Steffen Mischke
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Large Asian Lakes in a Changing World

Natural State and Human Impact

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Editor
Steffen Mischke
Institute of Earth Sciences
University of Iceland
Reykjavík, Iceland

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Chapter 5
Geological History and Present Conditions of Lake Balkhash

Renato Sala, Jean-Marc Deom, Nikolai V. Aladin, Igor S. Plotnikov and Sabyr Nurtazin

Abstract Lake Balkhash is a large endorheic water body, the third largest by size in Eurasia and the second largest salt lake of the world. With its half-moon elongated morphology and 78% of inflows provided by the Ili River from the West, the lake has a freshwater basin in the West and saline water basin in the East, separated by the 4-km narrow and 6-m deep Uzunaral Strait. The average bathymetry is shallow, with a maximum water depth of 11 m in the West and 26 m in the East. According to investigations of the geological history of the lake in Soviet times and in international projects during the last 15 years, a large lake was formed by the Ili River in the Balkhash region encompassing the present area of the Kapchagai Reservoir during the Middle Pleistocene. The large lake basin was subsequently transformed by a series of tectonic deformations. Around 300 kiloyears before present (ka BP) the Ili River was diverted to the North where it formed a large megalake, the Ancient Balkhash, in the Balkhash-Alakol Depression. Around 110 ka BP, the lake became divided into two basins forming the Alakol Lake in the East and the modern Lake Balkhash in the West. Hydrological conditions mostly controlled by precipitation, evaporation and meltwater discharge caused three different lake-level stages in the Late Pleistocene and Holocene: lake levels between 349 and 355 m above sea level (asl) prevailed during glacial periods, between 341 and 348 m asl during the pluvial early and middle Holocene, and between 335 and 348 m asl during the arid late

R. Sala (✉) · J.-M. Deom
Laboratory of GeoArchaeology, Faculty of History Archaeology Ethnology, Al-Farabi Kazakh National University KazNU, 71 Ave. Al-Farabi, 050040 Almaty, Kazakhstan
e-mail: ispkz@yahoo.com

N. V. Aladin · I. S. Plotnikov
Laboratory of Brackish Water Hydrobiology, Zoological Institute, Russian Academy of Sciences, Universitetskaya nab. 1, 199034 St. Petersburg, Russia
e-mail: Nikolai.Aladin@zin.ru

I. S. Plotnikov
e-mail: Igor.Plotnikov@zin.ru

S. Nurtazin
Department of Biodiversity and Bioresources, Faculty of Biology, Al-Farabi Kazakh National University, 71 Ave. Al-Farabi, 050040 Almaty, Kazakhstan
e-mail: Sabyr.Nurtazin@kaznu.kz

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Holocene when extreme regressions at ca. 5.0, 1.2 and 0.8 ka BP divided the lake into more than one basin. The present lake water balance results from a major regression due to a recent phase of aridization and the filling of the Kapchagai Reservoir in the 1970s and 1980s and the compensation of lower precipitation by increased meltwater discharge from glaciers. However, meltwater runoff will diminish with rapidly shrinking glaciers in the next 50 years. This alarming perspective requires careful water-basin management which was not yet implemented. Lake Balkhash is exposed to the threat of exaggerated anthropogenic water subtraction due to an accelerated infrastructural and demographic boost that doubled the irrigated farmlands in the Chinese part of the catchment in less than 20 years. Due to the lake's hydrology, catchment rock and hydrochemical conditions, the water of the Eastern Balkhash has high concentrations of potassium and magnesium, unfavorable for hydrobionts. Any further increase in salinity will soon cause a considerable diminution of the lake's biomass. The ichthyofauna of the lake has been intensively manipulated during the twentieth century, with the introduction of new species and the decline of the original ones. The substitution of the native fish fauna by introduced species caused a decrease of valuable commercial fish in the lake and a decrease of the total fish catch. Thus, Lake Balkhash faces serious environmental risks today and its near future depends on the collective will and decisions of the responsible agencies.

Keywords Balkhash-Alakol depression · Ili River · Kapchagai Reservoir · Water balance · Salinity

5.1 Geographical and Hydrological Features of Modern Balkhash

The Balkhash is a permanent, endorheic (terminal, closed, athalassic), large, shallow, and slightly saline lake, 588–614 km long and 9–74 km wide, covering an area of 18,210 km^2 between 44°57′–49°19′ N and 73°24′–79°14′ E. The lake represents an oasis in the Saryesik-Atyrau Desert and lowest part of the Balkhash-Alakol Depression. Lake Balkhash drains waters from a 413,000 km^2 large region of which 153,000 km^2 actively contribute water to the lake. Salinity of the terminal lake is in a range from 0.2 to 5.0 g/L (Fig. 5.1).

The climate of the Balkhash region is arid continental (BWk) with a mean annual temperature of 5.8 °C (mean January temperature −15.2 °C, mean July temperature 24.3 °C), continentality index of 39.5, diurnality index of 11.1, mean annual precipitation of 142 mm (maximum in May 17 mm, minimum in September 4 mm), annual evapotranspiration of 668 mm, aridity index of 4.7, and an arid season from 15 April to 30 October (Algazi meteorological station, data series 1936–1960). Lake Balkhash receives the highest river inflow between May and August, peaking in July, and its water surface is frozen from November-December to March-April. Predominating winds are from the East and Northeast, inducing waves up to 3.0–3.5 m in the East and no more than 2.5 m in the West, and currents along the lake's longitudinal axis.

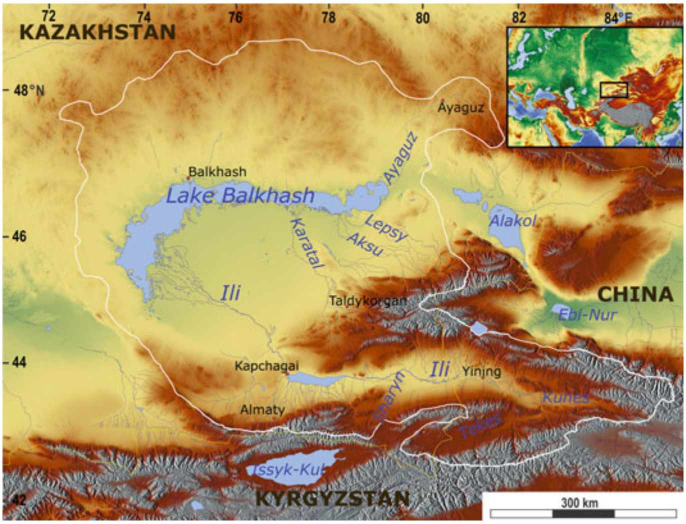

Fig. 5.1 Hydrological basin of the modern Lake Balkhash (outlined in white)

The mean hydrological characteristics of Lake Balkhash in the years 1939–1969 and similarly during 2000-2020 are: water volume of 106 km^3, water surface of 18,210 km^2, water level at 342 m asl (with seasonal variation between 340.8 and 343.1 m asl) and average depth of 5.7 m (Fig. 5.2a).

The equation of the average lake-water balance includes a total yearly water input of 18 km^3 which represents river inflow (15.1 km^3, 83.9%), local precipitation (2.1 km^3, 11.7%), and shore-spring runoff (0.8 km^3, 4.4%), balanced by a corresponding water output as evaporation (−17.2 km^3, 95.6%) and groundwater infiltration (−0.8 km^3, 4.4%; Fig. 5.2b, c). The annual river inflow volume would be 3.0 km^3 higher without water withdrawal from tributaries of Lake Balkhash for irrigation farming (Shnitnikov 1973; Kezer and Matsuyama 2006; Dostay 2009).

The lake is characterized by high and accelerated variability under changing climate conditions.[1] The sedimentary deposits carried by rivers into the lake do not account for more than 0.005 km^3 per year. Ice-melt water is variable, depending from glaciological parameters. Annual meltwater discharge accounted for ca. 0.8 km^3, i.e., ca. 4.4% of the annual inflow, in the last decades. Of the 15.1 km^3 of river inflow, 11.8 km^3 come from the Ili River (78%) and 3.2 km^3 (21%) from the rivers Karatal, Aksu-Lepsy and Ayaguz (Figs. 5.1 and 5.2c).

The quantity of natural and anthropogenic water subtraction above the lake's basin is more or less equivalent to the amount of actual river inflow: 15.1 km^3 per year consisting of 7.0 km^3 of water subtraction by riparian vegetation and of 7.9 km^3 for human use (values of 2014). Without riparian and anthropogenic water subtraction,

[1]During the pluvial years 1958–1961 the total annual river inflow in the lake rose to 23.88 km^3, which with evaporation levels of 17.63 km^3, supported a sensible increase of water level to 343 m asl (Shnitnikov 1973, 134).

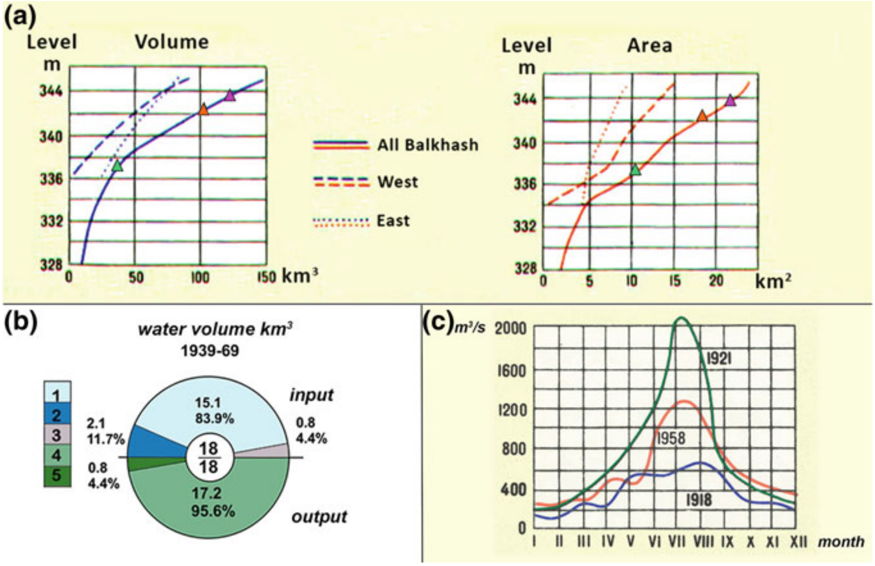

Fig. 5.2 Hydrological parameters of Lake Balkhash. **a** Relationship of water level (m asl) and water volume (km^3) at left and area (km^2) at right. Triangular marks indicate three water-level stages: average at 342 m in 1939–1969 and today (orange), high at 343.5 m in 1908 (magenta), critically low at 337 m at the end of the 18th century (green). **b** Water balance volumes (km^3) for 1939–1969: 1 river inflow, 2 precipitation, 3 groundwater and shore springs, 4 evaporation, 5 infiltration. **c** Ili River mean monthly discharge (m^3/s): low in 1918 (blue), average in 1958 (red), high in 1921 (green). Adapted from Atlas (1982)

the virtual water volume of Lake Balkhash would be 123 km^3, the surface area of the lake 22,000 km^2, and its water level at 343.5 m asl. This high lake level was reached for the last time during the transgressive phase in 1908 (Fig. 5.2a).

In order to discuss the hydrological balance of Lake Balkhash, it must be underlined that its average water volume of 106 km^3 in the year 2000 corresponds to less than seven years of water input (or evaporation, i.e., ca. 17.2 km^3 per year) and to an almost similar amount of water stored as ice in the mountain glaciers of the basin (ca. 90 km^3 per year). Therefore, the hydrological balance of the lake is very sensitive to temperature-driven changes of ice volumes in the uppermost reaches of the tributaries. Effects of climate change on lake-water volumes, levels, salinity, etc., might be delayed. At the start of an arid and warm phase as it occurs at present, the increase of ice melting will postpone the decrease of the lake level by a few tens of years until glaciers reached a new equilibrium or disappeared. In contrast, at the start of a cold pluvial phase, the additional accumulation of ice would postpone the rise of Lake Balkhash's level for more than one century until glaciers grew and reached a new equilibrium.[2]

[2]The high salinity levels of Lake Balkhash reconstructed for the period from 2.4 to 2.2 ka BP in spite of the cold and moist climate phase between 2.5 and 2.0 ka are attributed by Feng et al. (2013) to

The hydrological regime of Lake Balkhash is strongly determined by its shape: latitudinally outstretched as a narrow crescent of 600 km length, with a shallow bottom progressively sloping West to East from 333 to 316 m asl, and with its western and eastern parts separated by the 4-km wide and 6-m deep Uzunaral Strait (Fig. 5.3).

The Western Balkhash Basin is larger (10,600 km^2, 58% of the total lake area) and wider (74 km) but shallower (average depth of 4.8 m, maximum depth of 11 m at 331 m asl) and less voluminous (47.8 km^3). The Eastern Balkhash Basin is smaller (7500 km^2) and narrower (9–19 km) but significantly deeper (average depth 9.0 m, maximum depth 26 m at 316 m asl) and holding 56.6 km^3, i.e., 54% of the total water volume.

The Western Balkhash is mostly fed by the Ili River (78%), which carries sediments responsible for its turbidity and yellow-gray colour (visibility 5–10 m) and for its even silty-sandy lake bottom. The Ili River inflow causes the low mineralization rates (0.8–1.8 g/L) of the western basin. The Eastern Balkhash receives a significantly lower input from smaller rivers that all together constitute only 21.1% of the total river inflow. It experiences a yearly water deficit of 1.15–2.80 km^3 that requires an equivalent amount of water inflow from the western basin and makes its water five times saltier (3.5–4.2 g/L) with emerald-blue waters of higher turbidity (visibility 0.4–1.0 m) and an undulatory lake bottom covered by light-grey limy silts including authigenic dolomite.

Besides the Ili River, the other tributaries Karatal, Aksu and Lepsy were and are still discharging into the Eastern Balkhash. Their discharge alone does not support the actual water level of the eastern basin, which is co-fed by water inflow from the Ili and Western Balkhash. The Ayaguz River used to enter the lake from the North, but is has no surface inflow today. As a whole the sediments of all tributary deltas contributed to the partition of the Balkhash basin in five different subbasins of different depth (Fig. 5.3).[3]

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reduced runoff from glacial meltwater. Similarly, the water-level rise (+8.1 cm per year) during the period 1992–2010 under increasing temperature (+0.08 °C per year) and precipitation (+11.6 mm per year) is largely attributed to the increasing contribution of glacial meltwater by Propastin (2012).

[3] The modern Balkhash is divided in five basins: West-South, West-North, Middle, Lepsinsky and Burly-Tyubin, with depth increasing from West to East, i.e., lake bottom at 334, 333, 327, 326 and 316 m asl, respectively (corresponding to water depths of 10, 11, 15, 16 and 26 m today).

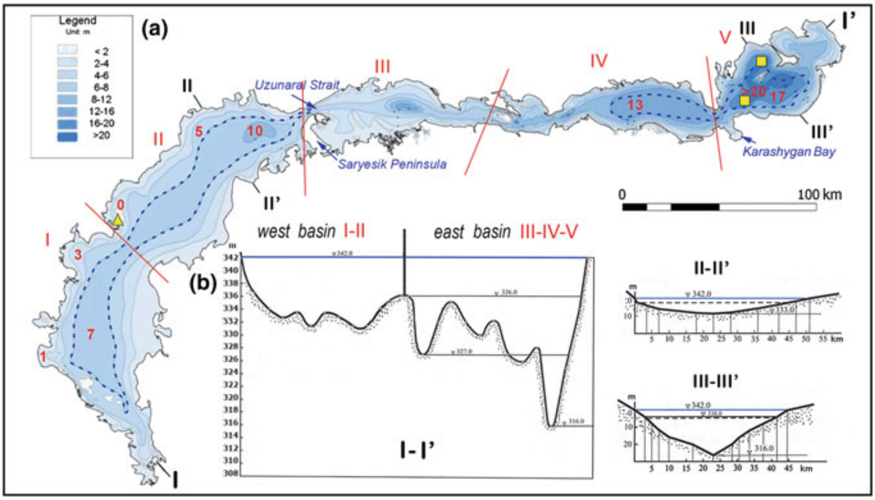

Fig. 5.3 Bathymetric map of Lake Balkhash. **a** Roman numerals I–V in red define the main morphometric partitions of the lake; Arabic numerals show average water depth in metres. Punctuated blue line: Balkhash reservoir under the worst forecasted scenario, with water levels at 337 m asl (Tursunov 2002). Yellow triangle: position of core BAL07; yellow squares: position of cores 0901 and 0902. **b** Morphology of bottom relief: line I–I′ is a W-E profile, and lines II–II′ and III–III′ are N-S profiles of the Western and Eastern basins, respectively. Adapted from Dostay (2009), Myrzakhmetov et al. (2017)

5.2 Geological History of the Lake Balkhash Region

The history of the research of Lake Balkhash during Soviet times can be summarized in three major campaigns of data acquisition and knowledge integration: the works of the 1940s led by D. G. Sapozhnikov who organized the collection and analyses of sediment cores from 160 sites (Sapozhnikov 1951); the studies of Quaternary deposits in the area of the Balkhash-Alakol Depression led by T. N. Dzhurkashev in the 1960s; and the collective researches of the 1970s and 1980s led by N. N. Verzilin who supervised new analyses and introduced the first absolute chronology for lake deposits (which, unfortunately, resulted in a misleading interpretation of the lake history still often used nowadays).[4]

[4]The first important studies of the geological history of the modern Balkhash, although focused on geological characters with scanty information about hydrological phases, had been published by Berg (1904), by Rusakov (1933), and Kostenko (1946), constituting for decennia the main references on the lake. Besides the fundamental studies of Sapozhnikov (1951), other important contributions have been those of Kurdyukov (1958) and Tarasov (1961). Dzhurkashev (1964, 1972) started to consider water-level fluctuations and found evidence for a short-term isolation of the Eastern Balkhash in the early eighteenth century, which decreased its water level by 6–7 m. Only later on, under the stimuli of the Balkhash regression provoked by the realization of the Kapchagai Reservoir, Venus (1985) studied buried peat bogs and inferred regression events, and N. N. Verzilin provided the first qualitative reconstruction of the Holocene lake-level fluctuations on the basis of

Concerning more recent international researches following the perestroika, significant investigations of the modern Lake Balkhash were conducted during the years 2007–2012 in the frame of the Kazakh-Japanese research project "Historical interaction between multi-cultural societies and the natural environment in a semi-arid region in Central Asia"[5] (hereafter shortened as "Ili Project"). The accumulated data enabled the quantitative evaluation of the historical scenario already drawn by N. N. Kostenko and T. N. Dzhurkashev. Among the main results of the fieldwork surveys and laboratory analyses are reconstructions of transgressive hydrological events during the last 35 ka BP based on dating of gravel bars exposed on the northern shore, and a detailed reconstruction of the Balkhash history for the last 8000 years decoded from three cores of bottom sediments (Watanabe and Kubota 2010; Sala et al. 2016).[6]

5.2.1 *History of the Ancient and Modern Balkhash Basins Since 300 ka BP*

Lake Balkhash did not exist until ca. 300 ka BP. The tectonic Balkhash-Alakol Depression was already established ca. 10–15 millions years ago as a lacustrine landscape made of ponds fed by little streams flowing down the Dzungarian Alatau and the northern Pre-Balkhash hillocks. The largest water body of the basin was the Ili Lake, which was extending West of the present Chinese border, occupying the bed

mineralogical, hydrochemical and biotic analyses of sediment cores (Sevastyanov 1991; Tursunov 2002; Dostay 2009). Y. P. Khrustalev and Y. G. Chernousov published an article in 1992 reproducing their historical reconstruction of the lake already included in Sevastyanov (1991) which constitutes today the main (and unfortunately partly confusing) reference concerning the Holocene lake history (see also note 8).

[5]The "Ili Project" was based on the cooperation between the "Research Institute for Humanity and Nature" (RIHN) of Kyoto and three organizations based in Almaty: the "Institute of Geological Sciences named after KI Satpaev", the "Kazakh State Research Institute of the Cultural Heritage of the Nomads" and the "Laboratory of Geoarchaeology". The researches of the Ili Project focused on the Ili-Balkhash basin (Semirechie) and included several fields: the reconstruction of palaeoclimate-environmental changes, historical fluctuations of Balkhash's lake levels and of ice deposits, archaeological traces of land and water use, Late Medieval historical accounts concerning the territory, and Soviet documents and post-Soviet interviews about the pastoralist and agricultural activities in the basin.

[6]The investigation of lake sediments was initiated in 2007 by two international teams working in cooperation with the Satpaev Institute of Geological Sciences of Kazakhstan (B. Aubekerov): a Chinese team led by Zhaodong Feng and Chengjun Zhang, and a Japanese team of the RHIN Institute led by Jumpei Kubota. That year, both teams drilled sediment cores at short distance from each other in the lake near the Tasaral Island in the western basin of Lake Balkhash. The preliminary analyses of the 'Japanese' core BAL07 were published in 2010 (Endo et al. 2010) and more detailed results based on fossil diatom assemblages were issued in 2016 (Chiba et al. 2016). The pollen-based study of the 'Chinese' core BK-A was published with incorrect location of the coring site by Feng et al. (2013) and an additional study of the ostracod record of the same core by Mischke et al. (2020). In 2009, the Japanese team drilled two additional cores (0901 and 0902) in the easternmost part of Lake Balkhash, and preliminary analyses of the cores were published by Endo et al. (2012; Sect. 5.2.2).

of the modern Kapchagai Reservoir and proceeding further West as Ili River until its confluence with the Chu River and reaching the Aral Sea.

Under the tectonic rise of the Zailisky Alatau, the water inflow increased progressively and a critical deformation uplifted the Karaoi Plateau (700 m asl), all together provoking a northward deviation of the Ili Lake that was displaced into the southwestern part of the Balkhash-Alakol Depression (at the time at 200–250 m asl, 200 m lower than today) and formed here its first Ili Delta (Akdala Delta; Dzhurkashev 1972).

As shown in Fig. 5.4b, the Paleozoic substratum of the Balkhash-Alakol Depression has a cup-like profile with a central depression at -100 m asl in the region

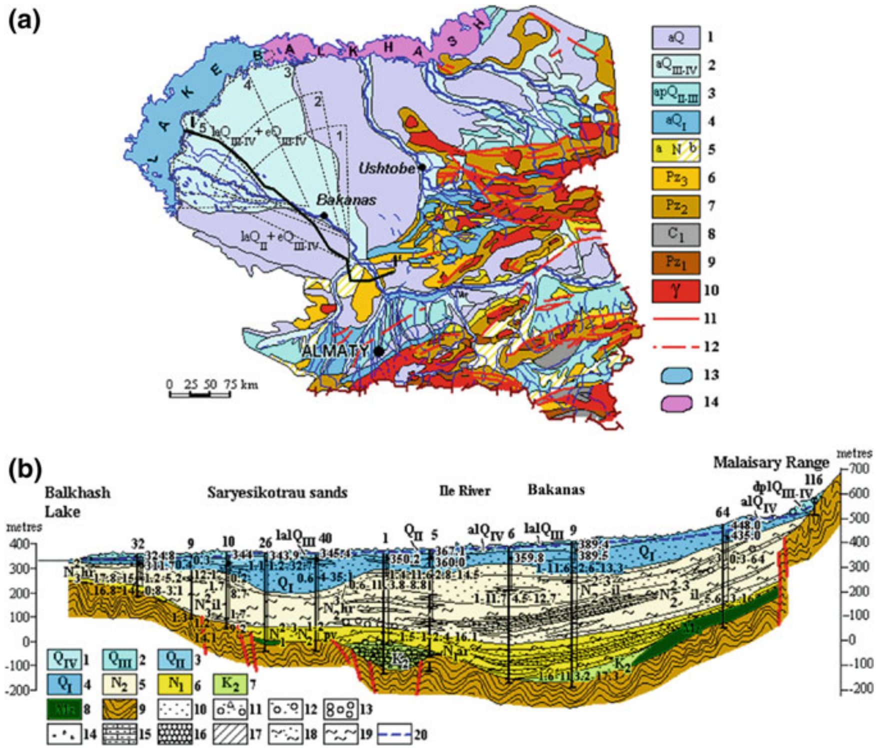

Fig. 5.4 Hydrogeological map and longitudinal section of the South Balkhash Depression. **a** Map of the region showing the successive historical deltas of the Ili River (dotted fans numbered 1–5) crossed by the transect I-I' (black line); 1–4 Quaternary deposits, 5 Neogene, 6–10 Paleozoic, 11–12 aquiferous fissures, 13 freshwater lake, 14 slightly saline lake. **b** Hydrogeological section along transect I-I' from the southern shore of the Western Balkhash to the Malaisary Range (Northwestern piedmonts of Dzungarian Alatau); 1–4 Quaternary deposits, 5–6 Neogene, 7 Upper Cretaceous, 8 Mesozoic, 9 Paleozoic, 10–19 soil and rock features, aquiferous faults, 20 shallow aquifer. Acronyms inside the section refer to locations: il Ili Suite, al alluvial lake, dp deluvial-proluvial deposits. (Adapted from Akhmedsafin et al. 1973; http://www.water.unesco.kz/bal_ch_5_e.htm; and Abdrasilov 1996)

of Bakanas village rising to +250 m asl on both sides against the Zhungarian and the northern Pre-Balkhash pre-mountain zones. Middle Pleistocene deposits (Q_{II}) between +230 to +330 m asl, suggest that, following the Ili diversion, at first a lake (Bakanas Lake) or a system of several lakes was formed in depressions around Bakanas, which then had been filled and displaced North-East by the accumulation of Ili River sediments and the formation of the Ili Delta. Gradually, between 300 and 100 ka BP, a huge lake called Ancient Balkhash was 'sediment-dammed' and seized the entire northeastern part of the depression unifying the present Balkhash, Sasykkol, Alakol and Aibi basins.

This mega-lake was reshaped at the very beginning of the last glacial period (ca. 110 ka BP) following intensive orogeny of the Dzungarian Alatau that hoisted the Arkarly Mountains at 780 m asl dividing the Ancient Balkhash in two different water bodies: the Alakol Lake in the East (today at 347 m asl) and the modern Lake Balkhash (inclusive of its eastern and western parts) in the West (today at 342 m asl; Kurdyukov 1958; Dzhurkashev 1972; Aubekerov et al. 2009a, 2010).[7,8]

The configuration of the shorelines of the modern Lake Balkhash is determined by a 20–30-m high, tectonically disturbed rocky terrain in the West and North and by flat sandy alluvial and aeolian deposits in the South. The lake as a whole is lying on the most elevated and faulted northern slopes of the Paleozoic depression which favors groundwater circulation between the lake bottom and the vertical overflow of pressure waters of the southern Pre-Balkhash artesian basin, across a few hundred metres of semi-permeable sediments. The lowest reaches of a huge accumulation of alluvial

[7]The average sediment thickness in the area of the modern Western Balkhash is 70 m, parted as 44 m of Neogene and 26 m of Quaternary deposits, the latter with distinct 2–3 horizons (the second horizon uneven and eroded). Total sediments' thickness decreases from 70 m in Western Balkhash to 50 m in Eastern Balkhash on the account of the lesser river and sediment input of the eastern basin (Sevastyanov 1991).

[8]The reconstruction of the history of the lake provided by Khrustalev and Chernousov (1992) is relatively different and confusing. Using a chronological framework established by Maksimov (1961) for the glacial stages of the Dzungarian Alatau, the authors attribute the appearance of an Ancient Balkhash ("Balkhash-Alakol") basin outrivaling the Aral Sea in size, even if not reached yet by the Ili River inflow to the post-glacial early Holocene period. The disappearance of the Ili Lake by Ili River diversion is assigned to the end of the Atlantic period (5.6 ka BP) and is quoted as responsible for the formation of the "Balkhash", so that, in the view of the authors, the entire formation and rotation of the Ili deltas occurred during the last 5 ka.

Then, ignoring geological reports and only referring to lithological and chemical data from core samples provided by N. N. Verzilin's fieldwork in 1979–1981, Khrustalev and Chernousov reconstructed the succession of four stages of the lake during the Holocene, each stage starting with a transgression (T) and ending with a regression (R). These fluctuations are named by four specific toponyms and approximate chronological boundaries (all in ka BP) were provided: (I)-Ancient Balkhash (T 10.3, R 8.3–5.6), (II)-Balkhash (T 5.6, R 4.4–3.5), (III)-New Balkhash (T 3.5, R 2.6–1.9), (IV)-Modern Balkhash (T 1.9, R intermittent). The present authors infer that three of these regressive events reduced the Eastern Balkhash into a series of "isolated or semi-isolated pools": between 8.3 and 5.6, at 3.8 and 0.75 ka BP (quoted from Venus 1985).

The described middle-late Holocene history of the modern Balkhash, by being the most recent and best furnished in terms of radiometric ages, has been diffused and adopted as reference by many scientists (e.g., Tursunov 2002; Solomina and Alverson 2004; Krylov et al. 2014; etc.) against the reliable geochronology of the basin established by geologists before.

sediments in its South favor the water input from rivers and from shallow aquifers. The resulting groundwater dynamics, accompanied by seepage of ion-enriched lake waters, contribute with other processes such as the dispersion of coastal salt deposits by wind, to the maintenance of a relatively low salinity of the endorheic lake (Smolyar and Mustafaev 2007).[9]

The Ili Delta has always been the principal feeder of the lake by freshwater and biomass during the late Pleistocene and Holocene, and it continuously evolved, changing its morphology, location and size. Arid phases, through diminishing the discharge of delta distributaries, favor the lowering and erosion of the existing river channels, the formation of terraces and, in general, the stabilization of the existing delta morphology. The establishment of a new delta typically coincides with pluvial phases that enhance the energy levels of the distributaries and promote diversions in various directions.

The Late Pleistocene, postglacial and Holocene evolution of the Ili Delta occurred in five stages (Fig. 5.4a), featuring as a whole a gradual northern and anticlockwise rotary displacement under the forcing of sedimentary and tectonic factors (Abdrasilov 1996; Deom et al. 2019):

(I) The first stage, barely detectable, refers to the Akdala Delta (possibly several superposed deltas): the head was around Bakbakty village, and the delta area was huge, with distributaries feeding the eastern part of the modern Lake Balkhash during the glacial period.

(II) The Bakbakty Delta was created during the postglacial period: it was fed by the so-called Palaeo-Ili River course with head at Birlyk, 30 km North of the former one and an anticlockwise rotation of the distributaries.

(III) With the start of the Holocene, ca. 10 ka BP, the Uzunaral Delta (or Older Bakanas Delta) was created, with head displaced further North-West (30 km southeast of Bakanas village, at 500 m asl) and the delta front reaching the present lake shore in correspondence with the Saryesik Peninsula. The last consists of alluvial sediments of 30–50 m thickness, shaping the connection between the Western and Eastern Balkhash into a narrow and shallow strait (the Uzunaral Strait, today 6 m deep).

(IV) Only ca. 2 ka BP, the new Ili course became activated, parallel to the Palaeo-Ili in the West, and opening a delta with head at Bereke (30 km North of Bakanas). It further rotated anticlockwise, and in that way, the Bakanas Delta (or Younger Bakanas Delta) was established, significantly reduced in size and discharging in the western part of the lake.

(V) Only recently, during the pluvial phase of the sixteenth to eighteenth centuries, the delta rotated further West to form the modern Ili Delta (Dzhurkashev 1964).

[9]Especially aeolian processes promote the relatively low salinity of the lake's water: "The stock of salt reserves in the lake's area amounts to only 260–300 million tons, which is not large since, in addition to their consumption in the process of carbonate formation, some of them are lost by entering the numerous bays of the winding coastline. During phases of water level recession, the bays separate from the lake, dry out, and their salt deposits are blown by the wind, thus reducing the salt's reserve of the lake" (Sevastyanov 1991).

5.2.2 Hydrological Stages of Lake Balkhash During the Late Pleistocene and Holocene

The most recent changes of the modern Balkhash across the Last Glacial Maximum up to now occurred mostly under the activity of rivers and changing climate, as a result of sediment accumulation and transgression-regression cycles, because no major tectonic events arose anymore. In that sense, the “Ili Project” focused on the analysis of Balkhash’s water level changes during the last 40 ka; and significant study objects became the tracers of water-level variations, such as the absolute heights of sand bars on the shore and the physical, chemical and biotic composition of the lake sediments.

The study and optically stimulated luminescence (OSL) dating of exposed gravel bars at the shore of the Karashygan Bay in the southeastern part of the lake (Fig. 5.3) revealed the presence of very relevant transgressions, the oldest to 354 m asl (+13 m higher than today’s water level), dated to 36 ka BP, ascribed to the interstadial stage of Marine Isotope Stage 3. Two successive transgressions of lesser entity were detected at ca. 10 m above the present lake and dated to the LGM between 25 and 17 ka BP. The early Holocene lake level had decreased significantly ca. 8.4 ka BP when the lake reached for the first time its present level at 342 m asl. These events attest a tendency to very high lake levels during the very cold phases with minimal evaporation of the Last Glacial Maximum and postglacial period, followed by lower water levels during the drier middle and late Holocene.

Analyses of the lake sediments of two cores drilled in the deepest part of the eastern basin (cores 0901 and 0902) and one core from the shallow western basin (BAL07; Fig. 5.3) allow the quantitative reconstruction of Balkhash’s water-level fluctuations during the last 8 ka BP.

The sedimentary columns of cores 0901 and 0902 have been recovered at a water depth of 20 m in the easternmost Burlyutyubin Basin of the Eastern Balkhash, with a length of 6 m and a chronology of the last 8 ka BP (Fig. 5.5). The sediments were dated using the radiocarbon technique, and examined by complex analyses including lithology, geochemistry, magnetic susceptibility, fossil diatoms (siliceous algae) and ostracods (micro-crustaceans), pollen and spores which are partly still not completed. The recorded data indicate a transgressive mode during the pluvial Atlantic period (7.0–5.5 ka BP) and three main regressions at 5.5–5.0, 2.7–2.4 and 1.3–0.8 ka BP. If the second and third regressions were severe but presumably not falling below 336 m asl, the first regression at 5.5–5.0 ka BP definitely went below 336 m asl which is the level of the Uzunaral Strait floor at which the Western and Eastern Balkhash become separated water bodies. Thus, the two basins were disconnected and isolated lakes formed in the Eastern Balkhash in the middle Holocene.

At 3.7–3.0 m of their columns (the sediments at 2.9 m depth in core 0901 have an age of 4.7 ka BP), both cores revealed sediments characteristic of an arid or semiarid environment. Core 0902 contains a layer of abundant gypsum at 3.67 m, indicating strong evaporation effects on the lake waters. Core 0901 includes laminated sediments rich in Fe and Si at 3.50 m which are overlain by silt and fluvial sand (Sugai

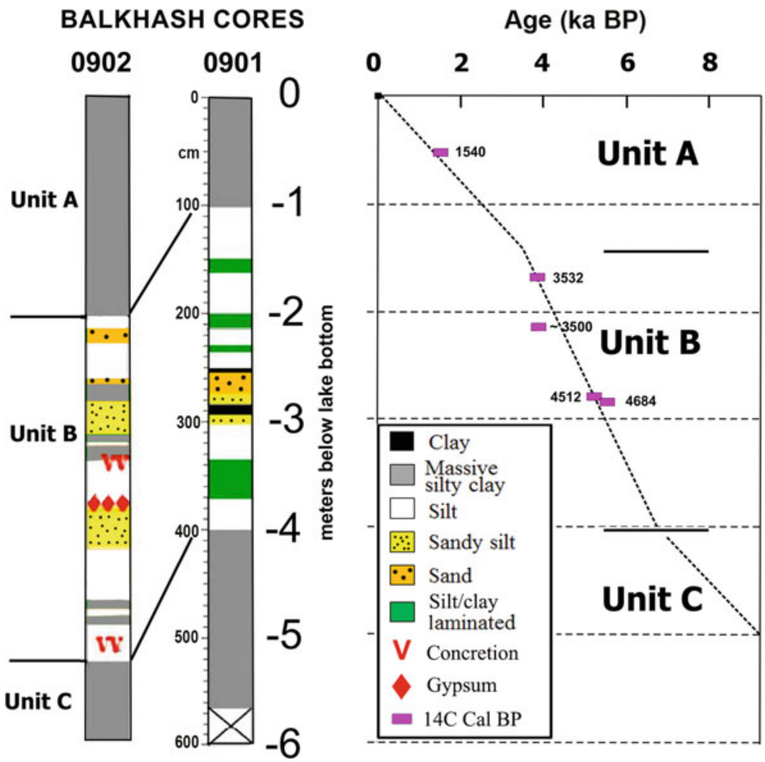

Fig. 5.5 Lithological profiles and age-depth plot (approximate accumulation rate 0.5 m/ka; Endo et al. 2012) of cores 0901 and 0902 from the Eastern Balkhash (original figure published in Endo et al. 2012, Fig. 5)

et al. 2011). The depth of the gypsum layer in core 0902 corresponds to ca. 318–319 m asl, i.e., 23–24 m below the present water surface of the lake, suggesting an extreme lake-level drop of 24 m in the Burlyutyubin Basin and the reduction of the lake to a small brackish pond ca. 5.5–5.0 ka BP.[10]

A similar inference is confirmed by the biotic proxies: palynological spectra, ratios of benthic saline and planktonic freshwater diatoms, and the contraction and diversity change of different ostracod species (Endo et al. 2012, 46).

Several peat layers have also been recorded by Soviet geologists (Sapozhnikov 1951; Dzhurkashev 1972; Venus 1985) but a significant lake-level drop as those in the middle Holocene was not detected previously, not even suspected, underlining the vulnerability of the Eastern Balkhash Basin and the importance of this discovery.

The core BAL07 was drilled in the shallow western part of the lake near the Tasaral Island at a water depth of 3 m. The core is 6 m long and covers the time span of the last 2000 years. Its lithology and biotic content disclosed two major

[10]Taking into account sedimentation rates, such pond could have been 4–5 m deep.

medieval regressions dated to 750 and 1150 AD, roughly the start and the end of the Medieval Warm Period (MWP).[11] The water level dropped by ca. 5 m during the earlier backset and the Uzunaral Strait might have desiccated (which at that time was supposedly crossed by a caravan road linking the delta to the northern shore). The later regression was less intense but longer (Fig. 5.6). Afterwards, the lake experienced a long transgressive phase under the pluvial climate of the Little Ice Age, between 1300–1800 AD, interrupted by three regressions at the start and the end of the sixteenth century and around the late eighteenth century.

Two main factors are regarded as the causes of the historical lake-level regressions: climatic aridification diminishing the river inflow and enhancing evaporation, and anomalous transmission losses, natural or anthropogenic.

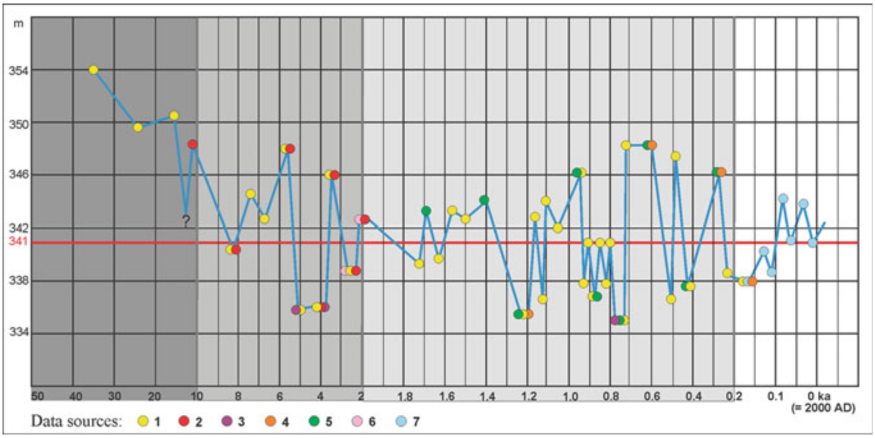

Fig. 5.6 Synoptic reconstruction of the water level of Lake Balkhash during the last 36 ka. *Sources* 1 OSL data of gravel bars of the Karashygan Bay (earliest transgressions dated to 36, 25 and 17 ka BP), and ^{14}C data of cores 0901, 0902 and BAL07 (Endo et al. 2012; Chiba et al. 2016); 2 ^{14}C data from Y. P. Khrustalev's lithological analyses (10.3, 8.3, 5.6, 4.4, 3.6, 2.7 ka BP) extended by the dating of an additional peat layer by N. N. Verzilin (3.97 ka BP; Sevastyanov 1991), 3 ^{14}C data from B. G. Venus' analyses of peat layers (5.05, 3.86, 0.75 ka BP; Venus 1985); 4 palynological data of core BAL07 (Aubekerov et al. 2009b); 5 inferred climatic phases: multi-secular long minimum (~1.25 ka BP) at 335.5 m, multi-secular long maximum (0.7–0.5 ka BP) at 348.5 m, secular maximum (0.27 ka BP) at 346 m, secular minimum (0.16 ka BP) at 338 m (Kurdin 1976; Shnitnikov 1957); 6 ^{14}C, pollen and ostracod data from the core BK-A (Feng et al. 2013; Mischke et al. 2020) 7 Gauge measurements of water levels for the period 1879–1967 (Semenov and Kurdin 1970). The decreasing intensity of gray shading refers to four different chronological scales, from left to right: 10 ka, 1 ka, 0.1 ka, 0.05 ka

[11] Using diatom assemblages correlated with Ca content in ostracods radiometrically dated, the Japanese team placed the two low-level stands in a series of seven regressive periods: 0–300, 330–360, 750–790, 1060–1260, 1560–1600, 1780–1840, 1950–1990 AD (Chiba et al. 2016). The pollen-based reconstruction by Feng and co-authors confines itself to the outline of three climatic stages in the basin: cool-wet (500 BC–200 AD), moderately warm-dry (200–1350 AD) and cool-wet for the past 650 years with a last warm-dry century (Feng et al. 2013).

The climate of the Balkhash region is under the influence of the northern Atlantic atmospheric circulation, which evolves over the northern Atlantic Ocean in response to sea surface temperature fluctuations driven by the Atlantic Multidecadal Oscillation (AMO), and to atmospheric pressure changes of the North Atlantic Oscillation (NAO). In western Central Asia, the late Holocene and in particular the Subatlantic period was characterized by the alternation of hot-dry and cold-wet climate phases. Arid phases were detected at 5.4–5.2, 4.6–3.9, 3.2–2.8, 2.0–1.6 and 1.3–0.8 ka BP, intercalated by moist phases (Chen et al. 2008; Hill 2018). Moreover, the effects of fluctuations between arid and humid phases on decreasing or increasing levels of Lake Balkhash are postponed by negative or positive changes in glacial ice volumes (Footnote 3; Feng et al. 2013).

The tributary rivers of Lake Balkhash are flowing on broad flat plains with discharges significantly decreasing downstream, particularly in the very variable deltaic courses with dense riparian vegetation partly crossing isolated evaporation pans. Delta distributaries can be diverted into isolated evaporation basins, or instead they can widen and merge, in both cases increasing the wetlands surface with significant transport losses by ponding in terminal storages, infiltration and evapotranspiration. The first case is suggested by the geomorphological study of the palaeo-terraces of the Lepsy River where large Late Holocene regressions of Eastern Balkhash could have been enhanced by switches of the very unstable Lepsy River bed, diverting its waters southwestward in separate depressions (Dzhurkashev 1972; Endo et al. 2012, 44). The second case is represented by some apparently not climatically triggered lake-level regressions of the sixteenth and late eighteenth century attributed by Dzhurkashev (1964) to the widening of the deltaic surface due to the contemporary activation of both the Bakanas and Ili deltas.

The Late Pleistocene and Holocene hydrological regime of Lake Balkhash can be summarized as three successive stages, each correlated to specific climate conditions and lake-level ranges (Fig. 5.6):

- the first stage, with high water levels between 355 and 349 m asl, is connected with glacial and postglacial conditions with very low evaporation;
- the second stage, with water levels between 348 and 341 m asl, occurred during the early and middle Holocene, and is characterized by warm and moderately wet conditions and still significant accumulation of glacier ice in the mountains of the catchment;
- the third and present stage, with water levels between 348 and 335 m asl, exists since the late Holocene, and is characterized by an arid climate and small volumes of glacier ice, and by relevant lake-level fluctuations between arid and humid phases. Henceforth, three main phases can be distinguished within this third stage: regressive (5.0, 1.2, 0.8 ka BP), transgressive (0.7–0.1 ka BP), and regressive (0.2, 0.1, 0 ka BP).

5.3 Modern Balkhash: Present Hydrological Conditions Under Increasing Climate Warming and Water Subtraction

The history of Lake Balkhash is significantly better known for the last 120 years thanks to gauge stations introduced in 1879. Today, quantified data concerning the lake level, water quality and biological environment are regularly collected, analyzed and used for monitoring by three main institutes based in Almaty: the Hydrometeorological Institute "Kazhydromet", the Department of Water Resources of the Institute of Geography, and the Akmedsafin Institute of Hydrogeology and Geoecology.

According to their annual measurements, Lake Balkhash, like most Central Asian lakes, manifests a tendency of progressive desiccation during the last century, with the exception of two high stands in 1908–1912 (343.7 m) and in 1960–1972 (343 m). The lake level increase after 2000 (342.5 m) is attributed to melting of glaciers (Fig. 5.7a).

During the period 1960–1986, the lake was confronted with three major regressive factors: the continuation of the secular dry climate trend, the filling of the Kapchagai Reservoir (1970–1986), and the increase of the irrigation area within the basin from 300,000 to 550,000 ha and of anthropogenic water withdrawal from 3.5 to 5.5 km^3. The total river inflow decreased by 3.8 km^3 per year (−23%), of which 62% were attributed to natural variability and 38% to anthropogenic subtraction; and Balkhash's water level fell from 343 m asl in 1970 to 340.6 m in 1986 when the Kapchagai crisis culminated. This lake-level decrease was accompanied by a very sensible decrease of the water surface by 25% with shorelines receding 2–8 km, and by a reduction of the water volume by 40% (Kezer and Matsuyama 2006).

Balkhash's lake level regained to 341.5 m asl between 1986 and 2008, following the reduction of the active capacity of the Kapchagai Reservoir to 6.64 km^3 (23.7% of the originally projected capacity)[12] and the post-perestroika economical crisis in Kazakhstan which was, anyhow, counterbalanced by an increasing use of Ili River waters on the territory of the People's Republic of China (Shaporenko 1995; Fig. 5.7).

During the period from 1955 to 2000, the accelerated melting of the glacier ice in Balkhash's catchment basin exceeded the global average ice melting by a factor of four. Thus, the meltwater surplus compensated the increased evaporation losses from the lake as a result of the warming trend. Ice volume in Balkhash's catchment decreased from 122 to 90 km^3, i.e., −26% between 1955 and 2000 (−0.8 km^3 on average per year; Bolch 2015; Severskiy et al. 2016). The corresponding surface decreased from 2000 to 1500 km^2, i.e., −25% between 1960 and 2007 (−0.6 km^2 per year; Xu et al 2015; Severskiy et al. 2016). The persisting glacier shrinkage provides a significant 5–10% excess of yearly river inflow that will disappear under ongoing climate trends and glacier retreat within less than 50 years.

The shallow bathymetry of Lake Balkhash with an average depth of 5.7 m makes it sensitive to inflow changes. The ratio between water surface (18,210 km^2) and

[12] A water volume of 6.6 km^3 in the Kapchagai Reservoir corresponds to a water surface of 1250 km^2 (7.1% of Lake Balkhash's surface) and an annual evaporation of 1.2 km^3.

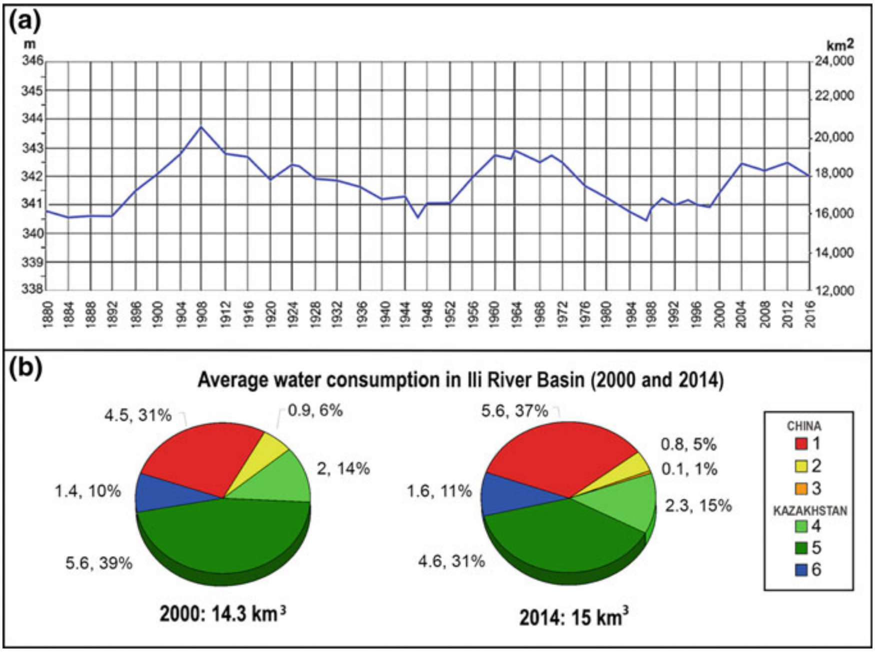

Fig. 5.7 Historical development of Lake Balkhash's level (left axis) and area (right axis) since 1880 and of water consumption in the Ili River Basin after 2000. **a** Water-level and area fluctuations between 1880 and 2016 (based on data from Semenov and Kurdin 1970; Propastin 2012; Myrzakhmetov et al. 2017). **b** Water consumption (km^3) in the Ili River Basin in 2000 (37% in China, 63% in Kazakhstan) and in 2014 (43% in China, 57% in Kazakhstan). Legend: China 1 Agriculture, 2 Riparian vegetation, 3 Lakes and reservoirs; Kazakhstan 4 Agriculture, 5 Riparian vegetation (including delta vegetation), 6 Lakes and reservoirs (Balkhash excluded; data from Thevs et al. 2017)

water volume (106 km^3) is very high and implies a correspondingly large volume of evaporated water (yearly 17.2 km^3). Thus Balkhash's resilience is very low; the lake would disappear without water inflows in less than seven years.

Today, a mean annual water input of 18 km^3 ensures a lake level at 342 m asl but future decreases of meltwater discharge and increasing aridification with higher evaporation will result in a lower lake level. Moreover, demands for anthropogenic water withdrawal are rising, mostly through the expansion of irrigated surfaces. Thus, Lake Balkhash requires a strict water management system for its catchment area including common rules for all water consumers because the current state of the lake can only be secured with a reduced and better use of the Ili River water.

The most recent change in the complex hydrological system of Lake Balkhash resulted from plans prepared in the 1990s to multiply the area of irrigated fields in the upper Ili Basin in Xinjiang by three to four times accompanied by a drastic demographic increase.[13] Today, the resulting irrigation farming and established infrastructure and population density reached the alarming capacity of a yearly subtraction of a few km^3 of water that may soon cause a drop of Balkhash's level below the critical height at 336 m asl and eventually the disappearance of the Eastern Balkhash.

The size of irrigated areas on the Chinese side grew between 2000 and 2014 from 400,000 to 500,000 ha and the water retention from 5.0 to 5.6 km^3, reaching the level of the implementations on the Kazakh side during Soviet times. On the Kazakh side, irrigated areas and water use were slowly increased after the collapse which followed perestroika. In 2014, an area of 250,000 ha was irrigated and 2.3 km^3 of water was used (Thevs et al. 2017).

The combined water withdrawal for irrigation purposes in Balkhash's catchment in Kazakhstan and China amounts to a total of 7.9 km^3 (52% of the river inflow) today which will further increase in the future (Fig. 5.7b). If the annual water consumption grows by additional 3 km^3, the lake level of Balkhash will drop to 340.2 m asl and the lake surface will shrink to 15,000 km^2. A higher increase of the consumed water by additional 6 km^3 would cause a lake-level fall to 338 m asl and a corresponding lake surface of 10,000 km^2. An even higher increase by additional 9 km^3 would result in a lake-level drop to less than 336 m asl and a division of the lake in three to six different basins of which some would completely desiccate (Propastin 2013).

5.4 Modern Balkhash: Lithology of the Sediments and Hydrochemistry of the Water Column

5.4.1 Types of Sediments

The geological features and hydrological conditions of the Balkhash Basin determine the character of the lake-bottom sediments and of the water (Sect. 5.4.2) and the character of its biotic components (Sect. 5.5).

The sediments of Lake Balkhash, suspended or dissolved[14] in the water column and precipitated to the lake bottom, consist of allochthonous materials transported by rivers, waves and winds, and of autochthonous materials produced within the lake itself by chemical processes and biotic activity. They consist of suspended inorganic and organic debris and of dissolved chemical particles differently distributed within the lake according to the location and discharge of the individual river deltas,

[13]Chinese authorities do not provide information about their hydraulic plans in the region and, up to now, did not respond to repeated requests for the establishment of an international consortium for the management of the trans-boundary hydrological system of the Ili-Balkhash Basin.

[14]A solution is the homogeneous mixture of a solute and a liquid where, in contrast to a suspension, the solute cannot be separated from the solvent by filtration.

the lithological and chemical characteristics of the water inflow, and the peculiar elongated morphometry and resulting water circulation in the basin (Fig. 5.8).

Within the total transported sediments, the clastic terrigenous materials, mainly in the form of sand, are by far the most abundant (ca. 4–6 million tons per year, 0.005 km^3), accounting for 92–93% of the annual total. They are made of mineral particles of quartz, feldspar, volcanic rock fragments, limestone and shale, sized between

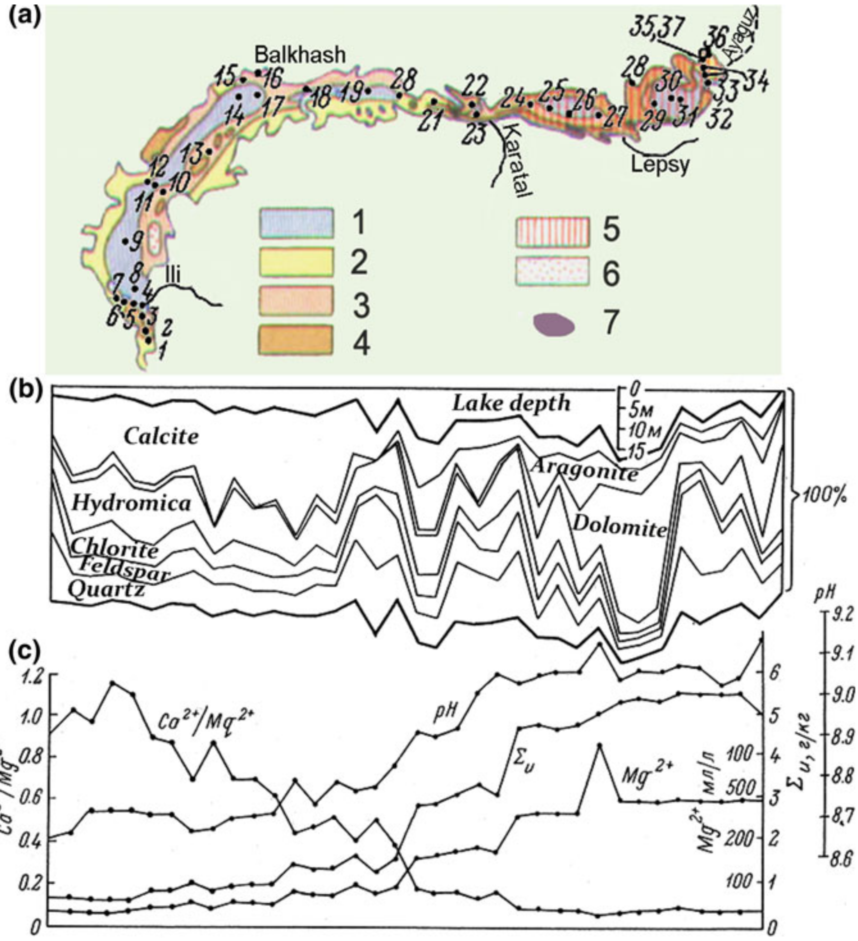

Fig. 5.8 Lithological and hydrochemical characteristics of Lake Balkhash. **a** Location of 36 sediment cores (6 m long) retrieved at regular intervals along the lake's long axis. Main granulometric concentration: 1 silt; 2 silty sand; 3 sandy silt; 4 pebbles, gravel; 5 dolomite; 6 sandbank; 7 Neogene clay. **b** Above: West-to-East profile of lake depth. Below: West-to-East profiles of ratios in percent of lithological composition of bottom sediments (calcite, aragonite, dolomite, etc.). **c** Hydrochemical composition of the water column (ratios of Ca^{2+}/Mg^{2+}, pH, salinity $\Sigma\nu$, Mg^{2+}; from Atlas Kazakhskoi SSR 1982: 59 and Sevastyanov 1991, Fig. 32)

clay and gravel. The mineral composition of the lake deposits highly depends on the transport mechanism and size of the sediment particles (Fig. 5.8a). Granulometric analyses of the bottom sediments (Fig. 5.8a) show that sands, mainly carbonaceous, constitute the absolute majority around delta mouths and account for more than 50% of the deposits in the middle part of the lake. The mineral composition of the lake deposits highly depends on the size of the sediment particles. Wind-transported aeolian silts, mainly siliceous, abound all along the dunes near the southern coast. Clays of different color and composition (mainly green chlorites and hydromicas) accumulate abundantly in the western basin and in the bays along the northern coast where they constitute more than 70% of the surficial lake-bottom sediments (Sapozhnikov 1951).

The mineralogy of the bottom sediments is dominated by rock-forming components from the same terrigenous geochemical province, i.e. mainly as a result of suspended materials carried by the Ili River to the lake (Fig. 5.8b). Carbonate minerals [calcite and aragonite $CaCO_3$, dolomite $CaMg(CO_3)_2$] are the most abundant components and also those reacting fastest and precipitating earliest from the waters, so that their portion is >50% in bottom sediments around the delta mouths (Ili, Aksu, Lepsy) and between 10 and 20% in the remote central regions of the basin, balanced here by an increase of more stable silica and sodium oxide. Iron concentration varies between 3 and 9% and is evenly distributed in high concentration along the northern coast. In contrast, sediments in the easternmost basin fed by the Lepsy and Ayaguz tributaries represent an anomalous mineralogical composition with a tenfold higher concentration of magnesium and manganese oxides, and a decrease of iron, resulting in a significantly different province of authigenic geochemical sediments there (Sevastyanov 1991).

Chemogenic sediments consist of solid and gaseous undissociated compounds, molecules and ions dissolved in water, from which a part precipitates by chemical reactions. Their yearly input from rivers represents a small fraction (less than 2–3%) of the yearly total sedimentary budget but they represent by far the main sedimentary components dissolved in the water column. A total mass of 13 million tons (i.e., a total volume of 0.025 km^3) precipitates per year from the water column. Their dissolved mass and composition result from thousands of years of chemogenic processes and, together with water inflow and evaporation, control the hydrochemical conditions of Balkhash's biotic system.

Biogenic materials consist of terrestrial macrofossils, phytoliths, pollen and charcoal from fires. They are suspended in low quantity in the water and practically absent in most bottom deposits. A larger fraction of the sediments is represented by calcareous and siliceous skeletal elements of aquatic organisms in the lake. These are mostly ostracod valves and diatom tests, and to a lesser degree also bivalve and gastropod shells. Organic carbon concentration of bottom sediments is ca. 1% in the proximity of delta mouths and less than 0.5% in the central parts of the lake (Sapozhnikov 1951).

5.4.2 Composition of the Water Column

Lake Balkhash's water is almost isothermal and isochemical without vertical stratification due to the shallow depth of the lake and the action of wind and currents.

Mean annual surface-water temperature is +1.1 °C, mean December surface-water temperature is −3.3 °C, and mean July surface-water temperature is +23.0 °C. Summer-water temperatures are close to ambient air temperatures (Sect. 5.1) but winter surface-water temperatures are significantly higher than air temperatures.

The solid particles suspended in the water are clay- and silt-sized, carried by flowing waters until they settle out when flow is insufficient to keep them in suspension. Together with dissolved chemical particles, they determine the moderate turbidity in the western basin (visibility 5–10 m) and the increasing turbidity to the East enhanced by winds, currents and salinity until a visibility of 1 m or less.

Among gases, dissolved oxygen (O_2) as the most critical indicator of a lake's environment and of a healthy aquatic ecosystem, is in a range from 6 to 10 mg/L in Lake Balkhash. Dissolved oxygen saturation is typically 100% at the surface and 90% at the lake bottom with variations due to local water temperature, salinity and depth.

Total Dissolved Solids (TDS) is defined as all substances contained in water (metals, minerals, salts, calcium and other compounds which can be both inorganic and organic) that can pass through a 2 micron filter. Thus, TDS is a measure of the sum of the amount of dissolved ions (as mg/L).[15] The relatively larger and most abundant ions or macro-components in Lake Balkhash are carbonates (hydrocarbon-bicarbonate HCO_3^- and carbonate CO_3^{2-}) and calcium (Ca^{2+}) in equal proportions (together accounting for ca. 68% of dissolved ions); magnesium Mg^{2+}, sulphate SO_4^{2-}, sodium Na^+, chloride Cl^- (together ca. 27%), and potassium K^+ (which is relatively abundant in Balkhash, 2%).[16] In addition, silicon Si^{4+} represents an important dietary requirement for various organisms with a concentration of 2–3 mg/L, in spite of its low reactivity. Micro-components or substances occurring in very low concentrations (1 μg/L < x < 1 mg/L) represent 3% of the total ionic mass in Lake Balkhash. However, they are very significant as most important nutrients including various inorganic and organic nitrogen compounds such as ammonium NH_4^+, nitrite NO_2^- and nitrate NO_3^- (0.01–0.7 mg/L), phosphorus (phosphate PO_4^{3-}), and iron Fe^{3+} (0.1–0.5 mg/L).

Salinity of Balkhash's waters mainly depends on the concentrations of Ca^{2+}, Mg^{2+} and HCO_3^- and thus, on water hardness. Salinity increases from 0.2 to 5.0 g/L from

[15] 1 mg/L is equivalent to 1 ppm (parts per million).

[16] The ionic composition of Lake Balkhash's water is relatively distinct if waters of different basins are compared: "The proportion of chloride (9–21 equiv. percent) is 2–3 times lower than the proportion of chloride in the sea. However, the proportions of potassium, calcium, magnesium, sulphate and carbonate/bicarbonate ions are significantly higher. In Eastern Balkhash, the proportion of potassium ions (2.9 equiv. percent) is very high in comparison to other waters (e.g., 0.6 equiv. percent in the ocean and the Aral Sea). The lower proportion of calcium ions, especially in comparison with the Aral and Caspian seas, is also notable" (Aladin and Plotnikov 1993, 5).

West to East (Fig. 5.8c).[17] The Ca^{2+}/Mg^{2+} ratio is a good indicator of salinity in Lake Balkhash (Fig. 5.8c).[18]

The water of Lake Balkhash is alkaline, with acidity (pH, power of hydrogen) decreasing from a pH of 8.65 in the West to 9.15 in the East.

In the Balkhash water, carbonate anions dominate over chloride (14%) and sulphate (18%) anions; and their concentration increase from West to East together with changes of associated cations (Ca, Mg, Na, K).

Among carbonates, the ratio of bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) depends on acidity: bicarbonate dominates in the Western Balkhash with pH values of 7–8.5, and carbonate dominates in the Eastern Balkhash at pH values > 8. In Western Balkhash bicarbonate associates with calcium and precipitates as calcite ($CaCO_3$), resulting in decreasing concentrations of both ions from West to East in Lake Balkhash. Bicarbonate concentrations decrease from 35–57 to 8%, and calcium concentrations from 11.8 to 1.2 mg/L from West to East. In Eastern Balkhash, carbonate associates mainly with magnesium, and magnesium concentrations increase from 40 to 400 mg/L from the West in the lake to its East due to the different sedimentary loads of the eastern river inflows and the higher effects of evaporative concentration in the East. The carbonate-magnesium combination favors the formation of dolomite [$CaMg(CO_3)_2$] and aragonite ($CaCO_3$). Similarly towards the East, salinity increases from 0.7–1.1 to 3.2–5.2 g/L.

The hydrochemical conditions are reflected by the mineralogy of the respective sediments on the lake floor (Fig. 5.8b) which contain 50% of calcite in the Western Balkhash, calcite and dolomite in similar proportions in the western basin of the Eastern Balkhash (i.e., in the Middle Basin; basin III in Fig. 5.3a), and 60% of dolomite and 7% of aragonite in the central basin of the Eastern Balkhash (i.e., in the Lepsinsky Basin; basin IV in Fig. 5.3a).

5.5 Modern Balkhash: Biota

5.5.1 Biological Productivity

Lake Balkhash has favorable temperature ranges and dissolved oxygen levels, but a low productivity. The low productivity results from the high concentrations of

[17] The amount of salts in the waters of the endorheic lake would be significantly higher given the sedimentary inputs if geological processes would not partly remove salts (Sect. 5.2.1 and Footnote 9).

[18] The amount of ions is directly correlated with the electrical conductivity (EC) of the water, which is also a good indicator of salinity (TDS = EC x 0.64), moreover by the fact that it keeps in consideration temperature gradients. EC is expressed in Siemens/metre (S/m or mho/m), conventionally calibrated at 25 °C, with 1 S/m equivalent to a salinity of 5 g/L. Going from West to East in Lake Balkhash, EC values at T = 1.1 °C increase from 1 S/m to more than 15 S/m. EC values increase 3% per 1 °C temperature increase and at a maximum water temperature of 26 °C reach up to 2 S/m in the westernmost and up to 27 S/m in the easternmost part of the lake.

potassium and magnesium in the Eastern Balkhash which are unfavorable for its biota (Karpevich 1975). Further increases in salinity and the concentrations of these ions will directly cause considerable reductions of biomass (Aladin and Plotnikov 1993, 6). Also other factors such as the relative isolation of the lake and the adaptation stress induced on organisms by frequent fluctuations of lake level and salinity reduce Balkhash's productivity to a medium-low rate, decreasing from West to East with increasing turbidity and salinity.

5.5.2 *Floral and Faunal Species*

5.5.2.1 Aquatic Flora

The aquatic flora of Lake Balkhash consists of microphytes (microalgae) living in the water column (planktonic) or on or in sediments (benthic), and macrophytes growing in or near the water. Phytoplankton and phytobenthos are represented by 350 species and varieties, including: 200 species of diatom microalgae, mainly benthic and almost constituting the totality of the benthic algae; ca. 65 species of green algae; ca. 50 of blue-green algae; eight of dinoflagellates; four of golden algae; one of yellow-green algae; six of euglenids; 18 of zygnematophyceans and some species of charophyceans (Fig. 5.9). Most of the algae forms are freshwater types (oligohalobionts) or adapted

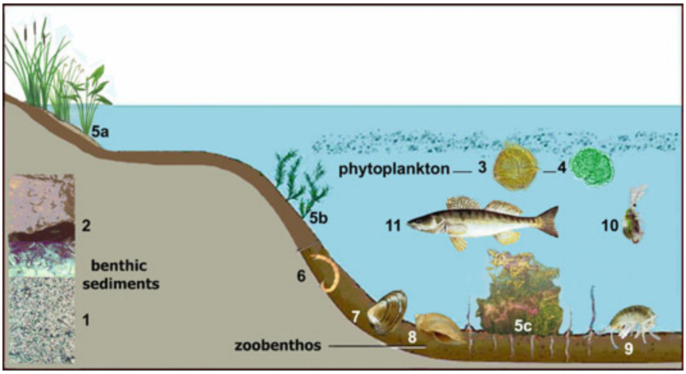

Fig. 5.9 Typical aquatic ecosystem of Lake Balkhash. Bottom sediments: 1 limy dolomitic white silt (upper strata of the lake-bottom cores of Eastern Balkhash; Sapozhnikov 1951); 2 silty sand with a peat layer, at depths between 8–60 cm in the central-western basin. Phytoplankton: 3 Dinophyte *Peridinium*, the most widespread dinoflagellate in the western basin; 4 Cyanophyte *Snowella lacustris* (blue-green algae). Macrophytes: 5a hydrophytic plants; 5b Charophyta green algae; 5c Chlorophyta green algae. Zoobenthos: 6 *Chironomus salinarius* (bloodworm midge); 7 bivalve *Pisidium henslowanum*; 8 gastropod *Radix ovata*; 9 amphipod *Gammarus lacustris*. Zooplankton: 10 *Daphnia galeata*, a common micro-crustacean in Eastern Balkhash. Ichtyofauna: 11 Balkhash perch, an endemic fish previously dominant that became rare (Red List IUCN) after the introduction of the bream

to a wide range of salinities (euryhaline). Benthic algae are mainly diatoms (Abrosov 1973; Karpevich 1975; Alekin 1984).

The basis of phytoplankton is made of a low number of species (Abrosov 1973). Before the 1950s, they were the blue-green algae *Microcystis flosaquae, Snowella lacustris, Planktolyngbya contorta, P. limnetica, Nodularia spumigena*; the dinoflagellates *Ceratium hirundinella, Peridiniopsis borgei*; the green algae *Pediastrum duplex, Pseudopediastrum boryanum*; and the diatoms *Aulacoseira granulata, Campylodiscus clypeus, Coscinodiscus lacustris, Cymatopleura elliptica* and *Entomoneis paludosa*. In the Eastern Balkhash, diatoms such as *Chaetoceros* spp. and the dinoflagellates *Chrysosporum bergii* and *Glenodinium berghii* were common.

Later, changes occurred in the phytoplankton assemblage. In 1973–1985, the common species were the blue-green algae *Merismopedia minima, M. tenuissima, Snowella lacustris, Microcystis pulverea, Coelosphaerium dubium*, the diatoms *Cyclotella comta* and *C. meneghiniana*, and the green alga *Oocystis submarina*. In Eastern Balkhash, species of genera *Cyclotella, Snowella* and *Chaetoceros* dominated (Abrosov 1973).

In the 2000s, the most common phytoplankton were the dinoflagellate *Peridinium* sp., the diatoms *Cyclotella meneghiniana* and *Navicula* sp., the euglenophyte *Trachelomonas* sp., the green alga *Franceia* sp., and the blue-green algae *Snowella lacustris, Gomphosphaeria aponina* and *Gloeocapsa* sp. (Barinova et al. 2017).

Diatoms dominate in spring and autumn, green algae during periods of increasing temperature, blue-green algae in summer. Freshwater and euryhaline forms dominate in the western part of the lake whilst freshwater forms disappear in the eastern part and become replaced by halophiles and mixed assemblages (holobionts) which spread to the West in phases of increasing salinity.

By the end of the 1970s, the average biomass of the phytoplankton in Western Balkhash fell by more than 50% as a result of increased salinity. Freshwater species became rare and substituted by more salt-resistant forms (Alekin 1984).

The variety of macrophyte flora in Lake Balkhash is relatively low. If the aquatic plants of the Ili River Delta are included, 35 species of higher plants and seven species of charophytic macroalgae occur. The causes for this low species number are the relatively high and variable salinity with macrophyte numbers decreasing with increasing salinity (Abrosov 1973), the relatively high turbidity of the water, the strong impact of coastal waves and the geographic isolation from other basins. High turbidity of water prevents the development of charophytic macroalgae. Charophytes are only found in those parts of the lake where the water transparency is high (Abrosov 1973). These parts are mainly in the Western Balkhash.

The hydrophytic plants restricted to low salinities in Lake Balkhash are the white water lily *Nymphaea candida*, the arrowhead *Sagittaria sagittifolia* and the duckweeds *Lemna minor* and *L. trisulca*. The higher plants most resistant to high salinity are the reed *Phragmites australis*, the sago pondweed *Stuckenia pectinata*, the horned pondweed *Zannichellia palustris*, the watermilfoil *Myriophyllum spicatum*, the bulrush *Scirpus kasachstanicus* and the beaked tasselweed *Ruppia maritima*. The charophytic macroalgae *Chara tomentosa* and *Nitellopsis obtusa* also tolerate relatively high salinities (Abrosov 1973; Barinova et al. 2017; Krupa et al. 2017).

Thickets of hydrophytes diminished in Lake Balkhash due to the increasing shallowing and salinization. Reed covered a 250-km long and 10–20-km wide stretch in the Western Balkhash in the past which was reduced to a 1–2 km wide reed belt in the 1970s (Abrosov 1973).

5.5.2.2 Zooplankton

The natural fauna of Lake Balkhash is considered as qualitatively and quantitatively poor due to its geographical isolation. Several allochthonous species have been artificially introduced during the last century.

The basic original zooplankton consisted of ciliates (*Codonella cratera*), rotifers (*Synchaeta* spp., *Filinia longiseta*, *F. longiseta* var. *limnetica, Polyarthra platypiera, Pompholyx sulcata, Keratella quadrata, K. quadrata* var. *valga, K. cochlearis, K. cochlearis* var. *tecta, Chromogaster ovalis, Hexarthra oxyuris*), copepods (*Arctodiaptomus salinus, Thermocyclops crassus, Mesocyclops leuckarti*), and cladocerans (*Daphnia galeata, Diaphanosoma lacustris, Chydorus sphaericus* and *Leptodora kindtii*; Rylov 1933; Fig. 5.9). Leading were rotifers, and *K. quadrata* predominated. Among copepods, the leading form was *A. salinus* which was more abundant in the Eastern Balkhash. Widespread, though not very abundant, was *M. leuckarti* (Abrosov 1973).

By 1978–1980, significant changes in the zooplankton had occurred due to the falling lake level and the increasing salinity, accompanied by a sharp decrease in nutrient inputs from river runoff. The number of freshwater and brackish-water rotifer species decreased, and to a lesser degree also the numbers of cladocerans and copepods. Of the latter two, *A. salinus* and *D. lacustris* became the dominating species.

By 1983–1985, with the continuously falling lake level and rising salinity, the total number of zooplankton species declined by more than a half compared to the end of the 1960s. Small forms or "fine" detritophages filter-feeders disappeared completely, reducing the number of species most valuable as food for juvenile commercial fish. Instead, the "rough" filter-feeders *D. lacustris* and *A. salinus*, characterized by relatively low nutritional values for juvenile fish, began to dominate. The cladoceran *Sida cristallina* became abundant and the typical inhabitant of the brackish waters.

By the end of the 1990s, the zooplankton composition of Lake Balkhash stabilized. The main species were *Brachionus calyciflorus, Euchlanis dilatata, Keratella cochleans tecta, K. quadrata quadrata, Hexarthra oxyuris, Daphnia galeata, D. cucullata* Sars, *Diaphanosoma lacustris, Eucyclops vicinus, Mesocyclops leuckarti* and *Arctodiaptomus salinus*.

The current zooplankton of the lake includes 123 species and subspecies of invertebrates: 82 rotifers, 22 cladocerans and 19 copepods (without harpacticoids). Only a few are found in high numbers: *Polyarthra dolichoptera dolichoptera, Euchlanis dilatata dilatata, Keratella cochlearis cochlearis* and *K. quadrata quadrata* among the rotifers; *Diaphanosoma lacustris* and *Daphnia galeata*, especially in

Eastern Balkhash, among the cladocerans; and *Arctodiaptomus salinus, Mesocyclops leuckarti* and *Thermocyclops crassus* among the copepods (Rylov 1933; Saduakasova 1972; Karpevich 1975; Krupa et al. 2013). The three cladocerans *Leptodora kindtii, Ceriodaphnia reticulata* and *Polyphemus pediculus* are rare. A few species of the cladoceran families Chydoridae and Macrothricidae and of the copepod genera *Eucyclops, Microcyclops* and *Macrocyclops* occur near the river mouths.

The specific ionic composition of Balkhash's water, especially the higher concentration of potassium and magnesium compared to other large saline lakes is unfavorable for hydrobionts. Potassium and magnesium are toxic to organisms but their toxicity is weakened by calcium and sodium. The abundance of planktonic crustaceans is largely controlled by the concentrations of these ions in the Eastern Balkhash. It decreases with increasing K^+/Na^+ and K^+/Ca^{2+} ratios. *Daphnia galeata* is the most resistant to higher potassium concentrations among the dominant species (Krupa et al. 2008).

5.5.2.3 Zoobenthos

The original zoobenthos of Lake Balkhash initially had a very poor species composition, mainly represented by larvae of terrestrial insects, especially chironomids (more than 30 forms), dragonflies, mayflies, stoneflies, caddisflies and oligochaete worms (Abrosov 1973; Karpevich 1975). Gastropods, bivalves and malacostraca (shrimps and amphipods) were also relatively abundant members of the native benthic fauna.

Oligochaetes are widespread in the lake. Nine species were recorded: *Potamothrix hammoniensis, P. bavaricus, Limnodrilus profundicola, L. hoffmeisteri, Tubifex tubifex, Uncinais uncinata, Nais pardalis, Spirosperma ferox* and *Stylaria lacustris* (Abrosov 1973). Leeches are represented by the three species *Piscicola geometra, Protoclepsis meyeri* and *Glossiphonia complanata* (Abrosov 1973). The free-living nematodes of Lake Balkhash did not receive proper studies and also only few information was gathered with respect to aquatic mites (Abrosov 1973).

The native mollusks included only freshwater species. The most common species were the bivalve *Pisidium henslowanum* and the gastropods *Valvata piscinalis* and *Planorbis planorbis* in the past, but their biomass is low today and their presence limited to the shallow fresher areas of the lake and the proximity of the river mouths (Samonov 1966; Karpevich 1975). *Pisidium henslowanum* is the only native bivalve in Lake Balkhash, but the native gastropods include the pond snail *Limnaea stagnalis, Radix auricularia, R. ovata* and *Galba truncatula*, the ramshorn snail *Gyraulus albus*, and the lake limpet *Acroloxus lacustris* in addition to the predominating *V. piscinalis* and *P. planorbis* (Fig. 5.9).[19]

Today, crustaceans are mostly represented by the shrimp *Palaemon superbus* and two species of amphipods—*Rivulogammarus lacustris* and, in Western Balkhash, *Dikerogammarus haemobaphes*.

[19] A number of researchers reported the presence of the gastropod *Bithynia caerulans*, but this endemic gastropod became apparently extinct (Zhadin 1952; Tyutenkov 1959).

Ostracods are represented by the six species *Ilyocypris* sp., *Neglecandona neglecta, Candona* sp., *Darwinula stevensoni, Cyprideis torosa* and *Limnocythere dubiosa* (Abrosov 1973). However, this list might be incomplete as crustaceans have been insufficiently investigated.

In 1953–1966, several species of invertebrates were introduced from the Caspian and the Azov seas as valuable food for fishes. The anellid polychaetes *Hypania invalida* and *Hypaniola kowalevski*, the bivalve mollusk *Monodacna colorata*, and the crustacean amphipod *Corophium curvispinum* and mysids (shrimp-like crustaceans) *Paramysis lacustris, P. intermedia, P. ullskyi* and *P. baeri* were naturalized. In addition to these intentional introductions, the freshwater bivalves *Anodonta cygnea* and *A. cellensis* were accidentally introduced together with the zander fish from the Ural River in 1957–1958 because their glochidia larvae were on the gills of fish (Karpevich 1975).

Since 1996, the zoobenthos biomass began to increase sharply as a result of the explosive development of the bivalve *Monodacna colorata* which is now underutilized by benthophagous fishes.

A total of 93 native and introduced invertebrate species are recorded for today's macro-zoobenthos of Lake Balkhash. During 2009–2013, the main taxonomic group represented native larval and adult insects including the large native larval chironomids *Chironomus salinarius* and *C. plumosus*, followed by introduced representatives of the Ponto-Caspian fauna.

The composition of the benthic fauna differs significantly in the Western and Eastern Balkhash due to the different salinity levels. Species diversity is lower in the more saline Eastern Balkhash, and the amphipod *Dikerogammarus haemobaphes* and some native and introduced freshwater mollusks such as *Monodacna colorata* do not occur anymore. With the exception of chironomids and other Diptera, insects are also less diverse in the Eastern Balkhash. Moving from West to East, mysids which are sensitive to water pollution and sometimes used as bioindicators to monitor water quality, progressively disappear. At first, *Paramysis baeri* disappears, then *P. lacustris*, further East in the lake follows *P. ullsky,* and finally *P. intermedia* which is not found in the easternmost part of the lake anymore (Alekin 1984).

5.5.2.4 Ichthyofauna

The ichthyofauna of Lake Balkhash has been intensively manipulated during the twentieth century with the introduction of species from other hydrological basins of the Soviet Union. Introductions caused major changes in the dominating species, replacing native ones by imported taxa. In general, the fish-species diversity decreased, and benefits of the substitution of native species by alien species on the potential total catch are doubtful (Mitrofanov and Petr 1999).

The modern ichthyofauna of Lake Balkhash includes 26 species. The Balkhash marinka *Schizothorax argentatus*, the Ili marinka *Sch. pseudaksaiensis pseudaksaiensis*, the Balkhash perch *Perca schrenkii*, the spotted stone loach *Triplophysa strauchi*, the plain thicklip loach *Barbatula labiata* and the Balkhash minnow

Lagowskiella poljakowi are native.[20] All other fishes are recent introductions or invaders.

Commercially valuable among native fishes are the Balkhash marinka, Ili marinka and Balkhash perch (Abrosov 1973; Karpevich 1975). The Balkhash marinka maintained commercial value and was found throughout the lake until the mid-1960s; but it is now, together with spotted stone loach, absent in the lake and only remaining in some rivers. The Balkhash perch is now found in small numbers, occurring only in the deltaic lakes of the Ili River, in some bays of Lake Balkhash, and in the Ayaguz River (Mamilov et al. 2013).

The ichthyofauna of the Balkhash and of the rivers of the basin was enhanced by 22 fish species during the twentieth century as a result of human activities, intentionally introduced or incidentally brought in together with intentionally introduced fish (Karpevich 1975).

- The first invader was the carp *Cyprinus carpio*. Originally (1905), it entered accidentally into the Ili River from a fish pond and then appeared in the lake. By the end of the 1920s, it became the main commercial species of the Balkhash.
- The Siberian dace *Leuciscus leuciscus* is also an auto-acclimatizant. It was initially brought into the Ayaguz River where it was discovered in 1928, and it appeared in the lake in 1950.
- In 1931, the Aral barbel *Barbus brachycephalus* was brought from the Syr Darya into the Ili from where it soon penetrated and settled into the lake (Karpevich 1975). The Aral barbel is currently not found in the lake anymore (Mamilov et al. 2013).
- In 1933–1934, the ship sturgeon *Acipenser nudiventris* was introduced from the Aral Sea. It became one of the widespread commercial species prior to the construction of the Kapchagai Reservoir (Karpevich 1975), but it is relatively rare today (Mamilov et al. 2013).
- In 1948, the tench *Tinca tinca*, although not recommended for introduction, was brought from the Zaisan Lake into the Ili River Basin.
- In 1949, the eastern bream *Abramis brama orientalis* (also not recommended) was introduced from the Syr Darya. It became a mass and commercial species. It is a food competitor of carp and marinka.
- In 1954, the Prussian carp *Carassius auratus gibelio* (also not recommended) was released into Karatal River and it then entered and settled in the lake, becoming a commercial species (Karpevich 1975).
- In 1957–1958, the zander *Sander lucioperca* was introduced as the first fish species recommended for acclimatization.
- Together with the zander, the predators wels *Silurus glanis*, asp *Aspius aspius* and the Volga zander *Sander volgensis* were accidentally also brought. They acclimatized successfully and became commercial fish species.
- In 1958 and in 1962, the recommended herbivorous grass carp *Cthenopharhyngodon idella* was introduced. This fish settled across the lake and penetrated into rivers, mostly in their deltas overgrown with aquatic vegetation (Karpevich 1975).

[20]The Ili marinka, Balkhash perch and spotted stone loach are endemics of Balkhash-Alakol Basin.

- Together with the grass carp, a coarse fish, the Chinese freshwater sleeper *Micropercops cinctus*, was brought into Balkhash (Seleznev 1974; Karpevich 1975; Reshetnikov 2010).
- In 1965, the not recommended vobla *Rutilus caspicus* and the Talas dace *Leuciscus lindbergi* were introduced accidentally.

5.5.3 Development of Fishery in Lake Balkhash During the Last 100 Years

Fisheries in Lake Balkhash developed in the early 1930s with the introduction of allochthonous species and the organization of collective fishing brigades. Catches, negligible during the 1920s (68–106 tons per year), soon increased and reached 14,650 tons in 1932, with common carp (*Cyprinus carpio*, accidentally introduced in 1905) accounting for 58–86% of the catch and the native perch and marinka for 4–30%, varying over the years.

During the 1940s and 1950s, following a natural reduction of the lake level and the lake's productivity, the average annual capture decreased by 40%. It recovered and reached former high numbers by the early 1960s. Then, the introduced common carp represented 76% of the total catch, native species such as perch and marinka 12 and 11%, respectively, and the freshwater bream the remaining 1%.

The building of the Kapchagai Reservoir (1970–1986) did not significantly affect the total catch but it changed the natural cycle of re-occurring spring floods. The hydrological regime of the Ili River was especially altered during the filling of the reservoir, and spawning and feeding areas of the commercially valuable *Cyprinus carpio* were reduced. Its populations consequently shrank by more than 90% and its yearly catch decreased from 12,000 to less than 2000 tons without recovery to high levels afterwards. The loss in catch of *Cyprinus carpio* was compensated by a higher catch of the freshwater bream which is a very adaptable and competitive but less valuable cyprinid. Its harvest grew from 100 to 8000 tons per year over the same period (Pueppke et al. 2018).

A clear drop of the annual catch accompanied the economical crisis that followed the end of the Soviet regime, attributed to several factors: (1) the decrease of lake productivity and reduction of spawning areas provoked by non-compliance with discharge schedules from the Kapchagai Reservoir; (2) the uncontrolled overexploitation of the fish stocks; and possibly (3) unregistered and unofficial catches by recreational trophy fishing. The re-establishment of controls and regulations temporarily improved the situation and the total catch recovered to 12,000 tons per year between 2002 and 2006. Afterwards, it fell again and the decline continued in most recent years. Between 2010 and 2017, the fish harvest decreased by 17%, mainly as a result of lower catches of the most valuable species (Pueppke et al. 2018).

5.6 Outlook

Lake Balkhash is facing serious risks in the near future totally depending on the collective will and decisions of the responsible agencies in Kazakhstan and China.

The most disastrous scenario would be an increase of the total water withdrawal from tributary rivers by 9 km^3, which would cause a lake-level drop to below 336 m asl and the division of Lake Balkhash in three to six different and partly dry basins and unbearable levels of salinization in the remaining water bodies.

Intermediate levels of water subtraction would also induce serious stress to the lake's ecosystem because the related increase of water salinity would restructure the ecological communities and deteriorate the reproduction conditions of aquatic organisms. The total gross production of phytoplankton, zooplankton and zoobenthos would be reduced (Krupa et al. 2013), and the overall decline in trophic state would have a devastating impact on the fish productivity of the lake.

Additional water withdrawal from the Ili River and non-compliance with discharge schedule from the Kapchagai Reservoir would inevitably affect the fish spawning areas. In the fresher western part of the lake, spawning areas would move following the retreat of the water, but in the eastern part, they would be reduced to the estuarine freshwater areas of the Karatal and Lepsy rivers with increasing lake-water mineralization.

The degradation of Lake Balkhash's ecosystem would favor the development of non-commercial and low-value fish species, while the number of fast-growing forms of carp, bream, asp and other commercial species would rapidly decline. As a result, fish resources of the lake would rapidly decline.

The water deficit will also lead to the degradation of the Ili River Delta (Dostay et al. 2012), which will lose most of its value for fishery. Shoaling and swamping of deltaic water bodies would be accompanied by overgrowth of tough vegetation, salinization and increasing concentration of humic acids with detrimental effects on the development of fish and other aquatic organisms.

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