

The Aral Sea Disaster

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Key Words

water, fish, Central Asia, irrigation, rivers, environmental degradation

Abstract

The Aral Sea is a huge terminal lake located among the deserts of Central Asia. Over the past 10 millennia, it has repeatedly filled and dried, owing both to natural and human forces. The most recent desiccation started in the early 1960s and owes overwhelmingly to the expansion of irrigation that has drained its two tributary rivers. Lake level has fallen 23 m, area shrunk 74%, volume decreased 90%, and salinity grew from 10 to more than 100g/l, causing negative ecological changes, including decimation of native fish species, initiation of dust/salt storms, degradation of deltaic biotic communities, and climate change around the former shoreline. The population residing around the lake has also been negatively impacted. There is little hope in the foreseeable future to fully restore the Aral Sea, but measures to preserve/rehabilitate parts of the water body and the deltas are feasible.

INTRODUCTION

The Aral Sea is located amid the great deserts of Central Asia (**Figure 1**). Its drainage basin covers 1.8 million square kilometers within seven nations: Uzbekistan, Turkmenistan, Kazakhstan, Afghanistan, Tajikistan, and Iran. Only Kazakhstan and Uzbekistan are riparian on the sea proper, with each possessing an approximately equal length of shoreline. The entire Aral coastline within Uzbekistan lies within that nation's Karakalpak Republic. A terminal lake, it has surface inflow but no surface outflow. Therefore, the balance between inflows from two rivers, the Amu and Syr (hereafter referred to as the Amu Dar'ya and Syr Dar'ya rivers, respectively, although dar'ya in the Turkic languages of central Asia means river) and net evaporation (evaporation from its surface minus precipitation on it) fundamentally determine its level. Net groundwater inflow, estimated at -1.3 to $3.4 \text{ km}^3 \text{ year}^{-1}$ has been considered an inconsequential part of the water balance (Bortnik & Chistyayeva 1990, p. 38). Although this part of the water balance has become a more important factor in the past several decades as surface inflow diminished.



Figure 1
Aral Sea Basin.

In the recent geologic past (past 10,000–15,000 years), the sea has endured significant level fluctuations, perhaps as much as 40 m (Micklin 2004). The major level changes prior to 1960 resulted from diversion of the Amu Dar'ya westward so that it flowed into the Sarykamysh hollow, and sometimes farther through the Uzboy channel to the Caspian Sea after it overtopped Sarykamysh, rather than into the Aral Sea. These diversions resulted from natural events (sedimentation of the bed and subsequent breaching of the river's left bank during spring floods) and from human actions, both inadvertent (e.g., failure of irrigation works) and purposeful (destruction of dikes and levees built to keep the river flowing to the Aral) during times of conflict.

RECENT WATER BALANCE CHANGES

From the mid-eighteenth century until the 1960s, sea level variations were less than 4.5 m (Bortnik 1996). Instrumental observation began in 1911. From then until the early 1960s, the sea's water balance was remarkably stable with annual inflow and net evaporation never far apart. The average of each of these water balance components was near 56 km³ during this period, with net evaporation consisting of evaporation of 66 km³ from the sea's surface (estimated by both theoretical and empirical formulae) minus precipitation on the sea's surface (calculated from measurements at shore and island stations) of 9 km³ (Figure 2) (Bortnik & Chistyayeva 1990, pp. 34–38). Hence,

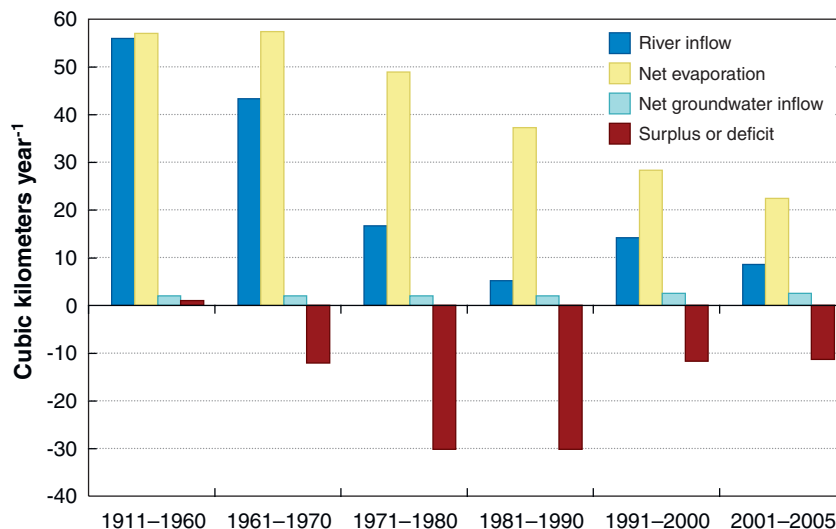
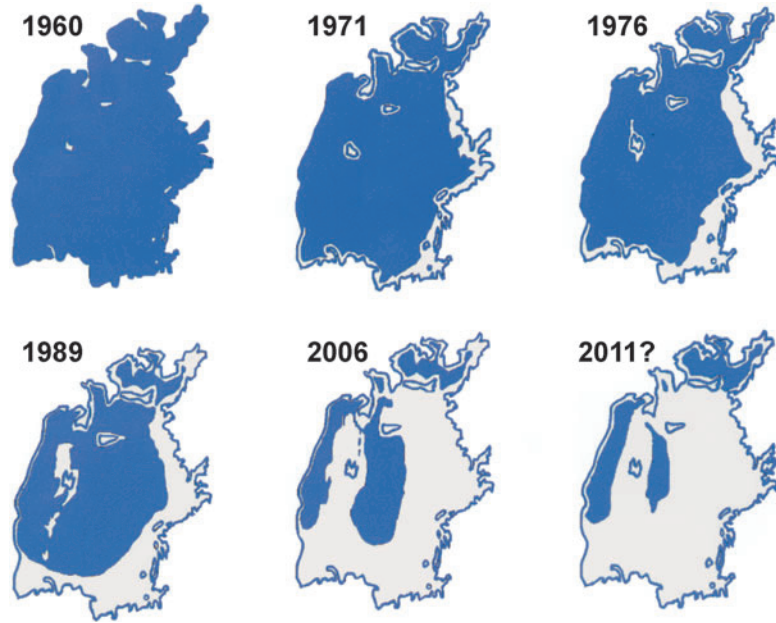


Figure 2

Average annual water balance for the Aral Sea (1911–2005). River inflow: flow of Syr Dar'ya and Amu Dar'ya to Aral Sea; net evaporation: evaporation from sea surface minus precipitation on it; net groundwater inflow: groundwater flow to sea minus flow from sea; surplus or deficit: (inflow to sea + net groundwater inflow) – net evaporation. From Bortnik & Chistyayeva 1990, table 4.1, p. 36; Uzglavgidromet 1994–2003, Micklin 1990–2006, Annual Data 1987, Shivareva et al. 1998.

Figure 3

Changing Profile of the Aral Sea 1960–2011.



Transpiration: evaporation of water from the leaves of plants and its corresponding uptake from roots in the soil

Phreatophytes: water-loving plants that grow along natural and artificial water courses in arid regions

the water balance was in long-term equilibrium with a maximum lake level variation of less than one meter.

At slightly more than 67,000 km², the Aral Sea, according to area, was the world's fourth largest inland water body in 1960 (Micklin 1991, pp. 42–54). As a brackish lake with salinity averaging near 10 g/l, which is one-third less than that found in the ocean, it was inhabited chiefly by fresh-water fish species. 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. They also supported irrigated agriculture, animal husbandry, hunting and trapping, fishing, and harvesting of reeds, which served as fodder for livestock as well as building materials.

The water balance, morphology, and ecology of the Aral Sea have changed dramatically since the early 1960s. The sea has steadily shrunk and salinized (**Figures 3, 4, and 5; Table 1**). Expanding irrigation that diminished discharge from the two tributary rivers to a fraction of earlier volumes has been the main cause. Irrigation has been practiced in the Aral Sea Basin for millennia, but until the 1960s it did not substantially diminish inflow to the sea, as water losses to this activity were largely compensated by reductions of natural evaporation; transpiration from phreatophytes, such as salt cedar (also known as tamarisk, *gallica* Linnaeus), willow (*Salix*), and cottonwood (*Populus*); and filtration in the deltas of the Amu Dar'ya and Syr Dar'ya, primarily owing to the truncation of spring floods (Micklin 2000, pp. 24–42). However, growth of this activity from around 5 million to 7.9 million hectares between 1965 and 2000 markedly reduced river discharge to this water body, as these compensational factors were overwhelmed by the construction of huge irrigation systems

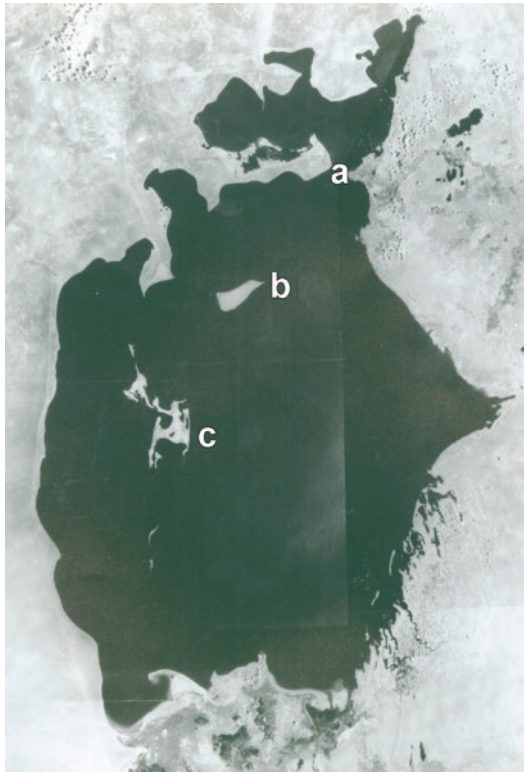


Figure 4

Landsat MSS composite image of the Aral Sea, summer 1977. (a) Berg Strait, (b) Barsekelmes Island, (c) Vozrozhdeniya Island.

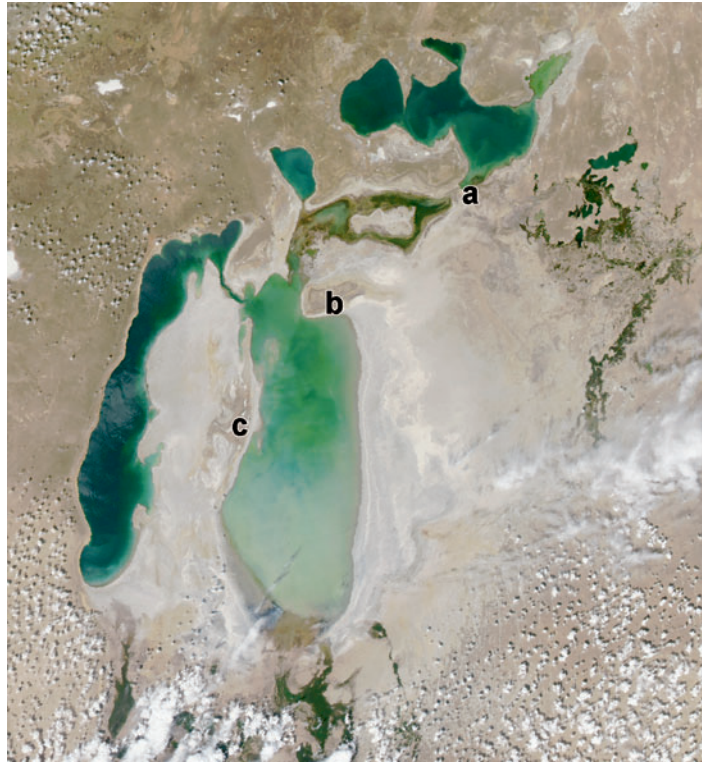
into the deserts. This led to a much larger share of water withdrawn from the Amu Dar'ya and Syr Dar'ya being lost to evaporation rather than returned to these rivers as had previously been the case when irrigation was mainly confined to the deltaic and littoral zones (Micklin 1991, pp. 44–46; Micklin 1996).

The dramatic drop in river inflow for the period after 1960 is clearly shown on **Figure 2**. For the 1960s, discharge to the sea averaged $43 \text{ km}^3 \text{ year}^{-1}$ and net groundwater inflow averaged perhaps $2.5 \text{ km}^3 \text{ year}^{-1}$, whereas net evaporation was $57 \text{ km}^3 \text{ year}^{-1}$, giving a deficit of $12 \text{ km}^3 \text{ year}^{-1}$. The difference between river inflow and net evaporation was particularly pronounced during the 1970s and 1980s, with water balance deficits for both periods above $30 \text{ km}^3 \text{ year}^{-1}$. Consequently, the sea dropped especially rapidly over these two decades. Reportedly, the Syr Dar'ya provided no flow to the Aral from 1974–86 and the Amu Dar'ya provided minimal or no flow for 1982–83, 1985–86, and in 1989 (Izrayel' & Anokhin 1991).

The Aral's water balance substantially improved during the 1990s owing to more precipitation in the flow generating mountains of the Aral Sea Basin and some reduction in water withdrawals for irrigation (12% between 1980 and 1995) (http://www.ec-ifas.org/Russian_version/Aral_crises/water_use). River discharge to the sea, averaging approximately $14 \text{ km}^3 \text{ year}^{-1}$, and a significant reduction in net evaporation reduced the water balance deficit to approximately $12 \text{ km}^3 \text{ year}^{-1}$. (Indeed,

Figure 5

MODIS 250 meter true-color image of Aral Sea, May 26, 2006. (a) Former Berg Strait, (b) former Barselkelmes Island, (c) former Vozrozhdeniya Island.



desiccating water bodies manifest a strong evaporation negative feedback mechanism: As the sea surface diminishes, so does evaporation, slowing the desiccation process). Severe drought affected the mountain zones, particularly the Pamirs, which were a source of water for the Amu Dar'ya, from 1999 into 2002 (Agrawala et al. 2001). Average annual inflow to the Aral Sea for 1999 through 2001 was near 5 km^3 , with nearly 90% provided by the Syr Dar'ya (P. Micklin 1990–2006, unpublished observations and data gathered by the author during an expedition to the Aral Sea, August 22–September 23, 2005, funded by the Comm. Res. Explor., Natl. Geogr. Soc., Grant 7825–05 2006). For the period 2001–2005, inflow to the sea averaged approximately 9 km^3 and net groundwater inflow averaged perhaps 2.5 km^3 , with net evaporation of approximately 22 km^3 , giving a deficit around 11 km^3 .

The Aral separated into two water bodies in 1987–89: a “Small” Aral Sea in the north and a “Large” Aral Sea in the south. The Syr Dar'ya flows into the former and the Amu Dar'ya into the latter. Between 1960 and January 2006, the level of the Small Aral fell by 13 m and the Large Aral fell by 23 m (Table 1). A channel (river) has connected the two lakes, with flow from the Small to the Large Aral. This flow has been primarily during the spring/early summer period when discharge from the Syr Dar'ya to the Small Aral is greatest. During most of the year, the flow is much less and it often entirely ceases. The area of both seas taken together diminished by

Table 1 Hydrological and salinity characteristics of the Aral Sea, 1960–2011

Year	Level (m asl)	Area (km ²)	% 1960	Volume (km ³)	% 1960	Avg. salinity (g/l)	% 1960
1960 (whole Aral Sea) ^a	53.4	67,499	100	1089	100	10	100
Large Aral Sea	53.4	61,381	100	1007	100	10	100
Small Aral Sea	53.4	6118	100	82	100	10	100
1971 (whole Aral Sea) ^a	51.1	60,200	89	925	85	12	120
1976 (whole Aral Sea) ^a	48.3	55,700	83	763	70	14	140
1989 (whole Aral Sea) ^b		39,734	59	364	33		
Large Aral Sea	39.1	36,930	60	341	34	30	300
Small Aral Sea	40.2	2804	46	23	28	30	300
2006 (whole Aral Sea) ^b		17,382	26	108	10		
Large Aral Sea	30.0	14,325	23	81	8	East Sea >100? West Sea 70–80	100 700–800
Small Aral Sea ^d	40.5	3057	50	21	26	12	120
2011 (whole Aral Sea)		12,130	18	90	8		
Large Aral Sea ^c	28.3	8550	14	62	6	>100	>1000
Small Aral Sea ^d	420	3258	53	27	33	~10	100

^aAnnual average.

^bOn January 1.

^cThe sea will have divided into a western and eastern part.

^dAfter implementation of north Aral project in 2005.

Data for 1960, 1971, and 1976 from Annual Data 1987 and Bortnik & Chistyayeva 1990, table 8.4, p. 72; data for 1989, 2006, and 2011 from Uzglavgidromet 1994–2003; Micklin 1990–2006, 2005; Ptichnikov 2000, 2002, 2002–2003.

74% and the volume by 90%. MODIS real-time satellite imagery shows that by late 2005, the Large Aral Sea became three distinct water bodies: a “deep” western lake and a “shallow” eastern lake with a narrow channel connecting them and a cut-off Gulf of Tshche-Bas (which, for the last several years, including 2006, has reconnected for a short period to the Large Aral during the spring/early summer period of heavier runoff) (MODIS Rapid Response System 2006).

Efforts to partially restore/preserve the Small Aral Sea are underway. The World Bank and the government of Kazakhstan completed an 85 million USD project in fall 2005 that created a 13-km dike to block the flow from the Small to Large Aral Seas (Micklin 2005) Because of heavier-than-expected winter inflow to the Small Aral from the Syr Dar’ya, the level has risen much more rapidly than expected (Greenberg 2006, Pala 2006). A comparison of the 1:200,000 Soviet-era bathymetric map of the Aral and MODIS satellite imagery indicates the level reached ~42 m by early May 2006, about 2 m above the figure immediately prior to the closure of the dike (MODIS Rapid Response System 2006, see **Figure 5**). Already, the dike discharge gates have been opened and flow again allowed to the Large Aral. The level of the Small Aral will be maintained at 42–m, freshening the water body and improving its ecological condition as well as fishery prospects.

Desertification:

degradation of land in arid, semiarid, and subhumid areas resulting from various factors, including climatic variations and human activities

Halophytes: plants and plant communities that are adapted to or can tolerate elevated levels of salinity in the root area

Xerophytes: plants and plant communities that have structural and physiological adaptations enabling survival in areas with very little free moisture

Tugay: vegetation communities of trees, bushes, and tall grasses growing along rivers in the deltas of the Syr Dar'ya and Amu Dar'ya

ECOLOGIC AND HUMAN CONSEQUENCES

The mainly human-induced desiccation of the Aral Sea and flow reduction, salinization, and pollution of its influent rivers has had severe negative effects (Micklin 2000, pp.13–23, 2004). Besides the consequences for the sea proper, a zone around the water body of several hundred thousand square kilometers with a population of several million has also been damaged (Khorovog 1992). The Republic of Karakalpakstan in Uzbekistan and portions of Kzyl-Orda Oblast in Kazakhstan have suffered the most harm. Turkmenistan, although not abutting on the sea, has one Oblast, Dashauz, that has been substantially impacted.

The substantial Aral fishing industries developed by Kazakhstan and Uzbekistan in the first half of the twentieth century ended in the early 1980s, as indigenous fish, which provided the basis for the commercial fishery, disappeared owing to rising salinity and loss of shallow spawning and feeding areas (Micklin 1991, pp. 49–50; 2000, p. 16; 2004; Williams & Aladin 1991; Zholdasova 1999; Ptichnikov 2002). However, fish still survive in the deltaic lakes and Amu Dar'ya and Syr Dar'ya rivers, except the Aral salmon (*Salmo trutta aralensis*), which has become extinct. The introduced kambala or Black Sea flounder (*Platichthys flesus luscus*) is flourishing in the Small Aral and providing a sizable catch (unpublished observations and data gathered by the author during an expedition to the Aral Sea, August 22–September 23, 2005, funded by the Comm. Res. Explor., Natl. Geogr. Soc., Grant 7825–05). With the decrease of salinity from the North Aral level stabilization project, indigenous species such as the sudak or pike-perch (*Lucioperca lucioperca*) and sazan (*Cyprinus carpio*), a type of carp, should make a strong comeback and enhance the fishery, although the competition for food and the lowered salinity may decrease the numbers and catch of kambala.

Because of the loss of the fishery, tens of thousands of people were thrown out of work. Navigation on the Aral also ceased by the 1980s, as efforts to keep the increasingly long channels open to the major ports of Aral'sk at the northern end of the sea in Kazakhstan and Muynak at the southern end in Karakalpakstan became too difficult and costly.

The rich and diverse ecosystems of the extensive Amu Dar'ya delta, primarily located in the Karakalpak Republic of Uzbekistan, have suffered considerable harm (Micklin 1991, pp. 50–52; 2004). The Syr Dar'ya delta in Kazakhstan has endured lesser, but still substantial, damage. Greatly reduced river flows through the deltas, the virtual elimination of spring floods in them (owing both to reduced river flow and construction of upstream storage reservoirs), and declining groundwater levels caused by the falling level of the Aral Sea have led to spreading and intensifying desertification. Halophytes and xerophytes are rapidly replacing endemic vegetation communities (Novikova 1996, 1997). In some places, salts have accumulated on the surface forming solonchak (salt pans) where practically nothing will grow. Expanses of unique tugay vegetation complexes that formerly stretched along all the main rivers and distributary channels have been particularly hard hit. According to Dr. Novikova (1996), a Russian geobotanist, and her scientific colleagues in Karakalpakstan, tugay covered 100,000 hectares in the Amu Dar'ya delta in 1950, but shrank to only 20,000

to 30,000 hectares by 1999 (Severskiy et al. 2005). Tugay complexes around the Aral Sea are habitats for a diverse array of animals, including 60 species of mammals, more than 300 types of birds, and 20 varieties of amphibians.

Prior to 1960, more than 70 species of mammals and 319 species of birds lived in the river deltas. Today, only 32 species of the former and 160 of the latter remain (http://www.ec-ifas.org/Russian_version/Aral_crisis/flora_founa.htm). A UNESCO (2000, pp. 44–46) report notes that of 282 bird species formerly observed in the Amu Dar'ya wetlands, approximately 30 have disappeared and approximately 88 are listed as rare. Desiccation of the deltas has significantly diminished the area of lakes, wetlands, and their associated reed communities. Between 1960 and 1980, the area of lakes in the Amu Dar'ya delta is estimated to have decreased from 49,000 to 8000 km² (Chub 2002, figure 3.3, p. 125). The area of reeds in the delta (as much as 500,000 hectares in 1965) also declined dramatically by the mid-1980s (Palvaniyazov 1989). This has resulted in serious ecological consequences as these zones provide prime habitat for a variety of permanent and migratory waterfowl, a number of which are endangered (Micklin 1991, p. 116). Diminution of the aggregate water surface area coupled with increasing pollution of the remaining water bodies (primarily from irrigation runoff containing salts, fertilizers, pesticides, herbicides, and cotton defoliants) adversely affected aquatic bird populations. Since the late 1980s, significant efforts have been made to restore wetlands, improve habitat conditions, and reduce pollution (Chub 2002, p. 125). A 1999 survey, for example, indicated that the area of reeds for the key lake/wetland in the lower delta (Sudochye) was 12,000 ha (V. Dukhovnyy, personal communication, June 23, 2003).

Irrigated agriculture in the deltas of the Amu Dar'ya and Syr Dar'ya has suffered from an inadequacy of water as inflow to the deltas has decreased owing to heavy upstream consumptive use for irrigation. Additionally, water that does reach the deltas has elevated salinity from the leaching of salts caused by repeated usage in the middle and upper courses of the rivers (World Bank 1998, pp. 3–5). At times over 2 g/l, these saline flows have lowered crop yields and, in conjunction with inadequate drainage of irrigated fields, promoted secondary soil salinization. Animal husbandry, both in the deltas and desert regions adjacent to the Aral Sea, has been damaged by reduction of area and declining productivity of pastures resulting from desertification, dropping groundwater levels, and replacement of natural vegetation suitable for grazing by inedible species.

Strong winds blow sand, salt, and dust from the dried bottom of the Aral Sea, large portions of which are a barren desert, onto surrounding lands. Since the mid-1970s, satellite images have revealed major salt/dust plumes extending as far as 500 km downwind that drop dust and salt over a considerable area adjacent to the sea in Uzbekistan, Kazakhstan, and to a lesser degree Turkmenistan (Micklin 1991, pp. 48–49, 2004; Glazovskiy 1990, pp. 20–23; Ptichnikov 2002). Although dust/salt storms affect the entire zone surrounding the Aral, most of the major storms occur with north and northeast winds, which most seriously impact the Ust-Urt Plateau to the sea's west and the Amu Dar'ya delta at the south end of the water body (Bortnik & Chistyayeva 1990, p. 27, figure 2.7). The latter is the most densely settled as well as economically and ecologically important region around the sea. Glazovskiy

Consumptive use: a measure of water withdrawn for irrigation that is lost to evaporation (from conveyance canals, fields, and irrigation formed terminal lakes) and transpired from or incorporated into crops

(1990, pp. 21–22), after analyzing estimates of the total deflated material (ranging from 13 million to as high as 231 million metric tons per year) that were made in the 1980s, concluded that the most probable figure was from 40 to 150 million tons.

Salts in dry and aerosol forms, the most harmful of which include sodium bicarbonate, sodium chloride, and sodium sulfate, settle on natural vegetation and crops, particularly in the Amu Dar'ya delta (Bel'gibayev 1984). In some cases, plants are killed outright, but more commonly, their growth (and for crops, yields) is substantially reduced. The salt and dust also have ill effects on wild and domestic animals by directly harming them and reducing their food supply (Palvaniyazov 1989). Local health experts also consider airborne salt and dust a factor contributing to high levels of respiratory illnesses and impairments, eye problems, and throat and esophageal cancer in the near-Aral region (Abdirrov et al. 1993, Tursunov 1989). More recent field work by a British-led group indicates that salt and dust blowing from the dried bottom (and likely from irrigated farmland in regions adjacent to the Aral Sea) is laced with pesticides and heavy metals, which would enhance the negative impacts on humans and other animals (O'Hara et al. 2000).

Owing to the sea's shrinkage, climate has changed in a band up to 100 km wide along the former shoreline in Kazakhstan and Uzbekistan (Micklin 1991, pp. 52–53; Glazovskiy 1990, pp. 19–21). Maritime conditions have been replaced by more continental and desertic regimes. Summers have warmed and winters cooled, spring frosts are later and fall frosts earlier, humidity is lower, and the growing season shorter. Uzbekistani climatological experts also believe that the increase in the levels of salt and dust in the atmosphere are reducing surface radiation and thereby photosynthetic activity, as well as increasing the acidity of precipitation (Chub 1998).

The population living in the so-called ecological disaster zone around the sea suffers acute health problems (Micklin 1992, *Medicins sans Frontieres* 2000). Some of these are direct consequences of the sea's recession (e.g., respiratory and digestive afflictions and possibly cancer from inhalation and ingestion of blowing salt and dust and poorer diets from the loss of Aral fish as a major food source). Other serious health-related problems result from environmental pollution associated with the heavy use of toxic chemicals (e.g., pesticides and defoliants for cotton) in irrigated agriculture, mainly during the Soviet era. Nevertheless, the most serious health issues are directly related to Third World medical, health, nutrition, and hygienic conditions and practices. Bacterial contamination of drinking water is pervasive and has led to very high rates of typhoid, paratyphoid, viral hepatitis, and dysentery. Tuberculosis is prevalent as is anemia, particularly in pregnant woman. Liver and kidney ailments are widespread; the latter is probably closely related to the excessively high salt content of much of the drinking water. Medical care is very poor, diets lack variety, and adequate sewage systems are rare.

Health conditions in the Karakalpak Republic in Uzbekistan are undoubtedly the worst in the Aral Sea Basin. Surveys conducted in the mid to late 1980s showed that rates of diseases such as cancer of the esophagus, tuberculosis, and various intestinal disorders had grown significantly compared to a decade earlier (Anokhin et al. 1991). The infant mortality rate, a basic indicator of general health conditions, rose from an average of 45/1000 live births in 1965 to 72/1000 in 1986, with the rate in several

districts adjacent to the former seashore ranging from 80 to over 100/1000. These are 3–4 times the national level in the former Soviet Union and 7–10 times that of the United States. Although efforts have been made in the post-Soviet period to improve health conditions here, there is little evidence these rates have declined substantially (Lean 2006).

Perhaps the most ironic and dark consequence of the Aral's shrinkage is the story of Vozrozhdeniya (Resurrection) Island. In the early 1950s, the Soviet military selected this, at the time, tiny, isolated island in the middle of the Aral Sea as the primary testing ground for its supersecret biological weapons program (Bozheyeva et al. 1999, Wijinsema 2000). From then until 1990, they tested various genetically modified and weaponized pathogens, including anthrax, plague, typhus, and smallpox, as well as other disease-causing organisms. These programs stopped with the collapse of the U.S.S.R. in 1991. Allegedly, the departing Soviet military took measures to decontaminate the island.

Since the 1960s, as the sea shrunk and shallowed, Vozrozhdeniya grew in size, and in 2001 it united with the mainland to the south as a huge peninsula extending into the Aral Sea (**Figure 5**). The fear is that some weaponized organisms survived and could escape to the mainland via infected rodents or that terrorists might gain access to them. In the early part of the new millennium, the United States contributed \$6,000,000 and sent a team of experts to the former island to help the Government of Uzbekistan ensure the destruction of any surviving weaponized pathogens (Bioweapons' Cleanup 2002).

IMPROVEMENT EFFORTS

The Soviet Union launched Aral improvement programs in the late 1980s when that government finally admitted the existence of a serious problem (Micklin 1991, pp. 68–81). The fundamental aims, but not the major players, have remained remarkably consistent since that time: better medical and health services, greater access to safe drinking water supplies, improved food supplies, and diversification of the economy for the people living near the sea; mitigation of negative ecological trends in the delta of the Amu Dar'ya; and rebuilding irrigation systems to raise their efficiency to deliver more water to the Aral Sea.

After the collapse of the U.S.S.R. in 1991, the new states of the region (Kyrgyzstan, Uzbekistan, Turkmenistan, Kazakhstan, and Tajikistan) assumed responsibility for dealing with the Aral situation. In March 1993, the presidents of the five republics signed an agreement to promote cooperation in solving the key problems (Micklin 2004). It established the Interstate Council on the Problems of the Aral Sea Basin (ICAS). A major purpose of the new organization was to facilitate assistance from the World Bank and other international donors as well as assume responsibility for various Aral Sea Basin assistance programs. The presidents also created an International Fund for the Aral Sea (IFAS) with the responsibility to collect revenue from each basin state for financing of rehabilitation efforts. The ICAS was abolished in 1997 and merged its functions into a restructured IFAS. The leadership of IFAS rotates in a two-year cycle among the Central Asian Heads of State.

Following independence, international aid donors began providing water resource management assistance in the Aral Sea Basin (Micklin 2004). The World Bank was the first major agency to become involved. In the early 1990s, the Bank cooperated with Aral Sea Basin governments to formulate an Aral Sea Basin Assistance Program (ASBP) to be carried out over 15 to 20 years. The initial cost estimate for this effort was set at 250 million USD, which was later increased to 470 million USD. The main goals of the program were (a) rehabilitation and development of the Aral Sea Disaster Zone, (b) strategic planning and comprehensive management of the water resources of the Amu Dar'ya and Syr Dar'ya, and (c) building institutions for planning and implementing the above programs. Afghanistan was invited to join the ASBP but did not respond to the overture (World Bank 1998, p. 9).

In 1996, the Bank did a major review to evaluate the strengths and weaknesses of the preparatory phase of the ASBP, which had cost \$15 million USD (Micklin 2000, p. 49). Out of this review came a new effort known as the Water and Environmental Management Project. Funded jointly with the Global Environmental Facility (GEF) at a cost of 21.5 million USD, the program was implemented between 1998–2003 (World Bank 1998, pp. 19–34). In line with a new emphasis on regional responsibility for the ASBP, the Executive Committee of IFAS managed the program, with the Bank playing a cooperative/advisory role.

IFAS has carried on the leading role in the latest effort entitled “Program of Specific Actions for Improving the Ecological and Social Situation in the Aral Sea Basin from 2003–2010” (IFAS 2003). It includes a broad range of measures to improve health, welfare, and the natural environment, including efforts to conserve and restore the tugay vegetation and lands usable for pasture in the Amu Dar'ya and Syr Dar'ya deltas, to combat desertification, and to develop measures for preventing salt and dust transfer from the dried bottom of the sea.

A number of other international donors have contributed to Aral Sea region improvement. The United States Agency for International Development (USAID) funded the Environmental Policy and Technology (EPT) project, running from 1993 to 1998, which financed measures to improve drinking water supplies in the Amu Dar'ya delta, aided in the formulation and implementation of regional water management policies and agreements, and provided advice on water management issues to specific governments (Micklin 1998). A smaller-scale follow-up project in 1999 and 2000 provided further assistance. USAID initiated a new, major effort in 2001 known as the Natural Resource Management Project (NRMP). This is a five-year effort focusing on providing assistance to Kazakhstan, Kyrgyzstan, Turkmenistan, Uzbekistan, and, to a lesser extent, Tajikistan to improve management of water, energy, and land (Micklin 2004).

The European Union initiated a major aid program for the Aral Sea Basin states in 1995 known as the Water Resources Management and Agricultural Production in the Central Asian Republics Project (WARMAP) (Micklin 1998). Phase 1 and 2 were completed by mid-1997. Major accomplishments of this program were the development of a GIS-based land and water database for the basin, providing help to the World Bank and ICAS (now IFAS) in their efforts to improve and legally codify the 1992 interstate water sharing agreement among the new states of the basin and

funding of training seminars and workshops, and an attempt to gather detailed data on irrigated water use at the farm level (World Bank 1998, pp. 8–9). The European Union has initiated follow-up programs to these efforts.

The United Nations has been providing assistance on the Aral Sea crisis since 1990 when a joint UNEP/Soviet working group on the Aral was formed (Micklin 1998). This aid has continued and expanded in scope in the post-Soviet era. UNESCO (United Nations Educational, Scientific and Cultural Organization) funded a research and monitoring program for the near-Aral region from 1992–1996 focusing on ecological research and monitoring in the Syr Dar'ya and Amu Dar'ya deltas (UNESCO 1998). The overall intent was to model the terrestrial and aquatic ecosystems of the study area to provide a scientific basis for implementation of ecologically sustainable development policies. The project relied mainly on the expertise of scientists and technicians from the Central Asian republics and Russia with limited involvement of foreign experts.

UNDP (United Nations Development Program) has also been very active in Aral Sea region activities (Micklin 2004). This organization has had two primary foci: strengthening regional organizations that have been established to deal with the Aral crisis and promoting sustainable development to improve conditions for the several million people who live in the so-called disaster zone adjacent to the sea. UNDP was instrumental in convincing the five Central Asian presidents to sign the Declaration of Central Asian States and International Organizations on Sustainable Development of the Aral Sea Basin in 1995, which commits the five states to pursue sustainable development in the management of land, water, biological resources, and human capital.

The North Atlantic Treaty Organization (NATO) has become involved in Aral Sea region activities through its Scientific and Environmental Affairs Division. The first NATO-sponsored event was an Advanced Research Workshop (ARW) on “Critical Scientific Issues of the Aral Sea Basin: State of Knowledge and Future Research Needs” held in Tashkent, Uzbekistan, during May 1994 (Micklin & Williams 1996). A second NATO ARW with an Aral theme took place in Wageningen, the Netherlands, in January 1995. The focus was on irrigation, drainage, and the environment in the Aral Sea Basin.

From 1995 to 2003, the NATO Science Division, primarily through its Science for Peace (SfP) Program, sponsored work to develop a land and water GIS for the Amu Dar'ya delta and Aral Sea (Ptichnikov 2000, 2002, 2002–2003). This system is intended to serve as a key tool for decision-making on land, water, and environmental management in the delta. The project cooperated closely with the government of Karakalpakstan to establish indigenous GIS capabilities through continuing development of a GIS center at Karakalpakstan State University in Nukus. The center serves as a training site for local specialists and scientists in GIS techniques and also operates a program for monitoring environmental conditions in the Amu Dar'ya delta and in the Aral Sea.

The SfP program has also supported another project to develop an environmentally appropriate water management regime, implemented through a decision support system based on GIS and a set of hydrologic models for the larger lakes/wetlands that

have been created or restored in the Amu Dar'ya delta (Scientific & Environmental Affairs 2003, pp. 189–190). This project involves cooperation between the Scientific Information Center of the ICWC in Tashkent and the private consulting firm Resource Analysis in the Netherlands.

THE FUTURE

What could the future hold for the Aral and its environs? Can the sea be returned to its pre-1960s level and size and the deltas of the Amu Dar'ya and Syr Dar'ya restored to their former ecological condition? If not, what improvement measures are rational and feasible to undertake.

Aral Sea Restoration

Assuming continuation of the pattern of basin withdrawals that has characterized the 1990s (the latest period for which we have data) and the pattern of more or less natural discharge from the mountain regions of flow generation that has characterized the years since the late 1950s, a conservative estimate of average annual discharge to the sea in the near and mid-term future (next 20–30 years) is 10 km^3 (Micklin 2000, p. 21; International Fund for Saving the Aral Sea 2004; Zholdasova 1999; Uzglavidromet 1994–2003). Based on this figure, to restore the Aral to its average level (53 m) and size ($67,000 \text{ km}^2$) during the first six decades of the twentieth century would require raising average annual discharge to the sea by approximately 46 km^3 , or 450%, bringing total inflow to 56 km^3 . This would necessitate a larger decrease in upstream withdrawals to compensate for natural losses of the net additions to flow before they reached the sea. In-stream losses have been estimated at 14%, which would require an additional 8 km^3 reduction in upstream use for a total of 54 km^3 .

In a regional context, the only realistic means for substantially increasing inflow to the Aral is reducing the consumptive use of water for irrigation in the sea's drainage basin. The reason is simple: This water-intensive activity, conducted on approximately 7.9 million hectares and the basis of agriculture here, accounts for 92% of withdrawals and an even larger share of consumptive use (Ruziev & Prikhod'ko 2002). The largest irrigated hectareage in the basin is found in Uzbekistan and Turkmenistan; these two nations, respectively, account for 54% and 22% of all irrigation withdrawals (Micklin 2000, p. 37). It is irrigation that has depleted the flow of the Amu Dar'ya and Syr Dar'ya and led to the great reduction in discharge of these rivers to the Aral.

Irrigation in the Aral Sea Basin is inefficient. Substantial technical, economic, and institutional improvements to it could save considerable water. Attempts are underway to implement improvement measures, but the substantial and comprehensive program needed would be extremely costly and it faces concerted opposition from forces within governments and from segments of the public. Taking costs as an example: Complete renovation of irrigation systems on 6 million hectares could likely save $12 \text{ km}^3 \text{ year}^{-1}$ but would cost at least 16 billion USD (Micklin 2004). To reach the maximum potential savings of 28 km^3 (based on technically, economically, and institutionally reforming irrigation on the "Israeli" model) would cost multiples more.

These figures are far beyond the willingness and ability of the basin states, in combination with international donors, to pay. Furthermore, the technical condition of irrigation systems in the basin, far from improving, is steadily deteriorating owing to inadequate funding for, and lack of management responsibility over, operation and maintenance activities.

Converting more of the irrigated area to less-water-intensive crops (e.g., substituting grains, soybeans, fruits, and vegetables for cotton and rice) and reduction of the irrigated area are other means of significantly reducing water usage in irrigation (Micklin 2004). The former strategy is being employed. Between 1990 and 1998, the area of cotton as a percent of the total irrigated area dropped from 45% to 25% percent, while the area of winter wheat rose to 28%. (Dukhovnyy & Sokolov 1999). This probably was a major factor in the drop in irrigation withdrawals from 109 to 92 km³ (16%) at the same time the irrigated area increased 10%. However, there are limits to such a program as the two primary irrigating nations (Uzbekistan and Turkmenistan) are intent on keeping cotton as a major crop because it plays a key role in earning foreign currency. Reductions in the irrigated area are unlikely in the near to mid-term future. All the former Soviet republics, except Kazakhstan, intend to expand irrigation, mainly to meet food needs for a growing population.

Thus, it is extremely doubtful that the Aral could be restored to its former grandeur in any foreseeable future. The amount of water that would need to be saved (51% of 1999 estimated withdrawals of 105 km³) is far above even the most optimistic and costly scenario of water use efficiency improvements. Such a reduction in withdrawals could only be met by a major cutback in irrigation that would wreak economic and social havoc on the countries of the basin,

On the other hand, the often-cited claim that the Aral Sea will dry up completely sometime in the twenty-first century is, of course, utterly false. Even in the unlikely event that river inflow from the Amu and Syr Dar'ya were reduced to zero, there would still be substantial residual input of irrigation drainage water, groundwater, and snow melt and rain that would maintain a much shrunken but still sizable set of as many as five separate water bodies: the eastern and western basins of the Small Aral Sea in the north, and three lakes formed from the current Large Aral (eastern and western basins and Tsche-Bas Gulf). These lakes would be hypersaline and of little ecological or economic value, except, perhaps, for the production of brine shrimp (*Artemia*) eggs.

Of course it is feasible through engineering to bring water to the Aral Sea from outside Central Asia. During the latter part of the Soviet period, water managers in Moscow and in Central Asia proposed diversion of massive flow, up to 60 km³, from Siberian rivers to the region as the panacea for perceived water shortage problems (Micklin 1991, pp. 60–68). The initial stage of this project would have taken 27 km³ from the Irtysh-Ob river system in the Western Siberian region of Russia. It was on the verge of implementation when stopped by the Gorbachev regime in 1986. Although real and serious potential ecological threats (of regional, not global, magnitude as claimed by some opponents) were given as the chief reason for canceling the project, economic considerations were the fundamental factors in this decision (Micklin 1987).

This grandiose scheme continues to be discussed and promoted in Central Asian water management and governmental circles and in the new millennium has, again, found a sympathetic ear among some water management professionals and bureaucrats in Russia, including Yuri Luzhkov, mayor of Moscow, and N.N. Mikheyev, the First Deputy Minister of Natural Resources (Mikheyev 2002, Polad-Zade 2002, Temirov 2003). However, implementation of this project in any but the far term, if ever, seems a pipe dream. Costs would be enormous, at least 30 billion USD, and even if Russia were willing to help finance the project, it is doubtful sufficient funds could be accumulated for construction (Temirov 2003). International donors, such as the World Bank, given their newfound sensitivity to environmental concerns, have stated opposition to such a project (Interfax Information Agency 2002). Finally, there is tremendous opposition among Russians to sending water from their precious Siberian rivers to Central Asia where, in their view, it would be wasted. Even if implemented, much less than the 27 km³ diverted, probably less than 15 km³, would reach the Aral owing to substantial evaporation and filtration losses in the transfer system, withdrawals along the route for irrigation and other purposes, and usage in Central Asia for irrigation. Certainly, it would be more rational to spend precious capital and effort on improving regional water management rather than importing water from Siberia (Kamalov 2003).

Mitigation Scenarios

Although restoration of the Aral to, or near, its pre-1960s level and ecological state is not viable in the foreseeable future, various partial rehabilitation scenarios for the sea and river deltas hold considerable promise. During August and September 2005, this author and Dr. Nikolay Aladin from the Zoological Institute, Russian Academy of Sciences, St. Petersburg, led an expedition, funded by the Committee for Research and Exploration of the National Geographic Society (Grant 7825-05), around both the northern and southern parts of the Aral Sea (**Figures 6 and 7**). Our purpose was to evaluate the ecological state of the sea and what it might portend for the future of this water body.

The Small Aral was in better shape than we had anticipated. Salinity levels were lower than expected (ranging from 3 g/l near the new Berg Strait dike to 24 g/l in the isolated Butakov Bay, with a rough estimated average for the entire water body of approximately 13 g/l). Dissolved oxygen levels were high everywhere and there appeared to be little evidence of any serious pollution. These positive factors contributed to a plentiful fish life, although, as noted above, mainly consisting of kambala (flounder) with two other species, sazan (carp) and sudak (pike-perch), making a strong comeback as salinity levels have decreased. We also were impressed by the number and diversity of aquatic birds (e.g., ducks, loons, swans), a positive indicator of ecological quality.

We mainly visited the western basin of the Large (southern) Aral Sea. Salinity levels were high, ranging from 70–80 g/l. Consequently, fish life was absent, but brine shrimp (*Artemia*) and several kinds of benthos were present. The water was sparkling clear and appeared to be very clean. Hence, as discussed below, there is even hope for this portion of the sea.



Figure 6

Nearly completed discharge gates for the dike across the former Berg Strait, August 2005. Photo by author.

What would the future Aral look like under the “conservative” future average annual inflow scenario of 10 km^3 ? The volume may reasonably be divided into 3.5 km^3 for the Small Aral from the Syr Dar’ya and 6.5 km^3 for the eastern basin of the Large Aral from the Amu Dar’ya. Flow of 3.5 km^3 to the Small Aral would allow maintaining its level at 42 m (the current maximum for the recently completed Berg Strait Dike)



Figure 7

Former cargo ship on the dried bottom of the Small Aral Sea, August 2005. Photo by author.

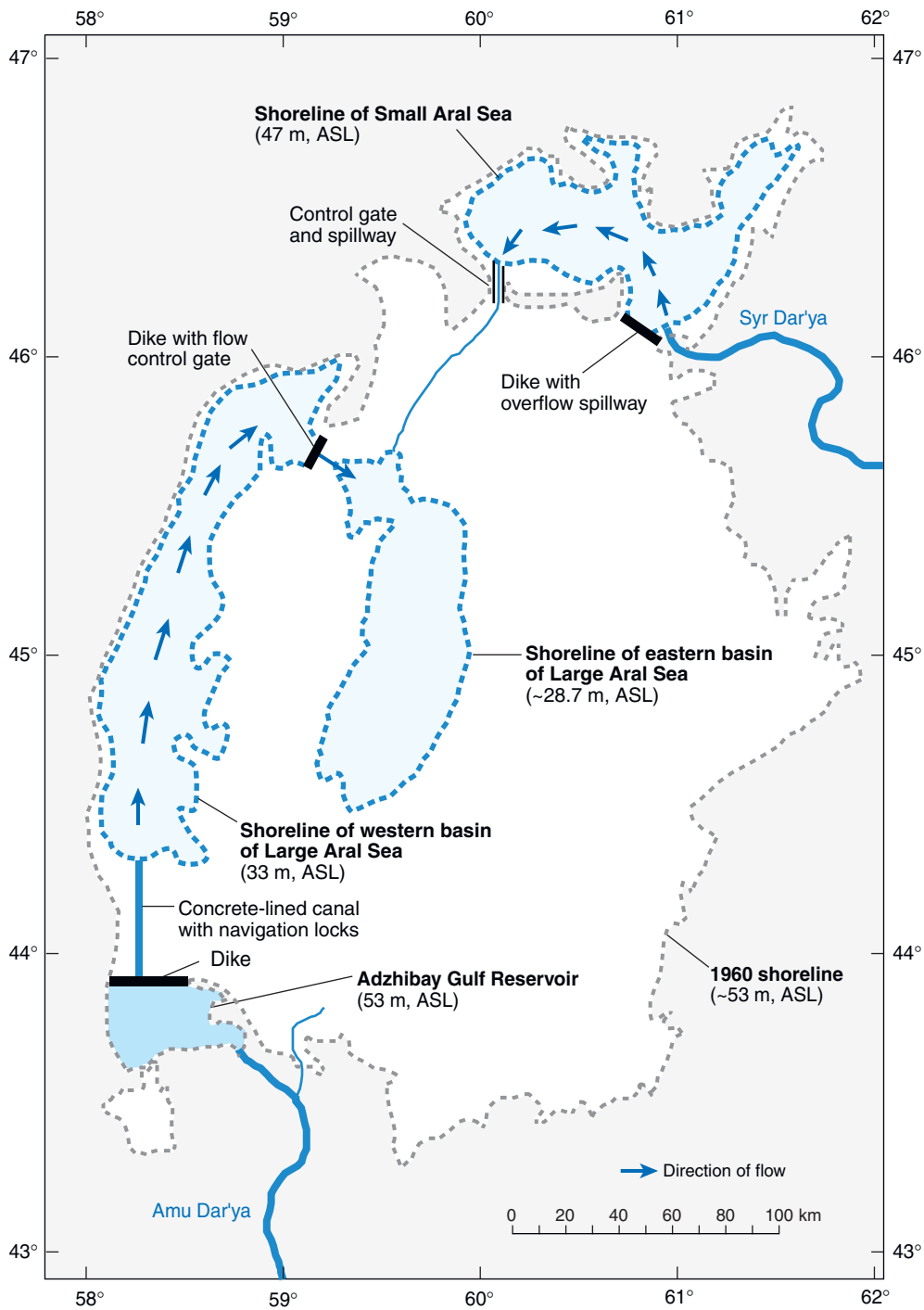
and area at 3258 km² with release of excess flow of around 1.20 km³ to the Large Aral. Average salinity could likely be maintained at 10–12 g/l, not much above levels prior to the beginning of the modern desiccation more than four decades ago. The North Aral Sea's ecology and fishery would not return to their earlier states, but they would significantly improve.

The eastern, shallow basin of the Large Aral would be maintained at about 29–30 m above sea level (it should fall to this level during 2006 or 2007), assuming 15% of the flow from the Small Aral reached the main part of this basin (much would be lost to high evaporation and transpiration in the extremely shallow flooded area south of the channel from the Small Aral to Large Aral seas). The western basin would be practically cut-off from the east, with a long, narrow, deep channel continuing to connect them and carrying a very modest amount of water from the eastern to western basin. The ultimate level and size of the western basin would largely depend on net groundwater inflow, which is not known with any degree of accuracy, but the level and area would decrease considerably from the current figures. The average salinity of the eastern basin would probably drop from its current level of >100 g/l owing to essentially no flow from it to the western basin (meaning that nearly all the “fresh” inflow from the Amu Dar'ya would be retained here). However, salinity would certainly remain above 70 g/l, too high to support any fish species. Because of the cut-off of nearly all flow from the east to west basin of the Large Aral, the west basin would continue on the path of hypersalinization, steadily moving toward conditions characteristic of the Great Salt Lake in the United States and the Dead Sea in the Middle East (200–300 g/l). Only brine shrimp (*Artemia*) and some bacteria could survive such harsh conditions.

There are, however, more optimistic scenarios for the future Aral. **Figure 8** shows a possible scenario developed by this author using data from his water balance model (Micklin 2004). It is based on concepts first put forward by L'vovich & Tsigelnaya (1978) almost 30 years ago. For the Small Aral Sea, it assumes average annual inflow from the Syr Dar'ya of 4.5 km³, which in fact was exceeded for the period 1990–2004, when discharge averaged 5 km³. The level of this water body could be raised and stabilized at approximately 47 m and the area expanded to ~4300 km². The new level would be only 6 m below the 53 m mark that is considered the average for modern predesiccation conditions. This would bring the shoreline of the Small Sea close enough to Aralsk, the major port city at the north end of the Aral, to allow rehabilitation of the earlier built channels connecting the city to the sea. This would be a boon to the fishing industry allowing large commercial fishing vessels that

Figure 8

One scenario of the Aral Sea in 2025. Small Aral Sea: level: 47 m; area: 4310 km²; volume: 46.5 km³; river inflow: 4.5 km³; outflow toward Large Aral: 1.4 km³, salinity: 7.59 g/l. Large Aral Sea, western basin: level 33 m; area 6203 km²; vol. 85 km³; river inflow 7.35 km³; outflow to eastern basin 3.05 km³; salinity 45 g/l by 2025, 21 g/l by 2050. Large Aral Sea, eastern basin: level 28.7 m, Area 5710 km²; vol. 21 km³; inflow from western basin 2.95 km³; inflow from Small Aral 1.03 km³, hypersaline (>200 g/l?).



could bring their catches to the city access to the sea and permitting reopening of the large fish cannery. General sea-borne commerce could also be resumed as well. There would be some improvement of fishery conditions from a further reduction of salinity. Flow from the Small to Large Sea would be, on average, approximately $1.4 \text{ km}^3 \text{ year}^{-1}$.

Of course, such a plan requires careful benefit/cost and environmental evaluation. It would be expensive as a much longer and higher dike across the former Berg Strait would be required as well as reconstruction of the discharge facility. As shown on **Figure 8**, it might make sense to move the main discharge facility to the western end of the Small Sea, as this would be optimal for controlling salinity for the whole water body.

Figure 8 also shows a possible rehabilitation scheme for Large Aral. It would require a modest increase in inflow from the Amu Dar'ya. Annual average flow for 1990–2004 was around 7 km^3 ; the project would require somewhat more than 8 km^3 . This should be easily obtainable, as it would require only minimal improvements in irrigation efficiency in the basin of the Amu Dar'ya. Nearly all of the residual flow of the Amu (after meeting needs of deltaic lakes and wetlands, described below) would need to be directed northeastward into the former Adzhibay Gulf refilling it to 53 m. The current channel that takes some river water to maintain a lake on part of the dried gulf could probably be deepened and widened to accomplish this. A restored Adzhibay Gulf would improve the local climate, be of great ecological value to migratory and nonmigratory birds and aquatic mammals, and could become a major fishery.

On average, a little more than $7 \text{ km}^3 \text{ year}^{-1}$ of water from the Adzhibay reservoir would be released via control gates to a channel connected to the western basin of the Large Aral Sea, maintaining a level of approximately 33 m and area a little over 6000 km^2 . The channel would need to be lined with concrete or clay to reduce filtration losses. A dike with discharge gates would be built across the Kulandy Strait at the north end of the basin. Outflow to the eastern basin would average approximately $3 \text{ km}^3 \text{ year}^{-1}$. The western basin would gradually freshen as more salt is carried out of the reservoir than is brought in, first allowing stocking with salt-tolerant fish (e.g., kambala) and, later, if salinities could be brought below 15 g/l, with endemic species such as sazan and sudak. It is likely that density stratification (already reported for the basin, see Kostianov et al. 2004), which creates a layer of saline water on the bottom and less saline on top, would enhance this process and allow development of a valuable fishery again.

This alternative has been little studied so cost estimates are highly speculative, although it would likely be much more expensive than the project to rehabilitate the small Aral Sea. Also, the range of potential negative environmental consequences is unknown (e.g., would the shrinking eastern sea leave a much larger salt desert that would significantly aggravate the problem of salt/dust storms?) Also, this option would eliminate the possibility of commercially raising brine shrimp in the western portion of the Large Aral, as salinities would be far too low.

Rehabilitation and partial preservation of the lower Amu Dar'ya delta and its wetlands has been a priority since the late 1980s, first by the Soviet government and

subsequently by the new states of Central Asia and international donors. The prime objective of the most recent program, known as the Aral Sea Wetland Restoration Project (ASWRP), which was implemented by the International Fund for the Aral Sea and funded by the Global Environmental Facility, has been partial ecosystem rehabilitation through creation of artificial ponds and wetlands in the delta and on the dry bed of the Aral Sea (IFAS 2000, pp. 19–23). Specific benefits of lake/wetland restoration 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 to arable lands (Aral Sea Basin Sustainable Development Commission 1998, pp.59–81). A companion measure is the revegetation/reforestation of parts of the dried bottom to stabilize them and lower their deflation potential. With the completion of parts 1 and 2 of the project, some 73,000 hectares enjoy improved conditions for both flora and fauna.

The aggregate cost of parts 1 and 2 was 6 million USD. Experts have estimated that 4–5 km³ of water (mainly relatively clean river flow supplemented by irrigation drainage) are needed to support minimally acceptable hydro-ecological conditions in the lower delta of the Amu Dar'ya, including the natural and artificially created lakes and wetlands (Intergov. Coord. Water Manag. Comm. 2002, p. 39). The remaining flow could be used to support the rehabilitation project for the Large Aral Sea described above.

A wild card in any attempt to design reasonable future scenarios of the Aral Sea is anthropogenic climate change. So-called global warming from elevated levels of greenhouse gases in the troposphere, chiefly CO₂ from the combustion of fossil fuels, is likely already underway and will increase in magnitude with time according to the overwhelming majority of experts. Although regional climate change is more difficult to decipher, Dr. V. Chub (2002, pp. 62–106) an expert on the climate of Central Asia and director of the Main Administration for Hydrometeorology in Tashkent, Uzbekistan, believes a general warming of 0.5 to 3.5°C is possible in different regions of the Aral Sea Basin by 2030 compared to the base period of 1961–1990. This would lead to longer, hotter summers with increased crop water needs and heightened irrigation requirements, which could reduce aggregate water savings from irrigation improvements and reduce inflow to the Aral Sea. On the other hand, some climate models indicate that the flow of the Amu Dar'ya and Syr Dar'ya could be increased somewhat by enhanced precipitation and melting of glaciers in the mountain zones of flow formation (Chub 2002, pp. 106–115). However, this increase would be at most 10% and unsustainable as the rate of melt of the glaciers would exceed their replenishment. Other models show substantial decreases of these rivers' flow.

SUMMARY POINTS

1. The Aral Sea has suffered severe desiccation since the 1960s owing to the expansion of irrigation in its drainage basin that has substantially reduced river inflow to this water body.

2. By 2006, the sea's level had dropped 23 m, the area shrunk by 74%, the volume decreased by 90%, and the salinity of the southern part of the sea raised more than 1000% to more than 100 g/l.
3. The sea and deltas of its influent rivers have suffered enormous ecological, environmental, and economic damage that has adversely affected the local population.
4. In its last years, the government of the Soviet Union started programs to cope with the ecological, environmental, and human problems associated with the drying of the Aral Sea.
5. After the collapse of the U.S.S.R., the governments of the new states of Central Asia, in cooperation with international donors, have continued programs to improve the situation.
6. Full restoration of the sea in the foreseeable future appears impossible.
7. However, there is definitely hope for the Aral as evidenced by the recent and (apparently) successful project to partially rehabilitate the separated northern part of the sea and programs completed and underway to improve the ecology of the lower Amu Dar'y delta.

FUTURE RESEARCH DIRECTIONS

1. There needs to be long-term monitoring of ecological/environmental changes in the North Aral Sea to evaluate the success of the restoration project and to provide "feedback" on how such efforts might be improved.
2. Research is needed on the Large (southern) Aral to see if it is worthwhile to attempt partial rehabilitation of the western basin by channeling the residual flow of the Amu Dar'ya into it.
3. Assuming continued salinization of the Large Aral, the potential of commercial-scale brine shrimp (*Artemia*) egg production here needs further research.
4. The "new" water balance of the Aral Sea needs to be carefully studied, as it was during the Soviet era. Modern technologies (e.g., satellite imagery and other remote sensing techniques) offer great promise in this effort, particularly where on-site measurements are not feasible.

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