Articles

Desiccation of the Aral Sea: A Water Management Disaster in the Soviet Union

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The Aral Sea in the Soviet Union, formerly the world's fourth largest lake in area, is disappearing. Between 1960 and 1987, its level dropped nearly 13 meters, and its area decreased by 40 percent. Recession has resulted from reduced inflow caused primarily by withdrawals of water for irrigation. Severe environmental problems have resulted. The sea could dry to a residual brine lake. Local water use is being improved and schemes to save parts of the sea have been proposed. Nevertheless, preservation of the Aral may require implementation of the controversial project to divert water from western Siberia into the Aral Sea basin.

THE ARAL SEA IS A HUGE, SHALLOW, SALINE BODY OF water located in the deserts of the south-central Soviet Union (Figs. 1 and 2). A terminal lake (having no outflow), its secular level is determined by the balance between river and ground-water inflow and precipitation on its surface on the one hand and evaporation from the sea on the other.

The Aral depression has repeatedly been flooded and desiccated since the Pliocene (*1; 2*, pp. 277–297). The most recent filling began in the late Pleistocene, around 140,000 years ago, when the Syr Dar'ya flowed into the lowest part of the hollow. The lake did not attain great size until the beginning of the Holocene (Recent) Epoch when inflow was increased some threefold by capture of the Amu Dar'ya. Marine fossils, relict shore terraces, archeological sites, and historical records point to repeated major recessions and advances of the sea during the past 10,000 years. Until the present century, fluctuations in its surface level were at least 20 m and possibly more than 40 m (*1, 3*). Significant cyclical variations of sea level during this period resulted from major changes in river discharge into it caused by climatic alteration, by natural diversions of the Amu Dar'ya away from the Aral, and during the past 3000 years by man. Human impacts included sizable withdrawals for irrigation from the Amu Dar'ya and diversions of this river westward into lower lying channels and hollows because of the destruction of dikes, dams, and irrigation systems during wars (*1, 4*).

From the middle 18th century until 1960, sea level varied 4 to 4.5 m (*1, 5*). Beginning in 1910, when accurate and regular level observations began, to 1960, the lake was in a "high" phase with level changes of less than 1 m (*6*). However, during the past 28 years the sea's surface has dropped precipitously. In 1960, sea level was 53.4 m, area 68,000 km^2, volume 1090 km^3, average depth 16 m, and average salinity near 10 g/liter (*7, 8*). The Aral was the world's fourth largest lake in area, behind the Caspian Sea, Lake Superior, and Lake Victoria. By the beginning of 1987, sea level had fallen 12.9 m, area decreased by 40%, volume diminished by 66%, average depth dropped to 9 m, and average salinity risen to 27 g/liter (Fig. 3). The sea had dropped to sixth in area among the world's lakes.

The recent recession has been the most rapid and pronounced in 1300 years (*1*). Human actions have been the primary cause. Desiccation continues at a rapid pace and if unchecked will shrink the sea to a briny remnant in the next century. Severe and

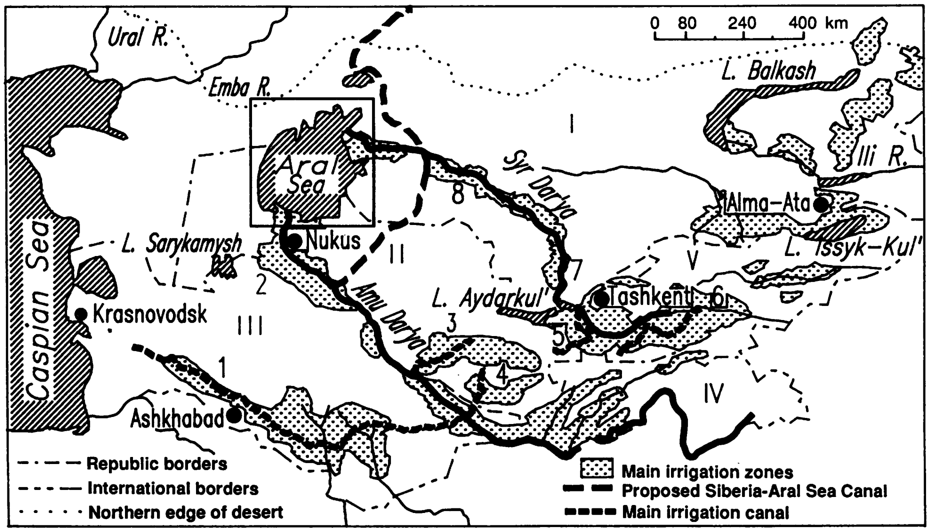

Fig. 1. The Aral Sea, located in the driest part of the Soviet Union. The population of this region is nearly 40 million, predominantly Muslim, and growing rapidly. Agriculture with extensive irrigation is the mainstay of the local economy. Major irrigation complexes are shown: 1, Karakum Canal; 2, Amu Dar'ya Delta; 3, Amu-Bukhara Canal; 4, Karshi Steppe; 5, Golodnaya Steppe; 6, Fergana Valley; 7, Kzyl-Kum Canal; and 8, Kzyl-Orda Canal. Roman numerals: I, Kazakh Republic; II, Uzbek Republic; III, Turkmen Republic; IV, Tadzhik Republic; and V, Kiryiz Republic. Area in the inset is enlarged in Fig. 2.

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widespread ecological, economic, and social consequences that are progressively worsening have resulted from the Aral's recession. The scale of impacts on this large a body of water for such a short period is unprecedented. Soviet commentators in recent years have referred to the Aral situation as "one of the very greatest ecological problems of our century" (*9*), an "impending disaster" (*10*), and as "a dangerous experiment with nature" (*11*).

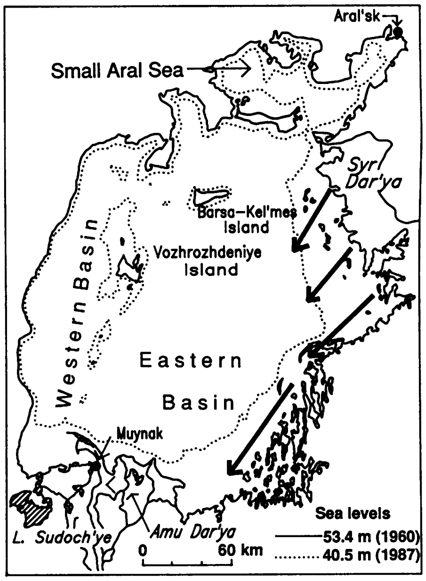


Fig. 2. The Aral Sea, fourth largest lake in the world by area in 1960. The Aral Sea has shrunk significantly because of a nearly total cutoff of river inflow from the Amu Dar'ya and Syr Dar'ya as a result of heavy withdrawals for irrigation. The deeper Western Basin has been less affected than the shallow Eastern Basin. The large area of exposed former bottom along the eastern shore is a source of major dust and salt storms (the black arrows indicate the source and direction of major storms) that are causing significant ecological and agricultural damage for hundreds of kilometers inland. The former ports of Aral'sk and Muynak are now tens of kilometers from the sea. Compiled from (*22*, figure 4) and satellite imagery (*61*).

Water Balance Changes

As in the past, the cause of the modern recession of the Aral is a marked diminution of inflow from the Syr Dar'ya and Amu Dar'ya, the sea's sole sources of surface water inflow, that has increasingly shifted the water balance toward the negative side (Table 1). The trend of river discharge has been steadily downward since 1960 (Fig. 4).

A shrinking body of water is dominantly a negative feedback mechanism, that is, one that resists change and promotes stability. Evaporative losses significantly diminish as area decreases, pushing the water balance system toward equilibrium. Hence, in the future, assuming some level of surface- and ground-water inflow, the Aral should stabilize. However, this is not likely to occur for decades. The primary determinant of level change, the difference between inflow and net evaporation, is currently large and negative. It will only decrease slowly as the sea shrinks to a much smaller size.

The causes of reduced inflow since 1960 are both climatic and anthropogenic. A series of dry years in the 1970s, particularly 1974–75, lowered discharge from the zones of flow formation of the Amu Dar'ya and Syr Dar'ya around 30 km^3 per year (27%) compared to the average during the preceding 45 years (*8*; *12*, p. 227). The 1982 to 1986 period has also suffered low flows (*12–14*). Nevertheless, the most important factor reducing river flow has been large consumptive withdrawals (that is, water withdrawn from rivers that is not returned to them), overwhelmingly for irrigation. Average annual river flow in the zones of formation of these rivers (high mountains to the southeast of the Aral Sea) averaged 111 km^3 from 1926 to 1970 (*12*). Under "natural" conditions only about half of this would reach the Aral because of losses to evaporation, transpiration, and filtration as these rivers cross the deserts and flow through their deltas (*12*).

Irrigation has been practiced in the lower reaches of the Amu Dar'ya and Syr Dar'ya for several millennia (*4*). In 1900 more than 3 million hectares were under irrigation in the Aral Sea basin, growing to 5 million by 1960 when consumptive withdrawals for it reached an estimated 40 km^3 (*1, 15*). However, irrigation withdrawals before the 1960s did not measurably reduce inflow to the Aral. These artificial losses were compensated by correspondingly large reductions of natural evaporation, transpiration, and filtration, particularly in the deltas of the Syr Dar'ya and Amu Dar'ya where truncated spring floods diminished floodplain inundation, the area of deltaic lakes, and the expanse of phreatophytes (*12, 15, 16*). Also, the installation of drainage networks increased irrigation return flows to these rivers.

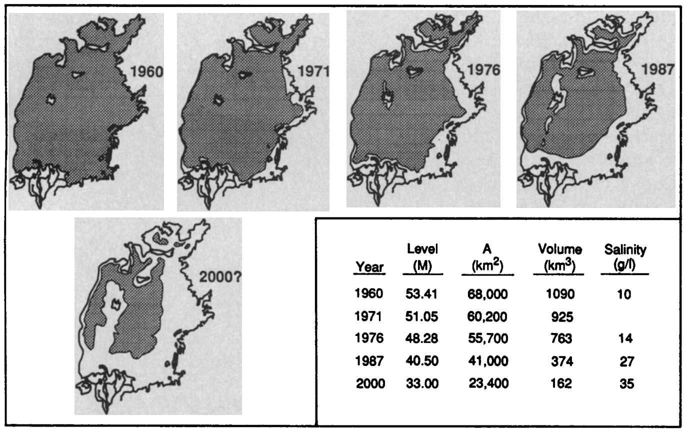
By 1980, the irrigated area in the Aral Sea basin had grown to nearly 6.5 million hectares (*17*; *18*, pp. 226–230). Withdrawals from the Amu Dar'ya and Syr Dar'ya for all purposes were 132 km^3 with consumptive use, including evaporation from reservoirs, of 85 km^3 (*18*, pp. 212–215). Irrigation accounted for 120 km^3 of withdrawals (91%) and for 80 km^3 of consumptive use (94%). Extrapolation, from data on area and rates of growth of irrigation for administrative units in the Aral Sea basin for the period 1980 to 1984 and 1980 to 1986, indicates that in 1987 about 7.6 million hectares were irrigated (*17*). Between 1980 and 1987, there was a major improvement in irrigation efficiency in the Aral Sea basin which lowered average withdrawals from 18,500 to 13,700 m^3/ha (*19*). Thus a 17% larger area was irrigated with considerably less water (104 km^3). Information on consumptive use in 1987 is not available but it probably remained near the 1980 figure because of the efficiency gains (that is, a higher percentage of withdrawn water was used by crops and a lower percentage was return flows).

Factors that compensated the earlier growth of consumptive withdrawals reached their limits in the 1960s (*2, 12, 15, 16*). Hence, as irrigation expanded during the past three decades, the increase in water use has not been balanced by commensurate reductions in natural losses. Furthermore, the irrigation of huge new areas such as the Golodnaya (Hungary) Steppe along the Syr Dar'ya consumed huge volumes of water to fill soil pore spaces (*20*), newly created giant reservoirs required filling and heightened evaporative losses, increased flushing of soils to counteract secondary salinization raised water use, and new irrigation systems discharged their drainage water into the desert or large hollows where it evaporated.

The Karakum Canal has been the single most important factor contributing to the diminution of inflow to the Aral in recent decades. The largest and longest irrigation canal in the Soviet Union, it stretches 1300 km westward from the Amu Dar'ya into the Kara-Kum Desert (Fig. 1). Between 1956 and 1986, 225 km^3 were diverted into it as annual withdrawals rose from less than 1 km^3 to more than 14 km^3 (*21*). All of the water sent along the Karakum Canal is lost to the Aral.

Environmental Impacts

During planning for a major expansion of irrigation in the Aral Sea basin, conducted in the 1950s and 1960s, it was predicted that this would reduce inflow to the sea and substantially reduce its size. At the time, a number of experts saw this as a worthwhile tradeoff: a cubic meter of river water used for irrigation would bring far more value than the same cubic meter delivered to the Aral Sea (*6, 22–25*). They based this calculation on a simple comparison of economic gains from irrigated agriculture against tangible economic benefits from the sea. Indeed, the ultimate shrinkage of the Aral to a residual



Year	Level (M)	A (km^2)	Volume (km^3)	Salinity (g/l)
1960	53.41	68,000	1090	10
1971	51.05	60,200	925	
1976	48.28	55,700	763	14
1987	40.50	41,000	374	27
2000	33.00	23,400	162	35

Fig. 3. The changing profile of the Aral Sea, 1960 to 2000 (*7*, *61*, *62*).

brine lake as all its inflow was devoted to agriculture and other economic needs was viewed as both desirable and inevitable.

These experts largely dismissed the possibility of significant adverse environmental consequences accompanying recession. For example, some scientists claimed the sea had little or no impact on the climate of adjacent territory and, therefore, its shrinkage would not perceptibly alter meteorological conditions beyond the immediate shore zone (*6*). They also foresaw little threat of large quantities of salt blowing from the dried bottom and damaging agriculture in adjacent areas (*22*). This theory rested, in the first place, on the assumption that during the initial phases of the Aral's drying only calcium carbonate and calcium sulfate would be deposited on the former bottom. Although friable and subject to deflation, these salts have low plant toxicity. Second, it was assumed that the more harmful compounds, chiefly sodium sulfate and sodium chloride, which would be deposited as the sea continued to shrink and salinize, would not be blown off because of the formation of a durable crust of sodium chloride. Some optimists even suggested the dried bottom would be suitable for farming (*22*).

Although a small number of scientists warned of serious negative effects from the sea's desiccation, they were not heeded (*14*, *24*). Time has proved the more cautious scientists not only correct but conservative in their predictions. A brief discussion of the most pronounced impacts follows.

Bottom exposure and salt and dust storms. The Aral contained an estimated 10 billion metric tons of salt in 1960, with sodium chloride (56%), magnesium sulfate (26%), and calcium sulfate (15%) the dominant compounds (*22*). As the sea shrank, enormous quantities of salts accumulated on its former bottom. This results from capillary uplift and subsequent evaporation of heavily mineralized ground water along the shore, seasonal level variations that promote evaporative deposition, and to winter storms that throw precipitated sulfates on the beaches (*25–27*).

Much of the 27,000 km^2 of bottom exposed between 1960 and 1987 is salt-covered. In contrast to earlier predictions that were based on a faulty understanding of the geochemistry of a shrinking and salinizing Aral, not only have calcium sulfate and calcium carbonate deposited but sodium chloride, sodium sulfate, and magnesium chloride have as well (*24*). Because of the concentration of toxic salts in the upper layer, a friable and mobile surface, and lack of nutrients and fresh water, the former bottom is proving extremely resistant to natural and artificial revegetation (*26*, *28*).

However, the most serious problem is the blowing of salt and dust from the dried bottom. There is as yet no evidence of the formation of a sodium chloride crust that would retard or prevent deflation (*24*). The largest plumes arise from the up to 100-km-wide dried stripe along the sea's northeastern and eastern coast and extend for 500 km (Fig. 2) (*11*, *25*). Recent reports state traces of Aral salt have been found 1000 km to the southeast of the sea in the fertile Fergana Valley, in Georgia on the Black Sea coast, and even along the arctic shore of the Soviet Union (*29*, *30*).

Soviet scientists report major storms as beginning in 1975 when they were first detected on satellite imagery. Between 1975 and 1981, scientists confirmed 29 large storms from analysis of *Meteor* (a high-resolution weather satellite) images (*11*). During this period, up to ten major storms occurred in 1 year. Recent observations by Soviet cosmonauts indicate the frequency and magnitude of the storms is growing as the Aral recedes (*31*). Sixty percent of the observed storms moved in a southwest direction which carried them over the delta of the Amu Dar'ya, a region with major ecological and agricultural importance (*11*). Twenty-five percent traveled westward and passed over the Ust-Yurt plateau, which is used for livestock pasturing.

An estimated 43 million metric tons of salt annually are carried from the sea's dried bottom into adjacent areas and deposited as aerosols by rain and dew over 150,000 to 200,000 km^2 (*11*, *13*, *32*). The dominant compound in the plumes is calcium sulfate but they also contain significant amounts of sodium chloride, sodium sulfate, magnesium sulfate, and calcium bicarbonate (*33*). Sodium chloride and sodium sulfate are especially toxic to plants, particularly during flowering. In spite of the expected increase in the area of former bottom, salt export is predicted to diminish slightly to 39 million metric tons per year by the year 2000 as a result of the exhaustion of deflatable materials, the leaching of salt into deeper layers, and through the process of diagenesis of the older surface (*32*).

Loss of biological productivity. As the sea has shallowed, shrunk, and salinized, biological productivity has steeply declined. By the early 1980s, 20 of 24 native fish species disappeared and the commercial catch (48,000 metric tons in 1957) fell to zero (*2*, pp. 507–524; *13*, *26*). Major fish canneries at Aral'sk and Muynak, formerly ports but now some distance from the shore, have slashed their work forces and barely survive on the processing of high cost fish brought from as far away as the Atlantic, Pacific, and Arctic oceans (*29*, *30*, *34*, *35*). Both plants in 1988 will be switched to *khozraschet* (economic principles of management) and may be forced to close (*30*). Residual commercial fishing continues in lakes such as Sudoch'ye in the Amu Dar'ya Delta and in the two largest irrigation drainage water lakes that have formed (Sarykamysh and Aydarkul'). However, levels of pesticides and herbicides, from cottom field runoff, in fish taken from Sarykamysh and Aydarkul' are dangerously high, prompting a halt to commercial fishing in the former in 1987 (*14*, *29*).

Employment directly and indirectly related to the Aral fishery, reportedly 60,000 in the 1950s, has disappeared (*36*). The demise of commercial fishing and other adverse consequences of the sea's drying has led to an exodus from Aral'sk and Muynak whereas many former fishing villages have been completely abandoned (*30*, *34*). During recent years, more than 40,000 have left the districts of Kzyl-Orda Oblast that abut the Aral on the east and northeast (*30*).

Deterioration of deltaic ecosystems. The shrinking of the Aral along with the greatly diminished flow of the Syr Dar'ya and Amu Dar'ya has had particularly devastating effects on these rivers' deltas (*11*, *13*, *14*, *26*, *37*). Prior to 1960, these oases surrounded by desert not only possessed great ecological value because of the richness of their flora and fauna but provided a natural feed base for livestock, spawning grounds for commercial fish, reeds harvested for industry, and opportunities for commercial hunting and trapping. Deltaic environments deteriorated as river flow diminished and sea level fell, leading to the drying or entrenchment of distributary and even main channels, the cessation of spring inundation of floodplains, and the shrinking or disappearance of lakes. Between 1960 and 1974, the

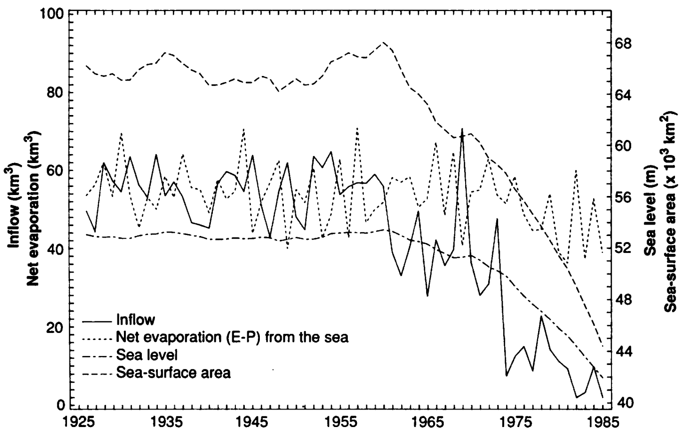


Fig. 4. Annual hydrologic parameters of the Aral Sea, 1926 to 1985. For the period 1926 to 1960, there was little difference between inflow and net evaporation (sea-surface evaporation minus sea-surface precipitation). Consequently, sea level and area varied insignificantly. Since 1960, with the exception of the unusually heavy flow year of 1969, discharge to the Aral Sea has trended steadily downward. Net evaporation has diminished somewhat as the sea's area contracted but the gap between it and river flow has grown steadily larger, accelerating the rate of level drop and area decrease (7).

area of natural lakes in the Syr Dar'ya Delta decreased from 500 km^2 to several tens of square kilometers, whereas in the Amu Dar'ya Delta from the 1960s until 1980, 11 of the 25 largest lakes disappeared and all but 4 of the remainder significantly receded (*38, 39*).

Native plant communities have degraded and disappeared. *Tugay* forests, composed of dense stands of phreatophytes mixed with shrubs and tall grasses fringing delta arms and channels to a depth of several kilometers, have particularly suffered. The expanse of *Tugay* in the Amu Dar'ya Delta, estimated at 13,000 km^2 in the 1950s, had been halved by 1980 (*37*). The major cause of deltaic vegetation impoverishment has been the 3 to 8 m drop of ground water along with the end of floodplain inundation.

Degradation of vegetational complexes and drops in the water table have initiated desertification in both deltas. Satellite imagery and photography from manned spacecraft indicate that desert is spreading rapidly (*11*). Livestock raising has also suffered considerable damage because of a decline in yields and a reduction of suitable areas. In the Amu Dar'ya Delta between 1960 and 1980 the area of hayfields and pastures decreased by 81% and yields fell by more than 50% (*26*).

Habitat deterioration has harmed delta fauna, which once included muskrat, wild boar, deer, jackel, many kinds of birds, and even a few tigers. At one time 173 animal species lived around the Aral, mainly in the deltas; 38 have survived (*26, 30*). Commercial hunting and trapping have largely disappeared. The harvest of muskrat skins in the Amu Dar'ya Delta has fallen to 2,500 per year from 650,000 in 1960 (*14*).

Climate changes. Earlier claims to the contrary notwithstanding, research over the past two decades has established that the Aral affects temperature and moisture conditions in an adjacent stripe estimated to be 50 to 80 km wide on its north, east, and west shores and 200 to 300 km wide to the south and southwest (*13, 26, 40*). With contraction, the sea's influence on climate has substantially diminished. Summers have become warmer, winters cooler, spring frosts later, and fall frosts earlier, the growing season has shortened, humidity has lowered, and there has been an overall trend toward greater continentality. The most noticeable changes have occurred in the Amu Dar'ya Delta. At Kungrad, now located about 100 km south of the Aral, comparison of the period 1935 to 1960 with that of 1960 to 1981 indicates that relative humidity diminished substantially, the average May temperature rose 3 to 3.2 degrees Celsius, and the average October temperature decreased 0.7 to 1.5 degrees Celsius (*13*). The growing season in the northern Amu Dar'ya Delta has been reduced an average of 10 days, forcing cotton plantations to switch to rice growing (*14, 26*).

Ground-water depression. The drop in the level of the Aral has been accompanied by a reduction of the pressure and flow of artesian wells and a decline of the water table all around the sea (*13*). Soviet scientists have estimated that a 15-m sea level drop, likely by the early 1990s, could reduce ground-water levels by 7 to 12 m in the coastal zone and affect the water table 80 to 170 km inland (*41*). The sinking water table has had significant adverse impacts outside the Amu Dar'ya and Syr Dar'ya deltas, drying wells and springs and degrading natural plant communities, pastures, and hayfields.

Water supply and health concerns. The reduction of river flow, salinization and pollution of what is left, and lowering of ground-water levels has caused drinking water supply problems for communities around the sea. Problems are especially acute in the more heavily populated deltas (*13, 26*). To provide a reliable, safe water supply to Nukus (1987 population of 152,000) in the Amu Dar'ya Delta, a 200-km pipeline costing 200 million rubles (officially a ruble is about $1.60) is under construction from the upstream Tyuyamuyun Reservoir. The declining quality of drinking water is cited as the main factor increasing intestinal illnesses, particularly among children, and throat cancer incidence in the lower reaches of the Amu Dar'ya and Syr Dar'ya (*26, 34, 35*). There is fear of epidemics because of the deterioration of the quality of the water supply and the increasing rodent population (*8, 35*). Desert animals who use the Aral Sea as a drinking source have died from its greatly increased mineral content (*26*).

Economic losses. There are no accurate figures on damages associated with the Aral's recession. Soviet scientists and economists have attempted to estimate the costs of the more tangible consequences. A 1979 study concluded that aggregate damages within the Uzbek Republic, which has suffered the greatest harm, totaled 5.4 to 5.7 billion rubles (*42*). A 1983 evaluation concluded that annual damages in the lower course of the Amu Dar'ya were 92.6 million rubles with the following distribution: agriculture, 42%; fisheries, 31%; hunting and trapping, 13%; river and sea transport, 8%; and living and working conditions, 6% (*26*). A recent popular article listed, without elaborating, a figure of 1.5 to 2 billion rubles as the annual losses for the entire Aral Sea region (*14*).

The Fate of the Aral

What does the future hold for the Aral Sea? If surface inflow remains at the low levels of recent years, it averaged only 5.2 km^3/year between 1981 and 1985, and was reportedly near zero in 1986 (*7, 14, 43*), shrinkage will continue into the next century. By the year 2000, the sea could consist of a main body in the south with the salinity of the open ocean and several small brine lakes in the north (Fig. 3). Subsequently, assuming a residual inflow of irrigation drainage water and ground water totaling around 10 km^3, the southern sea will separate into two parts with an aggregate area around 12,000 km^2, 8% of the Aral's size in 1960 (*44*). Salinity would rise to 140 g/liter.

This scenario is not inevitable. The sea's recession could be halted if considerably more water reached it. Water balance calculations indicate that to maintain the 1987 size (41,000 km^2) would require river inflow around 30 km^3/year (*27*, table 2). This discharge is possible if consumptive irrigation withdrawals from the Amu Dar'ya and Syr Dar'ya were to be markedly reduced. However, irrigation is the economic mainstay of the Aral Sea basin where over 90% of the harvest comes from irrigated lands (*45*). Although plans for irrigation expansion in the Aral Sea basin have been somewhat scaled back under the Gorbachev regime in light of the region's ecological problems and strained water balance, many water management experts see continued growth of this sector a necessity (*45, 46*).

There is a national campaign to improve irrigation water use. Reclamation agencies are implementing, among other measures, reconstruction of old irrigation systems, automation and remote control of water allocation and delivery systems for entire river basins, use of more efficient water application techniques (for example, sprinklers, drip and subsurface), and "programming" of harvests, involving the use of simulation-optimization models to minimize inputs and maximize outputs given a set of production objectives and constraints (*45, 47*).

The average efficiency of irrigation systems (ratio of water used productively at the fields to headworks withdrawals) was around 60% in the Aral Sea basin in the early 1980s, the lowest of any region in the Soviet Union (*48*). On the basis of 1980 irrigation withdrawals of 120 km^3, raising average system efficiency from 60% to between 74 and 80%, the goal (*49, 50*) would allow irrigation of the same area with 23 to 30 km^3 lower annual withdrawals. However, the net addition to river flow would be less because of the diminution of return flows from irrigated areas associated with the increase in efficiency. Furthermore, a water use limitation program, introduced for the region in 1982 because of the increasingly dire water supply situation, mandated lower crop application rates and may already have raised average efficiencies to near 70% (*19*). Using 1987 withdrawals (104 km^3) and assuming an efficiency of 70%, the improvement to 74 to 80% would only save 6 to 13 km^3/year. The most knowledgeable Soviet experts estimate realistic future water savings from renovation of irrigation systems in the Aral Sea basin at 10 to 22 km^3/year (*43, 46, 49, 50*).

Modernization of irrigation in the Aral basin is necessary not only to save water but to improve yields, prevent secondary salinization, and cope with waterlogging. Nevertheless, it is an expensive and time-consuming process. Cost of a comprehensive program could reach 95 billion rubles (*51*). Furthermore, most of the "freed" water will be needed to irrigate new lands to provide more food for the region's rapidly expanding population, growing around 2.7% annually, as well as to meet increasing municipal and industrial water needs (*46, 47, 50*).

Ground water could make a larger contribution to regional water supplies. Subsurface storage is huge but little used (*47*). However, much of the reserve lies at great depth or is heavily mineralized. Up to 17 km^3/year of ground water could be consumed in the Aral Sea basin without adversely affecting river flow (*18*, pp. 182–183).

Another means of supplementing the Aral's water balance would be to channel irrigation drainage water to it. Soviet experts estimate that 34 km^3 of drainage were generated annually in the Aral basin in the early 1980s (*12*). Approximately 21 km^3 returned to rivers, leaving 13 km^3 to evaporate from the desert or accumulate in depressions (*12*). The lakes formed in the latter hold around 40 km^3 (*50*). Perhaps 10 to 12 km^3 of drainage water annually could be sent to the Aral by collectors running parallel to the Amu Dar'ya and Syr Dar'ya (*9*). However, drainage water is saline, frequently above 3 g/liter, and is pesticide- and herbicide-laden; drainage should be purified and demineralized before discharge to the sea (*27, 29, 52*). Indeed, the need to keep this flow out of the two rivers stimulates interest in such a scheme as much as the need to provide more water to the Aral. Work on an enormous project to collect drainage water along 1500 km of the right bank of the Amu Dar'ya for delivery to the Aral has started (*53*). At the same time, the program to improve irrigation efficiency will significantly reduce the amount of drainage water available for delivery to the Aral.

Channeling irrigation drainage water to the sea will dry the two largest lakes supported from this source, Aydarkul' and Sarykamysh, with areas in excess of 2000 km^2 each (Fig. 1). Since their origins in the 1960s, each has developed considerable wildlife, fishery, and recreation importance (*47*).

Schemes to Preserve the Aral

Delivery of 12 km^3 of irrigation drainage water plus 4 km^3 of net ground-water inflow to the Aral would support a sea of only 20,000 km^2 whose salinity would be high (40 to 50 g/liter) and ecological value and economic uses minimal (*27, 43*). Hence, additional measures will be necessary if the Aral is to be preserved as a greatly shrunken but viable body of water and to reduce the adverse impacts of its recession. One approach, first suggested in the 1970s, is to partition the sea with dikes to preserve low salinity conditions in a portion of it while allowing the remainder to dry or become a residual brine lake receiving outflow from the freshened part (*5, 27, 41*). Most of the designs are obsolete since they would require considerably more surface inflow (25 to 30 km^3/year) than realistically will be available. A scheme put forward in 1986 to preserve a 12,000-km^2 sea with a salinity of 8 g/liter in the Eastern Basin (Fig. 2) shows some promise as it needs inflow of only 8 to 9 km^3/year (*44*).

A recent proposal, which assumes meager future inflow to the sea, focuses on restoring and preserving the deltas of the Amu Dar'ya and Syr Dar'ya because of their great ecological and economic value (*13*). The plan for the former would involve constructing a 225-km dike in front of the delta to create a system of polders with a surface elevation 8 m above current sea level but 5 m below that of 1960. This would raise ground- and surface-water levels in the delta. Low earth dams and regulating reservoirs would be built in the delta to

Table 1. Average annual water balances for the Aral Sea, 1926 to 1985. The computational form of the annual water balance equation for the Aral Sea is $Qr + Qu + (PF)/10^6 = (EF)/10^6 \pm (\delta hF)/10^6$, where Qr is the annual river inflow (km^3), Qu is the annual net ground-water inflow (km^3), P is the annual precipitation on the sea (mm), E is the annual evaporation from the sea (mm), F is the average annual sea area (km^2), δh is the net annual sea level change (mm), and 10^6 is a proportionality constant (mm/km). Net ground-water inflow is small (around 3 to 4 km^3) and is ignored in the table calculations. The water balance was in essential equilibrium from 1926 to 1960 and sea level was stable. River flow declined substantially between 1960 and 1970, and sea level fell at a moderate rate. For the period 1970 to 1985, river flow fell drastically and sea level declined rapidly (*7*).

Period	Average area (km^2)	Gain (km^3)			Evaporation loss (km^3)	Net volume change (km^3)
		River flow	Precipitation	Total		
1926–60	65,780	55.2	8.2	63.4	64.1	0.7
1960–70	64,470	42.8	8.4	51.2	63.3	−12.2
1970–85	53,660	16.3	6.6	22.9	56.2	−33.3

provide further water control.

A mixture of fresh river water and saline irrigation drainage water would be delivered to the polders. The dried seabed in front of the delta would be stabilized to prevent the encroachment of sand dunes and the blowing of salt and dust. Additional efforts would be undertaken to restore plant and animal communities as well as improve irrigation, livestock raising, fisheries, and trapping. The scheme would require drainage water and fresh flow totaling 8 to 9 km^3/year. The estimated cost is 406 million rubles. A similar plan for the Syr Dar'ya Delta would require 7 km^3/year.

Regardless of what, if any, scheme is implemented to preserve a residual Aral Sea, it is essential to stabilize the exposed bottom to reduce the blowing of salt and dust. There has been some success in establishing salt-tolerant xerophytic shrubs (for example, black saksaul—*Haloxylon aphullum*). But this program is so far limited to relatively small areas with the most favorable conditions and the survival rate is low (*52, 54*). Scientists are also investigating the feasibility of using mechanical and chemical means of binding the loose surface (*13, 28*).

The Aral's water balance could also be improved by importing water from more humid regions. Such a project was formulated in the 1970s and early 1980s by the National Water Management Design Institute (*Soyuzgiprovodkhoz*), a subagency of the Ministry of Reclamation and Water Management (*55*). Providing more water for irrigation was the plan's main purpose but it would have helped the Aral as well. Central Asian party and government officials enthusiastically supported the scheme. Part of the flow from the arctic draining Ob' and Irtysh rivers, situated to the north in Western Siberia, would be transferred southward. Water would be sent 2500 km to the Amu Dar'ya by a system of low dams, pumping stations, and a huge canal (popularly named "Sibaral," Siberian to the Aral Sea Canal) (Fig. 1). The project's first stage (27 km^3/year) was undergoing final engineering design in 1985 and was scheduled for implementation by the late 1980s or early 1990s.

Following Gorbachev's ascension to Soviet leadership in March 1985, the fortunes of the Siberian scheme, as well as a companion project for the European part of the country, waned. He and his advisers see north-south water transfer projects as a poor investment of scarce resources and believe less costly, more effective local means of solving water supply problems in the arid regions of the Soviet Union are available. The diversion schemes had been periodically attacked during the 1970s and early 1980s by some scientists and a group of Russian national writers who foresaw severe ecological, economic, and cultural damage occurring in northern regions of water export. In a dramatic policy reversal, the Communist Party and Soviet government, in August 1986, ordered a cessation of construction and design work on these projects (*56*). However, the decree directed that research on the scientific problems associated with water diversions, stressing ecological and economic concerns, continue.

In spite of the suspension of work on water transfers, critics have remained on the offensive. They have bitterly denounced in the popular Soviet media those directly or indirectly involved with project planning or evaluation (*57*). Evidently, they fear that the projects could be revived. The most vociferous opponents have engaged in personal attacks as well as exaggeration and misrepresentation (*59*).

Conclusions

The modern recession of the Aral Sea, the most severe in 1300 years, has resulted from excessive consumptive use of river inflow to the sea. Processes of potential ecological change were not carefully evaluated nor clearly understood when the water management decisions leading to the drop in the sea's level were made. Water management planners ignored warnings of dire consequences from some scientists. The future is not bright. River inflow by the mid-1980s was near zero, and the sea continues to rapidly shrink and salinize. The Aral could become several residual, lifeless, brine lakes early in the next century. Already substantial ecological damages and economic losses will grow worse.

Scientific study of the "Aral problem" and its amelioration has been a national effort since 1976 under the aegis of the State Committee on Science and Technology (*25, 52*). The August 1986 decree ordering the cessation of work on water diversion projects directed that Soviet scientific and planning agencies devise a comprehensive program for the development of Central Asia to the year 2010, considering the demographic, water management, and agricultural situation (*56*). Because of worsening conditions, a special government commission was appointed in December 1986 to study ecological problems around the Aral (*46*). Its 1987 report recommended several measures to improve drinking water supplies and health conditions for people living near the sea. The commission also supported a plan to preserve the delta of the Amu Dar'ya.

In spite of all the studies and recommendations, other than starting construction on a water collector to carry irrigation drainage from the Amu Dar'ya basin to the sea, a project that will take years to complete, the government has taken no concrete measures to improve the condition of the Aral. Help may come too late: some say that the sea may be beyond rescue (*60*).

However, local inhabitants are far from accepting this grim fate. Although party and government officials from the two republics adjacent to the Aral (Uzbekistan and Kazakhstan) have been silent for the last several years, scientists, writers, and journalists from the region continue to plead angrily and sometimes eloquently, in the regional as well as national press, for action to save the Aral (*9, 10, 29, 30, 34, 35*).

As the situation worsens, those living around the sea will put great pressure on the national government to resurrect the Siberian diversion plan in order to provide minimum inflow to the Aral while maintaining irrigation. The campaign has already begun. In March 1988, the president of the Uzbek Academy of Sciences along with a well-known expert on the Aral Sea problem publicly stated that the ecological and social and economic difficulties of the Aral region could not be solved without diversion of water from Siberian rivers (*46*). The Moscow correspondent of the *Manchester Guardian* reported that Gorbachev, during his April 1988 visit to Tashkent, capital of the Uzbek Republic, after pleas from local officials, agreed to a new feasibility study of the project (*59*).

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Chemistry of the Metal-Polymer Interfacial Region

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In many polymer-metal systems, chemical bonds are formed that involve metal-oxygen-carbon complexes. Infrared and Mössbauer spectroscopic studies indicate that carboxylate groups play an important role in some systems. The oxygen sources may be the polymer, the oxygen present in the oxide on the metal surface, or atmospheric oxygen. Diffusion of metal ions from the substrate into the polymer interphase may occur in some systems that are cured at elevated temperatures. It is unclear whether a similar, less extensive diffusion occurs over long time periods in systems maintained at room temperature. The interfacial region is dynamic, and chemical changes occur with aging at room temperature. Positron annihilation spectroscopy may have application to characterizing the voids at the metal-polymer interface.

A QUANTITATIVE CHARACTERIZATION OF THE INTERFACIAL region between a metal and an organic polymer has long been a goal of surface science. Attempts to achieve this goal have reached a new degree of intensity during the past decade, as many industrial products now depend on the integrity of metal-polymer systems. Examples include metallized plastics, metal-polymer laminates such as those used in retort pouches and protective food packaging, corrosion protective coatings for metals, metal food containers with polymer linings, foil-coated products, packaged electronic components, photoresists and other products formed by lithography, and prosthetic devices. Metal-polymer adherence can be destroyed by processes such as the intrusion of water (*1*), by

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