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Large Asian Lakes in a Changing World

Natural State and Human Impact

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Preface

Lakes represent important ecosystems which are often biodiversity hotspots and important habitats for aquatic organisms and migratory birds. They represent economic resources for local fishery sectors and tourism activities, and provide invaluable ecosystem services. Concerns about biodiversity loss due to degraded water quality, shrinking lake areas and ecological consequences of species introductions inspired systematic and intensive monitoring programmes to support their sustainable use, improved management and more efficient conservation.

However, human impacts on lakes are almost omnipresent now, and there are only few regions on Earth left where lakes are not directly affected by local human activities. Even lakes in remote areas cannot be considered as pristine and in a fully natural state anymore due to anthropogenic changes of climate and biogeochemical cycles through emissions of greenhouse gases and reactive nitrogen which became apparent since the middle of the last century (Wolfe et al. 2013; Zalasiewicz et al. 2017).

Significant human impacts on lakes may have started much earlier than in the middle of the last century or even long before the Industrial Revolution in the eighteenth and nineteenth century, and it is not trivial to define a desired lake state more or less representing natural conditions as a baseline for the assessment of lake restoration measures (Kostianoy et al. 2004).

This book describes large lakes in Asia and their present state as a result of man-made alterations and conditions assumed as their natural state. Examples from mostly closed-basin lakes examine cases which are especially prone to human impacts on their catchment's water balance (Fig. 1). Past anthropogenic alterations of the lake systems may have been as dramatic as the included Aral and Dead seas. Described is also an oppositional example of a large closed-basin lake in Mongolia which experienced relatively minor impacts on the lake ecosystem so far.

The book provides a reference for the natural state of some of the largest lakes in Asia. Information on the natural states of lakes was collected from many sources including hardly accessible reports and data collections. Observational data from pre-impact periods were gathered, and proxy data from drilled or exposed lake sediment records were assessed to describe the natural state of lakes. Information

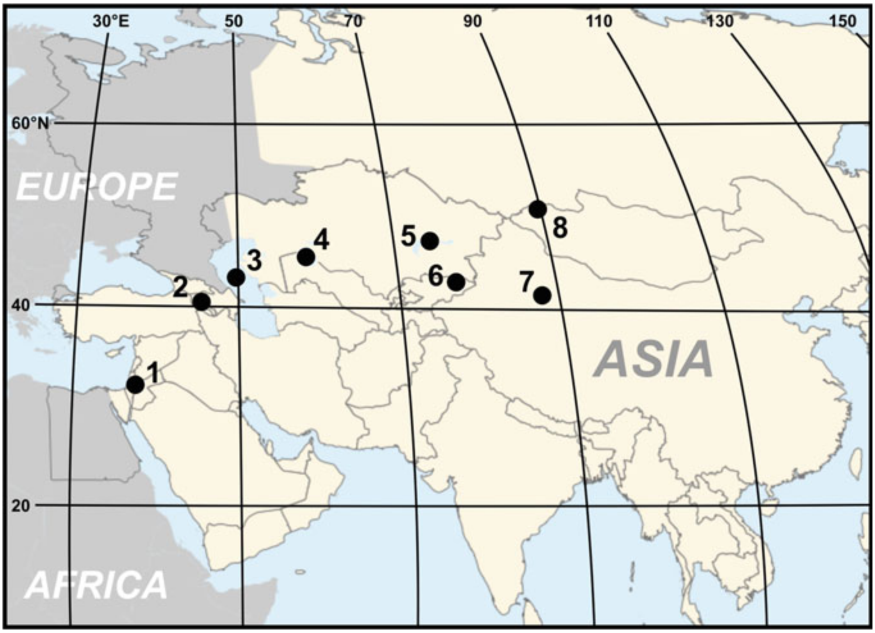

Fig. 1 Lakes included in this book: (1) the Dead Sea, (2) Lake Sevan, (3) the Caspian Sea, (4) the Aral Sea, (5) Lake Balkhash, (6) Lake Issyk-Kul, (7) Lake Lop Nur and (8) Lake Uvs Nuur

with respect to human impacts in the catchment of lakes such as water withdrawal from tributaries and concerning direct impacts on lakes (e.g. due to fishery activities and the introduction of alien species) were assembled. Both types of information, on the natural state of a lake and its alteration history as a result of human activities, will be crucial for the assessment of lake conditions in future and for endeavours of lake ecosystem restorations.

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Contents

Chapter 4
The Aral Sea: A Story of Devastation and Partial Recovery of a Large Lake

Philip Micklin, Nikolai V. Aladin, Tetsuro Chida, Nikolaus Boroffka, Igor S. Plotnikov, Sergey Krivonogov and Kristopher White

Abstract The Aral Sea was a huge brackish-water lake lying in a tectonic depression amidst the deserts of Central Asia. Water bodies of various dimensions have repeatedly filled this depression over the past several million years. Its modern incarnation is thought to be somewhat more than 20,000 years in age. In modern times, the sea supported a major fishery and functioned as a key regional transportation route. But since the 1960s, the Aral has undergone rapid desiccation and salinization, overwhelmingly the result of unsustainable expansion of irrigation that largely dried up its two tributary rivers, the Amu Dar'ya and Syr Dar'ya (dar'ya in the Turkic languages of Central Asia means river) before they reached the Aral Sea. The desiccation of the Aral Sea has had severe negative impacts, including, among others,

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the demise of commercial fishing, devastation of the floral and faunal biodiversity of the native ecosystems of the Syr and Amu Deltas, and increased frequency and strength of salt/dust storms. However, efforts have been and are being made to partially restore the sea's hydrology along with its biodiversity, and economic value. The northern part of the Aral has been separated from the southern part by a dike and dam, leading to a level rise and lower salinity. This has allowed native fishes to return from the rivers and revitalized the fishing industry. Partial preservation of the Western Basin of the southern Aral Sea may be possible, but these plans need much further environmental and economic analysis.

Keywords Lake history · Lake level · Irrigation · Water diversion · Dust · Salt

4.1 Introduction

The Aral Sea, in Russian "Aralskoye more" and in the Turkic languages of Central Asia "Aral Tengizi" (Kazak) or "Arol Dengizi" (Uzbek) is a terminal or closed-basin (endorheic) lake, lying amidst the vast deserts of Central Asia (Fig. 4.1). From the mid-seventeenth century until the 1960s, lake level variations were less than 4.5 m (Micklin 2016). During the first six decades of the twentieth century, the sea's water balance was remarkably stable and its annual average level fluctuated less

Fig. 4.1 Location of the Aral Sea in Central Asia. *Source* Micklin (2007)

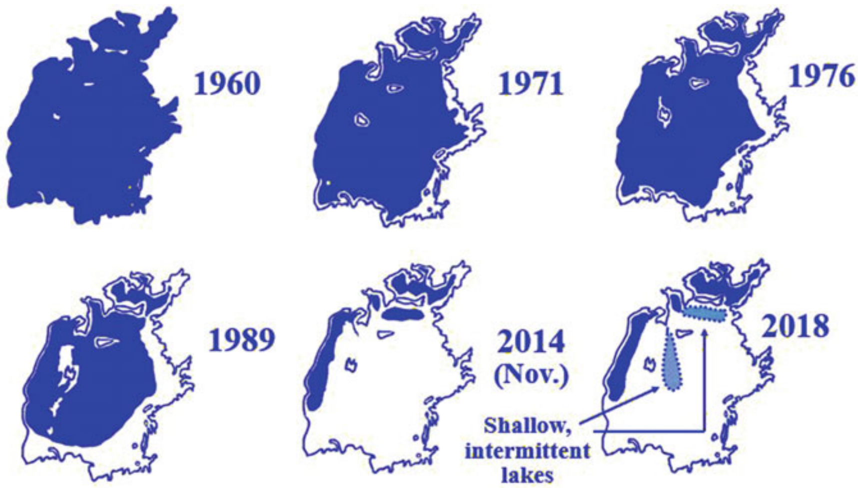


Fig. 4.2 The changing Aral Sea: 1960–2018

than a meter. At 67,500 km^2 in 1960, the Aral Sea was the world's fourth largest lake in surface area (Micklin 2010; Zonn et al. 2009). A brackish lake with salinity averaging near 10 grams/liter (g/l), less than a third of the ocean, it was inhabited by both freshwater and brackish-water fish species (Kostianoy and Kosarev 2010). The sea supported a major fishery and functioned as a key regional transportation route. The extensive deltas of the Syr Dar'ya and Amu Dar'ya sustained a diversity of flora and fauna, including endangered species. The deltas also had considerable economic importance supporting irrigated agriculture, animal husbandry, hunting and trapping, fishing, and harvesting of reeds, which served as fodder for livestock as well as building materials.

Post 1960, the Aral has undergone rapid desiccation and salinization, overwhelmingly the result of unsustainable expansion of irrigation that largely drained the two influent rivers (Fig. 4.2; Table 4.1). By June 2018 the Aral Sea consisted of five separate water bodies that at times are connected (Fig. 4.3). In summer 2014 the Eastern Basin of the Aral entirely dried. Its aggregate area and volume at that time were only 10% and 4%, respectively, of 1960 (Micklin 2016). Subsequently, the Eastern Basin has expanded and shrunk on a seasonal rhythm depending on inflow from tributary rivers. By June 2018, the level of the deeper Western Basin of the Aral Sea had fallen to a record low of a bit more than 23 m above the Kronstadt gauge (situated on the Gulf of Finland near St. Petersburg, Russia which has a zero 20 cm above ocean level), while owing to significant winter and spring inflow from the Amu Dar'ya and Syr Dar'ya, the very shallow Eastern Basin was somewhat higher (Table 4.1).

In the sections that follow we give a basic characterization of the Aral Sea in terms of basin history, natural state prior to the modern desiccation, human impacts on the lake, and future of the water body.

Table 4.1 Hydrological and salinity characteristics of the Aral Sea, 1960–2018

Year and portion of sea	Level (meters above Baltic Sea)	Area (km^2)	% 1960 area	Volume (km^3)	% 1960 volume	Average depth (meters)	Avg. salinity (g/l)	% 1960 salinity
1960 (all)	53.4	67,499	100	1089	100	16.1	10	100
Large	53.4	61,381	100	1007	100	16.4	10	100
Small	53.4	6118	100	82	100	13.4	10	100
1971 (all)	51.1	60,200	89	925	85	15.4	12	120
1976 (all)	48.3	55,700	83	763	70	13.7	14	140
1989 (all)		39,734	59	364	33	9.2		
Large	39.1	36,930	60	341	34	9.2	30	300
Small	40.2	2804	46	23	28	8.2	30	300
Sept 22, 2009 (all)		7146	10.6	83	7.7	10.8		
W. Basin Large	27	3588	26.2	56	17.9	15.1	>100	>1000
E. Basin Large	27	516	1.1	0.64	0.07	0.7	>150	>1500
Tshche-bas Gulf	28	292		0.51	7.1	1.4	~85	850
Small	42	3200	52	27	33	8.4	8	100–130
8/29 and 11/25, 2014 (all)		6990	10.4	81.7	4.4	6.9		
W. Basin Large	25.0	3120	22.8	54	17.2	15.4	>150	>1000

(continued)

Table 4.1 (continued)

E. Basin Large		0	0	0	0	0	0	0
Tshche-bas Gulf	28.5	372	NA	0.72	NA	1.4	89	890
Small	41.9	3197	52.3	27	33.2	8.5	8	80
6/20 and 6/21, 2018		9668	14.3	78.9	7.2	8.2		
W. Basin Large	23	2894	21	48	15.5	14.6	>150	>1500
E. Basin Large	27	2537	5.4	1.3	1.9	0.5	NA	NA
Tshche bas Gulf	28	403	NA	0.78	NA	1.9	85?	850?
Central Aral	29	422	NA	NA	NA	NA	NA	NA
Small	42+	3412	55.7	28.8	35.1	8.4	7	60

Sources (1) Values for 1960–1989 from Micklin (2010). (2) Area data for 2009, 2014 and 2018 calculated from MODIS 250-m resolution natural color images and Landsat 8 natural color images (30-m resolution) using ImageJ software (freeware developed by U.S. National Institutes of Health). (3) Volume data for 2009, 2014 and 2018 estimated from area changes. (4) Salinity data for 2009 are estimates based on measurements taken with a YSI-85 electronic meter during an expedition to the Aral Sea in September 2007 and in 2008. (5) Salinity data for 2013 based on measurements taken with the YSI-85 meter and an optical refractometer during an expedition to the Aral Sea in August and September 2011. (6) Salinity data for 2014 based on own data and data provided by Z. Ermakhanov, director of the Aral'sk Affiliate of the Kazakhstan Fisheries Institute. (7) Salinity data for 2018 based on data gathered at the Berg Strait dike and at Tastubek on the North Aral shore on May 31 and June 3, 2017

NA Not Available

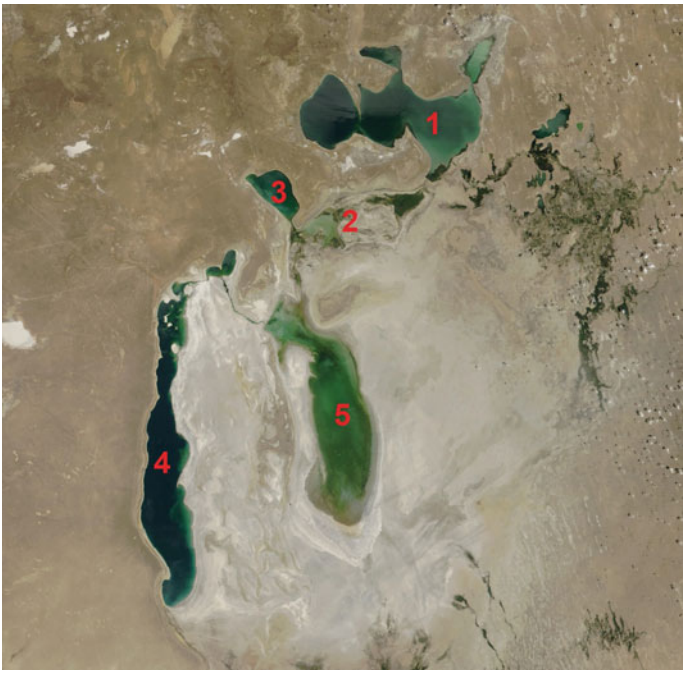


Fig. 4.3 MODIS 250-m resolution natural color image of the Aral Sea on June 20, 2018. Numbers indicate: 1—North Aral; 2—Central Aral; 3—Tshche-Bas Gulf; 4—Western Basin of Large Aral; 5—Eastern Basin of Large Aral. *Source* MODIS Rapid Response System (https://lance-modis.eosdis.nasa.gov/cgi-bin/imagery/realtime.cgi)

4.2 Basin History

Over the past three million years the Aral region was part of the Neogene Ponto-Caspian ancient seas (Akchagyl and Apsheron) and became a separate depression in the Pleistocene. Most experts believe that it began as a small depression, which collected local surface water. This runoff was slightly saline due to the dissolution of local salt deposits. When the water evaporated, it left behind a thin veneer of salts. The surface layer was highly sensitive to wind erosion. The process eventually deepened and enlarged the depression. The area was dry during a major part of the Pleistocene but geological data (Kes 1969, 1995; Rubanov et al. 1987) suggest large rivers reached the depression by the end of the middle to the beginning of the late Pleistocene, i.e., approximately 140,000 years before present (BP).

There have been several age estimates for the Aral Sea initiation. Lopatin (1957) calculated 18,000 years for the age of the Amu Dar'ya delta from its total volume and sedimentation rate. Chalov (1968), based on Uranium-isotope-ratio dating, concluded that the Aral Sea is as old as 139,000 ± 12,000 years, and that the Syr Dar'ya was the sole water source at that time. The Amu Dar'ya started to discharge water into the Aral Sea not earlier than 22,000 years ago. Kes (1995) believed that the highest level of the Aral Sea, up to 72 m above Kronstadt gauge occurred during the Last Glacial Maximum (LGM), and she referred to a terrace-derived ^{14}C date of 24,820 ± 820 years BP (Pshenin et al. 1984). Other experts, based on the bottom-sediment records, concluded the Aral is very young, up to 10,000 years, and the sediments reflect two shallow and deep-water stages in the middle Holocene (Nikolaev 1991, 1995). The most recent drilling data imply age of the deepest subbase layers of the lake sediments coarsely extrapolated to 19,000 years BP (Boomer 2012). The non-lacustrine substratum was dated to 23,800 years BP (Krivonogov 2014; Krivonogov et al. 2010). These ages were obtained from a cluster of boreholes to the south and north from Barsakelmes Island. The farthest to the south and the deepest borehole B-05-2009 is 15 m deep and includes 11 m of the Aral Sea sediments with a basal age of ca. 17,600 years BP (Burr et al. 2019). The previously published borehole depth (B-2008-01) east of Barsakelmes, where the sediments have been dated to 24,000 years BP, includes only 7 m of lacustrine sediments.

In general, researchers have placed the original filling stage of the Aral to 20,000 years BP (Oreshkin 1990, pp. 3–4). At this time and for a considerable period afterward, the Amu Dar'ya flowed westward into the Caspian Sea rather than northward into the Aral. The lake did not attain significant size until the Amu Dar'ya switched its course northward into the Aral Sea. This increased inflow to the lake by some threefold. It is believed to have occurred 10,000–20,000 years BP and was most likely due to a wetter climate that increased river discharge (Aladin et al. 1996). The Small (North) Aral only filled after the addition of the Amu's flow.

Approximately the last 10 millennia (corresponding with the Holocene Epoch) constitute the modern geological history of the Aral Sea (Micklin 2014a). Soviet scientists during the post-World War II era (from the late 1940s to 1991) intensively studied the evolution of the Aral over this time-period. Dating of relict shore terraces, fossils and deposits of various salts precipitating from the sea contained in sediment cores from the sea bottom, and of archeological sites, along with historical records point to repeated major recessions and transgressions of the sea.

Kes (1978), based on studies of terraces, believed lake level could have been as high as 57–58, 62–63 or even 70–73 m, measured above the Kronstadt gauge. The highest reliable standings of the sea discussed in early literature (e.g., Lymarev 1967; Rubanov et al. 1987) are the "Ancient Aral Transgression" that reached an estimated 57–58 m and lasted from approximately 2800–2000 years BP, "New Aral" at 54–55 m reached around 1000 years ago and the pre-1960 level around 53 m that dates from around the middle seventeenth century (350 years BP). More recent investigations using GIS and GPS techniques indicate the highest level the Aral reached over the last 10,000 years was no more than 54–55 m above sea level (Boomer et al. 2009; Boroffka et al. 2006; Reinhardt et al. 2008) and confirm the idea of Berg (1908) that the Aral never overflowed into the Sarykamysh Lake and Uzboy channel leading to the Caspian Sea. Feeding of the Sarykamysh and Uzboy was from direct diversions of the Amu Dar'ya. Diversions of the Amu Dar'ya westward toward the Caspian Sea caused regressions of the Aral. The change from a wetter to dryer climate leading to less flow into the Aral from both the Syr Dar'ya and Amu Dar'ya no doubt also affected lake levels.

Researchers from Moscow State University (Mayev et al. 1983, 1991; Mayeva and Mayev 1991) were the first who investigated and dated the Aral Sea sediment cores. They believed there were nine major regression/transgression cycles during the Holocene and showed that deep regressions were typical features in the Aral history. The deepest regression recorded by these authors was the so-called stage of the "Oxus swamp" that occurred about 1600 years BP (the radiocarbon dates were calibrated by Krivonogov et al. 2014), when the delta of the Syr Dar'ya was situated near the central part of the Large Aral Basin. The early transgressions and regressions of the sea are still not as well-known as later events. The level history for the second half of the Holocene (6000 years BP to the beginning of the modern drying in the 1960s) is better understood and the history of the last 2000 years is even more fully comprehended (Boroffka et al. 2006; Oberhänsli et al. 2007).

Regressions of the sea are related to the partial or full diversion of the Amu Dar'ya westward into the Sarykamysh Depression and from there via the Uzboy channel to the Caspian Sea. The change from a wetter to dryer climate leading to less flow into the Aral from both the Syr Dar'ya and Amu Dar'ya no doubt also played a role but cannot account for the size and rapidity of the most significant level declines.

Ancient civilizations also affected Aral levels. Human impacts included sizable irrigation withdrawals and periodic diversions of the Amu Dar'ya westward into the Sarykamysh Depression and Uzboy Channel. The first evidence of irrigation along the Amu dates to 3000 years ago (Kes 1978; Lunezheva et al. 1987, 1988) and irrigation may have covered five million hectares at times during the fourth century B.C. to fourth century A.D. (Micklin 2014b). However, the impact of ancient irrigation on river inflow to the sea was probably not as significant as it might seem (Kes 1978). Fields were small and withdrawals per hectare irrigated were much less than modern. Also, a much larger percentage of water withdrawn was returned via drainage flows to the rivers rather than being "lost" to evaporation in the arid surrounding deserts. Finally, canals were built and abandoned over time so that the area irrigated in a specific year was far smaller than the area covered by canal systems.

Human-caused diversions were by far the most important influence on levels over the past millennium. Some of these were accidental, caused by breaching of dikes and dams constructed for irrigation purposes during heavy flows of the river. Others occurred during wars and were purposeful with the intent to deprive an enemy of both water for drinking and irrigating crops. Thus, in 1221 the forces of Genghis Khan wrecked irrigation systems in Khorezem Khanate (Bartold 1902; Berg 1908). This caused the Amu to turn its course from northward to the Aral to westward into the Sarykamysh Depression and the Caspian Sea. A similar story is reported about Timur (Tamerlane) who is reputed to have diverted the Amu Dar'ya westward in 1406 to flood the city of Urgench in order to force its surrender. There is ample archeological and historical evidence of repeated settlement and agriculture around the Sarykamysh Depression and along the Uzboy, which would only be possible when the former was flooded and the latter contained a river (Vainberg 1999).

Research on historic level fluctuations of the Aral diminished greatly after the collapse of the USSR in 1991. The lake was no longer of great interest to research institutions in Moscow and Leningrad that had studied it both during Tsarist and Soviet times. Since the late 1990s, however, there has been resurgent interest in the topic. Motivating factors have been the need to better understand the modern regression by delving into past drying events and the fact that the receding sea is uncovering shoreline terraces, former river beds, archeological finds, and other evidence whose analysis provides a much clearer picture of past regressions than had hitherto been possible.

The most ambitious effort was developed within the CLIMAN Project (Holocene Climatic Variability and Evolution of Human Settlement in the Aral Sea Basin) in 2002–2005, funded by the European Union's INTAS Project (1993–1993–2007). The Aral-related program was intended as an interdisciplinary study to help distinguish between climatic variations and anthropogenically controlled environmental changes in the past (Boroffka et al. 2006; Oberhänsli et al. 2007). The focus was on previous lake levels and the evolution of human settlement and agriculture in the Aral Sea Basin. Differential GPS elevation measurements of shorelines around the sea convincingly argued against the Aral's level standing any higher than about 55 m for at least the past 35,000 years (Reinhardt et al. 2008). Based on archeological evidence, relict shorelines, and sediment core analyses, the CLIMAN group delineated seven transgressions and six regressions over the past 5,000 years. However, the best documented of these (by sediment cores analyses and shoreline traces) are four regressions dated to 350–450, 700–780, around 1400, and 1600–2000 years BP (Austin et al. 2007; Huang et al. 2011; Oberhänsli et al. 2011; Sorrel et al. 2006, 2007a, b).

The second post-Soviet effort to reveal changes of the Aral Sea level was the joint US CRDF—Russian RFBR project "Environmental history of the Aral Sea in the last 10,000 years: natural and anthropogenic components" in 2008–2010. The key activity was drilling and dating the sediments in the dry bottom of the Large Aral Basin. A series of high and low stands were identified through the Holocene (Krivonogov 2014; Krivonogov et al. 2010). Special attention was paid to the last 2000 years, for which two large regressions and two transgressions (prior to the modern technogenic regression) were substantiated by multiproxy data both original and published by predecessors (Krivonogov et al. 2014). Special attention was paid to the extent and timing of the last major desiccation of the Aral prior to the modern drying (Krivonogov 2009; Krivonogov et al. 2014).

The regression occurred from the 11th to sixteenth centuries when the level may have fallen below 29 m above the zero level of the Kronstadt gauge. Historical records as well as archeological sites, preserved tree stumps, and relict river channels on the dried bottom of the Aral attest to this event. The most convincing evidence was the discovery by Kazakh hunters at the end of the twentieth century of a mazar (Islamic holy gravesite) on the dried bottom of the Eastern Large Aral, northeast of the former Island of Barsakelmes, which in the early 1960s was 19 m below the surface of the Aral (Boroffka et al. 2005, 2006; Micklin 2007; Smagulov 2001, 2002). The gravesite is known as Kerdery #1. Consequently, two other archeological sites were found at about ten kilometers from Kerdery #1: Aral-Asar settlement and Kerdery #2 gravesite (Catalogue 2007). Archeologists date the sites in the range from late 13th to early fifteenth centuries. Radiocarbon dating of wood and bones from the sites (Krivonogov et al. 2010, 2014) gave a range of 500–1000 years BP.

The major cause of this recession very likely was an anthropogenic diversion of the Amu westward toward the Caspian Sea prior to the Mongol invasion of Central Asia in the thirteenth century. The Mongol intrusion probably increased this effect. The Amu returned (or was returned) to the Aral and the sea recovered by the mid-1600s. The sea was generally in a relatively stable "high" phase until the modern regression began in the early 1960s. Level fluctuations were no more than 4–4.5 m and were chiefly related to climatic variation with, perhaps, some effects from irrigation.

4.3 Natural State of the Aral Sea Prior to the Modern Desiccation

The Aral Sea, as nearly all the earth's large lakes, has suffered significantly from human actions for some time. So, to speak of its "natural state" we would need to go back several thousand years as made clear in the section above on the lake's history. The discussion below is focused primarily on the condition of the lake during the first six decades of the twentieth century prior to the modern desiccation that started in the 1960s.

4.3.1 Geographical Setting of the Aral Sea

The Aral Sea is in the heart of Central Asia on the Eurasian continent (Fig. 4.1). Its drainage basin covers 2.2 million km^2 (World Bank 1998, p. 1). The basin is mainly lowland desert (Micklin 2014a). The climate is desert and semi-desert with cold winters and hot summers in the north and central parts and very hot summers and cool winters in the south (Goode's World Atlas 1982, pp. 8–9). High mountains ring the basin on the east and south (Tian Shan, Pamir, Kopet-Dag), with peaks in the Pamirs over 7000 m.

Annual precipitation in the lowland deserts ranges from less than 100 mm to the south and east of the Aral Sea to near 200 mm approaching the foothills of the southeastern mountains (Atlas of the USSR 1983, p. 102) The foothills and valleys of the mountainous south and southeast are substantially more humid with precipitation ranging from 200 to over 500 mm. The high Pamir and Tian Shan ranges are wet with average annual precipitation from 800 to 1600 mm giving this zone a marked surplus of moisture. This, in turn, has created large permanent snow-fields and glaciers that feed the two major rivers, the Amu Dar'ya and Syr Dar'ya, flowing across the deserts to the Aral Sea.

4.3.2 Hydrology of the Aral Sea Basin

Although the majority of the Aral Sea Basin is desert, it has substantial water resources. The mountains on the south and southeast capture the plentiful precipitation, storing most of it in snowfields and glaciers (Micklin 2014a, c). Runoff from these, heaviest during the spring-early summer thaw, feeds the region's rivers. Estimated average annual river flow in the Aral Sea Basin is 116 km^3, including flow of the drainage basins of the Amu Dar'ya and Syr Dar'ya.

The Amu is the most important river within the Aral Sea Basin. Originating primarily among the glaciers and snowfields of the Pamir Mountains of Tajikistan, its drainage basin covers 465,000 km^2. The river flows 2620 km from the mountains across the Kara-Kum Desert and into the Aral Sea. During this journey, the river flows along the borders and across four Central Asian nations: Tajikistan, Afghanistan, Turkmenistan, and Uzbekistan, entering, leaving, and reentering the last two states several times (Fig. 4.1).

Average annual flow from the drainage basin of the Amu is around 79 km^3. This includes not only the flow of the Amu Dar'ya and its tributaries but several "terminal" rivers that disappear in the deserts (Micklin 2000, pp. 6–7). The Amu is "exotic," which, hydrologically means that essentially all its flow originates in the well-watered Pamir Mountains, but that this flow is substantially diminished by evaporation, transpiration from vegetation growing along its banks, and bed exfiltration as the river passes across the Kara–Kum Desert to the Aral Sea. The Amu Delta accounted for very large flow losses owing to evaporation and transpiration. Prior to the Aral Sea's modern desiccation, average annual inflow of the river to it decreased to 40 km^3 from the 62 km^3 coming out of the Pamir Mountains on to the desert plain of Turkmenistan.

The Syr Dar'ya flows from the Tian Shan Mountains, located to the north of the Pamirs. The melt of glaciers and snowfields are its main source of water. Its drainage basin covers 462,000 km^2. With a length of 3078 km, it is longer than the Amu (Micklin 2014a). Average annual flow of the Syr at 37 km^3, is considerably less than that of the Amu. Prior to the 1960s, flow diminution was substantial during its long journey across the Kyzyl-Kum Desert with less than half (around 15 km^3 on an average annual basis) of the water coming from the mountains reaching the Aral Sea.

4.3.3 Physical Characteristics of the Aral Sea Before the Modern Desiccation

The Aral Sea lies at the bottom of the Turan Depression by the eastern edge of the Ust-Urt Plateau (Bortnik and Chistyayeva 1990, p. 6). Its name derives from the word Aral, which means "island" in the Turkic languages of Central Asia. It may have been thusly named because it was an "island of water" in the vastness of the

Central Asian deserts. The name may also be connected to the many islands present in the sea prior to its modern desiccation (Ashirbekov and Zonn 2003, p. 6).

The Aral Sea occupies the lowest part of a vast erosional-tectonic hollow of middle Cenozoic age (Micklin 2016). It is geologically young, having arisen at the end of the Quaternary period, coincident with the last glacial epoch about 20,000 years BP (Boomer 2012; Burr et al. 2019; Krivonogov 2014). The lake's level in 1960 was 53.4 m with an area of 67,499 km^2, making it the world's fourth largest lake in extent at that time after the Caspian Sea in Eurasia (371,000 km^2), Lake Superior in North America (82,414 km^2) and Lake Victoria in Africa (69,485 km^2; Micklin 2014a; Table 4.1). The Aral in 1960 had a maximum depth of 69 m, average depth of 16 m, volume of 1089 km^3, and shoreline stretching for more than 4430 km. More than 1100 islands, with an aggregate area of 2235 km^2 dotted the sea. The largest were Kok-Aral (311 km^2), Barsakelmes (170 km^2) and Vozrozhdeniya (170 km^2; Kosarev 1975, p. 23).

The Aral was divided into a so-called "Small Sea" (or "North Aral") on the north and "Large Sea" (or "South Aral") to the south, which were connected by the Berg Strait. The Small Aral had an area of 6118 km^2, volume of 82 km^3, maximum depth of 29 m and average depth of 13.4 m (Table 4.1). It consisted of a deeper central basin and several shallower gulfs. The largest town and most important port and fishing center (Aral'sk) was situated at the northern end of the Gulf of Saryshaganak.

The Large Aral had a considerably greater surface area and volume (61,381 km^2 and 1007 km^3). It was divided into two basins by a north-south stretching underwater ridge that protruded through the surface to form a chain of small islands, the largest of which was named Vozrozhdeniye ("Resurrection"). This island became famous, perhaps better to say "infamous" as the location of the USSR's most important, super-secret testing grounds for biological weapons. The Eastern Basin had an area of 47,461 km^2 and the Western Basin 13,920 km^2. However, the former was shallow (maximum depth of 28.4 m and average depth of 14.7 m) whereas the Western Basin was considerably deeper with a maximum depth of 69 m and average depth of 22.2 m (Micklin 2014a).

The estimated average annual water balance for the Aral Sea for 1911–1960 (considered the quasi-stationary period for the Aral's level) is below (Bortnik and Chistyayeva 1990, Table 4.1, p. 36, Fig. 2.5, p. 20, pp. 34–39).

1. **Gain**: river inflow (56 km^3) + sea-surface precipitation (9.1 km^3) = 65.1 km^3
2. **Loss**: sea-surface evaporation = 66.1 km^3
3. **Volume change** = (−1.0 km^3)

The main elements determining the Aral's level, area, and volume were river inflow and surface evaporation, with sea-surface precipitation playing a secondary role on the gain side of the balance. There was also a net groundwater inflow, but it was believed small (up to 3.4 km^3) and ignored in calculating the sea's water budget.

The Aral Sea was brackish with an average salinity around 10 g/l, slightly less than one-third that of the open ocean. Salinity was lower than the average near the entrance of the two main rivers, particularly during peak-river inflow in spring/early summer when it could fall below 4 g/l near the mouth of the Amu. High salinity levels (17–18 g/l) were reached during summer and winter in the gulfs of the east and southeast part of the Large Aral owing to high rates of evaporation during summer and ice formation (which concentrates salts in the remaining water volume thus raising salinity) in winter (Kosarev 1975, p. 228). Levels of salinity in isolated portions of the Gulf of Saryshaganak could reach 80–150 g/l.

Researchers considered Aral water exceptionally transparent (Zenkevich 1963, p. 510). On average, a Secchi disk, used to determine this, could be seen at 8.2 m, with maximum readings of 23.5 m in the central part of the Large Aral, 24 m in the Small Aral, and 27 m in Chernishov Gulf at the northern end of the Western Basin of the Large Sea (Bortnik and Chistyayeva 1990, p. 95).

Maximum water temperatures were reached in July and August, when the surface layer along the shoreline could reach 29 °C and 24–26 °C in the open sea (Bortnik and Chistyayeva 1990, pp. 43–49; Zenkevich 1963, Table 236, p. 510). As heating of the water mass progressed, a significant thermocline and temperature discontinuity formed in the deep Western Basin of the Large Sea, where the surface temperature would average around 24 °C while at depths below 30 m it would range from 2 to 6 °C. The shallower Eastern Basin of the Large Sea, on the other hand, had relatively uniform temperatures throughout the water column, with a difference of only a few degrees between the surface and bottom.

Vertical stability was primarily determined by temperature and only in the southern parts of the sea by both temperature and salinity (Bortnik and Chistyayeva 1990, pp. 82–85; Kosarev 1975, pp. 237–240, 247–260). Intensive heating of the Aral's surface waters in spring and summer led to the formation of a stable surface layer (down to the temperature discontinuity) and a stable bottom layer below that. Hence mixing between the surface and bottom layers was prevented. With the onset of cooling in fall, the surface to bottom temperature gradient weakened considerably, sometimes turning negative, leading to greatly diminished stability and convective mixing. During winter, ice formation and the resulting salt concentration increased surface water layer density and further enhanced convective mixing. The fall-winter convective mixing, which affected all parts of the sea and encompassed all water layers was considered the most important process determining the hydrologic structure of the Aral waters, particularly for the deeper parts of the sea.

4.3.4 Biology of the Aral Sea Prior to the Modern Desiccation

The aboriginal fauna of the Aral Sea was represented by more than 200 species of free-living invertebrates (Mordukhai-Boltovskoi 1974; Plotnikov 2016), over 200 species of parasitic invertebrates (Osmanov et al. 1976) and 20 species of fish (Nikolsky 1940). Among the species of free-living invertebrates, the inhabitants of freshwater, brackish-water and saline continental waterbodies composed 78% Ponto-Caspian species (species originating from the Black and Caspian seas that are relict fauna of the ancient Paratethys Ocean—these seas are its remnants). In modern times, most

Ponto-Caspian species are endemics living primarily in the Black Sea, Sea of Azov and Caspian Sea; only a few lived in the Aral prior to its modern drying.

The abundance of only a few species of free-living invertebrates in the Aral was high. Among the zooplankton, the most numerous copepod *Arctodiaptomus salinus* represented fauna of continental saline water bodies. Ponto-Caspian cladocerans *Cercopagis pengoi aralensis, Evadne anonyx, Podonevadne camptonyx* and *P. angusta* were also numerous. Among the freshwater euryhaline Cyclopoida, the most common was *Mesocyclops leuckarti*. The highest diversity of zooplankton was in the freshened parts of the sea due to freshwater species (Andreev 1989; Kortunova 1975).

Freshwater and Caspian species prevailed in the aboriginal benthic fauna of the Aral Sea. Its basis was mollusks, oligochaetes, higher crustaceans and larvae of Chironomidae (Mordukhai-Boltovskoi 1974). Bivalve mollusks were numerous, including *Dreissena* spp. and *Hypanis* spp., oligochaetes *Nais elingius* and *Paranais simplex*, ostracod *Cyprideis torosa*, amphipod *Dikerogammarus aralensis*, larval chironomids *Chironomus behningi* and caddis flies *Oecetis intima.* Mollusks accounted for 63% of zoobenthos biomass, and chironomid larvae for 33% (Karpevich 1975).

Almost all aboriginal ichthyofauna of the Aral Sea consisted of generatively freshwater (usually breeding in freshwater) species. In it, 60% were cyprinids (Ermakhanov et al. 2012; Nikolsky 1940). The best places for spawning were freshened bayside deltas, rivers and deltaic lakes. All aboriginal fish, except for the stickleback, *Pungitius platygaster aralensis*, whose main food was zooplankton, were benthophagous (feeding on bottom-dwelling organisms) or predators (Nikolsky 1940).

Vegetation and flora of aquatic and coastal-aquatic plants were monotonous and poor by species. Only two species and two plant communities dominated—reeds in coastal shallow waters and eelgrass (*Zostera*) at depths of up to 11 m on silty sands. In the central part on muds charophytes were found at depths of 11–22 m, and in the shallows—watermilfoil *Myriophyllum* sp. and pondweed *Potamogeton perfoliatus*. By the 1960s in the Aral Sea flora 24 species of higher plants, six species of charophytes and about 40 other species of macroalgae were known. Aquatic vegetation formed zones of helophytes (plants rooted in the bottom, but with leaves above the waterline) and zones of hydrophytes (plants that complete their entire life cycle submerged, or with only their flowers above the waterline). Along the shore reed-beds of *Phragmites australis* dominated. In the northern part of the sea beyond the reed zone often was a zone of bulrush *Scirpus kasachstanicum*. Other helophytes did not form large thickets (Plotnikov et al. 2014a).

Communities of hydrophytes presented diverse associations that formed vast underwater meadows. Extensive deep-water thickets of Charophyta existed at the beginning of the twentieth century but were absent by the 1950s. In their place, yellow-green algae *Vaucheria dichotoma* were found. In freshened bays, the basis of macrophytobenthos was higher flowering plants. In closed saline bays and inlets charophytes dominated (Plotnikov et al. 2014a).

4.4 Human Impact on the Aral in the Modern Era (Mainly Post 1960)

Humans have affected the Aral Sea in important ways for millennia as has been discussed above in Sect. 4.2 on Basin History. However, the human touch has been especially dramatic, powerful and far reaching since the 1960s. The subsections that follow provide a description and discussion of the major changes that have and are unfolding.

4.4.1 The Changing Physical Character of the Sea and Surrounding Region

The physical character of the Aral has undergone unprecedented changes since 1960. Sadly, these have not been as well studied, documented and analyzed as one would wish as the well-developed and pursued research and monitoring effort on the Aral Sea in the years 1925–1941 and after World-War II faltered in the 1970s and 1980s as the sea shrank and shallowed at a rapid pace, hydrometeorological stations closed and cruises by research ships became more difficult and infrequent (Bortnik and Chistyayeva 1990). The situation worsened after the Soviet Union collapsed at the end of 1991, and the Aral Sea became part of the two new riparian countries Kazakhstan and Uzbekistan. But since the mid-1990s matters have somewhat improved as research on the Aral has been renewed and revitalized by funding from national, regional, and international organizations and conducted by both national and international research teams.

Since the early 1960s, the sea has steadily shrunk and salinized (Table 4.1). The main causative factor has been expanding irrigation that greatly diminished discharge from the two tributary rivers Amu Dar'ya and Syr Dar'ya (Micklin 2014c, 2016). Irrigation has been practiced in the Aral Sea Basin for at least three millennia. Until the 1960s this did not substantially diminish inflow to the sea, owing to substantial return flows from irrigated fields to the Amu Dar'ya and Syr Dar'ya and other compensatory factors such as reduced losses to transpiration from phreatophytes (water-loving plants) along the lower courses of the rivers and in the deltas as well as lowered evaporation from reduced spring flooding in the deltas of these rivers. However, growth in the irrigated area from around 5 million ha in 1960 to 8.2 million by 2010 pushed irrigation development beyond the point of sustainability reducing or eliminating these compensatory effects and leading to a marked reduction of river discharge to the Aral.

River inflow to the Aral began declining in the 1960s and accelerated in the 1970s and 1980s. More precipitation in the mountains and some reduction in irrigation withdrawals increased river discharge during the 1990s and reduced the water balance deficit, slowing the sea's recession (Cretaux et al. 2019). There was a severe drought in 2000–2001 and, consequently, river inflow was very low (Micklin 2014c). Higher inflows on the Amu Dar'ya characterized the period 2002 through 2005 and water balance deficits for the Large Aral were significantly lessened. However, dry conditions returned from 2006 to the middle of 2009 resulting in rapid drop of lake level, reduction of surface area and volume accompanied by rising salinity (Table 4.1).

The Aral separated into two water bodies in 1987–1989—a "Small" Aral Sea in the north, also known as the North Aral Sea and a "Large" Aral Sea in the south (Micklin 2014e). The Syr Dar'ya flows into the Small Aral, and the Amu Dar'ya into the Large Aral. A channel formed connecting the two lakes, allowing water to flow from the former to the latter. Local authorities constructed an earthen dike in 1992 to block outflow to raise the level of the Small Sea, lower salinity, and improve ecological and fishery conditions. This makeshift construction breached and was repaired several times. In April 1999 after the level of the Small Aral had risen well over 43 m, the dike was overtopped, breached and destroyed during a wind storm, with the death of two people.

Under study and design since 1993, the World Bank and the Government of Kazakhstan funded construction of an engineeringly sound 13-km earthen dike with a concrete, gated outflow-control structure to regulate the flow from the Small to Large seas. Construction was completed from 2003 to 2005 (Aladin 2014; Dam of the North Aral Sea and the hydrocomplex Aklak 2017; Micklin 2014e, 2016; World Bank 2001, 2014). The structure raised and stabilized the level of the Small Aral at near 42 m above the Baltic Sea in early 2006. The total cost of this project was 23.2 million USD, but other related infrastructure projects along the Syr Dar'ya added another 62.6 million USD to project costs for a total of 85.8 million. The World Bank provided a loan of 64.5 million and the Government of Kazakhstan funded the remaining 21.3 million.

The desiccation of the Aral Sea has had severe negative impacts (Micklin 2007, 2014d, 2014f, 2016; Micklin and Aladin 2008). The vibrant commercial fishing industry ended in the early 1980s as the brackish-water indigenous species that provided the basis for the fishery disappeared owing to their inability to adjust to rising salinity. The more salinity-tolerant Black Sea flounder (*Platichthys flesus lulscus*) was introduced to the Aral in the 1970s. It flourished in the Small Aral and provided a sizable non-commercial catch. But it disappeared from the Large Aral as salinity rose. Tens-of-thousands of people were thrown out of work because of the loss of the commercial fishery and associated activities. Employment in these occupations today, although rising owing to the partial recovery of the North Aral Sea (discussed below), remains only a fraction of what it was.

The level-stabilization project reinvigorated the fishery in the North Aral by lowering average salinity below the 10 g/l level of the early 1960s (Ermakhanov et al. 2012; Plotnikov et al. 2014a, b; Toman et al. 2015; White 2016). This has allowed the return and flourishing of commercially valuable indigenous species such as the Sudak or Pike-perch (*Lucioperca lucioperca*), Sazan (*Cyprinus carpio*) and Lyeshch or Bream (*Abramis brama orientalis*), types of carp, Plotva or Roach (*Rutilis rutilis aralensis*) as well as several other species. The North Aral catch rose from 695 metric tons in 2005 to 6000 metric tons in 2016 (Micklin et al. 2018). Unfortunately, millions of fish are being carried over the discharge gates of the Kok-Aral dam and ending up in the Central Aral where they perish from higher salinity and temperatures and lower dissolved oxygen than in the North Aral.

The formerly biologically diverse and rich ecosystems of the deltas of the Amu Dar'ya and Syr Dar'ya have suffered considerable harm from reduced river flows, elimination of spring floods, and declining groundwater levels leading to spreading desertification (Micklin 2000, pp. 13–23; 2014d; Novikova 1999). Salts have formed pans (solonchak) on the surface where practically nothing will grow. Expanses of unique Tugay forests along the main and secondary watercourses have drastically shrunk. Desiccation of the deltas has significantly diminished the area of lakes, wetlands, and their associated reed communities. These changes caused the number of species of mammals and birds to drop precipitously. Strong winds blow sand, salt and dust from the dried bottom of the Aral Sea onto surrounding lands causing harm to natural vegetation, crops, and wild and domestic animals (Indoitu et al. 2015; Novikova 1996, 1999). As most of the sea has dried and more of the bottom has been exposed, dust storms with entrained salts in particulate and aerosol (a colloid of fine solid particles or liquid droplets in air) form have become more frequent and intense, covering at times more than 100,000 km^2 and extending downwind more than 500 km.

Owing to the sea's shrinkage, climate has significantly changed in a band up to 100 km wide along the former shoreline in Kazakhstan and Uzbekistan (Micklin 2014a). Summers have warmed and winters cooled, spring frosts are later and fall frosts earlier, humidity is lower, and the growing season shorter. The population living around the sea suffers acute health problems (Micklin 2007, 2014d). Some of these are direct consequences of the sea's recession such as respiratory and digestive afflictions from inhalation of blowing salt and dust and poorer diets from the loss of Aral fish as a major protein source.

The darkest consequence of the Aral's modern shrinkage is what has happened to Vozrozhdeniya Island (Micklin 2007, 2014d). The Soviet military in the early 1950s selected this, at the time, tiny, isolated island in the middle of the Aral Sea, as the primary testing ground for its super-secret bioweapons program. This program stopped with the collapse of the USSR in 1991. As the sea shrank, Vozrozhdeniya grew and in 2001 united with the mainland to the south as a peninsula. There was concern that weaponized organisms survived decontamination measures by the departing Russian military and could escape to the mainland via infected rodents or that terrorists might gain access to them. The U.S. government worked with the Government of Uzbekistan to ensure the destruction of any surviving weaponized pathogens in 2000.

By September 2009, the Aral had shrunk to a small remnant of its 1960 size and separated into four parts (Table 4.1). The dike and dam constructed to regulate flow from the Small to Large Aral had raised and stabilized the level of the former leading to greatly improved ecological conditions and a revitalized fishery. The Large Sea in the south was not so fortunate. The level of the deeper Western Basin (max. depth 69 m in 1960) had fallen 26 m and salinities reached over 100 g/l, creating conditions where fishes could not survive. The Eastern Basin became a shallow pond with salinity likely above 150 g/l. It appeared that it would dry up completely during the summer of 2010. However, a heavy flow year on the Amu in 2010 partially revitalized the basin. In summer 2014 the Eastern Basin dried completely for probably the first time in 600 years. Since then, the Eastern Basin has expanded and shrunk on a seasonal rhythm related to the annual hydrologic flow pattern combined with longer-term cycles of wet and dry years in the Aral Sea Basin. Table 4.1 and Fig. 4.2 show the physical characteristics of the Aral in June 2018.

The physical and chemical character of the Aral Sea has also changed dramatically as the unitary water body shrunk, salinized and separated into multiple lakes with different hydrologic parameters. A dearth of primary field work has made a comprehensive picture of changes impossible. But according to scientists from the Shirshov Institute of Oceanology in Moscow who along with an international team studied the Aral (mainly the deeper Western Basin, of the Large Aral) in 12 expeditions between 2002 and 2010 (Zavialov et al. 2012, p. 212.):

> The shallowing of the sea and accompanying changes of its morphometric characteristics, mainly the catastrophic salinization led to deep transformations of its physical and chemical regimes, all processes determining its condition and dynamics – from large-scale circulation to turbulent mixing and from the variability of the ionic-salt composition to the energy exchange with the atmosphere.

Among other findings, instrumental measurements found a strong vertical stratification in temperature, salinity and density that resulted in hydrogen sulfide contamination of the deeper portions of the basin owing to lack of exchange with upper layers.

Other international teams of investigators concentrated mainly on the North Aral in expeditions in 2005, 2007 and 2011, chiefly focusing on measuring salinity, dissolved oxygen, and temperature at shoreline and shallow water locations (Micklin 2014e). These showed that salinities around this water body were steadily falling and were in the range favorable for the native brackish-water fish species. High dissolved oxygen levels were also found – another positive sign for fish and other desirable aquatic species.

4.4.2 Changes in the Biological Character of the Sea

By the 1950s, it became clear to fishery experts that given irrigation-expansion plans for the basin of the Aral Sea, river runoff would be significantly reduced, and the salinity of the Aral Sea would increase. It was anticipated the freshwater and brackish-water species that formed the basis of the biota would gradually disappear and the sea would lose its fishery importance. Therefore, it was necessary in advance to form a salt-tolerant biota by acclimating suitable species. First, it was necessary to create a phytoplankton, then zooplankton and then zoobenthos food base, and only then introduce fish, but only benthophagous and predators. However, this was not done carefully, and several unwanted species of invertebrates and fish were introduced (Karpevich 1975).

In 1954–1956 during unsuccessful introduction of the mullets *Liza aurata* and *L. saliens* from the Caspian Sea, unwanted non-commercial fishes were introduced:

atherine *Atherina boyeri caspia*, pipefish *Syngnatus abaster caspius* and six species of gobies: *Knipowitschia caucasicus, Neogobius fluviatilis*, *N. melanostomus, N. syrman* and *N. kessleri*, and *Proterorhinus marmoratus* (Ermakhanov et al. 2012). In addition, the shrimp *Palaemon elegans* was brought to the sea (Karpevich 1975). This naturalized shrimp became a competitor with the aboriginal amphipod *Dikerogammarus aralensis* and even ate it. This, but not salinization, caused the disappearance of the amphipod by 1973 (Aladin and Kotov 1989; Aladin and Potts 1992; Andreeva 1989; Mordukhai-Boltovskoi 1972).

The most profound consequences were caused by the planktophage Baltic herring *Clupea harengus membras* introduced in 1954–1956 (Karpevich 1975). Because of the introduction of this alien species, as well as atherine and gobies, the abundance and biomass of zooplankton crustaceans sharply decreased. This led to the mass death of herring and atherine from starvation in ensuing years (Kortunova 1975; Kortunova and Lukonina 1970; Osmanov 1961).

The first purposely introduced invertebrates in the Aral Sea (1958–1960) were Ponto-Caspian misyds—a valuable food for fish and able to tolerate salinity of 17–20 g/l (Karpevich 1960). Of the three species—*Paramysis lacustris, P. intermedia* and *P. baeri*—taken from the delta of the Don, only the first two were naturalized. A fourth species, *Paramysis ullskyi*, migrated independently from reservoirs on the Syr Dar'ya where it was introduced earlier (Kortunova 1970). The next planned invertebrate species to be introduced (1960–1961) was the euryhaline polychaete worm *Hediste diversicolor* from the Sea of Azov. This worm quickly naturalized and settled (1973–1974) the whole Aral (Karpevich 1975). The euryhaline bivalve *Syndosmya segmentum* was introduced from the Azov Sea in 1960–1963. By 1973, it settled all over the sea and became the main component of zoobenthos (Karpevich 1975).

The euryhaline marine planktonic copepod *Calanipeda aquaedulcis* was introduced from the Sea of Azov in 1965 and 1970. By 1971 this crustacean became one of the species dominating the zooplankton (Andreev 1989; Karpevich 1975). By 1974, *C. aquaedulcis* displaced *Arctodiaptomus salinus* (Mordukhai-Boltovskoi 1972) and the latter species became extinct in the Aral Sea.

In the deltaic areas of the Syr Dar'ya and Amu Dar'ya, commercial freshwater fishes were acclimatized in 1958–1960: macro-phytophage grass carp *Ctenopharyngodon idella*, phyto-planktophague silver carp *Hypophtalmichthys molifrix*, zooplanktophage bighead carp *Aristichtys nobilis* and introduced inadvertently benthophage black carp *Mylopharyngodon piceus*. Except for bighead carp, all were successfully naturalized and became commercially important (Karpevich 1975).

Another cause of changes in the composition of the biota has been anthropogenic change in the hydrological regime of the Aral Sea, its desiccation and salinization. During the period 1961–1970 the Aral Sea desiccation and increase of its salinity occurred very slowly. Over these 10 years salinity increased only by 1.5 g/l, and by 1971 it reached 11.5 g/l. At this early stage of the Aral Sea's modern regression, changes in the species composition of its fauna were mostly the result of the introduction of new fishes and invertebrate species and to a lesser extent were the result of increasing salinity.

Throughout the period 1961–1971 the species composition of larval Chironomidae fauna in the Aral Sea remained unchanged. A small increase in salinity of the Aral Sea caused a very significant reduction in the total number of bivalves *Dreissena* after 1964. It should be noted that this slight salinization was unfavorable only for *D. polymorpha aralensis* and *D. p. obtusecarinata* but not for *D. caspia pallasi*, more resistant to salinity and not numerous (Andreeva 1989).

In the 1970s the rate of Aral Sea desiccation and salinity rise increased. Since that time, the main factor influencing the fauna of the Aral Sea has been continued increase in salinity of its waters. In 1971–1976 invertebrate fauna of the Aral Sea passed through the first crisis period caused by salinization over 12–13 g/l (Plotnikov et al. 1991). Increasing salinity became an obstacle for further existence of freshwater species.

During this first crisis period the most species-rich, freshwater component of fauna disappeared. Only eight species of rotifers remained. From them only a few species of the genus *Synchaeta* were common and numerous. With increasing salinity *Ceriodaphnia reticulata* and *Alona rectangula* disappeared by 1974. By 1975, of Cladocera species in the fauna only representatives of the Ponto-Caspian fauna *Evadne anonyx, Podonevadne camptonyx, P. angusta* and *Cercopagis pengoi aralensis* remained. Instead of freshwater *Mesocyclops leuckarti* the most numerous species became euryhaline marine *Halicyclops rotundipes aralensis* (Andreev 1989).

All mollusks from the genus *Hypanis – H. vitrea bergi, H. minima minima* and *H. m. sidorovi* disappeared after 1977. Further increases in salinity affected the sea forms of *Dreissena* inhabiting the sea differently. It was unfavorable for *Dreissena polymorpha aralensis* and *D. p. obtusicarinata*, but favorable for *D. caspia pallasi* that tolerates higher salinities. The growth of salinity led to the reduction in the area and number of the bivalve *Cerastoderma rhomboides rhomboides*, and conversely was favorable for *C. isthmicum*. After 1978 *C. rhomboides rhomboides* was no longer found and *C. isthmicum* took its place. Rising of salinity above 12–14 g/l favored the mollusk *Syndosmya segmentum*. The abundance of the halophilic gastropods *Caspiohydrobia* spp. began to grow. Since 1973, when the salinity of the sea reached 12 g/l, Oligochaeta were no longer found. By 1974 most of larval Chironomidae species had disappeared and only *Chironomus salinarius* and *Ch. halophilus* remained in the salinized bays (Andreeva 1989). By 1980, the leading forms of zoobenthos were *Syndosmya segmentum*, *Cerastoderma isthmicum, Hediste diversicolor* and *Caspiohydrobia* spp. After 1977 when the salinity had reached 15 g/l, all mysids were absent from the sea but were preserved in the rivers and their deltas (Andreeva 1989).

As a result of this first crisis, freshwater and brackish-water species of freshwater origin disappeared from the free-living invertebrate fauna of the Aral Sea. This provided an advantage to Caspian and marine euryhaline species and halophilic species (Andreev 1989). Despite the continuing salinity growth, the first crisis period for the free-living invertebrate fauna of the Aral Sea transitioned into a period of relative stability between 1977 and 1985.

By 1987 salinity of the Aral Sea rose to 27 g/l. Crossing this boundary meant free-living invertebrate fauna of the Aral Sea entered the period of the second crisis during which occurred the next reduction of species diversity (Plotnikov et al. 1991).

Because of this all the Ponto-Caspian cladocerans of the family Podonidae disappeared by 1990. After the second crisis period, of the native zooplankton species in the sea, remained only the rotifers *Synchaeta* spp., *Notholca squamula, N. acuminata, Keratella quadrata, Brachionus plicatilis, B. quadridentatus* and perhaps a few species of copepods (*Calanipeda aquaedulcis* and *Halicyclops rotundipes aralensis*), as well as several species of Harpacticoida. Among aboriginal species in the benthic fauna only the mollusks *Cerastoderma isthmicum, Caspiohydrobia* spp. and ostracod *Cyprideis torosa* survived. Among introduced species only the polychaete *Hediste diversicolor*, mollusk *Syndosmya segmentum*, crab *Rhithropanopeus harrisii tridentata* and the shrimp *Palaemon elegans* remained. After this crisis period, in the free-living invertebrate fauna of the Aral Sea were marine species and euryhaline species of marine origin as well as representatives of euryhaline halophilic fauna of inland saline waters. This crisis was followed by a new period of relative stability (Plotnikov 2016).

Soon after the separation of the Aral Sea into two parts (North or Small Aral and South or Large Aral) in 1987–1989, when the decrease in salinity in the Small Aral began, reappeared *Podonevadne camptonyx* from dormant eggs. In 1999 were larvae of Chironomidae found in the benthos again (Aladin et al. 2000).

Salinity in the separated Large Aral grew and it was transformed into a hypersaline water body. In the mid-1990s when salinity exceeded 47–52 g/l came another period of crisis. A rapid change in the composition of all the Large Aral biota occurred. By 2004, when salinity became 100–105 g/l, most invertebrates disappeared. Only rotifers *Hexarthra fennica* and *Brachionus plicatilis*, ostracod *Cyprideis torosa*, Turbellaria *Mecynostomum agile*, and some species of Foraminifera, Nematoda and Harpacticoida remained. But by this time in the Large Aral appeared some halophilous invertebrates such as ciliates *Fabrea salina* and *Frontonia marina*, copepod *Apocyclops dengizicus*, ostracod *Eucypris mareotica*, brine shrimp *Artemia parthenogenetica*, and larval chironomids *Beotendipes noctivaga* (Aladin and Plotnikov 2008; Mokievsky and Miljutina 2011).

4.4.2.1 Aral Fishery

Freshened deltaic bays and lakes were the best places for fish spawning (Bervald 1964). Decline in the Aral Sea water level, salinization and drying of deltas significantly altered the living conditions for fishes, especially for their reproduction (Ermakhanov et al. 2012). This sharply affected the state of commercial fish populations. The first signs of the negative impacts of salinization on the ichthyofauna occurred in the mid-1960s, as salinity reached 12–14 g/l. Salinity increased faster in shallow spawning areas than in the open sea, exceeding 14 g/l in 1965–1967. At the end of the 1960s, spawning conditions for semi-anadromous fishes significantly worsened.

Beginning in 1971, when average salinity in the open sea reached 12 g/l, the first signs of negative effects of salinity on adult fishes appeared. The rate of growth slowed for many fish species, with their numbers falling sharply. By the middle of the

1970s, when the average salinity of the sea exceeded 14 g/l, the natural reproduction of Aral fishes was destroyed. As a result, in the second half of the 1970s, recruitment of new members was absent for the populations of many fish species. By 1981, when salinity exceeded 18 g/l, the Aral Sea had completely lost its fishery. The remaining ichthyofauna consisted of nine-spined stickle-back, as well as gobies, atherine and Baltic herring. Aboriginal commercial fishes survived only in the Syr Dar'ya and Amu Dar'ya rivers and deltaic lakes (Ermakhanov et al. 2012).

To restore the Aral Sea fishery, the flounder-gloss *Platichthys flesus luscus* from the Sea of Azov was successfully introduced in 1979–1987 (Lim 1986). This marine fish can reproduce at salinities from 17 to 60 g/l. A fishery was established by the early 1990s. Acclimatized flounder-gloss remained the only commercial fish species in the Aral Sea from 1991 to 2000 (Ermakhanov et al. 2012).

After construction of the Kok-Aral dike, freshening of the Small Aral Sea began, and the zone with lower salinity began increasing. Aboriginal fish, including Aral roach, bream, carp, zander, and asp began to be found again in the Small Aral Sea after many years. The fish fauna expanded their spawning and feeding zones to almost the entire area of the Small Aral Sea, except Butakov Bay, where the salinity remained too high (Ermakhanov et al. 2012). By the end of the 1990s, the salinity of the Large Aral reached 60–70 g/l, resulting in the complete disappearance of all fish. It has become a lake without fishes since that time (Ermakhanov et al. 2012).

4.4.2.2 Aral Aquatic Vegetation

Regression and salinization of the Aral Sea caused the destruction of the majority of vegetational complexes. Freshwater and freshwater-brackish water submerged higher plants were not able to survive. During the 1970s, the species composition was depleted and a few euryhaline species became dominant. Reed-beds in the 1980s disappeared completely owing to rising salinity. By the end of the 1980s there was only *Ruppia* spp. tolerating salinity of 50 g/l (Plotnikov et al. 2014b).

In the Small Aral in the 1990s, the bulk of macrophytobenthos production belonged to the macroalgae *Chaetomorpha linum, Cladophora glomerata* and *Cl. fracta*. Macrophyte communities were formed of flowering plants *Phragmites australis, Ruppia cirrhosa, Ruppia maritima, Zostera noltii*, and charophytes *Lamprothamnium papulosum* and *Chara aculeolata*. Near the Syr Dar'ya delta reed-beds began to form. At present, the salinity of the Small Aral Sea continues to gradually decrease, and this water body is being settled widely by species of hydrophytes and helophytes coming from other continental brackish water bodies (Plotnikov et al. 2014b).

In the hypersaline Large Aral microphytobenthos (diatoms and blue-green algae) dominates. Among macrophytobenthos only *Cladophora* and *Vaucheria* were found. From higher plants sterile specimens of *Ruppia* sp. were found (Plotnikov et al. 2014b; Zavialov et al. 2012).

4.5 Future of the Aral Sea

The view by some that the Aral Sea is destined to dry up completely in the twenty-first century is false (Micklin 2010, 2014f). Even if river inflow from the Amu Dar'ya and Syr Dar'ya were reduced to zero, a very improbable scenario, there would still be residual input of irrigation drainage water, groundwater, and snow melt and rain that would maintain at least two substantial lakes: the deeper western (Shevchenko Gulf) and deeper parts of the central Small Aral Sea in the north, and the Western Basin of the Large Sea in the south. These lakes would be hypersaline and of little ecological or economic value, except, perhaps for the commercial production of brine shrimp (*Artemia*) eggs.

Return of the sea to its early 1960s state is possible but very unlikely in the foreseeable future. Based on a spreadsheet fill-time model developed by Micklin (2016), it would necessitate restoring average annual river inflow to 56 km^3 and take more than 100 years. Restoration would follow a logistic curve: rapid at first as inflow greatly exceeded net evaporation, then slowing and approaching zero as net evaporation grew and approached inflow. However, the sea would reach an area of 60,000 km^2 (91% of stability area) and level of 50 m in 45 years. Estimated average annual inflow to the entire sea from 1992 to 2011 is 8.8 km^3−16% of what would be needed for realization of this scenario. The only realistic means for substantially increasing inflow to the Aral is reducing the use of Aral Sea Basin river flow for irrigation as it accounts for 92% of water withdrawals (Micklin 2014b, c). Irrigation efficiency in this region is low and certainly could be raised to free more water for the Aral. But the cost would be huge and the time to implement long. Hence, to free the large amount of water needed would also require a substantial reduction in the area irrigated. Given the dependence of Aral Sea Basin nations' economies on this activity, such a reduction is improbable, if not impossible, any time soon.

It is engineeringly possible to bring water to the Aral Sea from outside Central Asia (Micklin 2014g). The Soviet government developed plans in the 1960s and 1970s to divert up to 60 km^3 from the Siberian rivers Irtysh and Ob' to the Aral Sea Basin as the best means to solve regional water problems for the long-term. The initial phase (27 km^3) was near implementation when stopped in 1986 by Gorbachev, then head of the USSR Government and Communist Party. Attempts have been made to revitalize the project, but they appear futile.

4.5.1 Further Restoration of the North (Small) Aral

On the other hand, various partial rehabilitation scenarios for the Aral Sea hold considerable promise (Micklin 2014f, 2016). About 3.24 km^3/year, on average, is the inflow needed from the Syr Dar'ya to maintain the current nominal level of the Small Aral (42 m above the Kronstadt gauge) with an area of 3200–3300 km^2 and allow sufficient outflow through the Berg Strait (Kok-Aral) Dam to regulate salinity.

For 1992–2016 the average annual inflow was around 5.9 km^3 indicating there is more than enough water available to maintain the current stabilized hydrologic status of the Small Aral Sea.

The Kazakhstan Government, with World Bank support, is planning a second phase of the Small Aral restoration project (Micklin 2016; World Bank 2014). One of the two alternatives is to raise the level of water only in the Gulf of Saryshaganak, which extends northeast off the eastern part of the Small Sea, to 50 m above the Kronstadt gauge (Figs. 4.4 and 4.5). For this a new dike and dam, with an outflow structure and navigation locks for ingress and egress, would be necessary at the Gulf's mouth. Part of the flow of the Syr Dar'ya would be diverted northward via a canal into Saryshaganak to maintain its level. The gulf now converted into a reservoir with an area of 825 km^2, volume of 6.3 km^3, and average depth of 7.6 m, would be brought back very near the town of Aral'sk the former main port at the northern end of the Aral Sea. This would allow fishing vessels via a short canal direct access to the new and rebuilt fish processing plants in that town. Cost of this project is estimated at 150 million USD (World Bank 2014).

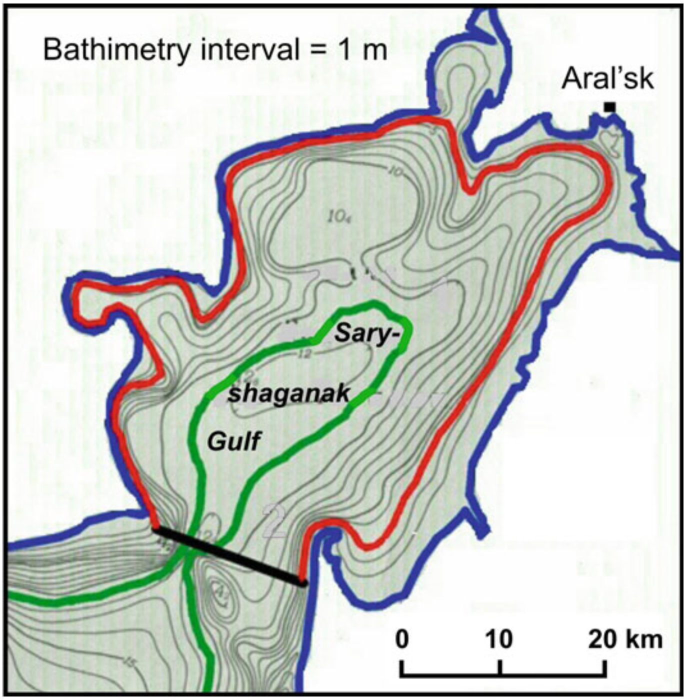
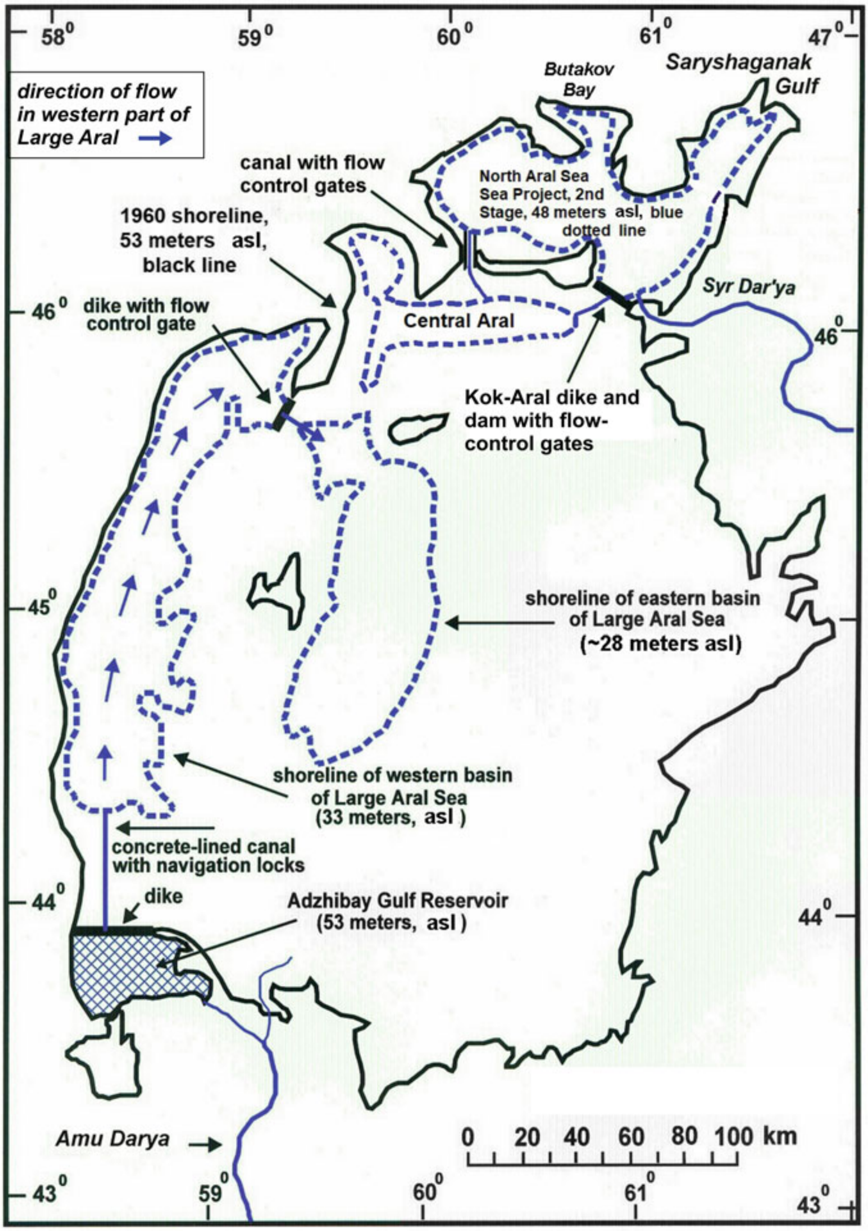


Fig. 4.4 Saryshaganak Gulf Reservoir Plan. Black line shows position of proposed dike and dam. Blue line is 1960 level (53 meters above Kronstadt gauge), red line is level at 50 meters as proposed in 2nd stage of Saryshaganak Plan, green line is 2019 level (42 m). Base map is digitized version of 1:500,000 bathymetric map of the Aral Sea produced by the Institute of Water Problems, Soviet Academy of Sciences in 1981. *Source* Micklin (2016)



58°
59°
60°
61°
47°
46°
45°
44°
43°
direction of flow in western part of Large Aral
Butakov Bay
Saryshaganak Gulf
canal with flow control gates
North Aral Sea Sea Project, 2nd Stage, 48 meters asl, blue dotted line
1960 shoreline, 53 meters asl, black line
Syr Dar'ya
dike with flow control gate
Central Aral
Kok-Aral dike and dam with flow-control gates
shoreline of eastern basin of Large Aral Sea (~28 meters asl)
shoreline of western basin of Large Aral Sea (33 meters, asl)
concrete-lined canal with navigation locks
dike
Adzhibay Gulf Reservoir (53 meters, asl)
Amu Darya
0 20 40 60 80 100 km

◀**Fig. 4.5** Optimistic Scenario of the Future Aral Sea (after 2030). Legend (figures are average annual values). Small Aral Sea: level – 8 m, surface area – 4927 km^2, volume 54 km^3, river inflow – 5.0 km^3, net groundwater inflow – 0.1 km^3, outflow – 1.0 km^3, salinity – 6–7 g/l. Western Basin of Large Aral Sea: level – 3 m, surface area – 6200 km^2, volume – 85 km^3, river inflow – 6.4 km^3, net groundwater influx 2.0 km^3, outflow to Eastern Basin – 3.6 km^3, salinity steadily decreasing reaching 42 g/l by 2055 and 15 g/l by 2110. Eastern Basin of Large Aral Sea: level ~28.0 m, surface area ~3800 km^2, volume ~7.6 km^3, inflow from Western Basin Aral 3.6 km^3, inflow from Central Aral highly variable, salinity >200 g/l. Adzhibay Gulf Reservoir: level – 53 m, surface area – 1147 km^2, volume – 6.43 km^3, inflow – 8 km^3, outflow to Western Basin of Aral Sea – 6.6 km^3, salinity – 2 g/l. Level in meters above the Kronstadt gauge on the Baltic Sea near St. Petersburg, Russia. *Source* Micklin (2016)

The other alternative would rebuild the Kok-Aral dike and dam, raising the level of the entire lake to 48 m above the Kronstadt gauge (Fig. 4.5). At this level, the area of the Small Aral would be 4927 km^2. Inflow from the Syr Dar'ya to maintain such a level, including outflow to manage salinity, is 4.85 km^3. This alternative would likely provide more economic and ecological benefits than the Saryshaganak Reservoir plan but would also require more discharge from the Syr Dar'ya. The lake could be filled to 48 m in 17 years with average annual inflow of 5.0 km^3. After reaching design level, releases, on average, of about 1 km^3/year would maintain a relatively stable level. Salinity, over time, would reach about 6 g/l, which would be ideal for the 11 most important commercially caught fish in the North Aral Sea in 2016 (Micklin et al. 2018; White 2016).

As the salinity of the North Aral decreases, the species diversity will rise as a result of natural reintroduction of many species that disappeared due to the earlier salinity growth. Reintroduction of planktonic invertebrates can occur by waterfowl transfer or by wind from fresh or brackish water bodies. It is also possible to take these organisms for reintroduction from the Syr Dar'ya and from associated lakes in its lower reaches, which act as refugia. Further decrease in the salinity of the North Aral Sea can cause new changes in the composition of its fauna. Strong freshening will be unfavorable for marine species and representatives of the fauna of saline water bodies of arid zone, favored by the salinization of the Aral Sea, as well as for brackish-water species.

4.5.2 Fate of the Large Aral

The future for the Large (Southern) Aral Sea is more problematic (Micklin 2014f). The Eastern Basin, depending on inflow from the outflow over the Berg Strait Dam and inflow from the Amu Dar'ya, is at times an extensive, very shallow lake or a dry playa basin contributing to salt/dust storms arising from the dried Aral Sea bottom (also often called simply Aralkum which means Aral Desert). The lake when present has high salinity and limited ecological value except to mitigate salt/dust storms by reducing the area of dry bottom subject to wind deflation. The Eastern Basin also has some potential for raising brine shrimp and harvesting their eggs, but the commercial promise of this is limited. The deeper Western Basin depends largely on net groundwater inflow, direct runoff from rain and snowmelt, and some input from the Central Aral (via the connecting channel) when that water body is sufficiently filled by outflow from the Small Aral. The Western Basin also receives inflow via the connecting channel from the Eastern Basin when that water body is sufficiently filled by inflow from the Amu Dar'ya. On June 20–21, 2018, its level was around 23 m above the Kronstadt gauge and its area was about 2894 km^2 (Table 4.1). The Eastern Basin on those dates was a few meters higher and had an area about 2537 km^2.

Given a continuation of present trends, the level of the Western Basin will continue to decrease for some time, perhaps stabilizing around 21 m above the Kronstadt gauge. At that level its area would be 2560 km^2. It would continue toward hyper-salinization. As salinity of the Western Basin grows, a new reduction in the species diversity of its fauna will begin. Ostracod *Cyprideis torosa* and all rotifers will disappear. When salinity exceeds 250 g/l, only *Artemia*, which can tolerate up to 350 g/l, would remain, If the salinity exceeds this limit, the remainder of the Large Aral will become like the Dead Sea (Oren et al. 2010; Plotnikov 2016).

But there are more optimistic scenarios for the Western Basin of the Large Aral (Micklin 2016). Figure 4.5 shows a more hopeful future and is based on earlier work by two Soviet experts (Lvovich and Tsigelnaya 1978). It would require an average annual inflow in the lowest reaches of the Amu Dar'ya of around 12.5 km^3, a bit more than double recent estimated average annual flow (5.4 km^3/year for 1992–2011), which could be accomplished via feasible improvements in irrigation efficiency in the Amu Dar'ya River Basin. This alternative would likely cost more than the 85 million USD expended on the first stage of the Small Aral restoration. The greatest obstacles to implementation of this plan are political and economic related to the fact that the plan would complicate the ongoing exploration for and exploitation of oil and gas deposits from parts of the now dried bottom of the southern part of the Western Basin of the Aral Sea.

Rehabilitation and preservation of the lower Amu Dar'ya delta through creation of artificial ponds and wetlands and rehabilitation of former lakes and wetlands in the delta and on the dry bed of the Aral Sea has been a priority since the late 1980s (Micklin 2016; Novikova 1999). Benefits are enhanced biodiversity, improved fisheries, greater forage production, treatment of wastewater by aquatic vegetation, and some reduction in salt and dust transfer from the dried sea bottom. Efforts to improve wetlands and lakes in the lower Syr Dar'ya delta have also been made.

Since the early 1990s efforts have been made to stabilize the dried bottom of the Large Aral in Uzbekistan and to lower the deflation potential with planting of salt-tolerant shrubs, grasses and trees. The largest scale project in this regard is the "Stabilization of the desiccated Aral Sea bottom in Central Asia" (Dukhovny et al. 2007). This program has been managed by the German foreign aid agency (GTZ) and the Forestry Research Institute of Uzbekistan. Between 1995 and 2007 drought-resistant tree and shrub species, primarily Black Saksaul were planted on 300 km^2. Since 2005 the project has also included an integrated remote sensing/GIS and sea bed-based monitoring component to assess surficial dynamics, desertification risks, and other negative impacts of the continuing drying.

4.6 Conclusions

The Aral Sea is geologically a relatively young large lake, no more than 20 thousand years old. As a terminal water body, strongly impacted by human actions, its history has been turbulent. Levels have risen and fallen significantly accompanied by major transgressions and recessions of the shoreline, changes in salinity and accompanying alterations in biotic communities. Early fluctuations owed to natural forces of climate change and diversions of the Amu Dar'ya away from the sea. But for several millennia man has had a growing influence through irrigation related reductions of inflow and inadvertent and purposeful diversions of the Amu westward toward the Caspian Sea and away from the Aral.

The most dramatic human-caused impacts occurred in the twentieth century, particularly after 1960, and have continued into the twenty-first century. Invertebrates and fishes (and their parasites) were introduced both consciously and inadvertently beginning early in the 1920s. Some of these substantially and negatively affected native species. But by far the most damaging action was the major expansion of irrigation beyond the point of hydrologic sustainability that began in the 1950s and that led to the modern desiccation of the Aral after 1960. This ongoing process, by 2018, has likely led to the greatest level drop, most dramatic shoreline retreat and highest salinities experienced by the Aral in the past several millennia. These physical changes have devasted and simplified the biologic communities of most of what was formerly the Large Aral and destroyed their ecologic and economic value.

But is all lost? The answer is clearly "no". The partial restoration project for the North Aral has, so far, been a resounding success with major positive ecologic and economic impacts. A further stage of restoration for this water body is contemplated that could bring even greater benefits. The picture for the South Aral is much gloomier. Major restoration would require additional flow from the Amu Dar'ya that is not in the cards in the short or medium term but might be possible in the long perspective. Somewhat raising, stabilizing, and bringing back into ecologic and economic use the deeper Western Basin is possible by realizable improvements in irrigation efficiency to increase the Amu's inflow, but economic justification and political will for this seems absent.

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