. Due to the periodic

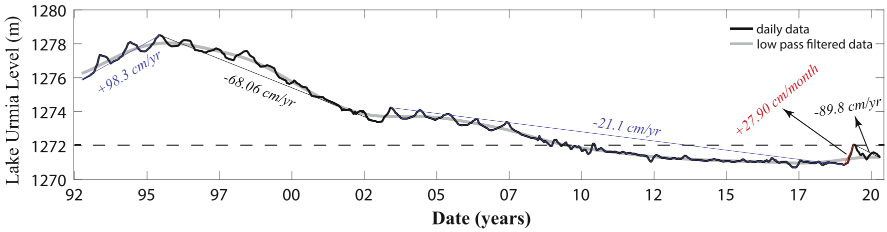

Fig. 2 Lake Urmia level variation. Modified from [4]

shallowing and filling of the lake, its salt composition is constantly changing. Before the lake level began to drop rapidly (1995, see Fig. 2), the brine of Lake Urmia was classified as Na–K–Cl–Mg–SO_4. In 2010, the ionic signature of Urmia brine was shifted to Na–K–SO_4–Mg–Cl, and the total salinity at least doubled [10].

3.2 Aral Sea

The Aral Sea was one of the largest lakes on Earth and was an oasis in the middle of the desert that was fed by two large rivers, Amu-Darya and Syr-Darya. Due to the combined effect of climate change and the massive irrigation projects, the river flows into the Aral Sea decreased from more than 50 km^3 per year to only a few cubic kilometers per year in the 1980s. In 1989, the sea surface sank to a level of about 38 m [11], and for the first time, the lake split into two separate water bodies – the Small Aral in the north and the Large Aral in the south (Fig. 3). In 2003, the Large Aral Sea also split into two basins – the eastern and western [12–14]. By 2004, this lake has lost 75% of its surface and about 90% of its water [13], according to [15] – 87.85% by 2018. To date, it has fallen by 56 m (Fig. 4). The consequences of the drying up of the Aral Sea were climate change in the region with an increase in continentality, a decline in the economy, fishing, a catastrophic decline in the biodiversity of the natural ecosystems of the sea itself, and sections of the river deltas.

The area decrease of the Aral Sea has led to the formation of desert around the reservoir playa. The area of Central Asia playa is about 60,000 km^2, in which the

Fig. 3 Map showing the remaining water bodies of the Aral Sea

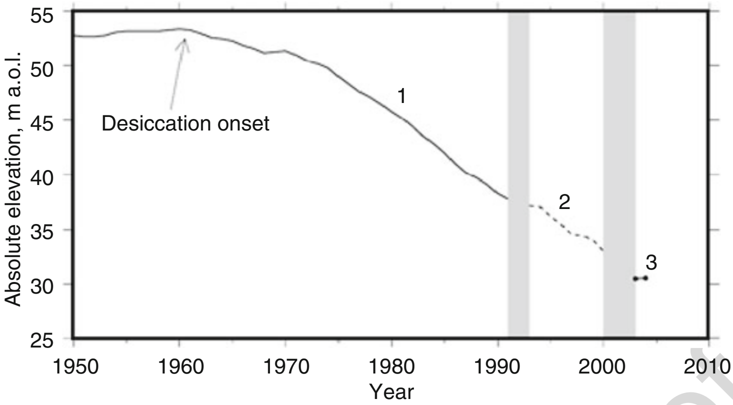

Fig. 4 Long-term changes of the Aral Sea surface level (meters above ocean level): (1) historical data after [16]; (2) TOPEX/Poseidon satellite altimetry reconstruction (http://www-aviso.els.fr); (3) direct geodesic measurements in the surveys of 2002–2004 [14]. Gray shading indicates gaps in the data [13]

area of the playa of the Aral Sea share exceeds half of that. They contribute to the emergence and intensification of dust and salt storms, which negatively affect the ecology and health of the population of the region [11, 17–20]. The scale of dust collection of the dried bottom of the Aral Sea is estimated by different authors from 15 to 75 million tons per year or more [21]. The residual lakes capture dust particles to some extent and mitigate the negative impact of dust storms on the environment [22].

3.3 Dead Sea

The Dead Sea is a deep terminal lake (length: ~80 km, width: ~17 km, depth: <300 m) located about 416 m below the World Ocean level, which makes the lake the lowest land spot on Earth [23]. Only Jordan river and groundwater flow into the Dead Sea. The river inflow decreased from 1.5 $km^3 year^{-1}$ in the 1950s to almost 0.15 $km^3 year^{-1}$ in 2000. The lake used to consist of two basins. The large-deep northern and the small-shallow southern parts were separated by a peninsula and connected through a narrow strait. The southern basin dried completely by 1977, except for the areas occupied by the evaporation ponds [24]. Mainly due to river runoff, there was stable stratification in the Dead Sea, with salinity increasing from about 300 g/l in the upper layer (about 40 m) to about 332 g L^{-1} at the bottom [25]. Consequently, the lower layer was anoxic and sulfide-containing [23]. Following an increase in anthropogenic drainage of river water and progress in drying, vertical density stratification eventually weakened, leading to a major overturning event in 1979 [26, 27]. Today condition of the sea is well-mixed. Since the middle of

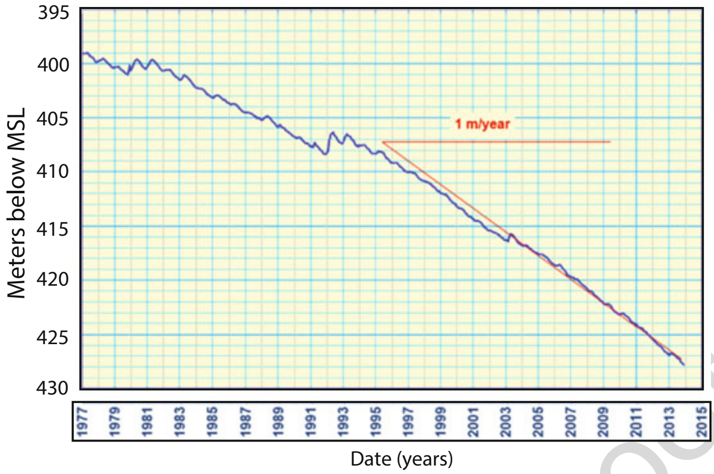

Fig. 5 Inter-annual changes of the Dead Sea level

the twentieth century, the surface level of the Dead Sea has dropped about 21 m (Fig. 5). On average its level has decreased by 1 m per year. It is expected that the rate of volume reduction due to evaporation in the future will decrease due to an increase in the concentration of ions in the water [28]. Model predictions suggest that the Dead Sea level will continue to fall until equilibrium is reached [29]. Due to the expected decrease in evaporation following an increase in salinity during progressive desiccation and the high hygroscopicity of the Dead Sea's solutes, the lake will never dry out completely, even if the river tributary is set to zero [30]. A significant factor in lowering the level of the lake is currently the industrial extraction of mineral salts. Its impact on the overall decline in the annual level is estimated at 30–40 cm. These industries consume 0.2–0.3 km^3 of the Dead Sea volume per year, diverting a significant amount of water to the evaporation ponds and returning only part of the water to the saltier final brine [23]. Here halite completely precipitates, and the brine reaches such saturation when carnallite ($KMgCl3 \cdot 6\ (H_2O)$) is used to produce potash.

3.4 *Lake Issyk Kul*

Issyk-Kul is a closed lake in the Northern Tien Shan in the northeastern part of Kyrgyzstan, one of the largest mountain lakes in the world. It is located at an altitude of 1,608 m above sea level. Glaciers are the source of many rivers in the Issyk-Kul basin and play an important role in the formation of the chemical composition of its waters [31]. A feature of the lake is the amazing homogeneity of water both in the water area and in-depth, as evidenced by the relative constancy of density, salinity, and chemical composition over more than 100 years. This was noted by early research and is being observed in modern times. The first results of hydrochemical analysis of lake waters were obtained by V.P. Matveev in 1928. It is known that the salinity of the lake at that time was 5.823 g kg^{-1}. Even then, the lake had a relative constancy of the salt composition.

4 Results

4.1 Lake Urmia Salt Composition Changes

Based on collected in 2014–2017 as well as previously published data [32, 33] we analyzed the temporal variability of the chemical composition of Lake Urmia. We merged these data into a database that contains averaged values and ranges of the variability of parameters across the lake with a monthly resolution in time. Referring to studies by [32], Lake Urmia is geochemically highly uniform both horizontally and vertically. However, as we explain in this work, a question about vertical structure remains open.

Figure 6 shows the variation of ions concentrations in Lake Urmia based on the available historic data. As it is seen from these figures, the concentrations are characterized by significantly different scales. The spatial and temporal variability, unharmonized data collection, applying the different methodology, equipment, and accuracy could lead to abrupt changes in the measured ionic concentration. As shown in the figures, the concentrations of sodium increased from 60–100 g L^{-1} to 70–120 g L^{-1} in 2007–2011, then its concentrations started to decrease to 40–80 g L^{-1} in 2013. The magnesium and potassium concentrations were at low concentrations before 2007 (5–10 and 1–3 g L^{-1} correspondingly) and then increased to 10–60 g L^{-1} and 4–12 g L^{-1}) in 2010–2014. Calcium content had an opposite trend of a slight decrease of concentrations in 2010–2014 to 0.2–1.2 g L^{-1} from 0.4–1.5 g L^{-1} in 2005–2010. The typical concentrations of chloride changed from 70–15 g L^{-1} in 1985–2005 to 10–25 g L^{-1} in 2005–2014 without a clear trend in the last period. Concentrations of sulfate and bicarbonate were of a smaller level in 1982–2005 (10–20 g L^{-1} and 0.3–0.4 g L^{-1} correspondingly) and had a trend to increase to 60–120 g L^{-1} and 1–4 g L^{-1} in 2013. Bromide concentrations were measured only in the 1980s (about 0.2 g L^{-1}). AU4

The measured values of nutrients (silicate, phosphate, and nitrate) for the 1970s–1990s are in a reasonable range. Nutrient measurements after 2005 show very high values, which probably can be related to the analytical technique applicability for high salinity. A comparison between the Dead Sea and Lake Urmia values could be illustrative. E.g., the nitrate and phosphate values in the Dead Sea are 0.5 mg L^{-1} and 35 μg L^{-1} [34], and 4,000 mg/L and >800 mg L^{-1} for Lake Urmia, respectively. Concentrations of dissolved oxygen are below 3 mg L^{-1}, which can be explained by a low saturation value due to high salinity. pH values were majorly in the range from 7 to 8 through all the period of observations with a decrease to 5–7 in 2013. A single observation on alkalinity (about 6 mEql^{-1}) was recorded in 1985. Total dissolved

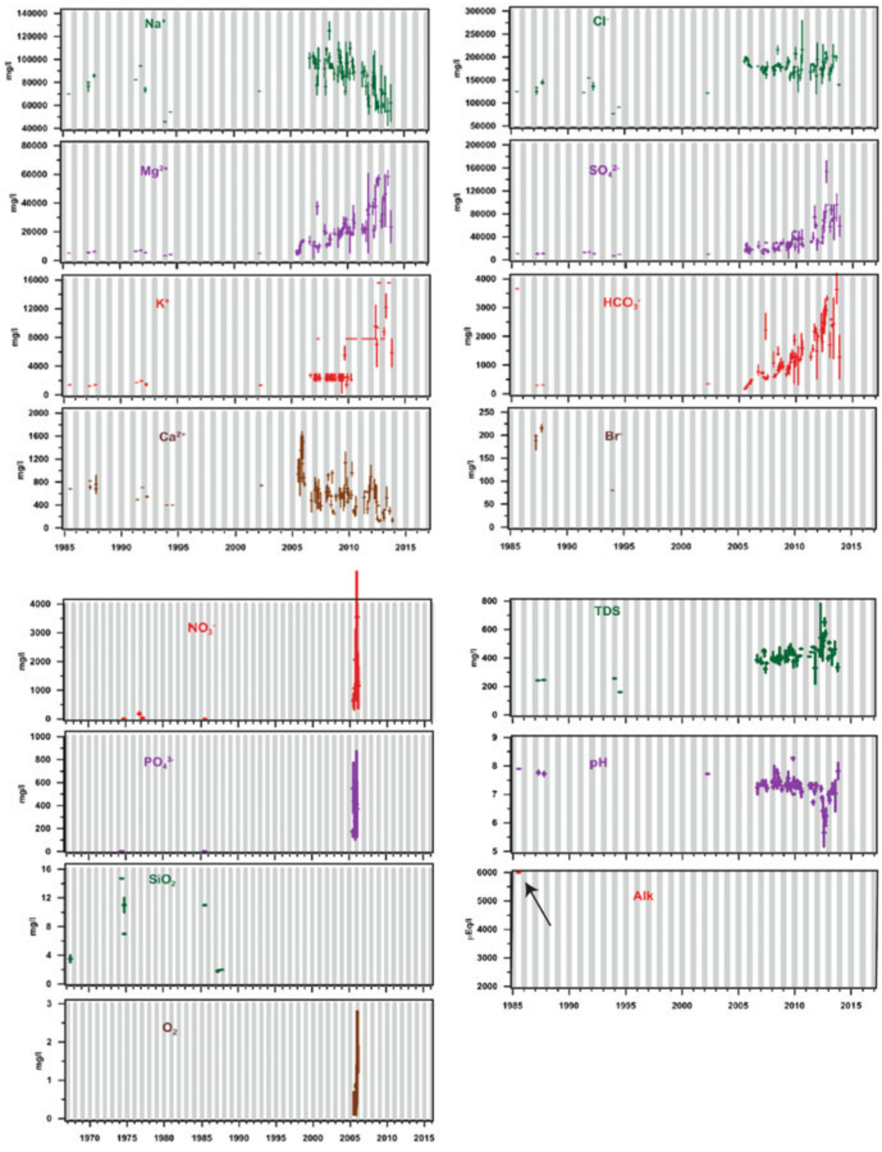

Fig. 6 Inter-annual variability of the major cations, anions, nutrients, dissolved oxygen, TDS, pH and Alk in Lake Urmia. The gray vertical line marks out the winter periods. Data as average values (horizontal ovals) or ranges (vertical color lines) are given for months where the expeditions were reported AU5 AU6

substances content increased from a typical value of 100–300 mg L^{-1} before 2007 to 300–500 mg L^{-1} after 2007 with a temporal increase to 400–600 mg L^{-1} in 2013.

4.2 Aral Sea Salt Composition Changes

The remaining water bodies (Fig. 7) from the historical Aral Sea developed their own hydrological and physicochemical peculiarities, and none of them can be representative of generic Aral water. It is important to note that the physicochemical properties of individual lakes representing the modern Aral Sea differ both between lakes and within the same water body. The massive drying up of the sea caused an increase in water salinity and a change in the ratios of the components of its chemical composition [35, 36].

4.2.1 The Large Aral Sea

Comparing ionic composition for the Large Aral before 1960 and 2019 (Fig. 7, left) reveals that the relative content of chlorine ions changed 1.5 times, sodium ions −1.05 times, potassium −3.2 times, magnesium −1.5 times. The content of other

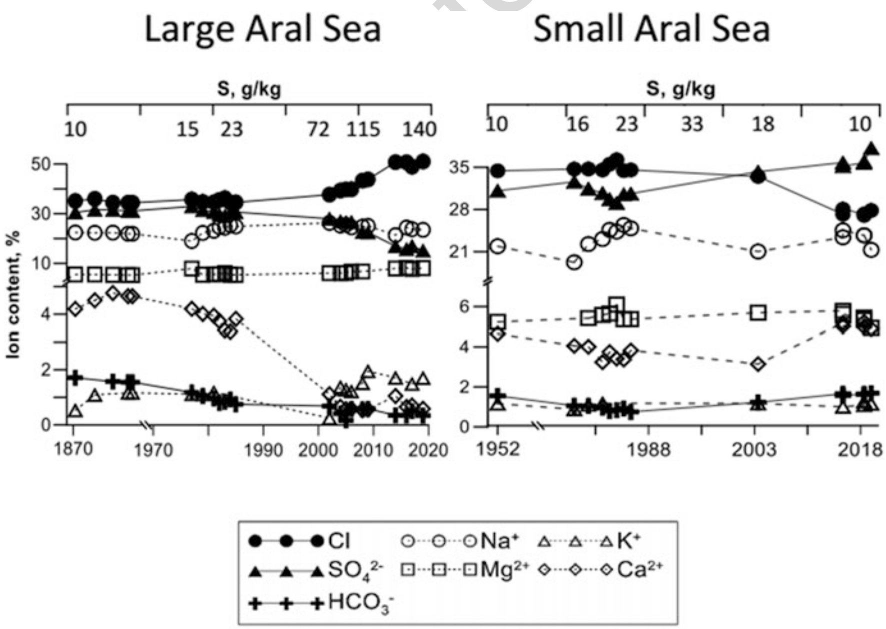

Fig. 7 Evolution of the major ionic composition of the Aral Seas: (**a**) large Aral Sea, (**b**) small Aral Sea

components also altered as follows: sulfates −2 times, hydrocarbonate −5 times, calcium ions −7 times [37]. The lake water initially was in an intermediate position between marine sodium-chloride and continental hydrocarbonate-calcium water. In 1952, the SO_4/Cl mass ratio for the Large Aral Sea was about 0.9 [38], which decreased 2.6 times and averaged around 0.35.

For the half-century drying phase of the Aral Sea, magnesium carbonates accounted for only 2% of the total precipitated salts [39]. The relative content of magnesium in the surface layer of the water of the Large Aral was stable for a long period. Almost the same trend was evident for potassium. Potassium and magnesium are the most conservative cations. Potassium salts are usually deposited in salt lakes and form Sylvite (KCl) in modern salt lakes by precipitation from residual brine in the upper layer of the salt deposit during the period of drying [40].

During the last two decades, hydrogen sulfide and methane were detected consecutively in 2014, 2017, and 2019 in the bottom layer of residual water bodies of the Aral Sea. The presence of hydrogen sulfide testifies to the anaerobic conditions in deep-sea waters. These conditions have a significant impact on the hydrochemical regime and geochemistry of waters. The thickness of the bottom oxygen-free layer in the western basin of the Large Aral varied over a wide range (from 15 to 35 m), and the values of H_2S concentrations varied from 5 to 80 mg/L [36, 41–43]. Convection events, e.g., the deep winter convections that happened in 2003–2004 [39], can break up anaerobic conditions.

4.2.2 The Small Aral Sea

In the historical Aral Sea, salinity in the area of the modern Small Aral was around 10–10.5 g kg^{-1} [38]. After drying and partitioning of the sea, the salinity of the Small Sea increased, e.g., it reached about 34 g/kg in the early 2000s [44]. Holding the flow of the Syr Darya River (constructing Kokaral dam in 2005) gradually returned salinity to its previous values. But the ion-salt composition changed significantly. From 1952 to 2019, the SO_4/Cl mass ratio for the Small Aral increased 1.5 times [37]. This trend seems paradoxical since in the process of chemical metamorphization the sulfate ion should primarily be consumed. Therefore, a decrease rather than an increase in the sulfate-chloride ratio should be expected. But, the Syr Darya River, which is characterized by a high content of sulfates, hydrocarbonate, and magnesium ions, profoundly affects the ionic composition of the chemical composition of the Small Aral Sea [44]. The amount of sulfate supplied with river waters is large enough and an increase in the relative sulfate ion content over time. The salinity and the ratio of the main ionic composition are relatively uniform along the water column (Fig. 7 right). In a temporal sense, comparing 2002 (Friedrich et al. 2003) by 2019 reveals significant alteration ratios for the main ionic composition as follows: (SO_4/Cl) 1.3 times, (HCO_3/Cl) −1.6 times, (Ca/Cl) −1.8 times, (Na/Cl) −1.2 times, (Ca/Mg) −1.8 times [37]. Based on our observations and results, it is highly likely the ionic composition of the Small Seawater will continue AU7 to change toward an increase in the concentration of ions prevailing in the river, especially sulfates.

4.3 Dead Sea Salt Composition Changes

The Dead Sea waters were probably formed from seawater. The arid climate led to the deposition of thick layers of minerals. Recirculation of the brain between the surface and the ground has played an important role in the geochemistry of the Dead Sea [45]. The salt composition of the Dead Sea water is rather peculiar and significantly different from the composition of the Aral Sea and Lake Urmia. SO_4/Cl for the Dead Sea is smaller than that for the Aral Sea by a factor of about 450. The Dead Sea water has a Ca-chloride type composition [13].

As in Lake Urmia and the Aral Sea, the precipitation of compounds from the oversaturated water has played an important role in the chemical regime of the Dead Sea. At present, the lake is saturated with halite NaCl, aragonite $CaCO_3$, and anhydrite $CaSO_4$ [46]. In the course of the salinization, halite and gypsum $CaSO_4{\cdot}2H_2O$ have precipitated massively [23, 27]. During the last few years, the depletion of sulfate and bicarbonate due to low river inflow led to relatively small precipitation of halite. Nonetheless, the precipitation of halite has already resulted in a considerable change in the ion composition, in particular, the molar ratio NaCl has decreased by about 20%, while the ratio Mg/K has increased by about 10% since the 1960s [23].

Figure 8 shows the evolution of the surface waters of the Dead Sea from 1977 to 2019. The IO RAS data we obtained in 2017, 2018, and 2019 are marked with black markers. It should be noted that samples 2008–2019 were obtained in the deepest part of the lake (EG 320 station). Salinity in this area was averaged 300 g kg^{-1}. Data of 2017 were obtained at the northernmost point of the lake in the Kalia region [33]. Salinity in this area averaged 280 g kg^{-1} in 2017. A significant increase is evident in sodium, potassium, and sulfates by 2019 on the surface in the deepest part of the lake. The reason for the sharp change in the content of the main ions can be an increase in salinity of more than 300 g kg^{-1} both as a result of an annual drop in sea level and as a result of an intense discharge of highly mineralized return waters from evaporation basins. Over the year of our observations, the relative content of halogen-ions in the Dead Sea water composition decreased by an average of 0.5%, and magnesium cations by 9%.

The ionic composition of the Dead Sea is unstable due to the precipitation of salts, mainly NaCl, and the inflow of return water from the evaporation pools [28]. Residual water, the so-called final brine (about 50% of the volume used) returns to the Dead Sea with a relatively high content Mg–Ca–Cl with salinity 470–500 g L^{-1} and density 1.33–1.35 kg L^{-1}.

The Dead Sea experienced deepening of the surface mixed layer from 12–15 m to 25–30 m from 1992 to 1995. This trend stopped from 1979 onward, and the lake becomes holomictic with a relatively stable upper mixed layer with autumn and

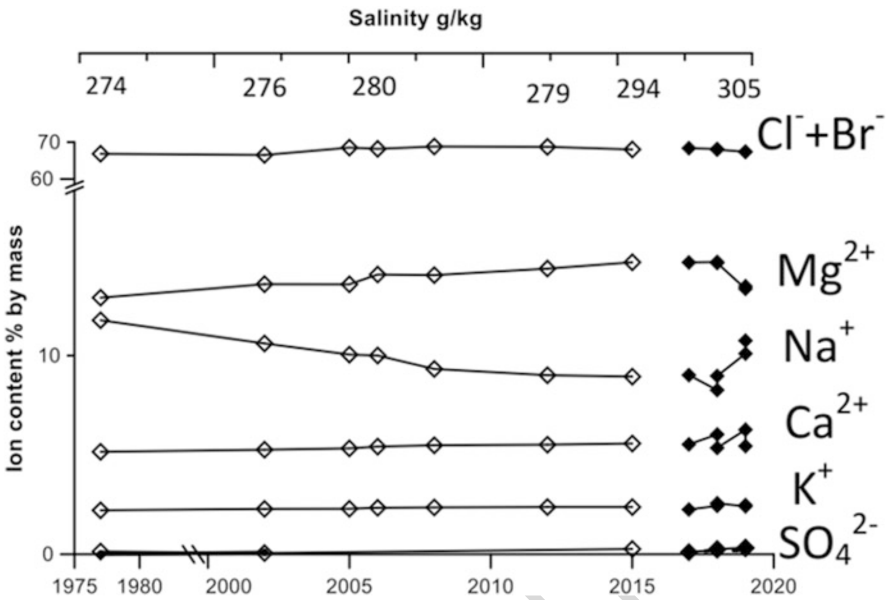

Fig. 8 The evolution of the main ionic composition of the Dead Sea waters in the period from 1977 to 2019. White rhombuses indicate historical values from literary sources 1977–2015 [25, 34, 45], black rhombuses 2017–2019 [33, 37]

winter convection mixing and ventilating the water column. There are some intermittent relatively short meromictic periods (1980–1981, 1992–1994), caused by rainy conditions and elevated river discharges, which always accompanied by a temporary rise of the lake surface level by 1–2 m and a surface salinity drop by up to 30% [23]. In the holomictic regime, stable density stratification in summer is controlled by a thermocline where the temperature decreases from up to 36°C in and immediately below the mixed layer to only about 22°C at the bottom. The temperature drop in the vertical profile is sufficiently large to offset the upper layer salinity increase due to enhanced summer evaporation. In autumn, cooling leads to a relaxation of thermal stratification and an overturning of the water column [24]. The seasonal cycle of salinity and temperature has been modulated by a considerable general positive trend over the last decades [47, 48].

The peculiarity of the carbonate system of the lake led to a significantly lower pH than in Lake Urmia and other lakes. In the water of the Dead Sea, there is practically no carbonate and hydrocarbonate alkalinity due to their precipitation in the form of aragonite ($CaCO_3$) and mainly borate alkalinity is present [49]. The extremely high ionic strength of the brine and the predominance of magnesium ions also contribute to the low pH [50]. In 1977, a pH value of 6.4 was recorded from [25], 6.2 from in 2002–5.9 [45], in 2018 and 2019, the pH at EG 320 ranged from 5.62 to 6.04. As a result, the pH value in the Dead Sea has not changed significantly over time and the slightly acidic reaction of the environment persists at present. However, the chemical composition of the brine and sediment suggests that aragonite continues to fall out of the water, albeit at a slower rate than in the past. DIC (dissolved inorganic carbon) in 1993–1994 was averaged 0.86–0.87 mmol kg^{-1} [51] and 0.86 mmol kg^{-1} in 2012–2014 and total alkalinity was 3.826 mmol kg^{-1} and total boron 4.6 mmol kg^{-1} in 2012–2014 [50].

4.4 Issyk-Kul Salt Composition

The predominant ions of the Lake Issyk-Kul water are sulfates, chlorides, sodium, and magnesium. Of the cations, Na and Mg predominate, and of the anions, Cl and SO_4. The predominance of sulfates determines the class of water in this lake. Therefore, the water in the lake belongs to the sulfate class and chloride-sulfate-sodium-magnesium type of mineralization. In coastal zones and bays, Na and Mg prevail over cations and Cl prevails over anions. The pH ranges from 8.69 to 8.75. Total alkalinity is mainly due to HCO_3 and partly to CO_3 ions. The concentration of other ions affecting the alkalinity of water (H_2BO_3, HPO_4^{2-}, H_2PO^{4-}, $HSiO_3$) is very low [31]. Due to rather a good horizontal and vertical water circulation [52], the main ions show a uniform distribution both horizontally and vertically (Fig. 9). This characteristic distinguishes Lake Issyk-Kul from many other salt lakes. Topographic features, particularly the underwater layers of paleo-rivers on the vast eastern shelf of the lake, might play a role in the horizontal and vertical exchange in this lake [53]. Figure 9a shows the depth distribution of the main ions in the water column using the example of water samples obtained during the 2017 expedition.

Interannual changes in salinity are insignificant (Fig. 9b). Temporal variations in river runoff practically do not affect the salinity distribution even in the upper layer. Temperature data (obtained by IO RAS researchers in June 2016 and November 2017) show the temperature at 500 m depth is around 4.4°C, which is the same as the year 2003. It seems that the significant 10-year warming of deep waters [54] is already stopped. However, in deep waters (500 m), a slight positive salinity trend, 0.05 g kg^{-1} increasing since 1984, is observed. Our data show that the mineralization rate of the bottom layer was 5.95 and 6.10 g kg^{-1}, in the years 2015 and 2017, respectively. According to historical data, the mineralization of the bottom layer was 6.11 and 6.02 g kg^{-1} in 1974 and 1984, respectively [31, 55]. Our data also show that the average salinity was 5.85 and 5.91 g kg^{-1}, in 2013 and 2017, respectively, which in comparison with historical values, i.e., 5.99 g kg^{-1} in 1983–1984 [55] and 6.21 g kg^{-1} in 2015 [56] shows a steady trend. The lake water is alkaline and our observations in 2014–2017 show the water pH is in the range of 7.95–8.82.

In general, there are no significant changes in the chemical composition of this lake from 1935 (data from [31]) to the present (Fig. 9b).

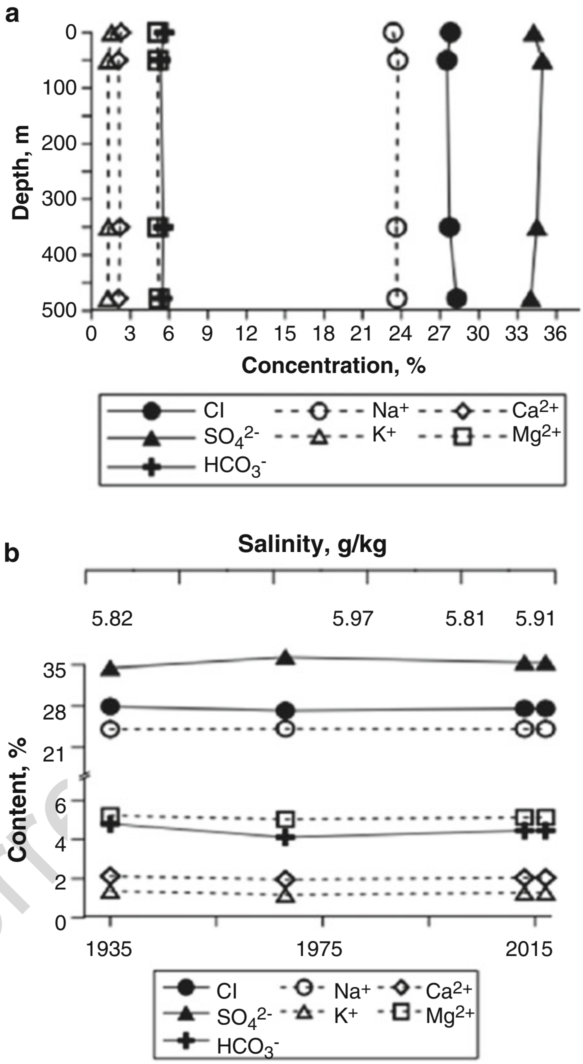

Fig. 9 Vertical (**a**), and temporal (**b**) distribution of the main ions in Lake Issyk-Kul. Water samples obtained during the 2017 expedition

5 Discussion

5.1 Compare Evolution Changes of Major Ion Compositions of Salt Lakes Understudy

In this work, we investigated the major Eurasian closed saline lakes that are mostly located in arid climatic zones (Fig. 1). Lake Urmia, the Aral, and the Dead Sea are hypersaline waters. The investigated lakes belong to the sulfate class, except the Dead Sea that belongs to the chloride class [31, 40]. Additionally, they show a trend of negative water balance and are subject to degradation mainly due to climate change and partly due to human activities. Over the past 5 years, the level of the Aral has dropped by 4 m. The Dead Sea level drops by 1 m per year [28]. Since the mid-twentieth century, the surface level of the Dead Sea has dropped by about 21 m.

Lake Urmia experiences strong depression and for the last two decades, its level dropped on average 21 cm per year [4]. Lake Issyk-Kul is the least susceptible to degradation. But observations revealed a gradual level decrease, i.e., 5.5 cm per year, for Issyk-Kul [31]. The decrease in the level of Lake Issyk-Kul is associated with climatic, tectonic, seismic processes, as well as economic activities of the population, mainly associated with irrigation.

Apart from hydrological and geomorphological features, climate change plays an important role in determining the chemical compositions and their evolution in the studied lakes. The ratio of the main ions of the studied lakes differs from the ratio of ions in the ocean. The main ions ratio has changed significantly in the Aral Sea over time. In Lake Urmia, the ratio is completely unstable due to massive levels of depression and strong seasonal fluctuations. Fluctuations in the lake level are usually controlled by the flow of continental and groundwater, which recently practically does not reach the lake.

To clearly show how different the evolutionary processes of the brines of the studied lakes are, we built graphs based on previously published data and our data. Comparison of the data with historical previously published data makes it possible to assess changes in salt composition in each lake. Figure 10 shows that the processes of ion deposition in lakes are different. Unlike hypersaline lakes, the slightly saline Lake Issyk-Kul demonstrates a relatively constant salt composition (Fig. 10), although there is a slight tendency toward a decrease in the content of sulfate and an increase in the content of bicarbonate ions in the surface layer of the lake. Moreover, in contrast to the composition of the Aral Sea and Lake Urmia, in the deep waters of Issyk-Kul, there are less sulfate and hydrocarbon than on the surface.

5.2 Comparative Analysis of the Present Chemical Composition of the Lakes Understudy

Theoretical changes of the major salinity components can be illustrated with a plot from [57] shown in Fig. 11. They studied the connection of the chemical composition varieties during basin evaporation. Two types of water, seawater and Na–HCO_3 groundwater are analyzed to illustrate the effect of the leakage ratio on brine evolution. The analysis suggests that brines evolve differently under different leakage conditions, but there are some general features. Changes in solute concentrations as the result of mineral precipitation are apparent. Sharp changes in slope in Fig. 11 occur in the curves of limiting elements (those elements whose supply is first exhausted during the evolution of brine) when a mineral begins to precipitate. Dolomite precipitation, which occurs from the beginning has little effect on

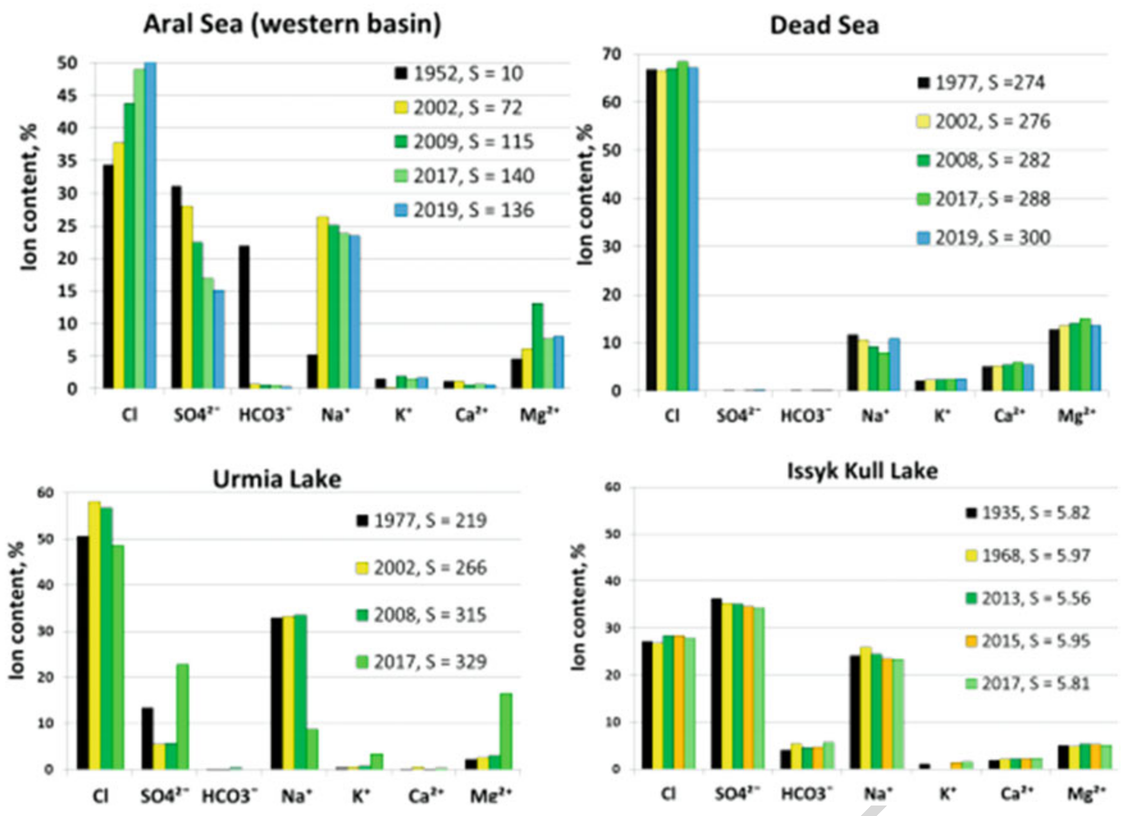

Fig. 10 Comparison of the obtained component composition of the surface layers of salt lakes with historical data (as a percentage of the total salinity of the sample)

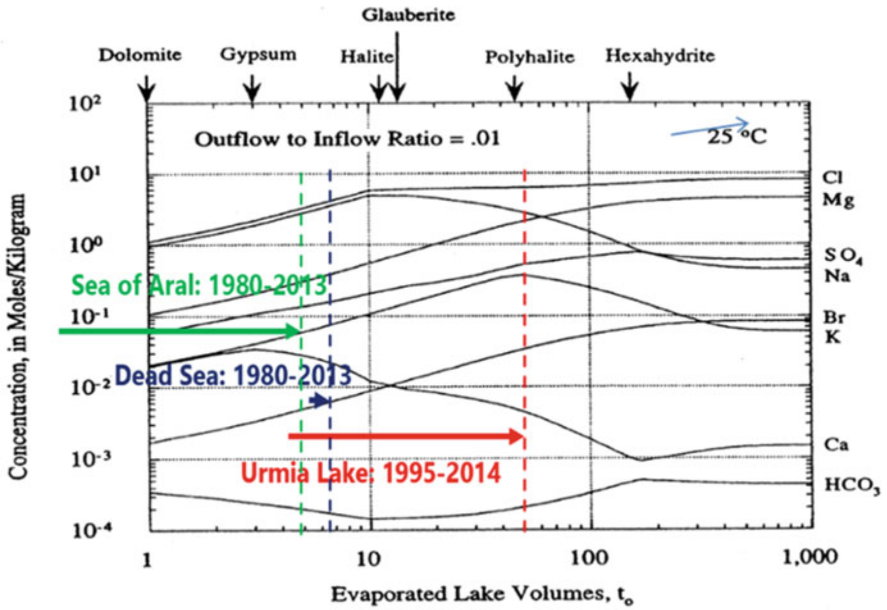

Fig. 11 Theoretical variation in mineral assemblage and the chemistry of the major brine, depending on the degree of openness of the system [57] and temporal changes for Lake Urmia, the Dead Sea, and the Aral Sea

magnesium concentration, as shown by the parallel nature of magnesium and bromide curves through much of the graph. However, dolomite precipitation prevents bicarbonate values from rising during evaporation. Gypsum precipitation causes calcium (which is limiting) to decline at approx. 3 evaporation volumes but has a little effect on sulfate. Halite precipitation at approximately 10 evaporation volumes causes sodium to decline but has a relatively minor effect on chloride. Precipitation of polychloride at approximately 38 evaporation volumes causes a perceptible change in the potassium concentration but only a small change in the sulfate concentration. Precipitation of more soluble magnesium sulfates and chlorides causes a further reduction in sodium, sulfate, and potassium concentrations. The brine reaches a pseudo-steady-state condition at about 180 evaporation volume [57]. Changes in volume (and salinity) in Lake Urmia, the Dead Sea, and the Aral Sea are illustrated in Fig. 11. We note that in all three basins there are quantitative and qualitative changes in the major chemical composition leading to deposition of different minerals during the water body evaporation, and these changes generally correspond to the theoretical ones. Therefore, it is possible to predict the development of the lake's chemical composition.

6 Conclusions

The performed analysis of the changes in the chemical composition of the inland salt lakes demonstrated that to a higher degree the climate variation affects salt lakes. Changes in river discharges, precipitation, and evaporation lead to catastrophic consequences. In the Eurasian region, the Aral Sea, which does not exist as a single water body anymore, experienced such an extreme alteration. Later, Lake Urmia showed a similar trend by a period of drastic volume depression. It is necessary to emphasize that on top of climate factors, these two lakes were objected to severe anthropogenic influences, where a tremendous volume of inflow water was diverted from those lakes for irrigation of vast agricultural fields. Initial ecosystems were eliminated, and it destroyed ecosystem services, i.e., fishery in the Aral Sea, production of artemia in the Urmia Lake, and tourist business in both lakes. Particularly in the Aral region, the environmental alterations not only did reshape the landscape and natural balance of the region, but they also affected dramatically the populations that live or used to live in this area. Public health, access to drinkable water, migrations due to changing landscape, and consequences of vanishing wildlife are all matters that turn out to rely on stable climatic and hydrologic conditions. The socio-economical consequence for the people who are living in that region was huge and it is already triggered some migration waves [58]. The Dead Sea has a larger initial volume and is historically known for its level oscillations, but even here industry became a powerful factor influencing its water budget. Recently, this lake had a principal shift of geochemical regime when the lake turned from meromictic to holomictic. Deep lake Issyk-Kul was not affected by large changes in the river discharges (both to climatic and anthropogenic factors, because of a limited agricultural activity here) and still preserves its properties. But, the probable future scenario of mountain glaciers melting can have dramatic consequences even for the lakes positioned in the high mountains. In conclusion, it can be mentioned that the Eurasian lakes are sensitive and reacting to the changes in climate and anthropogenic factors.

Acknowledgments This research was funded by -381-2-04 research grant awarded to Evgeniy Yakushev and in part by Norwegian Research Council project no. 272749 (“Aquatic Modeling Tools,” SkatteFUNN). The authors would like to thank Dr. Vitaliy Savenko for his valuable scientific discussion during the early stages of this work. The research was carried out within the framework of the RFBR and DFG grant within the framework of the scientific project No. 20-55-12007.

The authors are grateful to Dr. I. Gertman (IOLR) for providing water samples from the Dead Sea, to all employees of the IO RAS, participants of expeditions to Lake Issyk-Kul, and the Aral Sea.

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