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The Aral Sea

The Devastation and Partial Rehabilitation of a Great Lake

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The Aral Sea

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Foreword

The Aral Sea has long been a poster child of pollution and environment degradation. Pictures of camels grazing next to a big ship's rusted hull; parched land where a sea rich in fish and other resources used to be; abandoned economic hubs in dry harbors; dust and salt storms large enough to be visible from space … All these examples have entered the consciousness of lay citizens around the world, showing how human activities have slowly but steadily destroyed what was once a rich and productive region. As the effects of climate change are increasingly felt around the world, scientists, administrators and politicians need to heed the lessons from the Aral Sea and avoid similar, looming disasters in other regions.

This urgency has been noted in many publications, scientific and otherwise, including the authoritative and regular reports by the *Intergovernmental Panel on Climate Change* (IPCC, http://www.ipcc.ch). Already in 1997, the IPCC highlighted the importance of the Aral Sea as "a case study of the multiplicative effects of resource overuse, which can lead to local environmental and even climate change", noting however there had been no integrated assessment of its natural and human impacts. This clear gap is addressed by the present book, entitled "Destruction of the Aral Sea" and edited by experts of the Aral Sea who have spent decades of their professional lives measuring and understanding the evolution of the Aral Sea. In the true spirit of the Springer Earth System Sciences series, this book brings together a wealth of experts from seven different countries, spanning all fields from remote sensing to fisheries, geology, zoology, biodiversity and environmental management *inter alia*. Throughout 18 chapters, in close to 500 pages and with an extensive bibliography, sometimes summarizing innovative and important research not previously seen in the western literature, the authors show us how the Aral Sea has evolved, from long before human intervention to the latest years. This book is far from only a series of observations of "the Destruction", and its subtitle clearly shows the potential for a "Partial Rehabilitation of a Great Lake".

Masterfully organized and led by its editors, Philip Micklin, Nikolay V. Aladin and Igor Plotnikov, this book consists of an introductory chapter and three parts. Part I (Background to the Aral Problem) in three chapters provides essential information about the Aral Sea prior to its modern desiccation that gives context to what has happened to the lake in the modern era. Part II (Modern Recession of Aral) in nine chapters covers key aspects and consequences of the shrinking Aral Sea from the inception of this phenomenon in the early 1960s until today. The first four chapters of Part III (Aral Future) examine what may happen to this once grand lake and its environs in coming years, depending primarily on the human response to this disaster and showing that there is a way forward, provided clear commitments and actions on the ground are taken soon. The final summary chapter includes a discussion of the lessons to be gleaned from the Aral experience along with a suggested list of key research topics that need deeper investigation in order for optimal improvement of this water body. What has happened in this region, and what is happening now, concerns us all, as global citizens in a world increasingly affected by climate change and human impacts.

Having read the many chapters of this book as it was in the making, I have seen how they evolved to form a structured summary of such an internationally important region. I can therefore only recommend its readings to scientists, administrators and decision-makers around the world, to see how the lessons we are learning the hard way in the Aral Sea now, can be used everywhere in the future.

Bath, UK Philippe Blondel
October 2013

Acknowledgements

Philip Micklin, Chief Editor

My contribution to this book is based on three decades involvement with the Aral Sea issue and numerous trips to the Aral Sea region. Over these years I have received help from many individuals, and funding from organizations, in the United States, Soviet Union, Russia, Western Europe, Japan and Central Asia, particularly in Uzbekistan and Kazakhstan. I want to express my deepest thanks to these individuals and organizations too numerous to name. Special thanks, however, are in order to the Department of Geography, Western Michigan University, Kalamazoo, Michigan; the NATO Science for Peace Program; the U.S. National Academy of Sciences; the Committee for Research and Exploration of the National Geographic Society; the National Council for Soviet and East European Research; the United Nations Environment Program; the Institutes of Geography and Water Problems of the Russian Academy of Sciences in Moscow; Karakalpakstan State University in Nukus, Karakalpakstan (Uzbekistan), and, last but not least, the Zoological Institute of the Russian Academy of Sciences in St. Petersburg. I would also like to express my gratitude to my wife, left to handle family matters during my visits overseas, sometimes for extended periods, in connection with my research on the Aral Sea.

Nikolay Aladin and Igor Plotnikov, Associate Editors

We would like to thank all members of our Brackish Water Laboratory of the Zoological Institute of RAS and all members of the Fisheries Laboratory in Aralsk, Kazakhstan and all members of the International Fund for Saving the Aral Sea, all members of our expeditions to the Aral Sea from Russia, Kazakhstan, Uzbekistan, USA, Germany, UK, France, Spain, Japan, Australia, Sweden, Slovenia and some other countries. A special thanks is in order to our colleagues at St-Petersburg Pedagogic University headed by the famous botanist Lev Aleksandrovich Kusnetsov with whom we did our studies on the Barsakelmes Island in the Aral Sea. We also would like to thank all members of our families who remained without us when we were in our long lasting, numerous expeditions to the Aral Sea during the period from 1979 until 2013. Finally, we would like to remember those colleagues and friends who passed away and who helped us a lot in our Aral Sea studies: Dr. Evdokiya Markova (Kazakhstan), Dr. Nikolay Vorontzov (Russia), Dr. William Williams (Australia), Dr.William Potts (UK), Dr. Gilbert White (USA), Dr. Tatuo Kira (Japan), and especially Dr. David Davidovich Piriulin of our Laboratory.

Abbreviations and Acronyms

ASBP	Aral Sea Basin Program of the World Bank
AVHRR	Advanced Very High Resolution Radiometer
asl	Above sea level
BP	Before present
BVO	Basin Water Management Association (Authority)
ca.	Approximately
cal.	Calibrated
cm	Centimeter
DO	Dissolved oxygen
ESA	European Space Agency
EVI	Enhanced vegetation index
GEF	Global environmental facility
ha	Hectare
ICAS	Interstate Council on the Problems of the Aral Sea Basin
ICWC	Interstate Coordinating Water Management Commission
IFAS	International Fund for Saving the Aral Sea
ka	Thousand years
km	Kilometer
Landsat	Land satellite
km^2	Square kilometer
km^3	Cubic kilometer
l	Liter
m	Meter
m^3	Cubic meter
mt	Metric ton
MODIS	Moderate Resolution Imaging Spectroradiometer
NAS	North Aral Sea
NATO	North Atlantic Treaty Organization
NAWAPA	North American Water and Power Alliance
NDVI	Normalized difference vegetation index
RBO	River Basin Organization

SFC	Scientific Information Center (of ICWC)
Sibaral	Siberia to Aral Sea canal
UNDP	United Nations development programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
USAID	United States Agency for International Development
USD	United States dollars

Contents

Part III Aral Future

Chapter 1
Introduction

Philip Micklin

Abstract This first section of this chapter, in summary fashion, presents the basic parameters of the modern recession of the Aral Sea that began in 1960 and the complex, severe environmental, economic and human consequences of this catastrophe. This is followed by a review of improvement efforts to alleviate these problems begun during the last years of the Soviet Union and carried on by the new governments of the Aral Sea Basin aided by international donors after the collapse of the Soviet Union in 1991. The last section explains the purpose of the book, its relationship to other recent edited works on the Aral Sea and the organization of the chapters.

Keywords ICAS • IFAS • ASBP • USAID • World Bank • Storms • Climate • Tugay • Karakalpakistan • Health problems

1.1 The Modern Desiccation of the Aral Sea

The Aral Sea is a terminal, or closed-basin (endorheic) lake, lying amidst the vast deserts of Central Asia. As a terminal lake, it has surface inflow but no surface outflow. Therefore, the balance between inflows from two rivers, the Amu Darya and Syr Darya (darya in the Turkic languages of Central Asia means river) and net evaporation (evaporation from the lake surface minus precipitation on it) fundamentally determine its level. From the mid-seventeenth century until the 1960s, lake level variations were likely less than 4.5 m (Micklin 2010). During the first six decades of the twentieth century the sea's water balance was remarkably stable with annual river inflow and net evaporation never far apart, resulting in lake level variations over this period of less than 1 m. At around 67,500 km^2 in 1960, the

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Aral Sea was the world's fourth largest inland water body in area, behind the Caspian Sea in Asia, Lake Superior in North America and Lake Victoria in Africa (e.g., Micklin 2010). As a brackish lake with salinity averaging near 10 g/l, less than a third of 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 and Amu rivers sustained a diversity of flora and fauna, including a number of endangered species. They also had considerable economic importance supporting irrigated agriculture, animal husbandry, hunting and trapping, fishing, and harvesting of reeds, which served as fodder for livestock as well as building materials.

Since 1960, the Aral has undergone rapid desiccation and salinization, overwhelmingly the result of unsustainable expansion of irrigation that literally dried up the two influent rivers. By September 2011 the lake had separated into four parts with its aggregate area and volume shrinking by 85 % and 92 % respectively, suffered a maximum level drop in its most desiccated part (the Large Aral Sea) of nearly 26 m, while experiencing salinity levels here in excess of 100 g/l, more than ten times greater than in 1960 (see Table 15.1 in Chap. 15).

The Aral's recession has led to a plethora of severe negative ecological, economic, and human welfare consequences affecting not only the sea proper but a zone around the water body of several hundred thousand square kilometers with a population of several million (Micklin 2010; Micklin and Aladin 2008). The commercial fishing industry that developed during the first half of the twentieth century ended in the early 1980s as the indigenous species providing the basis for the fishery disappeared owing to rising salinity and loss of shallow spawning and feeding areas. Tens-of-thousands were thrown out of work because of the loss of the fishery and associated activities and employment in these occupations today, although increasing because of the project to revitalize the Small (northern) Aral is still only a tiny fraction of what it was. Navigation on the Aral also ceased by the 1980s as efforts to keep the increasingly long channels open to the ports of Aralsk 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 Darya Delta in the Karakalpakistan Republic of Uzbekistan, and the Syr Darya Delta in Kazakhstan have suffered considerable harm (Micklin 2010; Micklin and Aladin 2008). Greatly reduced river flows through the deltas, the virtual elimination of spring floods in them and declining ground water levels, caused by the falling level of the Aral Sea, have led to spreading and intensifying desertification. Halophytes (salt tolerant plants) and xerophytes (drought tolerant plants) have replaced endemic vegetation communities (Novikova 1996). The Tugay vegetation communities composed of trees, bushes, and tall grasses that formerly stretched along all the main rivers and distributary channels here have been particularly hard hit. Tugay covered 100,000 ha in the Amu Darya Delta in 1950, but shrank to only 20,000–30,000 ha by 1999 (Severskiy et al. 2005). Tugay complexes around the Aral Sea are habitats for a diversity 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 of birds lived in the river deltas. Today, only 32 species of the former and 160 of the latter remain (Micklin 2007).

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 Darya Delta is estimated to have decreased from 49,000 to 8,000 km^2 (Chub 2000, Fig. 3.3, p. 125). The area of reeds in the delta, which reportedly covered 500,000 ha in 1965, also declined dramatically by the mid 1980s (Palvaniyazov 1989). This 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. 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) has adversely affected aquatic bird populations.

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 been employed to monitor these storms and have revealed plumes extending as far as 600 km downwind that drop dust and salt over a considerable area adjacent to the sea in Uzbekistan, Kazakhstan, and Turkmenistan (Micklin 2010). The most severely impacted area has been the Amu Darya Delta at the south end of sea, which is the most densely settled and most ecologically and economically important region around the Aral. Dust and salt settle on natural vegetation and crops, particularly in the Amu Darya Delta. In some cases, plants are killed outright but more commonly their growth (and for crops, yields) is substantially reduced. 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.

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). Maritime conditions have been replaced by more continental and deseritic regimes. Summers have warmed and winters cooled, spring frosts are later and fall frosts earlier, humidity is lower, and the growing season shorter. Uzbekistani climatology 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 (Micklin 2007).

The population living around the sea suffers acute health problems (Micklin 2007; Micklin and Aladin 2008). Clearly some of these are direct consequences of the sea’s recession (e.g., respiratory and digestive afflictions, 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, however, owe to 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 endemic. The latter are probably 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, various intestinal disorders and kidney ailments 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 45/1,000 live births in 1965 to 72 in 1986, with the rate in several districts adjacent to the former seashore ranging from 80 to over 100/1,000. These are 3–4 times the national level in the former USSR and 7–10 times that of the U.S. International donors, the Uzbekistani Government, and NGOs have made significant efforts to improve health and medical conditions here in the 1990s and first decade of the twenty-first century. Improvements are evident, particularly in providing cleaner drinking water supplies. Since1991, the maternal death rate has dropped substantially, but tuberculosis has become more widespread as has bronchial asthma (Nazirov 2008). Nevertheless, it appears the overall health picture has not improved measurably from Soviet times (Lean 2006).

Perhaps the most ironic and dark consequence of the Aral's modern shrinkage is the story of Vozrozhdeniya (Resurrection) Island. The Soviet military in the early 1950s selected this, at the time, tiny, isolated island in the middle of the Aral Sea, as the primary testing ground for its super-secret biological weapons program (Micklin 2007, 2010). From then until 1990, they tested various genetically modified and "weaponized" pathogens, including anthrax, plague, typhus, smallpox as well as other disease causing organisms. These programs stopped with the collapse of the USSR in 1991. The departing Soviet (now Russian) military supposedly took measures to decontaminate the island.

As the sea shrunk and shallowed, Vozrozhdeniya grew in size and in 2001 united with the mainland to the south as a huge peninsula extending into the Aral Sea. There was concern that weaponized organisms survived whatever decontamination measures the Russian military used 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 U.S. 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 (Micklin 2010).

1.2 Improvement Efforts

The Soviet Union launched Aral improvement programs in the late 1980s when that government finally publicly admitted the existence of a serious problem (Micklin 1991, pp. 68–81). Plans were formulated to improve medical and health services, provide greater access to safe drinking water supplies, improve food supplies, diversify the economy to improve life for the people living in the zone of "Ecological devastation" near the sea, mitigate the most severe negative ecological trends in the delta of the Amu Darya, and rebuild irrigation systems to raise their efficiency in order to deliver more water to the Aral Sea. These programs were partially underway when the USSR collapsed in 1991.

After the dissolution of the Soviet Union, the new states of Central Asia (Kyrgyzstan, Uzbekistan, Turkmenistan, Kazakhstan and Tajikistan) assumed responsibility for dealing with the Aral situation (Micklin 2007). In January 1992, the presidents of the five republics accepted a decision to create the International Fund for Saving the Aral Sea (IFAS) (2011). This was followed in March 1993 by the creation of the Interstate Council on the Problems of the Aral Sea Basin (ICAS). The responsibility of IFAS was (and is) to collect revenue from each basin state for financing rehabilitation efforts. The duty of ICAS was to facilitate assistance from the World Bank and other international donors as well as assume responsibility for various Aral Sea Basin assistance programs. ICAS was abolished in 1997 and its functions merged into a restructured IFAS. The leadership of IFAS rotates in a 2-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 2007). The World Bank was the first major player. 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 15–20 years. The cost of this effort was set at 470 million USD. The main goals of the program were (1) rehabilitation and development of the Aral Sea disaster zone, (2) strategic planning and comprehensive management of the water resources of the Amu Darya and Syr Darya, and (3) building institutions for planning and implementing the above programs. Afghanistan was invited to join the ASBP but did not respond to the overture.

In 1996, the Bank did a major review to evaluate the strengths and weaknesses of the preparatory phase of the ASBP. Out of it came a new effort known as the Water and Environmental Management Project to be funded jointly with the Global Environmental Facility (GEF). The program was implemented between 1998 and 2003. 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 (2003) conducted a successor effort to this program (ASBP 2) from 2003 to 2010. Titled, "Program of Specific Actions for Improving the Ecological and Social Situation in the Aral Sea Basin," it included a broad range of measures to improve health, welfare, and the natural environment, including programs to conserve and restore the Tugay ecosystems and lands usable for pasture in the deltas of the Amu Darya and Syr Darya, to combat desertification, and to develop measures for preventing salt and dust transfer from the dried bottom of the sea. The total contribution to this program from the IFAS member governments is asserted to have been over one billion USD (Executive Committee of IFAS 2011, p. 18). Other donors to the program included UNDP (United Nations Development Program), the World Bank, the Asian Development Bank, USAID (United States Agency for

International Development), as well as the governments of Switzerland, Japan, Finland, Norway and others.

One of the most successful efforts planned under ASBP 1 and carried out during ASBP 2 was the Syr Darya Control and Northern Aral Sea Phase-I Project. The project entailed construction of a dike and dam to raise and control the level of the North (Small) Aral Sea and hydrologic improvements to the Syr Darya to increase its water delivery to this water body. The dike and dam were completed in 2005 and the improvements to the Syr Darya in 2011. (See Chap. 15 for more information on this project.)

The latest effort is ASBP 3 (Executive Committee of IFAS 2011). Titled, "From the Glaciers to the Deltas: Serving the People of Central Asia," it runs from 2011 to 2015. The main foci of the program are (1) integrated water resources management, (2) environmental protection, (3) socio-economic development, and (4) improving the institutional and legal instruments. It took until May 17, 2012, for all the member states of IFAS to sign-off on ASBP 3, but the program now is reported to be under implementation (http://www.ec-ifas.org).

Besides the World Bank, other international donors have been contributing to Aral Sea region improvement (Micklin 1998, 2007). 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 Darya Delta, aided in the formulation and implementation of regional water management policies and agreements, and provided advice on water management issues to specific governments. A smaller-scale follow-up project in 1999 and 2000 gave further assistance. USAID carried out a new, major effort from 2001 to 2006. Known as the "Natural Resource Management Project (NRMP)" it was intended to improve management of water, energy, and land with an investment of 23.5 million USD (UNDP 2008, p. 61). Most recently, USAID has been involved in two collaborative efforts with IFAS (2011). The first is to analyze the economic consequences of optimizing the hydroelectric resources of the Amu Darya and the Syr Darya while the second focuses on adapting the fragile energy infrastructure of Kazakhstan, Kyrgyzstan and Tadjikistan to climate change.

The European Union initiated an aid program for the Aral Sea Basin states in 1995. The "Water Resources Management and Agricultural Production in the Central Asian Republics Project" (WARMAP 1&2) ran from 1995 to 2002 (Micklin 1998; UNDP 2008, p. 57). Major accomplishments of this program were 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, funding training seminars and workshops, and gathering detailed data on irrigated water use at the farm level. The European Union and its member countries, particularly Germany, have remained active in efforts to deal with the most serious Aral Sea region problems (IFAS 2011).

The United Nations has been providing assistance on the Aral Sea Crisis since 1990 when a joint UNEP (United Nations Environment Program)/Soviet working group on the Aral was formed (Micklin 1998). UN 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 to 1996 focusing on ecological research and monitoring in the Syr Darya and Amu Darya deltas (UNESCO 1998). The overall intent was to model the terrestrial and aquatic ecosystems of the study area in order 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 a 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 this goal in the management of land, water, biological resources and human capital.

The North Atlantic Treaty Organization (NATO) became involved in Aral Sea region activities through its Scientific and Environmental Affairs Division. The first NATO sponsored event was an Advanced Research Workshop on “Critical Scientific Issues of the Aral Sea Basin: State of Knowledge and Future Research Needs” held in Tashkent, Uzbekistan during May 1994 (Micklin and 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 Program (SfP), sponsored work to develop a land and water GIS for the Amu Darya delta and Aral Sea (Ptichnikov et al. 2004). 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 conditions in the Amu Darya Delta and in the Aral Sea.

The Science for Peace program 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 Darya delta (Scientific and Environmental Affairs 2003, pp. 189–190). This project involved cooperation between the Scientific Information Center of the ICWC (Interstate Coordinating Water Management Commission) in Tashkent and the private consulting firm Resource Analysis in the Netherlands.

The ten largest international donors (multilateral and bilateral) of grants and loans between 1995 and 2005 measured in millions of USD for what UNDP defines as the "Aral Sea region" were in descending order The World bank (283.7), the Asian Development Bank (81.4), Germany (52.8), Japan (50.5), Kuwait (41.8), the U.S. (24.5), the Global Infrastructure Facility (16.3), the European Union (13.9), France (11.5), and Switzerland (11.1) (UNDP 2008, pp. 48–49). The contribution over this period from multilateral organizations was 415.4 million USD and 215.4 from bilateral groups for a total of 630.8 million USD. Local organizations provided an additional 194.2 USD for a grand total of 825 million USD. However, it should be noted that the "Aral Sea region" in this study included only the Karakalpakstan Republic and Khorezm Oblast in Uzbekistan and did not include expenditures in Kazakhstan or other Aral Sea Basin countries.

1.3 Purpose and Organization of the Book

This book is a collective work intended to present a broad, but scientifically sound, treatment of some of the key aspects of the modern desiccation of the Aral Sea. The authors who have contributed to the book are experts on the subjects they discuss. A number have spent considerable time engaged in field research on the Aral Sea and the surrounding region.

A sizable literature exists on the Aral Sea. An excellent selected bibliography published in 2002 lists more than 1,500 articles, books and conference papers on this topic during the twentieth century, published primarily in Russian but with a substantial contribution in English and several other languages as well (Nihoul et al. 2002). The editors of the volume note that the largest number, more than two thirds, were published or presented in the 20-year period 1980–2000 with a peak in the late 1980s and early 1990s at the end of the Soviet Union when there was intense domestic and international interest in the desiccation of the Aral Sea and how to improve the situation. A number of additional important works have been published since the turn of the new century.

Given the amount of extant literature, any sort of comprehensive treatment of all aspects of the so-called "Aral Sea Problem" in one volume would be very difficult if not impossible. This book does not attempt that. Rather it is a complement to two other recent collected works on the Aral Sea. Springer published the *Aral Sea Environment* in 2010 (Kostianoy and Kosarev 2010). This book covers a variety of topics, including those dealing with the past human and geological history of the Aral, socio-economic variables, use of satellite imagery to study the sea, hydrology of the Syr Darya and Amu Darya rivers, physical and chemical character of the Large Aral, and biodiversity of the Aral. Springer also published *Aralkum – a Man Made Desert* in 2012 (Breckle et al. 2012). This book, as the name implies, focuses on the desert that has been created on large parts of the dried bottom as the Aral Sea shrank over the past 50 years. Most of the chapters discuss in considerable detail one aspect or another of the physical and biological processes occurring there and measures such as phytoreclamation to ameliorate their negative consequences.

The present book while having little overlap with the Aralkum volume does cover similar topics to some chapters in the Aral Sea Environment book. But the approach to these is fresh and presents the latest available information from the literature as well as from field-work. And some chapters deal with important subjects, particularly related to human impacts on the environment and man-nature interactions, not discussed or treated only briefly, in the Aral Environment book. Below is a brief description of the organization and content of the book (for a longer summary of each chapter in one place, see the initial section of Chap. 18).

Part I deals with background information in order to better understand the modern desiccation of the Aral Sea. It contains three Chaps. 2, 3 and 4. Chapter 2 provides information on the physical, human and geographical character of the Aral Sea Basin, the physical character of the Aral Sea prior to its modern recession, prior level fluctuations of the Aral, and the history of research and exploration of the Aral to 1960. Chapter 3, written by the leading experts on biologic aspects of the Aral Sea, discusses the biologic dynamics of the Aral Sea from the beginning of the twentieth century to 1960. It mainly discusses invertebrates, but has sections on vertebrates (with emphasis on fishes) as well as flora. Chapter 4 examines the available data on past Aral Sea level changes and presents the current thinking on the sea's recessions and transgressions prior to its modern desiccation. The geomorphologic, sedimentologic, paleoenvironmental, archaeologic and historiographic evidence is reconsidered and combined on the basis of calibrated ^{14}C ages.

Part II examines the modern desiccation of the Aral. Nine Chaps. (5, 6, 7, 8, 9, 10, 11, 12 and 13) comprise this section. Chapter 5 describes and analyzes the water resources of the Aral Sea Basin and the water balance of the Aral Sea for the period 1911–1960 and by decadal periods from 1961 to 2010. Chapter 6 details the biological changes that have occurred in the Aral since 1960 owing to its shrinkage, salinization, and separation into four distinct water bodies. The main focus is again on invertebrates, but impacts on vertebrates (emphasizing fishes) and plants are also discussed. Chapter 7 is devoted to impacts of the Aral's recession on Karakalpakstan, the most seriously affected region around the sea. Local scientists with intimate knowledge of the situation prepared this chapter. Chapter 8 focuses on irrigation in the Aral Sea Basin, which has been the main cause of the sea's modern desiccation. Chapter 9 discusses the challenges of transboundary water resources management in Central Asia, the resolution of which is not only of vital importance to improving the state of the Aral Sea, but maintaining political stability in Central Asia. Chapters 10 and 11 deal with the use of remote sensing to study and monitor the changing character of the Aral Sea. Written by experts in the field, the former focuses on time series analysis of satellite remote sensing data for monitoring vegetation and landscape dynamics of the dried sea bottom adjacent to the lower Amu Darya Delta. The latter discusses the use of satellite imagery and radar altimetry to study and monitor the hydrology of the Aral Sea and water bodies in the lower Amu Darya Delta. Chapter 12 looks at the relationship between nature and economic development in the Aral Sea Basin from the point of view of sustainability, with particular focus on cotton raising and fishing. Chapter 13 describes an August-September 2011 expedition to the Aral Sea to give the reader a feel for the “nuts and bolts” (and difficulties) of field research on the Aral Sea.

Part III is devoted to what the future may hold in store for the Aral Sea and its immediate environs. Chapter 14 discusses the possible biological future for the water body. Chapter 15 takes a detailed look at the various efforts (implemented and proposed) to revive the Aral Sea and the lower reaches of the Amu Darya and Syr Darya deltas. Chapter 16 examines the massive project that was on the verge of implementation by the Soviet Union in the early 1980s, to transfer water from Siberian rivers to the Aral Sea Basin. Chapter 17 examines the potential impacts of Climate Change on the Aral Sea and its Basin.

The final chapter (18) provides a summary of all preceding chapters, the most important case study lessons that we should learn from the Aral experience and an annotated list of the key research and monitoring needs for the future Aral Sea.

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Part I
Background to the Aral Problem

Chapter 2
Introduction to the Aral Sea and Its Region

Philip Micklin

Abstract This chapter presents key background information on the Aral Sea and its region. The Aral Sea Basin's geographical setting is discussed, including location, climate, topography, soils, water resources, constituent nations, and basic demographic parameters. Next, the physical characteristics of the Aral Sea (size, depth, hydrochemistry, circulation patterns, temperature characteristics, water balance, etc.) prior to the modern desiccation that began in the 1960s are summarized. This is followed by treatment of level fluctuations of the Aral and their causes prior to the modern drying. The final section is devoted to tracing the most important events in the history of research and exploration of the Aral up to 1960.

Keywords Population • Climate • Currents • Butakov • Berg • Bartold • Exploration • Research

2.1 Geographical Setting

The Aral Sea is a large lake located in the heart of Central Asia on the Eurasian Continent (Figs. 2.1 and 2.2). Its basin covers a vast area that is variously delineated, estimates range from 1.5 to 2.7 million km^2, but I use the World Bank figure of 2.2 million km^2 (World Bank 1998, p. 1). The basin is mainly lowland desert (the Karakum, red desert, on the south and west and the Kyzyl-kum, black desert, on the north and east) (Micklin 1991, pp. 2–4). The lowland climate is desert and semi-desert with cold winters and hot summers in the north and central parts and desert with very hot summers and cool winters on the south (Goode's World Atlas 1982, pp. 8–9). High mountains ring the basin on the east and south (Tian Shan, Pamir, Kopet-Dog), with peaks in the Pamirs over 7,000 m. January

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Fig. 2.1 The location of the Former Soviet Central Asia in Eurasia (the outline of the United States is shown for size comparison). Numbers indicate: *1*. Kazakstan, *2*. Uzbekistan, *3*. Kyrgyzstan, *4*. Tajikistan, *5*. Turkmenistan, *6*. Aral Sea (Source: U.S. Dept. of State. “The New States of Central Asia,” INR/GE, 2351, 1993)

temperature averages range from −12 °C on the north to slightly above 0 °C on the south. July averages run from 24 °C on the north to more than 32 °C on the south (Atlas of the USSR 1983, p. 99).

Annual average precipitation in the lowland deserts is from less than 100 mm to the south and east of the Aral Sea to near 200 mm approaching the foothills of the southeastern mountains (Micklin 1991, pp. 2–4). Potential evapotranspiration (PET), a measure of water loss from the soil and plants assuming no moisture deficiency, ranges from 1,000 mm in the north to over 2,250 mm in the extreme south of the desert zone, resulting in severely arid conditions with moisture coefficients (precipitation divided by PET) below 0.10 common. The foothills and valleys of the mountainous south and southeast are substantially more humid with precipitation ranging from 200 to over 500 mm. PET is around 1,500 mm at the desert margins but declines markedly with altitude. Moisture coefficients range from around 0.2 to over 0.6. The high Pamir and Tian Shan ranges are wet with average annual precipitation from 800 to 1,600 mm whereas PET ranges from 1,000 to below 500 mm, giving this zone a marked surplus of moisture. This, in turn, has created large permanent snowfields and glaciers that feed the two major rivers, the Amu Darya and Syr Darya, which flow out across the desert and ultimately reach the Aral Sea.

Fig. 2.2 Location of Aral Sea Basin in Central Asia (Source: Micklin, P.: The Aral Sea disaster. In: Jeanloz, R. et al. (eds.) Annual Review of Earth and Planetary Sciences, vol. 35, Figure 1, p. 48. Annual Reviews, Palo Alto (2007))

A variety of soils are found here: serozem (desert), gray-brown desert, meadow, alluvial, sand, takyr (clay) and heavily salinized (Solonets and Solonchak in Russian) (Atlas of the USSR 1983, p. 104). These soils, with the exception of the heavily salinized, can be made agriculturally productive with irrigation. The area that could benefit from irrigation in the Aral Sea Basin has been estimated in excess of 50 million ha (Legostayev 1986), but this is likely a considerable exaggeration.

Although the majority of the Aral Sea Basin is desert, it has substantial water resources. The mountains on its southern and southeastern periphery capture the plentiful precipitation, storing most of it in snowfields and glaciers. Runoff from these, heaviest during the spring thaw, feeds the region's rivers. Estimated average annual river flow in the Aral Sea Basin is 116 km^3. It, in turn, encompasses the drainage basins of the Amu Darya [darya in Turkic means river] and Syr Darya.

The Amu is the most important river within the Aral Sea Basin. Originating among the glaciers and snowfields of the Pamir Mountains of Tajikistan, Kyrgyzstan and Afghanistan, its drainage basin covers 465,000 km^2 (Lvovich 1971, Table 2, p. 31). The river flows 2,620 km from the mountains across the Kara-Kum desert and into the Aral Sea. During this journey, the river, or its major tributaries, flow along the borders and across four states: Tajikistan, Afghanistan, Turkmenistan, and Uzbekistan, entering, leaving, and reentering the last two states several times (Fig. 2.2).

Average annual flow from the drainage basin of the Amu is around 79 km^3. This includes not only the flow of the Amu Darya and its tributaries but several "terminal" rivers (Zeravshan, Murgab, Tedjen, Kashkadarya) that disappear in the deserts (Micklin 1991, p. 4; Micklin 2000, pp. 6–7). Terminal rivers are not tributary to a body of water (river, lake, or sea). They are common in arid regions where they arise in humid mountainous zones and flow into deserts where evaporation rates are so high they lose all their water. The Amu Darya is an “exotic” river, which hydrologically means that essentially all its flow originates in the well-watered Pamir mountains, but that this flow is substantially diminished by evaporation, transpiration from phreatophytic vegetation (deep-rooted plants that draw water from the zone of saturation) growing along its banks, and bed exfiltration as the river passes across the Kara–Kum desert to the Aral Sea. The Amu Delta accounted for very large flow losses owing to evaporation and transpiration prior to its modern desiccation that began in the 1960s, particularly during the late spring/early summer period of extensive flooding. Because of these, average inflow of the river to the Aral Sea decreased to around 40 km^3 from the 62 km^3 coming out of the mountains. Tajikistan contributes 80 % of flow generated in the Amu Darya River Basin, followed by Afghanistan (8 %), Uzbekistan (6 %), Kyrgyzstan (3 %) and Turkmenistan and Iran together around 3 % (most of which is formed in Iran).

The Syr Darya flows from the Tian Shan Mountains, located to the north of the Pamirs. The melt of glaciers and snowfields are its main source of water. Its drainage basin covers 462,000 km^2. With a length of 3,078 km, it is longer than the Amu Darya (Lvovich 1971, Table 1, p. 31). The river (or its main tributaries the Naryn and Karadarya) flows from Kyrgyzstan into Uzbekistan, then across a narrow strip of Tajikistan that protrudes, thumb like, into Uzbekistan, and finally across Kazakhstan and into the Aral Sea (Micklin 2000, pp. 6–7). Average annual flow of the Syr at 37 km^3, is considerably less than that of the Amu. Kyrgyzstan contributes 74 % of river flow, Uzbekistan 11 %, Kazakhstan 12 %, and Tajikistan 3 %. Like the Amu Darya, the Syr Darya is exotic. Prior to the 1960s, flow diminution was substantial during its long journey across the Kyzyl-Kum Desert with less than half (around 15 km^3 on an average annual basis) of the water coming from the mountains reaching the Aral Sea.

The Amu, Syr and the terminal rivers in the basin of the Amu Darya provide, on an annual average basis, an estimated 116 km^3. Groundwater is an additional water source. Total renewable groundwater resources in the Aral Sea Basin may be 44 km^3/year with, perhaps, 16 km^3/year (36 %) usable (Micklin 2000, p. 8). Groundwater is a significant contributor to the flow of the Amu Darya and the Syr Darya in those rivers’ headwaters whereas in the desert regions along the middle and lower courses, the rivers are net suppliers of flow to groundwater. Hence, the net addition of groundwater to available basin water resources above and beyond the surface contribution to river flow, although likely positive, is difficult to ascertain.

Today, the basin includes territory of seven independent nations: Uzbekistan, Turkmenistan, Kazakhstan, Afghanistan, Tajikistan, Kyrgyzstan and Iran. Within its bound are found Kzyl-Orda and Chimkent oblasts (the Russian term for large administrative regions, now officially known as oblystar) in southern Kazakhstan, most of Kyrgyzstan with the exception of the northern and northeastern territory (drainage basins of Lake Issyk-Kul and the Chu and Talas rivers), nearly all of Uzbekistan with the exception of a part of the Ust-Urt Plateau situated in the far northeast of the country, all of Tajikistan, the northern part of Afghanistan, a small part of the extreme northeast of Iran, and all but the western one-third of Turkmenistan.

Lands that now constitute five of the seven basin states (Uzbekistan, Kazakhstan, Tajikistan, Turkmenistan, and Kyrgyzstan) were part of the Russian Empire and its successor, the Soviet Union, from the late nineteenth century until the collapse of the USSR in 1991. Eighty three percent of the basin was situated in the Soviet Union and this territory accounted for generation of over 90 % of basin river flow, a large share of which ran to the Aral Sea until the 1970s. Afghanistan and Iran control the residual portion of the basin and contribute together no more than 9 % of river discharge. Neither was ever part of the Soviet State nor the preceding Tsarist Empire.

The population of the basin, not including the portion lying in Iran, was an estimated 45.2 million (37.3 million in the former Soviet Republics and 7.9 million in Afghanistan) in 1996 (Tashkent Institute of Engineers of Irrigation and Agricultural Mechanization and The Aral Sea International Committee, 1998, Table 2.1). The population of the basin reached around 55 million by 2009 (Table 2.1). The majority of the population lives in rural areas, but the basin has a number of cities. The largest of these are Tashkent in Uzbekistan (2,209,647), Ashgabat in Turkmenistan (637,000), and Dushanbe in Tajikistan (704,000) (World Almanac Books 2012, pp. 840, 843, 849).

All of Tajikistan and its population lie within the basin, as do 98 % of the territory and 99.5 % of the population of Uzbekistan (Table 2.1). The basin covers close to 80 % of Turkmenistan where nearly all its people live. Over 70 % of Kyrgyzstan is in the basin and more than half its people reside here. Kazakhstan has 13 % of its territory and 15 % of its population in the basin whereas Afghanistan has 40 % of its area in the basin with 33 % of its population there. Only 2 % of Iranian territory, located in the extreme northeast of the country, is in the basin and only a minute portion of the national population.

A somewhat different picture emerges when we look at the contribution the states make to the basin's area and population. Clearly dominant is Uzbekistan with 25 % of the area and nearly 50 % of the population in 2009. Furthermore, this nation sits in the middle of the basin (and Central Asia), is the only country with a border on five of the other six basin states (Uzbekistan has no border with Iran), and has a significant area and population in both of the river sub basins of the Aral Sea drainage (the Syr Darya in the north and east and the Amu Darya in the south and west) (Fig. 2.2). Turkmenistan and Kazakhstan each has 21 % of the area and 9 % and 5 % of population, respectively. Afghanistan has 15 % of basin area and 20 % of population. Tajikistan and Kyrgyzstan are equal at 8 % of area but the former has 13 % of the population whereas the latter has only 5 %. Iran, again, trails far behind the rest with 2 % of the basin area and probably even a smaller a share of the population.

The Aral Sea Basin has great strategic importance. It is the heartland of Central Asia. One or more of the basin nations has borders with world powers China and Russia or with politically volatile Iran and Afghanistan. Three of the basin states are

Table 2.1 Geographic and demographic characteristics of the Aral Sea Basin and Riparian countries

State	Area (km^2)[a]	Area within Aral Sea Basin (km^2)[b]	% of total area of country within Aral Sea Basin	% of Aral Sea Basin area	Population in 2009 (millions)[c]	Population in Aral Sea Basin (2009) (millions)[d]	% of total population of country in Aral Sea Basin	% of Aral Sea Basin population
Uzbekistan	447,232	438,287	98 %	25 %	27.606	27.467	99.5	49.2
Turkmenistan	488,680	378,000	77 %	21 %	4.885	4.836	99	8.7
Kazakhstan	2,728,185	365,400	13 %	21 %	15.399	2.327	15.1	4.2
Tajikistan	143,271	143,271	100 %	8 %	7.349	7.349	100	13.2
Kyrgyzstan	198,737	144,000	72 %	8 %	5.432	2.804	51.6	5.0
Afghanistan	653,004	262,800	40 %	15 %	33.610	11.019	32.8	19.7
Iran	1,640,015	34,200	2 %	2 %	66.429	See note[e]	NA	NA
Total all countries	6,299,123	1,765,958	28 %	100 %	160.710	55.802	34.7	100 %

[a] *World Almanac and Book of Facts*, 1999 (Mahwah, NJ: Primedia 1998), pp. 760–861

[b] Measured by author from map in World Bank, *Aral Sea Basin Program (Kazakhstan, Kyrgyz Republic, Tajikistan, Turkmenistan and Uzbekistan)*: Water and Environmental Management Project, Washington, D.C., May 1998

[c] Mid-2009 estimates from "Info please: Area and Population of Countries" (http://www.infoplease.com/ipa/A0004379.html)

[d] Mid-2009 estimates derived by increasing 1996 population estimate from 1996 data in Tashkent Institute of Engineers of Irrigation and Agricultural Mechanization and The Aral Sea international Committee, "The Mirzaev Report," September 1996, demographic appendices, by average annual growth rate of each country from 1996 to 2009

[e] Information on size of Iranian population living within Aral Sea Basin is not available, but it is insignificant

fossil fuel rich, Kazakhstan with oil and Turkmenistan and Uzbekistan with natural gas. Uzbekistan annually produces about 3.5 million tons of raw cotton making it the sixth largest producer of cotton in the world while in 2010 it exported more than 600,000 t of fiber, second in the world (Uzbekistan Investment Guide 2012). Uzbekistan also has large reserves of gold and uranium. Since independence, these resources have garnered the attention and investments of the Western developed nations and China.

Water is of critical importance in this largely arid region. Agriculture remains the dominant economic activity here and is heavily dependent on extensive irrigation, with attendant application of huge quantities of water (see Chap. 8 for a detailed treatment of irrigation). Irrigation has strained the basins water resources to the limit and led to conflict among the basin states over equitable water sharing. Irrigation has also been the prime factor in the desiccation of the Aral Sea – once one of the world's most important lakes. Hence, the management of this key natural resource is of utmost importance to the economic, political, and ecological future of the region.

2.2 Physical Characteristics of the Aral Sea Prior to the Modern Desiccation

The Aral Sea (in Russian "Aralskoye more" and in Turkic languages of Central Asia "Aral Tengizi (Kazak) or Arol Dengizi" (Uzbek)) is a terminal lake, also known as an endorheic lake, lying at the bottom of the Turan Depression by the eastern edge of the Ust-Urt Plateau (Bortnik and Chistyayeva 1990, p. 6). Its name comes from the word Aral, which means, "Island". Many believe it was called Aral because it was an "island of water" in the vastness of the Central Asian deserts (Ashirbekov and Zonn 2003, p. 6). Others connect the name to the many islands present in the sea prior to its modern desiccation.

The Aral Sea occupies the lowest part of a vast erosional-tectonic hollow of middle Cenozoic age (Rubanov et al. 1987, p. 27). Geologically it is surprisingly young, having arisen at the end of the Quaternary period, coincident with the last glacial epoch about 10,000–20,000 years B.P., with the likelihood its age is closer to the former than later figure (Oreshkin 1990, p. 3; Kosarev 1975, p. 17). Terminal lakes lack surface outflow; hence, the balance between river inflow and net evaporation (surface evaporation minus surface precipitation) mainly determines their level. Such water bodies are typically saline and can range from hyper saline, such as the Great Salt Lake in the western United States with salinity around 300 g/l (grams/liter) to brackish at around 10 g/l such as the Aral Sea was prior to its modern desiccation that began in the early 1960s.

With an average annual level near 53 m for the period of instrumental measurement (1911–1960) that preceeded the beginning of the modern desiccation in the early 1960s, the lake had an area of 66,086 km^2 and was the world's fourth largest

Table 2.2 Hydrographic characteristics of the Aral Sea and its parts (circa 1960)

	Area in km^2				Volume in km^3			
Sea level (meters)	Small Sea	West Large Sea	East Large Sea	Entire Sea	Small Sea	West Large Sea	East Large Sea	Entire Sea
53	5,992	13,628	46,466	66,086	79.7	302.8	681.2	1063.7
51	5,361	13,364	40,885	59,610	68.7	275.9	593.8	938.4
48	4,830	12,962	37,556	55,348	53.5	236.3	476.3	766.1
43	3,846	11,385	31,417	46,648	31.9	175.2	304.1	511.2
33	1,363	6,203	15,817	23,383	6.0	85.0	70.1	161.1
23	–	2,689	–	2,689	–	40.8	–	40.8
13	–	1,597	–	1,597	–	20.6	–	20.6
3	–	954	–	954	–	8.6	–	8.6
−16	–	0	–	0	–	0	–	0

Source: Bortnik and Chistyaevaya (1990), Table 1.1, p. 8

inland water body according to surface area (Table 2.2) (Bortnik and Chistyayeva 1990, pp. 6–9; Rubanov et al. 1987, p. 7). The Caspian Sea in Eurasia (371,000 km^2), Lake Superior in North America (82,414 km^2) and Lake Victoria in Africa (69,485 km^2) exceeded the Aral in surface area. The Aral's level is measured above the level of the Kronstadt gauge in the Gulf of Finland near St. Petersburg and has a "zero" about 20 cm above ocean level. The Aral had a maximum depth of 69 m, volume of 1,064 km^3, average depth of 16 m and shoreline stretching for more than 4,430 km. The lake was elongated in a southwest to northeast direction with a maximum distance of 432 km and a maximum and average width, respectively, of 432 and 156 km. More than 1,100 islands, with an aggregate area of 2,235 km^2 dotted the sea. The largest were Kokaral (311 km^2), Barsakelmes (170 km^2) and Vozrozhdeniya (170 km^2) (Kosarev 1975, p. 23).

The Aral was divided into a so-called "Small Sea" (in Russian "Maloye more") on the north and "Large Sea" (in Russian "Bolshoye more") to the south, which were connected by the Berg Strait. The Small Aral had an area of 5,992 km^2, volume of 80 km^3, maximum depth of 29 m and average depth of 13.3 m (Table 2.2). It consisted of a deeper central basin and several shallower gulfs (Butakov, Shevchenko, and Saryshaganak). The largest town and most important port and fishing center (Aralsk) was situated at the northern end of Saryshaganak.

The Large Aral had a considerably greater surface area and volume (60,000 km^2 and 984 km^3). It was divided into two basins by a north–south stretching underwater ridge that protruded through the surface to form a chain of small islands, the largest of which was named Vozrozhdeniye ("Resurrection"). This Island become famous, perhaps better to say "infamous," as the location of the USSR's most important, super-secret testing grounds for biological weapons. The Eastern Basin had an area of 46,466 km^2 and the Western 13,628. However, the former was shallow (maximum depth of 28 m and average depth of 14.7 m) whereas the eastern was considerably deeper with a maximum depth of 69 m and average depth of 22.2 m (Aral Sea 1981). The southeastern part of the Eastern Basin, known as the

Akpetkinsk archipelago, was very shallow (predominate depths of 2–3 m) and contained more than 500 small islands (Kosarev 1975, p. 23).

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

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

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

Precipitation on the sea's surface derived from measurements at shore and island stations averaged 138 mm/year, but was greatest on the Small Aral (120–125 mm) and least for the southern portion of the large Aral (105 mm) (Bortnik and Chistyayeva 1990, Fig. 2.5, p. 20). Evaporation, calculated from formulae using atmospheric humidity, water and air temperature, and wind speed measurements, was estimated to be around 1 m, with the maximums reached in the shallow, southeastern part of the eastern Basin of the Large Sea (1,200–1,300 mm) and the minimum on the northeastern part of the Small Aral in the Gulf of Saryshaganak (700–800 mm) (Kosarev 1975, p. 29).

The Aral Sea prior to its modern desiccation was brackish with an average salinity around 10 g/l, slightly less than one-third that of the open ocean (35 g/l). The chief salts were sodium chloride ($NaCl$ – 54 %), magnesium sulfate ($MgSO_4$ – 26 %), and calcium sulfate ($CaSO_4$ – 15 %) (Zenkevich 1963, p. 511). The Aral was closer in its chemical composition to fresh rather than ocean water. Surface salinity was lower than the average near the entrance of the two main rivers (Amu in the south and Syr in the northeast), particularly during peak river inflow in spring/early summer when it could fall below 4 g/l near the mouth of the Amu. High salinity levels (17–18 g/l) were reached during summer and winter in the gulfs of the east and southeast part of the Large Aral owing to high rates of evaporation during summer and ice formation (which releases large amounts of salts) in winter (Kosarev 1975 p. 228). Levels of salinity in isolated portions of the Gulf of Saryshaganak (Small Aral Sea) in the early 1950s reached 80–150 g/l.

The Aral Sea, lying between 43° and 47° N. latitude in the heart of the Eurasian continent with no topographic barriers between it and Western Siberia to the north, is subject to severe winters. Average January temperatures range from −12 °C over the Small Sea to −6 °C on the south of the Large Aral (Bortnik and Chistyayeva 1990, Fig. 2.2, p. 14). Consequently, the sea developed an extensive ice cover. The date of first ice obviously depends on the severity of the winter in a particular year, but commonly freezing began on the north Aral (Small Aral Sea) in late November and spread to the coastal areas of the Large (southern) Aral across 2–3 weeks (Zenkevich 1963, p. 511; Kosarev 1975, p. 244; Bortnik and Chistyayeva 1990, pp. 50–60). However, the open parts of the Large Sea during an average winter remained open. Maximum ice extent and thickness (up to 1 m on the Small Aral during severe winters) was reached in mid-February. Breakup of the ice cover began in the second half of February to the first half of March. Full melting of the ice cover took place from the end of March on the south and southeast Aral to the middle of April on the north.

Several other physical characteristics of the Aral prior to its modern drying deserve mention. The current pattern of the sea was unusual (Kosarev 1975, pp. 213–215; Zenkevich 1963, p. 510). It was anticyclonic (clockwise) whereas most large water bodies of the northern hemisphere have cyclonic circulation owing to the coriolis force of the earth's rotation that turns moving objects to the left of their direction of motion. The accepted explanation for this is the predominance of northerly winds and the sea's bottom relief. Another factor that may have played a role is the inflow of the Amu along the western side of the Large Sea to the north and the inflow of the Syr Darya along the eastern side of the Large Sea to the South. However, strong winds from any direction could overcome this circulation pattern. Along the shallow eastern coast of the Aral, where the slope of the bottom and shore were nearly flat, strong winds could rapidly force water some distance inland with an on-shore direction or drive water far from the shore with wind from the opposite direction.

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

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

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

2.3 Level Fluctuations Prior to the Modern Desiccation (also see Chap. 4)

Over geologic time, the Aral depression has repeatedly been flooded and desiccated (Zenkevich 1963, pp. 277–297) . Rubanov (Aladin et al. 1996) considered that the Aral Sea Basin first formed about three million years ago, in the late Neogene period. Two key questions are how was the Aral Basin formed and second, how did it fill with water? Most experts believe that it began as a small depression, which collected local surface water. This runoff was slightly saline due to the dissolution of local salt deposits. When the water evaporated, it left behind a thin veneer of salts. The surface layer was highly sensitive to wind erosion. Repeated over and over again, this process eventually deepened and enlarged the depression. Subsequent discharge of the 'proto' Amu Darya into the basin from the south resulted in the deposition of sediments that divided the main basin into two smaller ones, the Sarykamysh Basin to the southwest and the Aral Basin to the northeast.

Kes (1978), based on Uranium isotope ratio dating, set the first significant filling of the Aral depression in the late Pleistocene, approximately 140,000 years B.P. (before present), when the Syr Darya, entering from the east, filled the lowest parts of the hollow (the Western Basin of the Large Sea, and, possibly, the deepest parts of the Eastern Basin). Other experts have placed the original filling stage of the Aral from 100,000 to 120,000 years B.P. (Oreshkin 1990, pp. 3–4). At this time and for a considerable period afterward, the Amu River flowed westward into the Caspian Sea rather than northward into the Aral.

The lake did not attain great size, i.e., its modern pre-desiccation form, until the Amu Darya switched its course northward into the Aral. This increased inflow to the lake by some threefold. The rate of accumulation of sand and sediments in the Amu Darya Delta has been employed to determine when this occurred. The range of estimates is 10,000–20,000 years B.P. The reason for the change in course of the Amu was most likely onset of a wetter climate that increased river flow, flooding the Amu Darya valley with subsequent spilling over into the valley of the Zaravshan River. The uniting of the two rivers led to breaching of low topographic barriers that allowed the Amu to flow northward to the Aral (Aladin et al. 1996). The Small (northern) Aral only filled after the addition of the Amu's flow.

In any case, approximately the last ten millennia (corresponding with the Holocene geological epoch) constitute the modern history of the Aral Sea. Soviet scientists during the post World War II era (from the late 1940s to 1991s) intensively studied the evolution of the Aral over this time period. Dating of relict shore terraces, of marine fossils and deposits of various salts precipitating from the sea contained in sediment cores from the sea bottom, and of archaeological sites, along with historical records point to repeated major recessions and transgressions of the sea.

One of the most respected researchers, Kes (1978), considered that there was strong evidence for relatively stable levels of some duration at 25–27, 30–31, 35–37, 43–45, and 50–51 m above sea level (asl). Based on terraces, Kes also believed sea level could have been as high as 57–58 m. However, he doubted claims for higher terraces that some say provided evidence for Aral levels of 62–63 or even 70–73 m (Mayev et al. 1991; Rubanov et al. 1987, pp. 51–54). Recent investigations using modern analysis techniques (see below) support Kes and indicate the highest level the Aral reached over the last 10,000 years was no more than 54–55 m asl and that at a sea level of 64–65 m the enlarged Aral would encompass and fill the Sarykamysh depression, leading to overflow into the Uzboy channel leading to the Caspian (Boroffka et al. 2006; Boomer et al. 2009). Hence the maximum level range for the sea over the past ten millennia would appear to be about 20 m.

The early transgressions and regressions of the sea, as you would expect, are not as well known as later events. The so-called Paskevich terrace at about 31 m dates to 9,000–11,000 B.P. and is associated with a shift in the climate of Central Asia from the moist conditions of the late Pleistocene, which led to the initial filling of the Aral Sea depression, to the cold/dry environment of the early Holocene (Aladin et al. 1996; Vinogradov and Mamedov 1991). During this time, evidently, only the Syr Darya fed the Aral, as the Amu flowed westward to the Caspian. This stage switched to warm and relatively moist steppe-like conditions, about 8,000 B.P., as the Amu changed course from the Caspian into the Aral, and the lake's level rose significantly, perhaps to 57–58 m. Vinogradov and Mamedov (1991) state the Aral rose to 72 m before overflowing to the Caspian, but as indicated above, recent analysis has discredited this level. This phase, known as the Lyavlyakansk pluvial, persisted until about 5,000 B.P. Favorable environmental conditions led to a flourishing of both fauna and flora, including the Auroch (*Bos primigenius*), a primitive form of cattle. These conditions were conducive to early human settlement, evidence of which has been found broadly distributed in the deserts, along the rivers, and around lakes in the Aral Sea Basin.

The level fluctuation history for the second half of the Holocene (approximately 5,000 B.P. to the beginning of the modern drying in the 1960s) is better understood. Researchers from the Institute of Ethnology and Anthropology in Moscow (Mayeva and Mayev 1991; Mayev et al. 1991) have provided a useful general overview of Aral level changes over this period. It is based primarily on the radiocarbon dating of distinct layers contained in sediment cores taken from the bottom of the Aral, supplemented by information drawn from analyses of terraces. The layers consisted of fine grained carbonate-clay silts, more coarse grained sand and silt, with entrained shells, and sulfate salts, primarily gypsum ($CaSO_4{\cdot}2H_2O$) and mirabilite ($NaSO_4{\cdot}10H_2O$).

They identified 19 lithologically different layers, representing nine transgressive-regressive cycles. Radio carbon dating of the carbonate in mollusk shells and remains of organic detritus were used to date the layers laid down when regression was underway. Sea levels and the duration of trangressions and regressions were determined by information on the thickness of layers indicating one or the other process and estimates of at what depths ranges different lithological precipitates were distributed in the modern Aral Sea. The general rule used was that carbonate clays accumulate in deep water conditions, indicative of transgression, whereas sandy layers with shells, especially containing sulfate salts, indicate shallowing conditions, indicating regression.

The cores they used for the analysis date to the beginning of the Holocene, some 10,000 years B.P. But the dating of layers prior to 5,000 B.P. was viewed as so problematic that they confined their analysis to the latter period only. Six of the nine major regression/transgression cycles occurred during this interval (Fig. 2.3). High standings of the Aral have been more common than low with the highest levels, reached 4,000–5,000 B.P., at over 70 m. However, Mayev and Mayeva as others were suspicious of this level based on a purported seashore terrace and, as indicated above, it is physically impossible. The authors also questioned the next highest level of 62–63 m dated to around 3,000 years ago. Probably the highest reliable standing of the sea is the “Ancient Aral Transgression” that reached an estimated 57–58 m asl and lasted from approximately 2,800–2,000 B.P. According to Mayev and Mayeva, there were also high levels of the Aral reached around 1,000 years ago (New Aral at 54–55 m), 800 B.P. (52 m) and, of course, the pre-1960 level around 53 m that dates from around the middle seventeenth century (350 B.P).

According to these authors, regressions of the sea have been, with one exception, of much shorter duration than transgressions. Probably all of them are related to the partial or full diversion of the Amu Darya westward into the Sarykamysh Depression and from there via the Uzboy channel to the Caspian Sea. The Amu carried a heavy suspended sediment load. Over time, the deposition of sediment built up the bed level and forced the river to break through its left bank and flow to the Sarykamysh Depression and further toward the Caspian. Subsequently, because of heavier flow on the Amu or other natural reasons, the bed sediments would erode, entrenching the river and causing it to resume its northerly flow to the Aral. The change from a wetter to dryer climate leading to less flow into the Aral from both the Syr and Amu no doubt also played a role, but cannot account for the size and rapidity of the most significant level declines.

Ancient civilizations, as well, had an effect on Aral levels. Human impacts included sizable irrigation withdrawals and periodic diversions of the Amu Darya westward into the Sarykamysh Depression and Uzboy channel. The first evidence of irrigation along the Amu dates to 3,000 years ago (Kes 1978; Lunezheva et al. 1987, 1988). Oberhaensli et al. (2007) note that Soviet researchers concluded irrigation during Classical Antiquity (fourth century BC to fourth century AD) was extensive with irrigation canals, some 20 m wide and stretching kilometers, found over 5–10 million ha around the Aral (although Kes based on the work of the well known Russian anthropologist B.V. Andrianov maintains the maximum irrigated

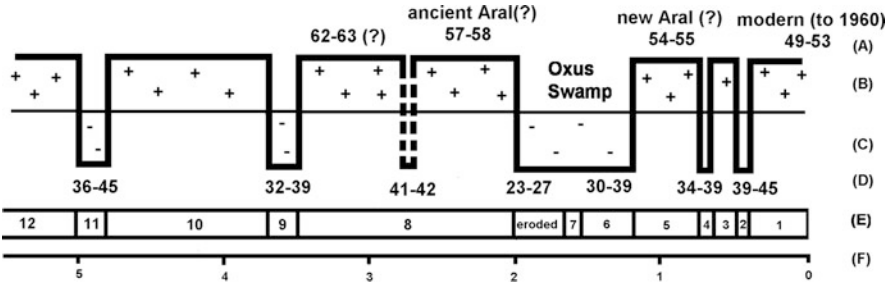

Fig. 2.3 Transgressive and regressive stages of the Aral Sea during the Middle and Late Pleistocene (according to Mayev, Mayeva and Karpychev). Legend: (*A*) Transgressive stage and level in meters above sea level (Based on literary data). (*B*) Transgressive stage. (*C*) Regressive stage. (*D*) Estimate of the regressive stage level in meters above sea level. (*E*). Layers of the bottom sediments. (*F*) Radiocarbon age in 1000s of years before present (B.P.) "+" transgressive stage; "−" regressive stage (Source: Modified and redrawn from Mayev et al. (1991), pp. 85–86)

area in antiquity never exceeded the former figure). Aladin et al. (1996) present a map showing extensive irrigated areas along both the lower Syr and lower Amu by 1,600 B.P.

However, the impact of ancient irrigation on river inflow to the sea was probably not as significant as it might seem (Kes 1978). Fields were small and withdrawals per ha irrigated were much less than modern. Irrigation was mainly confined to relatively moist low areas in the deltas (branch channels and cut-off parts of the river bed) and along the Amu and Syr. These locations under natural conditions were overgrown with hydrophytes (water lowing vegetation also known as phreatophytes) that transpired huge amounts of water. Replacing them with lower consumptive water use crops of wheat and oats increased flow rather than decreasing it. Also, a much larger percentage of water withdrawn was returned via drainage flows to the rivers rather than being "lost" to evaporation in the arid surrounding deserts. Finally, canals were built and abandoned over time so that the actual area irrigated in a particular season was far smaller than the area covered by canal systems.

Diversions were by far the most important human influence on levels. Some of these were accidental, caused by breaching of dikes and dams constructed for irrigation purposes during heavy flows on the river. Others occurred during wars and were purposeful with the intent to deprive an enemy of both water for drinking and irrigating crops. Thus, in 1,221 the forces of Genghis Khan wrecked irrigation systems in Khorezem to punish the local people for robbing one of his caravans (Oreshkin 1990, pp. 10–11; Oberhaensli et al. 2007). This caused the Amu to turn its course from northward to the Aral to westward into the Sarykamysh Depression and the Caspian. Timur (Tamerlane) in 1406 is reported to have diverted the Amu westward to flood the present day city of Urgench to force its surrender (Letolle et al. 2005). This, again, shifted the course of the Amu toward the Caspian and away from the Aral and is associated with a marked level drop and shrinkage of the Aral, attested to by mirabilite deposits in the Western Basin of the Large Sea. There is ample archeological and historical evidence of repeated settlement and agriculture around the Sarykamysh Depression and along the Uzboy, which would only be possible when both were flooded.

According to Mayeva and Mayev (1991) and Mayev et al. (1991), the most severe and long-lasting drop occurred between approximately 2,000 and 1,200 B.P., with the level perhaps falling as low as 23–27 m. This event was most certainly a result of a full diversion of the Amu westward and away from the Aral, leaving only the Syr Darya to feed the sea. It is also possible that for a time the flow of the Syr to the Aral was significantly diminished or even totally halted owing to its diversion southward into the Kyzyl-Kum Desert via the Zhana Darya channel. The only remaining parts of the water body would, have been the deep Western Basin of the Large Sea, a small, very shallow, and very saline remnant lake in the Eastern Basin of the Large Sea and probably a remnant of the Small Sea consisting of several lakes in the deepest parts of the western part of that water body fed by groundwater and local surface inflow.

Evidence for this stage is the thick mirabilite deposits in the western basins of the Large and Small seas and in Tshche-bas Gulf primarily discovered and dated by the noted Soviet geologist I.V. Rubanov in the 1970s and 1980s (Rubanov et al. 1987, p. 229; Cretaux et al. 2009). However, Rubanov et al. assigned a later date (1,500–1,000 B.P.) to this regression than Mayev and Mayeva and estimated a somewhat higher level (at least a drop to 28 m asl and possibly lower). The presence of thick beds of mirabilite indicates very high salinities according to Rubanov et al. (1987, p. 13), as this salt only begins to precipitate at 150 g/l., and hence low levels that lasted for a considerable period. Later in this phase lake level may have risen to between 30 and 39 m, creating a huge, shallow lake in the Eastern basin that has been named the Oxus Swamp (from the Greek name Oxus for the Amu Darya), which, according to Mayev and Mayeva (1991), was overgrown with phreatophytic (water loving) vegetation and sparingly supplied with water from the Syr and possibly the Amu. The inflow was sufficient to maintain the water body but not raise its level.

Research on the historic level fluctuations of the Aral diminished greatly after the collapse of the USSR at the end of 1991. The lake was no longer of great interest to research institutions in Moscow and Leningrad that had studied it during both Tsarist and Soviet times. Some scientists, particularly Dr. Aladin and Dr. Plotnikov, associate editors of this volume, and their colleagues at the Zoological Institute in St Petersburg (formerly Leningrad) did continue their work. Since the late 1990s, however, there has been a resurgent interest in the topic of past level changes. Two powerful motivating factors have been the need to better understand the modern regression by delving into past drying events and the fact that the receding sea is uncovering shoreline terraces, former river beds, archeological finds, and other evidence whose analysis provides a much clearer picture of past regressions than has hitherto been possible.

The most ambitious recent effort was developed as a subproject of the CLIMAN Project (Holocene climatic variability and evolution of human settlement in the Aral Sea Basin) (http://www.CLIMAN.gfzpotsdam), funded by the European Union's INTAS Project (1993–2007). INTAS supported cooperative efforts between scientists from European Union countries and scientists from countries of the former USSR. The Aral-related program was intended as an interdisciplinary study to help distinguish between climatic variations and anthropogenically controlled environmental changes in the past (Boroffka et al. 2006; Oberhaensli et al. 2007). The focus was on previous lake-levels and the evolution of human settlement and agriculture in the Aral Sea Basin. Field investigations in 2002 and 2003 conducted geomorphologic surveys to determine prior lake levels as recorded in shoreline marks and terraces created over the past 5,000 years and to relate these to archeological findings. Two sediment cores (6 and 12 m in length) retrieved from Chernishov Bay at the northern end of the Western Basin of the Large Sea in 2002 were used to decipher level changes over the past two millennia.

The researchers investigated both the northern and southern Aral coasts for archeological sites. They used GPS (Geographic Positioning System) equipment to precisely locate any found and attempted to relate these to ancient or modern shorelines. Sites were dated by conventional archeological methods and radiocarbon dating. To better understand Aral level history, the expeditions mapped beaches, terraces, and wave-cut cliffs. Differential GPS, much more accurate than regular GPS, was employed to determine the elevation of paleoshorelines. Landsat ETM (Enhanced Thematic Mapper) images and digital elevation model data were used for analyzing the spatial distribution and vertical position of littoral features at specific locations. Collected data were entered into a GIS (Geographic Information System). Two sediment cores were taken from Chernishov Bay at the northern end of the Western basin of the Large Aral and analized for their lithology.

The surveys found Paleolithic sites dated 50,000–35,000 B.P. near the former northern shore of the Aral. Lying at 60 m asl along the edge of cliffs, these sites were intact and had not been disturbed by wave action or covered by lacustrine (lake) or wind-blown sediments, providing convincing evidence that the Aral's level was never higher than 60 m. Furthermore, differential GPS elevation measurements made of a number of shorelines around the sea according to the CLIMAN group, convincingly argue against the Aral's level standing any higher than about 55 m for at least the past 35,000 years.

Kazakh hunters at the end of the twentieth century made an equally important discovery when they came across a *mazar* (Islamic holy gravesite) in the northern part of the Eastern Large Aral, northeast of the former Island of Barsakelmes, which in the early 1960s was about 18 m below the surface of the Aral (Aladin et al. 2008; Micklin 2006) (Figs. 2.4 and 2.5).[1] The CLIMAN Aral group found evidence of a

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[1] Micklin used the 1:500,000 Soviet bathymetric chart of the Aral published in 1981 and GPS coordinates for Kerdery #1 to determine the water depth. This chart uses 53 m for the long-term level of the lake, which gives an elevation for the site of near 35 m asl. The chart in the area of Kerdery shows bottom topography in 1-m increments. As the sea has shrunk, this chart has proven amazingly accurate. The CLIMAN group cites the level of the Kerdery grave as 32 m asl. They may have assumed the elevation was the same as the level of the Large Aral at the time (2002) because the site was adjacent to a large body of water. But the water seen was probably a shallow lake created by spring/summer outflow from the Small Aral and was at a higher level than the main part of the Eastern Large Aral.

Fig. 2.4 Kerdery 1 Masoleum with relict channel leading off former bed of Syr Darya in the background (Dr. Aladin is sitting by ceramic artifacts; photo by P. Micklin)

village next to this site and dated both to the thirteenth and fourteenth centuries. Bones of humans and domestic animals, ceramics, and other artifacts were also discovered here.

When the editors of this book, along with several other researchers, visited the site during an expedition to the Aral in August 2005, they also noticed clear evidence of a watercourse nearby, probably a relict channel that led off the Syr Darya that then flowed across the dry bottom of the Eastern Aral. This former river bed of the Syr was no doubt a water supply for the local inhabitants and also probably provided inflow to what was left of the Eastern Basin and to the deep Western Basin of the Aral. An analysis of Aral mirabilite deposits by Cretaux et al. (2009) adds weight to this view. The former riverbed of the Syr Darya clearly shows on Landsat imagery from September 11, 2007 and appears to end somewhat north of the former western end of Barsakelmes Island, in waters, which, according to the Soviet 1:500,000 bathymetric map (Aral Sea 1981) were about 22 m deep in the early 1960s (Fig. 2.6). This would indicate a minimum Aral level of about 31 m asl during this regression.

The gravesite is known as Kerdery #1. As the sea has retreated in ensuing years, other archeological finds (Kerdery #2–5) have been exposed. What the Kerdery finds and the discovery of the relict channel of the Syr Darya prove is that Aral levels in the thirteenth and fourteenth (and probably into the fifteenth) centuries were very low, but still several meters above levels in 2009, which were around 28 m asl. Two of the editors of this book (Aladin and Plotnikov 2009) and their research group found remains of Saksaul stumps (Haloxylon aphyllum) in the early 1990s when the level of the large Aral was around 37 m. They were radiocarbon dated to the mid 1600s (Aladin et al. 1996). Other Sauksaul stumps have subsequently "appeared" at lower levels but not been dated (Fig. 2.7). Nevertheless, the stumps, remants of Saksaul forests growing around the Aral shoreline, indicate a rising Aral

Fig. 2.5 Ceramic artifacts found at Kerdery 1 Masoleum (Photo by P. Micklin)

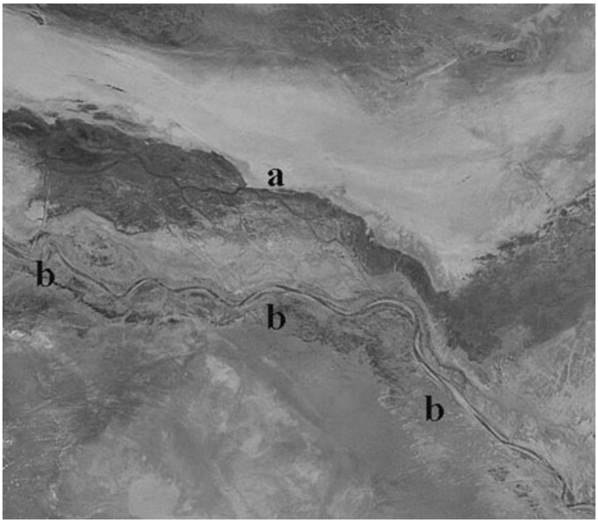

Fig. 2.6 Landsat band 5 Image of 9-11-07 showing late Medieval course of Syr Darya (*b* on image) on dried bottom of Eastern Basin of Large Aral with sub-channels (*a* on image is location of Kerdery-1) leading off to the northwest. North is toward the top

that flooded and killed the trees going back at least to the early seventeenth century and probably considerably earlier.

Based on archeological evidence, relict shorelines, and sediment core analyses, the CLIMAN group, delineated seven transgressions and six regressions over the past 5,000 years. However, the best documented of these (by sediment cores analysis and shoreline traces) are four regressions dated to 350–450, 700–780, around 1,400, and 1,600–2,000 years B.P.

The deepest recession identified by them is the late Medieval occurrence associated with the Kerdery archeological finds, which they believe may have lowered the sea to a about 30 m asl – consistent with the evidence from the relict bed of the Syr Darya. Other recessions are estimated to have not lowered the Aral

Fig. 2.7 Preserved stump of late Medieval Sauksaul (Halyoxen apphyllium) near shore of the Western Basin of the Large Aral Sea (September 2005; photo by P. Micklin)

level much below 40 m. The most important contribution of the CLIMAN efforts is reliably establishing the maximum trangression of the Aral at no more than 58 m asl and probably no higher than 55 m and establishing that the thirteenth to fifteenth century recession was much deeper than previously thought. The CLIMAN group also uncovered a previously unknown recession dating to the Bronze Age (4,000–3,000 B.P.) when the lake's level fell to 42–43 m.

Boomer et al. (2009) provide a useful review of paleoenvironmental research on the Aral, focusing on recent investigations of sediment cores and the insights these provide on level fluctuations over the past 2000 years. Earlier work by Boomer and colleagues based on analysis of two short cores taken from the Small Aral in 1994 suggested the main part of that water body dried for a short period, indicating that sea level fell as much as 30 m, to around 23 m asl, sometime between the late fifteenth and early seventeenth centuries (1440–1640 AD). If this figure is accurate, it would likely tie for the deepest recession of the Aral during the Holocene, the other occurring around 2,000 B.P. according to Mayeva and Mayev (1991). However, it may represent the desiccation of an isolated Northern Aral without inflow as once the entire Aral fell below about 39 m, the southern and northern parts of the sea would separate and the Syr Darya would have only flowed into the Large Aral on the south.

The review goes on to summarize the CLIMAN findings, already discussed above, as well as other research. Boomer et al. (2009) see convincing evidence (from analysis of sediment cores and their organic constituents and historical records) for a significant recession occurring sometime between 0 and 400 AD. They cite climate change to colder, drier conditions that would have reduced river inflow to the sea, along with diversion of the Amu westward toward the Caspian as the primary causes. After about 450 AD, there appears to have been a return to warmer, more moist conditions leading to a rise in Aral levels and a drop in salinity.

The evidence, according to them, points to another significant recessive period from about 1100–1300 AD. The authors contend the causative factor was chiefly climate change with possibly some impacts from expanded irrigation. They discuss the probable diversion of the Amu westward by the Mongol invaders in 1220, but state that based on archeological and core analysis the diversion and recession was short-lived. A new regressive phase initiated sometime between 1440 and 1640 AD. Historical records, sediment core analysis, and radiocarbon dating of Saksaul stumps support this, according to the authors. How low this phase went is not clear, but an undated Saksaul stump, obviously related to this regression, found along the west coast of the Large Aral in Sept. 2005 by the editors of this book (Fig. 2.7) was only a few meters above water level of about 31 m asl, which indicates this was a major event. Boomer et al. (2009) relate the recession to climate change that produced colder and drier conditions in the mountains, reducing the Syr and Amu inflow to the Aral. They discount the idea of human connected diversion of the Amu westward as a cause, but in somewhat of a contradiction, mention that a documented report from the time indicated the Amu's flow didn't return to the Aral until 1,573. It is questionable that climate change alone could have produced such a major desiccation.

Following the return of the Amu Darya to the Aral and the sea's recovery (certainly attained by the mid 1600s) the lake was in a relatively stable, transgressive phase until the modern regression that initiated in the early 1960s. Level fluctuations over this 300-year interval probably were limited to 4–4.5 m asl and were chiefly related to climatic fluctuations with, perhaps, some effect from expanding irrigation (Kes 1978; Bortnik 1996). During high flows on the Amu when its left bank would be breached, some water reached the Sarykamysh Depression. But this phenomenon was rare and brief and had little impact on the level of the Aral.

The famous Russian naturalist/geographer L.S. Berg and later V.P. Lvov studied the history of the Aral's level over recent centuries using literary and cartographic sources (Berg 1908; Lvov 1959). Berg and Lvov identified a sequence of high and low stages, lasting 50–60 years. According to them until the mid 1700s, lake level was in a high phase (53 m). A lower standing followed, reaching its nadir according to Rogov (1957, Fig. 72, p. 196) at 49 m in 1824. Based on two accurate maps of the sea compiled in the late 1840s (Butakov map, see Fig. 2.8) and in 1850 (Khanikov 1856), a rising phase ensued, likely taking the sea to 53 m by the late 1840s. This is deduced by the fact that on both maps the geographic features Kok-Aral on the north and Muynak on the south are shown as islands, not peninsulas, which requires a level of at least 53 m asl. According to Rogov, this was followed by a steady level decline, culminating in a low level of 49.5 m in 1890. As evidence for this lower sea level, Rogov (1957, Fig. 75, p. 203) shows an 1890 map of the Lower Amu delta on which Muynak is clearly depicted as a peninsula rather than an island. Rogov shows a subsequent rapid rise of the Aral level, which by 1907, according to a 1907 map showing Muynak again clearly as an island, must have reached 53 m. Since 1911 reliable measurements of Aral Sea level at a number of places around the sea are available. The level from 1911 to 1960 was very stable around 53 m with an annual variation less than 1 m (Uzglavgidromet 1994–2003).

Fig. 2.8 Butakov's map of the Aral Sea (Translated and published in the Journal of the Royal Geographical Society in 1853) (Source: Perry-Castañeda Library Map Collection, University of Texas (http://lib.utexas.edu/maps/historical/aral_1853.jpg))

2.4 History of Research and Exploration to 1960

Even though a huge water body, the Aral Sea was relatively unknown in the ancient world. According to the famous Russian orientalist V.V. Bartold, writing early in the twentieth century, a reference to it as the "North Sea" or "Western Sea" exists in Chinese documents dating to 200 BC (Ashirbekov and Zonn 2003, p. 13). The Byzantine ambassador referred to a sea-lake in the region in 568 AD. Arab geographers are credited with the first reliable references to the Aral. Ibn Ruste in the tenth century AD. provided a description of the lake and stated the Amu Darya (then designated the Oxus) flowed into it, but didn't name it (Ashirbekov and Zonn 2003, p. 19; Rubanov et al. 1987, p. 13).

Russian investigations of the Aral Sea region began in the early eighteenth century with the expedition of A. Bekovich-Cherkasskiy, sent by Peter-the Great in 1715–1716 (Bortnik and Chistyayeva 1990, p. 10). As Russian power and influence in Central Asia grew, more serious research began. In 1740–1741, one of the leaders of an expedition to the mouth of the Syr Darya, I. Muravin, utilizing instrumental surveys, composed a landscape map, which showed part of the Aral Sea, the Syr Darya Delta, and the Khiva Khanate. This is considered one of the oldest Russian maps of the area, showing cities that were later destroyed and also rivers whose beds shifted or that dried.

The nineteenth century saw much more extensive Russian research devoted to the Aral Sea and surrounding region. In the 1820s, E.A. Eversman studied the coastal zone of the Aral Sea, providing a description of its physical-geographical and geological character and advanced an opinion about the sea's drying. E.K. Meyndorf in 1820 made the first geological description of the near Aral region (Aladin and Plotnikov 2009). In 1823 and 1825–1826, the expedition of Colonel F.F. Berg studied the western shore of the Aral and also completed a survey (leveling) of the Ustyurt Plateau.

Lieutenant A. I. Butakov (later to become Admiral) led the most famous nineteenth century expedition to the Aral in 1848–1849 (Aladin and Plotnikov 2009; Rubanov et al. 1987, p. 13; Bortnik and Chistyayeva 1990, p. 10). He was first to directly investigate the Aral Sea proper from the decks of the Schooner "Constantine". Butakov measured depths, described the shoreline, investigated currents, surveyed the islands, sampled bottom sediments, gathered geological materials and natural samples, determined geographical coordinates, and conducted astronomical and meteorological observations. The famous Ukrainian poet T.G. Shevchenko accompanied Butakov on the expedition and composed an album of shore types as well as other drawings and watercolors of natural features, expedition life and local people (Rubanov et al. 1987, p. 13; Shevchenko 1954).

A key result of the expedition was publication of the first reliable marine chart of the Aral Sea by the Sea Ministry of the Russian Government. This and other information from the expedition allowed development of navigation and trade on the sea and the two influent rivers. However, only a short description of the expedition findings was published in 1853. The full expedition report would not appear for another century. The Aral map produced by the expedition was translated into English and published in the *Journal of the Royal Geographical Society* in 1853 (Fig. 2.8). The Butakov map shows the lake at a relatively high level, somewhat above 53 m, comparable to the level in the early 1960s. A more detailed map of the Aral Sea around 1850 attributed to M. Khanikov (Khanikoff) and drawn by the famous nineteenth century cartographer Augustus Petermann also shows the lake at a level a bit above 53 m.

The second half of the nineteenth century saw a flourishing of research on the Aral, leading to a marked increase of reliable scientific information about this lake (Aladin and Plotnikov 2009; Bortnik and Chistyayeva 1990, p. 10). In 1857, N.A. Severtsov and I.G. Bortshchov carried out physical-geographic observations on the northern and eastern coasts, including examining indicators of the sea's desiccation. An expedition sponsored by the Imperial Russian Geographical Society and the St. Petersburg Society of Naturalists studied the sea in 1874 and gathered much new knowledge about its flora and fauna. A second expedition mounted by the Russian Geographical Society investigated the Amu Darya in the same year. One of its members was a geodesist (A.A. Tillo) who determined the exact level of the sea and placed a geodesic marker on the northwest coast of the sea, which was subsequently used as a reliable basis for measuring Aral levels. The first chemical analysis of the Aral's water was published in 1870. In 1881, O. Grimm published a note about the history of the Aral based on its faunal composition.

Research on the Aral received a strong boost with the formation of the Turkestan Department of the Russian Geographical Society in Tashkent in 1897. This organization devoted considerable effort to the study of the Aral Sea. Its most illustrious Aral investigator was Lev Semyonivich Berg (Bortnik and Chistyayeva 1990, p. 10; Rubanov et al. 1987, pp. 14–15; Aladin and Plotnikov 2009). He led the expedition in 1899–1902 that conducted multifaceted geographic-hydrological investigations of the sea and surrounding region. Berg in 1904 installed the first sea level height gage near the present day city of Aralsk on the shore of the Gulf of Saryshaganak, which is part of the Small Aral Sea. He attempted to set-up an automated level recording device, but it worked irregularly providing only fragmentary records for several months of 1904 and 1905. Systematic instrumental observation of Aral levels began in 1911 at the hydrometeorological station named "Aral Sea," first opened near Aralsk in 1884.

Berg returned to the Small Aral in 1906 where he gathered new geological and zoological collections. In 1908, he published a 530-page book titled, *The Aral Sea: attempt at a physical-geographic monograph*, which presented not only his findings but also those of earlier researchers (Berg 1908). In this work, Berg discussed many aspects of the sea's hydrologic regime, including level fluctuations and water temperature, color, transparency and salinity. He also presented information on the connections between sea level and climate.

Berg asserted that there was no evidence that in historical times the Amu Darya flowed westward into the Sarykamysh Depression, and once it filled, through the Uzboy into the Caspian. A well-known contemporary, V.V. Bartold, who also worked in the Turkestan Department, based mainly on fifteenth century accounts

Fig. 2.9 Abandoned Hydrometeorological Station on the Eastern end of the former Barsekelmes Island in August 2005 (Photo by P. Micklin)

that didn't mention the Aral and in some cases even denied its existence, arrived at the conclusion that at this time the Aral Sea had completely dried (Bartold 1902). He also asserted that the Amu flowed westward into the Caspian during the fifteenth century and was the primary cause of the sea's desiccation. We now know, as discussed in the previous section, that Berg was wrong and Bartold right on this, although the latter went too far in stating the sea dried completely during the late Middle Ages. Berg did support the idea of prehistoric connections between the two seas.

Research on the Aral continued until the outbreak of World War I in 1914. A new levelling survey by the Turkestan Dept. of the Russian Geographical Society established that a new rise in sea level was under way Bortnik and Chistyayeva 1990, p. 11. For the most part, scientific investigations came to a standstill from 1915 to 1920 during the war and ensuing civil war in Russia. With the consolidation of Soviet power, research resumed. In 1920–1921, a commercially oriented expedition studied the Aral in terms of its fishery potential. A scientific fishery management station was created for the sea in 1929. V.Ya. Nikitinskiy, A.L. Bening, and G.V. Nikolskiy led efforts investigating the Aral's hydrochemistry, hydrobiology, and ichthyology. Their work was summarized in *Fishes of the Aral Sea* (Nikolskiy 1940).

Beginning in 1925, a network of hydrometerological stations was established around the Aral to supplement data collected at the first station set up near Aralsk in 1884 (Bortnik and Chistyayeva 1990, pp. 11–28). By 1960, this network consisted of 11 stations situated on the shore as well as on a number of islands (e.g., Barsakelmes, Vozrozdeniye, Uyali). These manned stations recorded data on water levels, salinity, and temperatures as well as wave and ice conditions. They also measured terrestrial meteorological parameters (air temperature, precipitation, humidity, barometric pressure, wind speed, and cloud cover) (Fig. 2.9). Beginning in 1941, research vessels also conducted hydrologic observations in the open sea.

In the postwar years (1946–1960), the Aral scientific fisheries management stations, the Government Oceanographic Institute (GOIN) and other organizations conducted studies of the hydrometeorological, hydrochemical, and hydrobiological regimes of the sea in connection with the construction of the Kara-Kum Canal and the major expansion of irrigation in the basins of the Amu Darya and Syr Darya (Bortnik and Chistyayeva 1990, p. 11). These entities also investigated the water and salt balances, the biology of fish propagation, and carried out measures for the introduction of new species from other water bodies. Research was expanded on the deltas of the Syr Darya and Amu Darya focusing on the regularities of formation of the shoreline, soil, and the vegetation cover along with studies on how to improve fishery conditions. Blinov (1956) published a summary of hydrochemical work on the Aral. This author also provided a forecast of level changes accruing from reductions in river inflow from irrigation and from diversions to the Kara-Kum Canal, which was under construction at that time (Rubanov et al. 1987, p. 16).

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Chapter 3
Biological Dynamics of the Aral Sea Before Its Modern Decline (1900–1960)

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Abstract Fauna of the Aral Sea has very poor species composition. Its poverty is connected to the geological history of the sea. Originally in the Aral Sea there were at least 180 species (without Protozoa) of free-living invertebrates. Their fauna had heterogeneous origins. Prior to the modern recession/salinization, species originating from freshwater, brackish-water and saline continental water bodies predominated. The remaining were representatives of Ponto-Caspian and marine Mediterranean-Atlantic faunas. Parasitic fauna had poor species composition: 201 species were indigenous and 21 were introduced together with fishes. It had a freshwater character. Ichthyofauna consisted of 20 aboriginal and 14 introduced species. The aboriginal fish fauna consisted of species whose reproduction typically occurs in fresh water. There was no fishery on the Aral Sea and local people caught a few of fish only from the rivers until in the mid 1870s Russians came here. After 1905, a newly built railway stimulated further development of commercial fishing, and the Aral Sea became an important fishing water body. The majority of fishes were commercial. Bream, carp and roach provided approximately two-thirds of commercial catch tonnage. In the twentieth century, there was an increase in species diversity. It was a result of intentional and accidental introductions of initially absent species. Though biodiversity grew by 14 species of fishes and 4 species of free-living invertebrates, only a few of them became commercially viable or valuable as food for fishes. A large number of vertebrate species inhabited the Aral Sea, its shore and islands, the Syr Darya and Amu Darya, and the deltas and lakes of these rivers in their lower reaches. The Aral Sea and its shores provided nesting sites for a large number of various floating and near shore birds. Tugay forests along the banks of the rivers constituted a type of oasis where many animal

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species lived. By the 1960s the flora of the Aral Sea included 24 species of higher plants, 6 species of charophytes and about 40 other species of macroalgae.

Keywords Aral Sea • Fauna • Invertebrates • Fishes • Parasites • Aquatic plants • Alien species • Acclimatization • Zooplankton • Zoobenthos

3.1 Invertebrates

The majority of scientists studying aquatic invertebrates of the Aral Sea noted the extreme paucity of its species composition. Still A.O. Grimm (1881), and later L.S. Berg (1908), as well as V.N. Beklemishev (1922) and many others indicated that in the Aral Sea there were not encountered such groups of animals as were to be found in the Caspian Sea. For example in the Aral there were no Spongia, Polychaeta, Mysidacea, Corophiidea, Cumacea, etc. Some authors tried to explain this by physicochemical characteristics of the modern Aral Sea water (Beklemishev 1922). Meanwhile successful acclimatization of aquatic invertebrates in the 1960s from other seas into Aral, their naturalization and wide distribution in the Sea have shown clearly, that the different from the oceanic salt composition could not be the cause of the absence here of many groups of aquatic invertebrates. The majority of researchers contended that the poverty of Aral Sea fauna is connected to the geological history of the sea.

3.1.1 Free Living Invertebrates

Originally in the Aral Sea there were at least 180 species (without Protozoa) of free-living invertebrates belonging to the following taxa: Coelenterata – 1 species, Nematoda – 1 species, Turbellaria – 12 species, Rotatoria – about 90 species, Bryozoa – 2 species, Oligochaeta – 10 species, Cladocera – 14 species, Copepoda – 7 species, Harpacticoida – 15 species, Ostracoda – 11 species, Malacostraca – 1 species, Hydracarina – 7 species, larval Insecta – 27 species, Bivalvia – 9 species, Gastropoda – 3 species (Mordukhai-Boltovskoi 1974).

Data about species composition of the Aral Sea hydrobionts, listed in the “Atlas of invertebrates of the Aral Sea” (1974) and accepted by the majority of researchers, as a rule, did not take into account the rich fauna of the strongly freshened areas of the sea in the mouths of the rivers Syr Darya and Amu Darya. In these zones there was a large diversity of freshwater animals (Akatova 1950; Grib 1950; Zhadin 1950; Pankratova 1950), which traditionally were considered alien to the Aral Sea fauna, though in coastal waters of the southern part of the sea they inhabited large water areas (Dengina 1954, 1957a, b, 1959b; Daribaev 1963, 1965, 1966; Bekmurzaev 1966; Anyutin and Daribaev 1967).

As a whole, despite a long period of faunistic research on the Aral Sea, the species composition of aquatic invertebrates, especially of micro-organisms, was and remains inadequately studied. Unfortunately, the changes which have happened in the ecosystem of the sea over the past 40 years now have practically deprived us of an opportunity to judge what species from insufficiently studied groups of the Aral Sea hydrobionts lived in the sea up to the 1960s.

In terms of zoogeographical composition, the fauna of the Aral Sea had heterogeneous origins. It consisted of freshwater species that were widespread in fresh and saline water bodies of the Paleoarctic and Caspian and Mediterranean-Atlantic species (Zenkevich 1963). Prior to the beginning of the modern recession/salinization of the sea, species originated from freshwater, brackish-water and saline continental water bodies predominated, accounting for 78 % of the total species. The Ponto-Caspian fauna at 17 % represented the next most numerous groups of free-living invertebrates. The remaining 5 % were representatives of marine Mediterranean-Atlantic fauna (Yablonskaya 1974).

Despite the isolation of the Aral Sea from the other basins, because of this water body's youth (Aladin and Plotnikov 1995; Boomer et al. 2000) endemism of fauna was, in contrast to the fauna of the Caspian Sea, very low. At the species level only three species of Harpacticoida – *Schizopera aralensis*, *S. reducta* and *Enhydrosoma birsteini* (Borutzkiy 1974) are considered endemic. At the level of subspecies endemics are Cyclops *Halicyclops rotundipes aralensis*, Aral-Caspian bivalve mollusks *Dreissena polymorpha aralensis*, *D. p. obtusecarinata*, *D. caspia pallasi*, *Hypanis minima minima* and *H. m. sidorovi* (Starobogatov 1974).

Prior to the modern desiccation, faunal group proportioned benthic invertebrates of the Aral Sea as follows. In macro-zoobenthos the group of freshwater species included oligochaetes (10 species) and larvae of insects (27 species). The group of Caspian species included two species of zebra mussels *Dreissena polymorpha* and *D. caspia*, two species of bivalves *Hypanis* – *H. minima* and *H. vitrea*, the gastropod *Theodoxus pallasi*, and the amphipod *Dikerogammarus aralensis* for a total of six species. The group of Mediterranean-Atlantic species included two species – the bivalves *Cerastoderma rhomboides rhomboides* and *C. isthmicum* (earlier they were related to one species *Cardium edule*). Besides this, in a separate group two species of gastropods from the genus *Caspiohydrobia*, which originated from saline water bodies in the arid zone of Central Asia, were included (Andreeva 1989).

Zooplankton have a similar breakdown. Aral Sea cladocerans were composed of four species of Ponto-Caspian endemics: *Cercopagis pengoi aralensis*, *Evadne anonyx*, *Podonevadne camptonyx* and *P. angusta* (Andreev 1989). The most abundant copepod species was the widespread representative of fauna of continental saline water bodies *Arctodiaptomus salinus*. In 1954–1957 it constituted 70–98 % of zooplankton biomass (Lukonina 1960a). Living in marine and saline waters cyclopid *Halicyclops rotundipes aralensis* also was found in all areas of Aral, but was not numerous (Borutzkiy 1974; Andreev 1989). The common element of Aral Sea zooplankton was larvae of bivalve mollusks of genera *Dreissena* and *Hypanis* (Behning 1934, 1935; Lukonina 1960a; Kortunova 1975; Andreev 1989, 1990).

Brackish-water mollusks *Dreissena* spp., *Hypanis* spp. *Theodoxus pallasi* and halophilic gastropods *Caspiohydrobia* spp. predominated in zoobenthos. They constituted about 67% of the total zoobenthos biomass. The second place

(32 % from the total biomass) belonged to larvae of insects, mainly chironomids, among which by biomass larvae of *Chironomus behningii* predominated. *Dreissena* spp., *Ch. behningii* and *Hypanis* spp. composed made more than 90 % of the total zoobenthos biomass.

The bivalve mollusks *Cerastoderma rhomboides rhomboides* and *C. isthmicum*, previously regarded as one species of *Cardium edule*, were relatively seldom found in the Aral Sea (Yablonskaya et al. 1973). These two species, having different salinity optima, lived in different parts of the Aral Sea (Starobogatov 1974; Andreeva 1989) and were not found together. If *C. rhomboides. rhomboides* inhabited the main area of the Aral Sea, then *C. isthmicum* inhabited only salinized bays of the eastern coast and salinized waters of the Akpetkinsky archipelago (known locally as "kultuks"). They obtained maximum abundance at salinities from 24 ‰ to 28 ‰ (Husainova 1960; Dengina 1959a; Yablonskaya 1960b).

Biomass of zoobenthos was the highest in the northern and central parts of the Aral Sea; in the southern and western parts it was low (Nikitinskiy 1933; Behning 1934, 1935). High biomass of benthos (more than 20 g/m^2) was found in bottom sediments with increased content of organic matter, and the lowest biomass (about 10 g/m^2) was on sandy bottoms of eastern and southern shoals and in the deepwater depression along the western shore of the Large Aral Sea. In the first case, benthos development was prevented by a lack of food and also predation by fishes. In the second case, it was prevented by low temperature of bottom water layers and presence of hydrogen sulphide (Yablonskaya 1960b). Areas with extremely low zoobenthos biomass were also in avandeltas of rivers that can be explained by the unfavorable effect on hydrobionts of the increased opacity of riverine water (Karpevich 1953). The greatest extent of zoobenthos fell within the isobaths of 10–30 m (Yablonskaya 1960a; Karpevich 1953).

The seasonal dynamics of the Aral Sea zoobenthos depended on the distribution and feeding habits of fishes. Thus three types of seasonal changes in zoobenthos (Yablonskaya 1961) were distinguished.

1. In shallow coastal areas where the density of benthos-eating fishes was higher in spring and in the first half of summer and then decreased during the second half of summer as fishes moved deeper, the biomass and abundance of benthos decreased from spring to the summer and increased to the autumn.
2. In deep water, far from spawning areas, where benthos-eating fishes came for feeding in the second half of summer, the benthos biomass increased from spring to the summer and then decreased in the autumn.
3. In areas, where fishes had little access to invertebrates (for example, in dense beds of charophytes), the biomass and abundance of benthos increased during all vegetative periods.

For the Aral Sea zoobenthos long-term fluctuations in number and biomass were characteristic. There was a correlation between the biomass of benthos and volume of river flow in the survey year and the preceding year. As the rivers are the main source of biogenic elements for the Aral Sea, an increase in river flow, apparently, created favorable conditions for development of phytoplankton. A growth of primary production supplemented the food reserves for zoobenthos and, in turn, increased biomass. Besides this, during high flow on the Amu Darya suspended matter was brought to the Aral Sea, increasing its content there and leading to a redistribution of biomass between various components. The biomass of larvae of chironomids that preferred silty grounds in particular was rising and the biomass of species preferring more solid grounds (i.e. *Dressena* spp., *Dikerogammarus aralensis*) was decreasing (Yablonskaya 1960a, b). A.F. Karpevich (1975) considered that a considerable role in the long-term fluctuation of zoobenthos abundance was played by consumption of benthic invertebrates by fishes. Periods of high riverine flow were favorable for fish reproduction and more abundant generations appeared in the Aral Sea. Thus when this period was alternated a period of low riverine flow these fish herds of high number caused benthos biomass to decrease.

The Aral Sea zooplankton had the highest species diversity, abundance and biomass from May until October, i.e. during hydrological summer (Behning 1935; Lukonina 1960a; Andreev 1989, 1990). In summer of 1932 in the open part of the Aral Sea, 61 % of zooplankton was composed of larvae of bivalve mollusks, 37 % – by copepods, 7 % – by cladocerans, whereas the portion of rotifers did not exceed 0.1 % (Behning 1934). The winter zooplankton of the Aral Sea was poor; only a small share of species usual for other seasons were present in it. Nevertheless, development of some species of zooplankton, for example, rotifers *Notholca acuminata*, was confirmed for the winter season (Behning 1935).

In spring the biomass of zooplankton was higher, as a rule, in the central part of the Aral Sea. In summer it was considerably increased in the areas of coastal shoals. In autumn in the coastal zone, the biomass of zooplankton decreased, but was little changed in the central part. The cause was a difference between the thermal regime of the central and coastal zone as well as the impact of the flow of rivers on the last. In the areas, which were affected by river flow, owing to freshening and the best supply of food, biomass of a zooplankton was higher. Changes of total biomass by depths and seasons first of all were determined by distribution and seasonal dynamics of *Arctodiaptomus salinus*. This species was characterized in the Aral Sea by low fertility and a long cycle (typically only one generation in a year) that is considered as adaptation of this species to living in water bodies with low primary production (Lukonina 1960a; Yablonskaya and Lukonina 1962).

The most consistent element of zooplankton from May to the end of October was larvae of the bivalve mollusks *Dreissena* and *Hypanis*. Reproduction of these bivalves started in May, their larvae at first appeared in the southern and eastern shoals and in the central part of the Large Aral. In June reproduction of bivalves ensued on a massive scale, and in August it spread over the entire sea. The peak of abundance and biomass of these larvae was in July-August, in the autumn their number decreased, and, as a rule, they occurred only as individuals. There are cases when the maximum numbers occurred in autumn (Behning 1935; Lukonina 1960a; Andreev 1990).

3.1.2 Parasitic Invertebrates

The first data on parasites (two species) of the Aral Sea fishes appeared in the nineteenth century (Fedchenko 1874). L.S. Berg's monograph (1908) contained some information about finding several species of parasites on Aral Sea fishes. Later this list was expanded to eight species (Krepkogorskaya 1927), but the parasitic fauna of the Aral Sea still remained practically unstudied.

The first broad investigation of Aral Sea parasite fauna was conducted in the 1930s. Examination of 22 species of fishes from the Aral Sea and some species of free living invertebrates increased the list of known parasites to 70 species. Thirteen new species of parasitic worms and protozoans were described (Dogiel and Bykhovsky 1934). Detailed research on the Aral Sea parasite fauna, including helminthofauna of piscivorous birds, was again renewed in the 1950s. The number of known species of parasites reached 123, of them 48 species were for the first time found in the Aral Sea (Osmanov et al. 1976). Parasitic fauna of mollusks from fresher parts of the Aral were studied in the 1960s (Arystanov 1969).

Parasitic fauna of the Aral Sea were characterized by poverty of species composition. By the end of the 1960s (when salinization of the Aral Sea began to affect its inhabitants) the structure of parasitic fauna of fishes constituted 222 species. From them, 201 species were indigenous and 21 were introduced incidentally together with fishes in the 1930s–1950s (Osmanov et al. 1976). From this number, Protozoa composed 25 %, Monogenea 29 %, Cestoda 9 %, Trematoda 15 %, Nematoda 13 % and parasitic Crustacea 3.6 %. The parasites that appeared in the Aral Sea together with fishes introduced in the 1930s–1950s were represented by 6 species of Protozoa, 11 species of Monogenea, 1 species of Cestoda, 2 species of Nematoda and 1 species of parasitic Coelenterata.

Palearctic species (32.7 %) were the most common parasitic fauna in the Aral Sea. There were somewhat less of Pont-Aral-Caspian (or Mediterranean) types (22.1 %). Also there were Turkestanic (5.8 %), Sino-Indian (2.2 %), marine (0.5 %), introduced (7.1 %) and species having unclear provenance (29.6 %). A characteristic feature of the Aral Sea parasitic fauna was the absence of endemic species just as endemics were lacking among fish species. Endemic species of parasites were absent among the Caspian species of fishes living in the Aral (Osmanov 1971).

Parasitic fauna of Aral Sea fishes can be characterized as impoverished parasitic fauna of the Caspian region with addition of the Central Asian elements. There were no species of the Black Sea region. Parasitic fauna of fishes was practically devoid of some elements of marine origin existing in the Caspian Sea. Exceptions were the trematode *Bunocotyle cingulata*, the introduced monogeneans *Nitzschia sturionis* and *Gyrodactylus bubyri*. Despite favorable conditions, in the Aral Sea were absent many northern species of parasites existing in the Caspian Sea, in particular *Thersitina gasterostei* and *Achtheres percarum* (Dogiel and Bykhovsky 1939; Schulman 1958; Osmanov 1959, 1971).

The lack in the Aral Sea of many species of parasites present in other water bodies of the Pont-Aral-Caspian region is a result of a number of causes. So, in the

Aral Sea fauna because of the poverty of invertebrate fauna there are absent many suitable intermediate hosts. It was proposed that the cause was the adverse influence of Aral Sea water, differing by its ionic composition from the oceanic, on parasites (myxosporidians first of all). It is especially necessary to emphasize the historical past of the Aral Sea (Dogiel and Bykhovsky 1939) because its fauna was formed in isolation from the Caspian Sea (Osmanov 1971).

Parasitic fauna of the Aral Sea had a freshwater character. In it, both in a qualitative and quantitative sense, larvae of parasitic worms prevailed, which developed to a final state in fish-eating birds. Distribution and development of the majority of parasites entirely or to a large degree were connected with fishes.

Distribution of parasitic species, which depended on the salinity of the Aral Sea, was also connected non-uniformly to the freshwater character of the parasitic fauna. If in the freshened areas almost all species of parasites were found in fishes, then in areas with normal salinity in fishes were recorded less than one third of their total number. Connected to this, such species, which would be found exclusively in areas with normal salinity, were not noted (Osmanov 1971; Osmanov et al. 1976).

The difference in the infestation of fishes with myxosporidians, which was seldom observed in the Aral Sea at its normal salinity, was especially strong. So, in the freshened areas 16 species and in the marine ones only 2 species were recorded (Osmanov 1971). Contamination with myxosporidians could occur only in the freshened areas because of sensitivity of their spores to salinity. It is possible that the raised concentrations of sulfates of magnesium and calcium in the Aral Sea water played some role in it (Dogiel and Bykhovsky 1934). The presence of myxosporidians on fishes from areas with normal salinity has been connected with their migration here from freshwater areas where contamination occurred (Osmanov 1967, 1971; Osmanov et al. 1971).

A similar difference was observed also in the infestation of Aral Sea fishes with other groups of parasites though it was not so sharp (Osmanov 1964). So, 10 species of trematodes in marine areas and 24 of those species in the freshened areas, 5 and 45 monogenean species, 5 and 19 cestode species, 10 and 30 species of nematodes accordingly have been recorded (Osmanov 1971). The first intermediate hosts of the majority of trematodes in the Aral Sea were freshwater gastropods and also bivalves living only in the mouths of rivers and the adjoining them freshened and low salinity bays (Osmanov et al. 1976). Thus infestation of these mollusks in the freshened bays (25 % in Abbas Bay) was higher than in saline (up to 0.32 % in the Bay of Muynak). The role of other mollusks as intermediate hosts of trematodes was minor. The bivalve mollusks *Cerastoderma* spp. and gastropod mollusks *Caspiohydrobia* spp. are the first intermediate hosts of the trematode *Asymphylodora kubanicum*. The life cycle of the trematode *Aspidogaster limacoides* was connected with the bivalve mollusk *Hypanis minima*. As the intermediate host of the trematode *Bucephalus polymorphus*, besides bivalves of genus *Anodonta*, was also recorded the zebra mussels *Dreissena* spp. Metacercariae belonging to an unknown species were recorded in the gastropod mollusks *Theodoxus pallasi*. In total 41 species of cercariae and 1 species of adult trematodes were found in mollusks (Arystanov 1969; Osmanov et al. 1976). From them, 26 species in the adult state are parasites of birds, 4 parasitize in fishes, 2 – in amphibians, and 3 – in mammals. The further development of other species is not known (Osmanov et al. 1976).

Tape worms, for which the first intermediate hosts are planktonic copepods and freshwater origin oligochaetes also were found mainly in fishes in the freshened areas of the Aral Sea. Acanthocephalans were not registered in the sea proper (Dogiel and Bykhovsky 1934), they were found only on fishes migrating to the Aral Sea from Amu Darya and Syr Darya (Osmanov et al. 1976). Outside the freshened areas trypanosoms were not found in the blood of fishes because leeches, which are their vectors, cannot tolerate the higher salinity and are not found here (Osmanov 1967, 1971).

Infestation of fishes in the Aral Sea with trematodes, cestodes and nematodes occurred mainly in the freshened areas where the majority of intermediate hosts were found. A characteristic exception is the euryhaline trematode of marine origin *Asymphylodora kubanicum* (Dogiel and Bykhovsky 1939) that was widespread throughout the Aral Sea. Its development can occur both in saline and fresh water (Osmanov 1967, 1971; Osmanov et al. 1976). Related to this, the contamination of fishes with this parasite was lower in the freshened areas.

Infestation of fishes with ectoparasites in marine areas of the Aral Sea also was lower than in the freshened ones. From protozoans only 1 species of ciliates – *Trichodina* sp. was found (Dogiel and Bykhovsky 1934; Osmanov 1971). Among the indigenous fauna in saline areas were absent monogeneans *Gyrodactylus*, except for *G. rarus* on stickleback and *G. medius* on bream whereas the portion of *Dactylogyrus* species, all species of *Diplozoon*, also *Silurodiscoides siluri* and *Nitzschia sturionis* were euryhaline. The nematode *Cystoopsis acipenseris* may also be considered as euryhaline. Among parasitic crustaceans the majority was euryhaline, first of all *Ergasilus sieboldi* and *Argulus foliaceus*, except for *Lernaea cyprinacea* and *Lamproglena pulchella* contamination, which occurs only in fresh water. Glochidia of the bivalve mollusks *Anodonta* spp., which cannot tolerate salinity, were absent outside freshened areas (Osmanov 1967, 1971; Osmanov et al. 1976).

The general infestation of fishes in the Aral Sea initially was high and reached 95–100 %, including 40–77 % with monogeneans, 59–91 % with trematodes and 58–86 % with nematodes (Osmanov et al. 1976).

The first changes in Aral Sea parasitic fauna followed acclimatization of new fish species. It began in the 1930s when the stellate sturgeon *Acipenser stellatus* was introduced from the Caspian Sea. The monogenean *Nitzschia sturionis* was introduced along with it. This parasite did not occur in ship sturgeon in the Aral Sea prior to this (Dogiel and Bykhovsky 1934). Because the new host did not possess immunity to it, strong epizootic disease began along with mass deaths (Dogiel and Lutta 1937). Apparently, the nematode *Cystoopsis aciperiseris* as well as the coelenterate *Polypodium hydriforme*, which paratizes sturgeon roe, neither of which was earlier found here, were also introduced into the Aral Sea with the stellate sturgeon (Dogiel and Bykhovsky 1934; Trusov 1947; Osmanov 1959, 1967, 1971).

In the 1950s and the early 1960s, the Aral Sea parasitic fauna was affected again by introduction of fishes (Osmanov 1959, 1962, 1971; Osmanov et al. 1976) from the Baltic Sea (Baltic herring), from the Caspian Sea (stellate sturgeon, gobies, atherine) and from water bodies of China (grass carp, black carp, silver carp, spotted silver carp and snakehead) (Karpevich 1975).

Because Baltic herring (*Clupea harengus membras*), unlike other introduced fishes, was brought to the Aral Sea as fertilized roe, it was free of parasites from the Baltic Sea. In the Aral Sea, Baltic herring only acquired a few parasites. Only the larvae of the nematode *Contracoecum spiculigerum* and metacercariae from an unknown species were found in it (Osmanov 1962; Osmanov et al. 1976). The lack of cestodes, with which it could be contaminated as a plankton-eater, is connected with the peculiarities of its biology (Osmanov 1971).

Nine species of parasites were found in the introduced to the Aral from the Caspian Sea atherine (*Atherina boyeri caspia).* It lost the parasites peculiar to it in the Caspian Sea, in particular *Gyrodactylus atherinae*, *Thersitina gasterostei* and trematode *Ascocotyle calcostoma*. The most usual parasites on the atherine in the Aral Sea were metacercariae of *Mesorchis denticulatus* and larvae of nematode *Contracoecum spiculigerum* (Osmanov 1962; Osmanov et al. 1976).

In gobies (bubyr *Knipowitschia caucasicus*, monkey goby *Neogobius fluviatilis* and round goby *N. melanostomus*) introduced from the Caspian Sea, were found 20 species of parasites; 5 species of them are from the Caspian Sea: ciliate *Trichodina domerguei*, myxosporidian *Glugea schulmani*, monogenean *Gyrodactylus bubyri* (it is specific to bubyr goby) and nematode *Cucullanellus minutus*. The composition of parasitic fauna of gobies reflects their feeding on benthos (mollusks; less often other invertebrates) and zooplankton. As a whole, parasitic fauna of gobies in the Aral Sea (Osmanov 1967, 1971; Osmanov et al. 1976) was and remains insufficiently studied.

Parasitic fauna of fishes from the Far East, acclimatized in the Aral Sea in the late 1950s, strongly differ from that in their native region. Snakehead *Channa argus* has lost its parasites. In the sea and delta of the Amu Dar'ya, its parasitic fauna consisted only of local species. The black carp *Mylopharyngodon piceus* was introduced in the Aral Sea in small numbers. Because of this, and also owing to its eating of mollusks, its parasitic fauna is poor, and native species of parasites from the Amur River Basin were completely lost. In it were transferred *A. kubanicum*, *Diplostomum spathaceum*, *D. paraspathaceum*. In grass carp *Ctenopharyngodon idella* in the Aral Sea were about 30 species of parasites of which 9 species were native (from them 7 are specific) and the others have transferred from local fishes. Twenty three species of parasites, 5 native and 4 specific, were found in silver carp *Hypophthalmichthys molitrix*. The presence in it of the cestode *Bothriocephalus gowkongensis* and cysticerci of Dilepididae is an indicator of the important role of zooplankton in its feeding. In bighead carp *Arystichthys nobilis* 20 species of parasites were found, of them only 4 are native (including 2 specific). The presence of the myxosporidian *Chloromyxum cyprini* in it reflects the lengthy periods it spends bottom feeding where it swallows spores. For all these fishes from the Amur basin, except for the black carp, the presence in them of the transferred together with them and broadly specific parasite *B. gowkongensis* indicated they consumed zooplankton. In the Aral Sea *B. gowkongensis* transferred into local cyprinids (asp, barbel, bream, sabrefish, carp, ide, rudd). It also was found on fishes of other families (pike-perch, pike, perch, silurus, ship sturgeon). Also the broadly specific Mediterranean nematode *Cucullanellus minutus*, introduced from the Caspian Sea gobies, transferred in the Aral Sea on to shemaya, silurus, asp, pike (Osmanov et al. 1976). Bottom feeding fishes are infested with it as a result of swallowing larvae from the substratum. Predators are infested with *C. minutus* by reinvasion. This parasite has been found only in the northern part of the Aral, where gobies settled. Its spread together with gobies was impeded by higher salinity in the central water area. The distributional pattern of *C. minutus* also shows that it does not tolerate fresher water (Lomakin 1970; Osmanov 1975).

The composition of parasitic fauna introduced into Aral fishes corresponded to the earlier ascertained regularities (Petrushevsky 1958). Their parasitic fauna became impoverished leading even to the complete disappearance of those endemic to their native water bodies. Baltic herring, transferred by fertilized roe, had no endemic to the Baltic parasites. The fishes introduced in small number and as adults (atherine, snakehead, black carp) lost specific and characteristic parasites. Thus local broadly specific species of parasites infested the invaders. Of the specific parasites, mainly monogeneans *Gyrodactylus*, *Dactylogyrus* and *Diplozoon* remained. From introduced to the Aral Sea parasites, 85 % had direct development (55 % of them were monogeneans characterized by high rates of survival during transportation). Of introduced parasites, 75 % were species specific and in new conditions they were only on their primary hosts. Two species – *Bothriocephalus gowkongensis* and *Cucullanellus minutus* – were more opportunistic and transferred to some species of aboriginal fish fauna. Three species – *Nitzschia sturionis*, *Cystoops, acipenseris* and *Polypodium hydriforrne* – transferred from stellate sturgeon to ship sturgeon belonging to the same genus *Acipenser* (Osmanov et al. 1976).

Besides the enrichment of the Aral Sea parasitic fauna with new species (about 10 % of initial number), acclimatization affected it also in other ways. As a result of introduction of planktivorous fishes the feeding pressure on zooplankton sharply increased and as a consequence the abundance and biomass of planktonic crustaceans fell sharply (Andreev 1989). The abundance of copepods, which were intermediate hosts of many cestodes and nematodes, declined. Gobies and atherine consumed large quantities of zooplankton in competition with other fishes. They became a barrier in the life cycle of cestodes that led to the decrease of their abundance. On the other hand, they were intermediate hosts of nematodes *Contracoecum spiculigerum*, *C. microcephalum* and, became a food source for predatory fishes (silurus, asp, perch). Playing the role of reservoir hosts more effectively than juveniles of indigenous cyprinids, they served as a transfer chain from the first intermediate host. Despite the decrease of copepods abundance this maintained the high infestation of predatory fishes with nematodes. Strengthening of the pressure by plankton-eaters also led to the decrease of infestation of fishes with parasitic crustaceans because of consumption of their floating larvae (Osmanov et al. 1976; Osmanov and Yusupov 1985).

Aral Sea stickleback, an aboriginal euryhaline inhabitant, had 10 species of parasites (Dogiel and Bykhovsky 1934; Osmanov 1971). Of these, seven species – (*Diplostomum spathaceum*, metacercariae of Echinostomatidae, *Bunocotyle cingulata*, *Proteocephalus cernuae*, cysticerci of Dilepididae, *Contracoecum spiculigerum*, *C. microcephalum* – were found on other fish and only three species – *Trichodina* sp., *Gyrodactylus rarus*, *Schistocephalus pungitii* – belong to specific parasitic fauna of sticklebacks) (Schulman and Schulman-Albova 1953; Osmanov 1971). The parasitic copepod *Thersitina gasterostei*, common on this fish in other water bodies, was not found in the Aral Sea.

3.2 Fishes and the Fishery

There were only 20 species from seven families in the aboriginal fish fauna of the Aral Sea (Table 3.1). The family Cyprinida accounted for the greatest number of species – 12 % (or 60 % of all fish fauna). Perches (Percidae) were represented by three species whereas sturgeons (Acipenseridae), salmons (Salmonidae), catfishes (Siluridae), pikes (Esocidae) and sticklebacks (Gasterosteidae) were each represented by one species. In the aboriginal fish fauna of the Aral Sea eurybiontic species predominated (about 95 %) (Nikolsky 1940).

Only three fishes out of the six, which composed the fish fauna of its basin, were found in the aboriginal ichthiofauna of the Aral Sea (Nikolsky 1940).

- Upper quaternary fauna to which belong pike *Esox lucius*, perch *Perca fluviatilis*, etc.
- Aral-Caspian fauna including representatives of the genera *Acipenser*, *Rutilus*, *Abramis*, *Aspius*, *Barbus*, *Pungitius*. All of them lived in the sea and in lower reaches of the rivers. This complex composed the basis of Aral fish fauna and included nine species or 45 % of all fish fauna.
- Northern immigrants. These were two groups of representatives of northern (mainly Siberian) fish fauna.
    - Stenothermal, cold-tolerant species of fishes, which were represented in the Aral Sea only by the Aral salmon *Salmo trutta aralensis*.
    - Eurythermal limnophylic species of fishes, which lived in the lower reaches of the rivers and partially settled the entire Aral Sea: silver crucian *Carassius auratus gibelio*, ide *Leuciscus idus oxianus* and the ruff *Gymnocephalus cernuus* (= *Acerina cernua*). The ide and crucian lived only in the fresher parts of the Aral Sea, but the ruff inhabited both saline and fresh water areas.

In the Aral Sea there were no endemic genera and species of fishes. Endemism took place only at the level of subspecies. The youth of the Aral as an isolated water body explains this feature. Apparently, fish fauna of the Aral arose from fish fauna

Table 3.1 Species composition of the Aral Sea aboriginal ichthyofauna

Species	Years				Status
	1950	1960–1979	1980–1990	1991–2004	
Acipenseridae					
Ship sturgeon *Acipenser nudiventris* Lovetsky	+	+	–	–	C-, E
Salmonidae					
Aral trout *Salmo trutta aralensis* Berg	+	+	–	–	C-, E
Esocidae					
Pike *Esox lucius* Linnaeus	+	+	–	+	C-
Cyprinidae					
Aral roach *Rutilus rutilus aralensis* Berg	+	+	–	+	C
Orfe *Leuciscus idus oxianus* (Kessler)	+	+	–	+	C-
Asp, zherekh *Aspius aspius iblioides* (Kessler)	+	+	–	+	C
Rudd *Scardinius erythropthalmus* (Linnaeus)	+	+	–	+	C-
Turkestan barbel *Barbus capito conocephalus* Kessler	+	+	–	–	C-, RB
Aral barbel *Barbus brachycephalus brachycephalus* Kessler	+	+	–	+	C-, RB
Bream *Abramis brama orientalis* Berg	+	+	–	+	C
White-eye bream *Abramis sapa aralensis* Tjapkin	+	+	–	+	C-
Aral shemaya *Chalcalburnus chalcoides aralensis* (Berg)	+	+	–	+	C-
Sabrefish *Pelecus cultratus* (Linnaeus)	+	+	–	+	C-
Crucian carp *Carassius carassius gibelio* Bloch	+	+	–	+	C-
Carp *Cyprinus carpio aralensis* Spitshakow	+	+	–	+	C
Siluridae					
Wels *Silurus glanis* Linnaeus	+	+	–	+	C-
Gasterostidae					
Nine-spined stickleback *Pungitius platygaster aralensis* (Kessler)	+	+	+	+	NC
Percidae					
Pike perch, zander *Stizostedion lucioperca* (Linnaeus)	+	+	–	+	C

(continued)

Table 3.1 (continued)

Species	Years				Status
	1950	1960–1979	1980–1990	1991–2004	
Perch *Perca fluviatilis* Linnaeus	+	+	–	+	C-
Ruff *Gymnocephalus cernuus* (Linnaeus)	+	+	–	–	NC

Note: + present, – absent, *C* commercial, *C-* commercial but low stocks, *NC* not commercial, *RB* in Red Book, *E* extinct now

of the Amu Darya and Syr Darya and represent a limnophylic group of fish fauna of the Pleistocene Oxus (Amu Darya) (Nikolsky 1940).

Almost all representatives of aboriginal fish fauna of the Aral Sea, as a rule, migrated. These were migrations of juveniles from spawning areas to deeper places, spawning migrations of adult fishes, their migration from spawning areas to places of fattening and migrations to places of wintering. According to the character of migrations of adult fishes, the aboriginal Aral fish fauna may be divided into seven groups (Nikolsky 1940).

- Anadromous fishes. To them are related ship sturgeon *Acipenser nudiventris*, Aral salmon and the Aral barbel *Barbus brachycephalus brachycephalus*. These fishes spawned in the Amu and Syr rivers where they flowed across the desert plains, sometimes across a stretch of 1,000 and more kilometers from the mouth (ship sturgeon). The majority of them came into the rivers with immature reproductive organs in the summer and spawned the next year. Places of their fattening were located in the sea beyond the influence of inflowing fresh riverine water.
- Semi-anadromous fishes. Here are white-eye bream *Abramis sapa aralensis* and asp *Aspius aspius iblioides*. These fishes in spring entered the rivers from the sea for spawning, but migrated not very far upstream. The main places of white-eye bream fattening were far from shore in the deepwater zone, whereas asp fattened exclusively in the coastal area.
- Fishes twice a year came from the open sea to the shore: during spring for spawning and in the autumn after fattening to deep places along the shore. Their spawning areas were not only in fresher parts of the sea, but also in regions with raised salinity. To this group belonged the basic commercial species of the Aral Sea: (roach *Rutilus rutilus aralensis,* bream *Abramis brama orientali*), saber fish *Pelecus cultratus* and pike-perch *Stizostedion lucioperca.*
- Fishes, which also twice yearly migrated from the open sea to the coastal zone: in spring for spawning and in the autumn for fattening. But the main places of their fattening were near to the shore. To this group are related the carp *Cyprinus carpio aralensis* and catfish *Silurus glanis.*
- Shemaya *Chalcalburnus chalcoides aralensis* which once a year migrated to the coastal zone (except for its freshened parts) and after spawning returned to the open sea.

- Fishes that permanently remained in the coastal zone, both in salinized bays and in freshened areas near the delta mouths, but did leave the zone of coastal vegetative growth. To this group were related the reed forms of roach, bream, carp and catfish, and also rudd *Scardinius erythropthalmus*, pike *Esox lucius*, perch *Perca fluviatilis* and ruff.
- Fishes that also were permanently in the coastal zone, but exclusively in the freshened areas around the delta. The ide and crucian were related to this group.

In the Aral Sea all aboriginal fishes migrated for reproduction into the coastal zone or into the rivers. There were no fishes reproducing in the open sea. Also there were no fishes, which remained in the deepwater zone for their entire lives. This also testifies to the origin of the Aral Sea fish fauna from the limnophylic (lake derived) faunas of the Amu Darya basin (Nikolsky 1940).

Fishes from the open parts of the Aral Sea, classified by the character of their diurnal vertical migrations, are divided into four groups (Nikolsky 1940).

- Fishes that during the entire vegetation period regularly rose at night to the surface layers of water and descended during the day to the bottom layers. The vertical temperature stratification did not influence the character of these migrations. In the Aral Sea, the saberfish and shemaya were related to this group.
- Fishes that during the whole vegetative period also regularly rose at night to the surface layers of water and descended during the day to the bottom layers. However such migrations only took place in spring and in autumn during vertical water circulation. Vertical migration ceased during the summer stagnation and fishes were found permanently in the hypolimnion. Roach and white-eyed bream were among this group.
- Fishes that during the entire vegetation period remained in the bottom layers and, as a rule, were not found in the surface layers. Bream in the Aral Sea belonged to this group.
- Fishes whose distribution in the water column, apparently, is little connected with the time of day, and their vertical migrations had a random character. They could be found day and night both in surface and in bottom layers of water, irrespective of the presence or absence of vertical temperature stratification. In the Aral Sea only the pike-perch belonged to this group.

In the coastal zone the distribution of fishes in the water column depended on weather. This factor also strongly influenced their vertical migrations, but they did not have a regular character (Nikolsky 1940). G.V. Nikolsky (1940) delineated two main fish communities in the Aral Sea: the open sea community and the coastal community. The main commercial fishes – bream, roach, pike-perch, white-eye bream, saberfish and shemaya fattened (but did not spawn) in the open part of the Aral Sea from the second half of May until October (Nikolsky 1940).

In summer in the open part of the Aral Sea the majority of fishes fed in the bottom water layer, remaining here all day. There were present only zoobenthophags, planktophags and predators; mud-eater and phytophagous fishes were absent. The basic source of nourishment of zoobenthophags was

Dikerogammarus aralensis, followed by bivalve mollusks and larvae of Chironomidae (Nikolsky 1940).

In the Aral Sea there were no aboriginal fishes that permanently lived in pelagic (open sea) environments and fed there on zooplankton and phytoplankton. But among them there were fishes partially nourished by pelagic plankton and partially by benthos. The important food source of fishes in the open sea were insect pupae, mainly forms of Chironomidae, that rose to the water surface during their mass flight exodus and also their imagoes (an insect in its sexually mature adult stage after metamorphosis) and imagoes of caddis flies. Then a significant part of benthophags switched to feeding on them. Main consumers of pupae and imagoes of Chironomidae were saberfish, shemaya, roach and white-eye bream. Zooplankton played a minor role in the nourishment of fishes of this community and they were only important for stickle back *Pungitius platygaster aralensis* (Nikolsky 1940).

The coastal zone of the Aral Sea was much richer with different biological groups of fishes and with the number of species in each group. In the coastal zone there were six species of zoobenthophags (bream, white-eye bream, barbel, perch, roach and carp) while in the open sea there were only four species of these. Here were found plant eating fishes (rudd and carp) and carp that partially ate plants. In the coastal zone lived more predators: besides pike-perch there were pike and catfish. Planktophags, as in the open sea, also were represented only by stickleback (Nikolsky 1940).

The species composition of food in the coastal zone of the Aral Sea differed from that in the open sea. So, the role of vegetation in the nourishment of those fishes, which far from the shore fed exclusively on animals, for example, roach, was considerably higher. The role of *D. aralensis* in feeding of fishes of coastal zone was essentially lower, and bivalve mollusks had considerably greater importance. Besides that, here in the food of zoobenthophags the importance of Ostracoda, whose role in the deepwater zone of the open sea was rather small, increased. Much greater diversity of food composition of individual species of fishes in comparison with the open sea was characteristic for this zone. In the coastal zone, the role of plankton in the feeding of adult fishes was much less than in the open sea (Nikolsky 1940).

The aboriginal fish fauna of the Aral Sea consisted of species whose reproduction typically occurs in fresh water. The best places for spawning of these fishes were freshened bays near deltas, deltaic lakes and the rivers entering the sea. There spawned about two-thirds of the main commercial fishes. The role of marine spawning areas was and remains unclear. Observations indicated that the main commercial fishes – bream, carp and roach can put roe in the Aral Sea in a wide range of salinities from strongly freshened up to fully saline water. However it still does not mean that the embryonic development will proceed normally at increased salinity and roe will not die and that juvenile fish will be healthy. Available data about the upper bound of salinities at which normal development of roe and larvae is possible, are inconsistent. Nevertheless, according to a series of experimental data for roach the upper bound of this range is equal or close to the normal salinity of the Aral Sea (around 10 g/l) prior to its modern desiccation. For carp it is lower, and even lower for bream. On the other hand, there were schools of bream (for example, along the western coast of the Large Aral) living permanently far from deltaic areas and spawning in fully saline water (Bervald 1950). Also there are observations of normal development of roe and larvae of Aral roach, bream and carp at salinities of 11.6, 10.5 and 10.6 g/l accordingly (Gosteeva 1956, 1957, 1959).

The Aral fishery had a short history. Until the middle of the 1870s it was still in an embryonic state. The local people (Kazakhs and Karakalpaks) caught with primitive gear a small quantity of fish only from the Syr Darya and Amu Darya. On the Aral Sea fisheries practically did not exist. The true fishery on the sea and the rivers started to develop only after resettlement here of Cossacks from the river Ural. They introduced the drift net, which become for the first time the main fishing gear on the rivers. Caravans to Orenburg, Tashkent and other places transported the fish. By 1885, the fishery on the Syr Darya had spread from Kazalinsk to the near delta areas of the sea. The more convenient seine started to replace the drift-net as the main fishing gear. In this period, fishing for anadromous (ship sturgeon, barbel) and semi-anadromous (such as bream and asp) fishes predominated. Fishing on the sea was poorly developed and began to expand only after 1899. Only in the northern part of the Aral Sea and in the lower reaches of the Syr Darya were caught 30,155 centners. Fishery targets were ship sturgeon, barbel, bream, carp, asp and catfish. Roach, white-eye bream and shemaya were not sought after. Winter ice fishing was not yet employed and fish were caught only in the summer and in the autumn (Zharkovsky 1950).

The first attempt to regulate the fishery and protect fish stocks in the Aral basin was undertaken in 1886. Permits were introduced for fishing rights on the Syr Darya. A prohibited fishing zone was established at its mouth and Sunday fishing was forbidden. Special horse patrols enforced the rules. In 1898–1899, fishing on the Syr Darya and along the northeast shore of the sea was regulated by establishment of a prohibited fishing zone around the mouth of the Syr Darya Delta and institution of fishing seasons for the river. But these measures did not ensure adequate protection of ship sturgeon and barbel because they appeared upstream of the protected zone after the prohibited catch period and were over fished. The fishery regulation and protection of fish stocks remained unsatisfactory. The almost complete disregard for the regulations promoted poaching. In 1900 new fishery regulations were introduced for the fishery on the Aral Sea and Syr Darya. A more specifically tailored prohibition on fishing in the Amu Darya was implemented with distinct fishing seasons for different sectors, establishment of a permanently protected zone in front of the delta and of prohibited days for fishing along with a ban on night fishing, prohibition of certain types of fishing equipment, and establishment of trade measures (Zharkovsky 1950).

In 1905 the Tashkent railway went into service. It passed by the northern tip of the Aral Sea, which solved the problem of rapid delivery of large quantities of fish products to the places where they were consumed. It stimulated further development of commercial fishing on the Aral. The settlement of Aralsk was founded with a railway station and port and turned into a center of the fishing industry. Fisherman from the Sea of Azov and the Danube Delta resettled on the Aral, Syr Darya and Amu Darya and brought new fishing gear and fishing methods. Major fishing industry entrepreneurs appeared who developed fisheries on the Astrakhan (a city located in the Volga Delta) model. The Aral Sea became an important fishing water body. Catches in its basin grew rapidly and by 1915 reached 483, 000 centners. New fishery regulations for the Aral Sea, Syr Darya and Amu Darya were instituted in 1914. The multifaceted regulations for the Syr Darya fishery were expanded to include a complete closed season for the whole sea and an expanded list of prohibited fishing gear. These rules mainly conformed to the principles of rational fisheries management, but still had essential inadequacies (Zharkovsky 1950).

In connection with the First World War, and then the Revolution and Civil war, catches fell to 27,710 centners in 1920 owing to a drop in the number of fisherman, fishing equipment, and fishing vessels. All large fishing enterprises were nationalized in 1918. Fishing gradually started to recover after 1921. The Aral fishery inspection service was set up in 1923. In 1925, the Aral state fishing trust was created. In 1926, the association of fishing companies and cooperatives within the Aral union of fishermen was started. The permanent statistical account of catches began to be made from 1928 (Zharkovsky 1950).

Pre-revolutionary fishery rules were used prior to the introduction in 1925 of new simplified temporary rules. In 1926 there were accepted new temporary rules for the Aral Sea, Syr Darya and Amu Darya, which introduced again restricted zones and fishing seasons. These rules were positive in that they prohibited the catch of ship sturgeon in the Syr Darya above Kzyl-Orda, protected approaches to spawning places and the very spawning beds themselves and prohibited fishing ship sturgeon in the Amu Darya where its stocks had been have been strongly degraded by intensive fishing. In 1936 the fishing for barbel in the Syr Darya was completely prohibited as was fishing for ship sturgeon as a result of its mass death from the introduced with the Caspian stellate sturgeon parasite *Nitzschia sturionis*. New rules established in 1940 completely prohibited fishing for ship sturgeon across the entire basin of the Aral Sea, and the fishing for barbel in Syr Darya and in a considerable part of the Amu Darya. A permanent restricted zone was instituted in the Syr Darya Delta and temporary restricted zones were established for the main spawning areas of the chief commercial fishes. Subsequently, improved fishing rules were developed for ensuring natural reproduction of the main commercial fishes of the Aral Sea Basin (Zharkovsky 1950).

The overwhelming majority of Aral Sea aboriginal and introduced fishes were commercial species, excepting the aboriginal Aral stickle-back. The Aral salmon because of its extremely low numbers had no commercial significance and was caught only incidentally as individuals. The ruff as a low value and not numerous fish had no commercial importance. Perch was not specifically fished for and only appeared as “by-catch” of more important species. It had no real importance. Turkestan barbel was not numerous, but sometimes was incidentally caught with Aral barbel. Crucian and Turkestan ide were rarely encountered in saline waters and had some commercial significance only in deltaic lakes. Rudd were not fished for in the Aral Sea, but was caught in the deltaic lakes of the Amu Darya. Commercial fishing of ship sturgeon was halted in 1937 because of the catastrophic drop in its numbers (Fortunatov et al. 1950). Among fishes introduced into the Aral Sea and river deltas intentionally and incidentally in the 1950s, gobies (bubyr goby, sand goby and round goby) and Caspian silverside were not considered commercial species. Such introduced commercial species as Baltic herring also were not commercial fishing targets. Grass carp, black carp, silver carp and snakehead, however, were considered among commercial species in the rivers, deltaic water bodies and, in to some extent, in the freshened zones of the sea.

Carp-like fishes (cyprinids), as the base of the Aral Sea fish fauna, yielded about 90 % of the commercial catch by weight. Only three species (bream, carp and roach) provided approximately two-thirds of the tonnage. The portion of the catch from the remaining commercial species of fishes (shemaya, pike, catfish, Aral barbel, pike-perch, asp, white-eye bream and saberfish) varied from 1 % to 5 %. The total weight of catches fluctuated. If in 1939 428,000 centners of fishes were caught, in 1946 it was only 236,000 centners. Such instability of catches was connected with fluctuating number of schools of the main commercial fishes – bream, carp and roach. The most unstable were catches of pike, shemaya and asp. The most stable were catches of pike-perch and catfish (Nikolsky 1944; Fortunatov et al. 1950).

In terminal lakes such as the Aral Sea, the state of fishery resources is determined by the interaction of such factors as the number of commercial fishes, conditions for their reproduction, food capacity of the basin and intensity of fishing. The main abiotic factors influencing fish resources of the Aral Sea were volume and character of river discharge, as well as changes in the structure of river deltas and sea level. River inflow determines the input of biogenic materials that in turn determine primary productivity, which determines the biomass of zoobenthos and zooplankton – the food source for fishes. The amount of river discharge also determines the size of the freshened zones, which were the main spawning areas in the Aral Sea, and also conditions of anadromous and semi-anadromous fishes migration to the rivers for spawning. Sea level fluctuations also had large impacts on the size and regime of spawning areas located in the Aral Sea, first of all in its shallow-water bays (Fortunatov et al. 1950).

From the beginning, the Aral fishery had a seasonal character. Maximum catches were in spring and autumn and were in the coastal zone. During the remaining times of the year, when fishes migrated out from the shores, the industry to a significant degree shut down. In summer months there was only a maximum catch of ship sturgeon and barbel. Mass fishing on spawning grounds destroyed the normal course of reproduction and besides that in spring the fish were least fattened and their commercial value was lowest. Therefore there was the necessity of transitioning fishing to places where fish pastured that would allow essentially to increase the general catch in summer and autumn and lower the spring catch (Nikolsky 1940).

Commercial fishing on the Aral Sea was mainly with large seines. Nets were thrown from the large fishing launches designed to hold 30–50 tons of fish, and also from boats (in this case nets were pulled out on the shore by camels). The postwar catch reached a maximum in 1958 when 44,000 metric tons of fish were harvested

(Tleuov 1981, pp. 168–176). The factories in Aralsk and Muynak processed the catch. After the Second World War, the canning plant in Muynak started to process Aral fish and production reached 22 million cans a year.

3.3 Invasive Species

In the twentieth century, there was an increase in the species diversity of the Aral Sea fauna. It was a result of introductions of invertebrate and fish species initially absent in the Aral Sea (Tables 3.2 and 3.3). People intentionally made these introductions for specific purposes. However, as a result of this activity some species were brought to the Aral accidentally, often as unintended "travelers" with those planned to be introduced (Aladin et al. 2004).

It may be true that in extreme antiquity some species of hydrobionts, now considered as aboriginal were inadvertently introduced to the Aral Sea from other water bodies by ancient peoples. There is a theory (Fedorov 1957, 1983), that about 5,000 years ago Neolithic tribes, wandering between the Aral and Caspian sea along the banks of the ancient river Uzboy and the shore of the ancient Sarykamysh Lake, carried from the Caspian sea into the Aral the Mediterranean-Atlantic bivalve mollusk *Cerastoderma rhomboides rhomboides* (= *Cardium edule*), which they used as a food source.

The question of the efficacy of introducing new species to the Aral Sea was first raised in the late 1920s. Fishes were the first to be introduced. Because of almost full absence in the Aral of true plankton-eating fishes, zooplankton was little eaten. The only typical plankton-eater was the scarce stickleback *Pungitius platygaster aralensis*. The main consumers of zooplankton were predatory zooplankters and also fry and juveniles of benthos-eating and predatory fishes. Zooplankton also provided food for adult shemaya *Chalcalburnus chalcoides aralensis* and sabrefish *Pelecus cultratus* (Pankratova 1935; Yablonskaya 1960a; Kortunova 1975). As a result, in the 1920s there was a view that in the Aral Sea zooplankton are underused as a food for fishes. Therefore, in order to increase production of commercial fishes it was believed necessary to supplement the indigenous Aral Sea ichthyofauna with true plankton-eating fishes.

The first such attempt was undertaken in 1929–1932 with the plankton-eater the Caspian diadromous shad *Alosa caspia* (Table 3.2). Some millions of developing spawn of this fish were placed in the Aral Sea. In 1931 in the south of the sea a few shad were caught, but by 1932 this fish had disappeared. It is probable, that the main obstacle for successful acclimatization were winter temperatures, which were too low for this species survival even in the southern Aral (Behning 1934, 1935). Touching on the question of the expediency of introducing plankton-eating fishes to the Aral Sea, A.L. Behning (1934, 1935) suggested studying the possibility of introducing the Caspian sprat, for which the dominant zooplankton in the Aral Sea, the copepod *Arctodiaptomus salinus,* would provide a favored food.

Table 3.2 Introduced fish species in the Aral Sea (Aladin et al. 2004, with changes)

Species	Years of introduction	Source	Way	Status	Impact	Status in the 2000s
Acipenseridae						
Stellate sturgeon *Acipenser stellatus* Pallas	1927–1934	Caspian Sea	A	–	–	–
	1948–1963	Caspian Sea	A	C-	0	–
Acipenser nudiventris derjavini Borzenko	1958	Ural River	A	–	–	–
Clupeidae						
Caspian shad *Alosa caspia* (Eichwald)	1929–1932	Caspian Sea	A	–	0	–
Baltic herring *Clupea harengus membras* (Linnaeus)	1954–1959	Baltic Sea	A	N, C-	–	R
Mugilidae						
Golden grey mullet *Liza aurata* (Risso)	1954–1956	Caspian Sea	A	–	0	–
Leaping mullet *Liza saliens* (Risso)	1954–1956	Caspian Sea	A	–	0	–
Cyprinidae						
Grass carp *Ctenopharyngodon idella* (Valenciennes)	1960–1961	China	A	C	+	C-
Silver carp *Hypophtalmichthys molitrix* (Valenciennes)	1960–1961	China	A	C	+	C-
Spotted silver carp *Aristichtys nobilis* (Richardson)	1960–1961	China	A	R	+	C-
Black carp *Mylopharyngodon piceus* (Richardson)	1960–1961	China	A+	C	0	C-
Syngnathidae						
Black-striped pipefish *Syngnathus abaster caspius* Eichwald	1954–1956	Caspian Sea	A+	N, NC	–	?
Atherinidae						
Caspian atherine *Atherina boyeri caspia* Eichwald	1954–1956	Caspian Sea	A+	N, NC	–	R, NC
Gobiidae						
Bubyr goby, transcaucasian goby *Pomatoschistus caucasicus* Berg [= *Knipowitschia caucasica* (Berg)]	1954–1956	Caspian Sea	A+	N, NC	–	NC
Sand goby *Neogobius fluviatilis pallasi* (Berg)	1954–1956	Caspian Sea	A+	N, NC	–	NC

(continued)

Table 3.2 (continued)

Species	Years of introduction	Source	Way	Status	Impact	Status in the 2000s
Round goby *Neogobius melanostomus affinis* (Eichwald)	1954–1956	Caspian Sea	A+	N, NC	–	NC
Syrman goby *Neogobius syrman eurystomus* (Kessler)	1954–1956	Caspian Sea	A+	R, NC	–	NC
Tubenose goby *Proterorchinus marmoratus* (Pallas)	1954–1966	Caspian Sea	A+	R, NC	–	NC
Bighead goby *Neogobius kessleri gorlap* Iljin	1954–1956	Caspian Sea	A+	R, NC	–	NC
Channidae						
Snakehead *Channa argus warpachowskii* Berg	1960s	Kara-Kum canal	A+	C	0	C
Pleuronectidae						
Black Sea flounder *Platichthys flesus* (Linnaeus)	1979–1987	Sea of Azov	A	N, C	+	N, C

Way of introduction: *A* acclimatization, *A+* incidentally at planned introduction
Status: *R* rare, *N* numerous, *C* commercial, *C-* commercial but low stocks, *NC* not commercial
Impact: − negative, + positive, 0 no effect

The only representative of sturgeon fishes living in the Aral Sea was the ship (*Acipenser nudiventris)*. Therefore, in the beginning of the 1930s, it was decided to introduce the Caspian sturgeon *A. stellatus* (Table 3.2) to the Aral in order to more rationally use the available food resources and to increase the population of sturgeon fishes. The presence of food reserve and a similarity of ecological conditions in both basins as well as the presence of spawning areas necessary for its reproduction in the rivers Syr Darya and Amu Darya were cited as justification for this introduction. In 1933–1934 mature and juvenile stellate sturgeon were brought by rail from the Volga and released in the lower part of the Syr Darya. Weakened by their trip, stellate sturgeon in the Aral Sea did not acclimatize and disappeared (Bykov 1970a). The first attempt of stellate sturgeon acclimatization in the Aral Sea was a failure, but it had extremely negative consequences. It initiated a mass die-off of the aboriginal ship sturgeon, which was caused by parasites normal to the stellate sturgeon and other Ponto-Caspian sturgeons, but absent on the Aral ship. Parasitization on the gills of these sturgeons by the monogenetic fluke *Nitzschia sturionis*, that had transferred from the stellate sturgeon, caused the strongest epizootic,[1] which caused mass deaths among the ship in 1936. The second parasite was coelenterate *Polypodium hydriforme* parasitizing in the roe of sturgeon fishes (Dogiel and Bykhovsky 1934;

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[1] Epizootic is the term applied to animal population analogous to the term epidemic applied to human population.

Table 3.3 Alien free-living invertebrates in the Aral Sea (Aladin et al. 2004, with changes)

Species	Source	Year of introduction	Status	Status in the 1990–2000s	Way	Impact
Ciliophora						
Fabrea salina Henneguy[a]	Aral region	1990s–2000s	N	N	N	0
Frontonia marina Fabre-Domergue[a]	Aral region	1990s–2000s	N	N	N	0
Branchiopoda						
Artemia parthenogenetica (Linnaeus)[a]	Aral region	1996	N	N	N	+
Ostracoda						
Eucypris inflata G.O. Sars[a]	Aral region	1990s–2000s	N	N	N	+
Mysidacea						
Paramysis baeri (Czerniavsky)	Don River	1958–1960	?	–	A	0
Paramysis lacustris (Czerniavsky)	Don River	1958–1960	N	In deltas	A	+
Paramysis intermedia (Czerniavsky)	Don River	1958–1960	N	–	A	+
Paramysis ullskyi (Czerniavsky)	Don River	1958–1960	R	–	AC	+
Decapoda						
Palaemon elegans Rathke	Caspian	1954–1966	N	N	A+	?
P. adspersus Rathke	Caspian	1954–1966	?	–	A+	?
Rhithropanopeus harrisii tridentata (Maitland)	Sea of Azov	1965, 1966	N	N	A+	+
Copepoda						
Calanipeda aquaedulcis Kritschagin	Sea of Azov	1965, 1966–1970	N	N	A	+
Heterocope caspia Sars	?	1971	–	–	A	0
Acartia clausi Giesbrecht	?	1985, 1986	–	–	A	0
Apocyclops dengizicus (Lepeschkin)	Aral region	2004	N	N	N	0
Polychaeta						
Hediste diversicolor (Müller)	Sea of Azov	1960–1961	N	N	A	+
Bivalvia						
Abra ovata (Philippi)	Sea of Azov	1960, 1961, 1963	N	N	A	+

(continued)

Table 3.3 (continued)

Species	Source	Year of introduction	Status	Status in the 1990–2000s	Way	Impact
Monodacna colorata (Eichwald)	?	1964, 1965	–	–	A	0
Mytilus galloprovincialis Lamarck	Sea of Azov	1984–1986	–	–	A	0
Mya arenaria Linnaeus	Sea of Azov	1984–1986	–	–	A	0

Means of introduction: *A* acclimatization, *AC* by accident, *A+* incidentally at planned introduction, *N* naturally. Status: *R* rare, *N* numerous, *C* commercial. Impact: − negative, + positive, 0 no effect, ? unknown

[a]Only in the Large Aral

Dogiel and Lutta 1937). As a result, the first attempts of new species introduction to the Aral Sea not only failed, but also adversely affected the population of such valuable commercial species as Aral ship sturgeon. The populations of sturgeon fishes instead of being enriched were degraded.

More purposeful and organized introduction of new species of aquatic invertebrates and fishes into the Aral Sea started in the mid 1950s. L.A. Zenkevich in 1934 wrote about the necessity to acclimatize in the Caspian and Aral seas new species of invertebrates that were lacking in these water bodies but that had value as food for fishes (Zenkevich and Birshtein 1934). Karpevich (1947, 1948, 1953, 1960a, 1960b, 1975) and others later developed the theoretical basis for acclimatization of aquatic organisms and substantiation of its necessity for the Aral Sea. These authors noted that in the Aral Sea fauna there were absent many species of aquatic invertebrates forming large biomasses in other water bodies and being the preferred, high-calorific food for fishes. Owing to low diversity of fauna, existing species were not capable of effectively using all the available food resources. Besides this it was considered that some species of benthic invertebrates used the existing food resources inefficiently. Hence, organic matter was carried from the Aral Sea by chironomids and other flying insects which appeared during the summer in large numbers along the coasts and were carried by winds into the surrounding deserts (Karpevich 1960b, 1975). A.F. Karpevich (1960b) noted that fish-productivity of the Aral Sea was limited by feeble development of zoobenthos in the coastal areas while zoobenthos in the open parts of the sea was underused by fishes. Related to this, it was proposed to strengthen the food reserves of coastal areas where juvenile commercial fishes lived by acclimatization (Yablonskaya 1961), and also to introduce fishes, capable of using food resources in the centre of the sea (Karpevich 1960b).

Because in the Aral Sea, especially in spring, more than 70 % of the zooplankton biomass consisted of only the copepod *Arctodiaptomus salinus* (Kortunova 1975), food needs of young fishes could not be completely satisfied. Besides this, the low fertility and extended life cycle (only one generation/year) of this crustacean essentially restricted food resources (Lukonina 1960a). The low productivity of the Aral Sea zooplankton (Yablonskaya and Lukonina 1962) did not allow the expectation of high productivity assumed for the introduction of plankton-eating fishes. Also, if in the freshened deltaic water bodies there were abundant freshwater rotifers, serving as food for larvae and young fishes, in the sea the number of rotifers was very low. Besides this in the open parts of the Aral the zooplankton biomass fell by summer, and only in the coastal water area where there were favorable conditions for freshwater species of zooplankton, production of plankton remained rather intensive (Karpevich 1975).

Because of low species diversity of the Aral Sea fauna its food resources remained underused. For example, there were absent many highly productive species of Crustacea such as *Heterocope*, *Calanipeda*, *Acartia*, *Centropages*, among the plankton, not only representing a valuable food for fishes, but also forming in those water bodies where they live, a great biomass (Karpevich 1960b, 1975).

Experts understood that the planned hydroconstruction and further development of irrigation in the Aral Sea Basin would inevitably lead to the reduction of river flow and, as a consequence, to shrinkage of the Aral with an attendant increase in its salinity. Even small withdrawal of fresh water riverine flow could cause essential changes in the ecosystem. As the main part of fauna was species of freshwater or brackish-water origins, they could not survive salinity increases. Therefore it was recognized as wise to reconstruct the Aral Sea fauna because many species would become extinct due to salinization. It was suggested to create in advance in the Aral Sea more euryhaline and resistant to higher salinity fauna by acclimatization of suitable species. It was proposed to subsequently and systematically form chains of all trophic levels: at first to strengthen phytoplankton, then zooplankton and zoobenthos, and only after that to take specific decisions on diversifying the fish fauna by introducing eurybiontic species of fishes (Karpevich 1960b, 1975).

Based on the results of analysis of the original Aral Sea ecosystem Karpevich (1960b) recommended introduction of a lot of species of planktonic algae, planktonic and benthic invertebrates, and also non predatory fishes. Brackish-water and marine species were recommended to strengthen the second pelagic trophic level (planktonic invertebrates). These were mainly detritophages,[2] which would replace or supplement the freshwater origin species in the zooplankton (Karpevich 1975). It was recommended to increase the number of species of brackish-water rotifers by acclimatization of those from the genus *Synchaeta* found in the Sea of Azov. There were recommended to introduce (from the Black, Azov, Caspian seas) such planktonic crustaceans, as *Calanipeda aquaedulcis*, *Heterocope caspia*, *Acartia clausi*, *A. latisetosa*, *Acanthocyclops vernalis*, *Halicyclops sarsi*, *Centropages kroeyeri*, and some species of benthic hydrobionts having planktonic larvae: polyhaete *Hediste diversicolor* (*Nereis diversicolor*), bivalves *Monodacna colorata*,

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[2] Heterotrophs obtain nutrients by consuming detritus and decomposing plant and animal parts as well as organic fecal matter.

Syndosmya segmentum (*Abra ovata*) and some others. Among fishes the first supposed to be introduced were benthophages and predators; as for introduction of planktophages it would be rational only to use them as secondary food sources and expanding of the nutritive base by introduction of new species such as planktonic invertebrates. The necessity was especially stressed to prevent incidental introduction of undesirable species together with the planned ones (Karpevich 1960b, 1975).

Against all recommendations that the first task was to strengthen the lower trophic levels, acclimatization started with introduction of fishes. This retreat from a scientifically founded sequencing was based on the reasoning that in the Aral Sea there were not enough planktophages as well as sturgeon. Thus it was considered, that simple introduction of new consumers of zooplankton and zoobenthos would be quite sufficient for the raising of fish productivity (Karpevich 1947, 1948, 1953, 1960b, 1975). Accordingly, the potential possibility of negative consequences from such a reversal in the order of new species introduction was not considered at all. As a result not only the recommended order of introductions was not observed but also acclimatization of fishes was implemented improperly and against what Karpevich recommended.

In 1948 a new attempt to introduce stellate sturgeon *Acipenser stellatus* to the Aral from the Caspian Sea was made (Table 3.2). This time fertilized roe were taken from the Ural River and incubated on site, and then larvae and juveniles were released into the lower reaches of the Syr Darya. This procedure was continued until 1963. During a 16-year period, 4.7 million larvae and 7.4 million juveniles were released. Beginning in 1960, single individuals of stellate sturgeon started to appear in catches, both in the Aral Sea, and in the Syr Darya and delta of the Amu Darya. In total only a few tens of stellate sturgeons were caught; this was some hundreds of times less than expected. This time the stellate sturgeon survived in the Aral, but was not naturalized. Apparently, it was due to low survival of juveniles during their migration from fresh riverine water into the more saline Aral (Bykov 1970b).

In 1954–1956 there was an unsuccessful attempt to introduce two species of Caspian mullets *Lisa auratus* and *L. salensis* (Table 3.2). This attempt was also unsuccessful possibly because these planktophages could not find a sufficient amount of suitable food to survive. In 1958 there was an attempt to introduce a ship sturgeon *Acipenser nudiventris derjavini* from the river Ural (Table 3.2), but this attempt failed (Karpevich 1975).

Together with planned commercial fish, non-commercial species and some invertebrates were accidentally introduced, some of which are undesirable. Invasion of such species into the Aral Sea negatively impacted the ecosystem. From Ponto-Caspian there came incidentally six species of gobies (Table 3.2): bubyr goby *Pomatoschistus caucasicus*, sand goby *Neogobius fluviatilis pallasi*, round goby *N. melanostomus affinis*, syrman goby *N. syrman eurystomus*, tubenose goby *Proterorhinus marmoratus* and bighead goby *N. kessleri gorlap*. Three of them – bubyr, sand goby and round goby – not only had naturalized successfully but also had become numerous (Karpevich 1975). After 1957, they rapidly increased and reached a maximum in 1958. Their high number lasted to 1963 (Doroshev 1968; Markova 1972). Being extremely eurybiontic and active euryphages, they for 3–4 years occupied all the coastal area of the sea, and then, having eaten all the accessible food, began to spread into the open areas of the sea (Karpevich 1975). The explosion in the number of gobies led to substantial growth of loads on zoobenthos and, as a result, to the sharp reduction of reserves of benthos in the Aral Sea in the middle of the 1960s (Yablonskaya et al. 1973).

Along with the introduction of mullets in the Aral Sea, incidentally were also introduced the plankton-eaters atherine *Atherina boyeri caspia* and pipefish *Syngnatus abaster caspius* (Table 3.2). These competitors of young fishes were successfully naturalized and quickly multiplied in number and settled over the entire sea (Karpevich 1975). Atherine fed not only on zooplankton, but also consumed small benthic organisms, i.e., practically all food objects. These alien species became competitors for young aboriginal fishes. As food for predatory fishes (sheatfish, catfish) atherine, in spite of their great numbers, only served as a supplementary food source (Garaev 1970).

Baltic herring *Clupea harengus membras* were introduced to the Aral between 1954 and 1956 from the brackish-water zone of the Baltic Sea (Table 3.2). This plankton-eater quickly and easily acclimatized and by 1957 was naturalized in the Aral Sea (Konovalov et al. 1958; Bykov et al. 1968). The number of Baltic herring increased rapidly and reached a maximum in 1960. With the appearance of Baltic herring in the Aral, and atherine and gobies before this, the consumption of zooplankton sharply increased. Prior to this time, zooplankton was not under pressure from plankton-eating fishes. Owing to their low productivity, zooplankton could not meet the food needs of herring. Because there were no measures taken to increase the food supply for plankton-eaters, Baltic herring along with atherine quickly exhausted the planktonic food supply and undermined the very base of its reproduction (Karpevich 1960b, 1975; Yablonskaya and Lukonina 1962; Kortunova 1975).

Owing to over-consumption by plankton-eaters, the numbers of large planktonic crustaceans *Arctodiaptomus salinus*, *Cercopagis pengoi aralensis*, *Moina mongolica*, *Ceriodaphnia reticulata*, and also Cyclops decreased to the greatest degree. The average summer biomass of zooplankton shrank more than tenfold. *A. salinus*, which has the lowest fertility and longest life cycle (typically only one generation per year that is considered an adaptation to living in water bodies with low primary productivity) suffered the most. As a result, after 1961 it became a minor component of the Aral Sea zooplankton (Lukonina 1960a; Yablonskaya and Lukonina 1962; Kortunova and Lukonina 1970; Kortunova 1975). Baltic herring quickly felt the loss of their food supply and this, in turn, impacted the population. In the 1960–1961 winter because of the food deficit, there was mass death of herring and atherine owing to starvation and exhaustion (Osmanov 1961; Bykov 1968; Kortunova and Lukonina 1970; Kortunova 1975). After this, the abundance of plankton-eating fishes in the Aral Sea never again reached a high level.

Plankton-eating fishes influenced not only zooplankton, but also zoobenthos because a considerable portion of zooplankton in the Aral Sea consisted of planktonic pelagic larvae of benthic hydrobionts – bivalve mollusks, trichopterans and chironomids (Lukonina 1960a; Husainova 1968, 1971).

Freshwater fishes were acclimatized in the deltaic areas of the Syr Darya and Amu Darya in 1958–1960. Three of the species were fresh-water fishes from China: macro-phytophague grass carp *Ctenopharyngodon idella*, phyto-planktophague silver carp *Hypophtalmichthys molifrix* and zoo-planktophague bighead carp *Aristichtys nobilis*. Introduced inadvertently with these three fishes, was one more representative of this complex: benthophague black carp *Mylopharyngodon piceus*; it is also a commercial fish species (Table 3.2). Grass carp, silver carp and bighead carp were not introduced intentionally into the deltaic areas of the Amu Darya. They came here via the Kara-Kum Canal where they were acclimatized earlier. Of these four species, except for bighead carp, three were successfully naturalized and became commercially important. These fishes migrated outside the bounds of the delta and became widespread in near-deltaic areas and even in the open sea far from the delta (Bykov 1970b; Karpevich 1975).

If we compare the results of acclimatization of these fishes in deltaic areas with their introduction directly into the Aral Sea, the process on the whole went well and had no negative consequences. But, even in this case, a significant increase of the commercial catch of fish in the Aral because of these naturalized species did not occur.

The first introduced free-living invertebrate was the shrimp *Palaemon elegans* (Table 3.3). This crustacean was incidentally introduced during unsuccessful acclimatization of mullets from the Caspian Sea into the Aral Sea in 1954–1956. Initially it was believed, that there were two species of shrimp – *P. elegans* (= *Leander squilla*) and *P. adspersus* (= *L. adspersus*) (Karpevich 1960b), however further studies (Malinovskaya 1961) showed that in the Aral Sea there is only one species *P. elegans*. For the first time shrimp were found in the Aral Sea in the summer of 1956. This shrimp spread over the entire Aral and became a food source for fishes (Konovalov 1959; Gavrilov 1970; Karpevich 1975). Obviously it became a competitor for benthos-eating fishes and that promoted a reduction of benthos abundance in the 1960s (Husainova 1968). However in this case there was no essential growth of food resources due to the new introduced species. This naturalized shrimp became a competitor with the aboriginal amphipod *Dikerogammarus aralensis* and even ate it (Malinovskaya 1961).

The planned acclimatization of invertebrates began in 1958 after the preliminary working out of the biological basis and biotechnology of their introduction. Mostly brackish water and marine species from the Sea of Azov and Caspian Sea were chosen as they were more adapted to the expected salinity rise than native species, as well as eurythermic, prolific and consumers of detritus (Karpevich 1958a, b, 1960a, b; Bokova 1960; Kiseleva 1960).

The first species chosen for introduction to the Aral Sea were relict Ponto-Caspian mysids, which were widespread in the brackish water areas of the Caspian Sea and the Sea of Azov as well as in the deltas of the Volga, Don, and Dnieper. There these crustaceans are a valuable food for fish. Their introduction into the Aral Sea would enhance and strengthen the food base of adult commercial benthophagous fishes and their juveniles, thereby increasing the overall productivity of this water body (Karpevich 1960a).

The planned introduction of mysids to the Aral Sea was in 1958–1960 (Table 3.3). These crustaceans were collected in the delta of the Don. *Paramysis lacustris* dominated among the captured mysids; the remainder were *P. intermedia* and single specimens of *P. baeri*. In 1958 mysids were released in Saryshaganak Gulf of the Small Aral (Karpevich 1960a). However, these crustaceans, which were transported from the freshened delta of the Don in water with salinity about 10 g/l, perished. Only in 1959–1960 were mysids successfully released near the mouth of the Syr Darya in the shallow freshened bay Karateren, and from here their settling in the Aral Sea began (Karpevich and Bokova 1970; Kortunova 1968). From the three species of mysids only *P. intermedia* and *P. lacustris* naturalized (Kortunova 1970). Introduction of *P. baeri* was unsuccessful. First, the number of individuals of this species was small. Second, the thermal regime of the Aral Sea, apparently, was less favorable for it than for the first two species (Karpevich and Bokova 1970).

By 1961 the fauna of the Aral Sea itself and its near-deltaic and deltaic water areas underwent significant changes as a result of the appearance of planned and accidental introduced species. Though biodiversity grew by 14 species of fishes and 4 species of free-living invertebrates, only a few of them became commercially viable or valuable as food for fishes. Connected to this, accidentally introduced fish species only increased the load on the food chain and did not have any benefit to the fishery. An expected increase of commercial fish catches and increase of the feeding value of benthic and planktonic communities of invertebrates practically did not occur. Also, because of consumption by introduced fishes or competition with introduced invertebrates, two planktonic crustaceans *Moina mongolica* and *Arctodiaptomus salinus* and aboriginal benthonic crustacean amphipod *Dikerogammarus aralensis* considerably decreased in abundance and later disappeared completely. Thus, all the complex of acclimatizations to the Aral Sea and deltas of the rivers from 1927 to 1961, as a whole did not meet expectations, and in some cases even had harmful impacts.

3.4 Vertebrates

A large number of vertebrate species inhabited the Aral Sea, its shore and islands, the Syr Darya and Amu Darya, and the deltas and lakes of these two rivers in their lower reaches. The most important species were floating and near-shore birds along with amphibians, reptiles, and mammals. Aquatic reptiles were represented on the Aral Sea by the dice snake *Natrix tessellata*. Its main food was fishes. This snake was widespread on almost all the shore of the Aral, but it was most numerous on the south and west.

The Aral Sea and its shores provided nesting sites for a large number of various floating and near shore birds. As the Aral, rivers and deltaic water bodies were ice covered they could not serve as wintering habitat for these birds. Besides the Aral

Sea was a stop along the spring and fall migration route for rest and feeding of migrants that did not nest here. All aquatic birds of the Aral Sea were migratory. The largest number of species of aquatic birds lived in reed thickets in the river deltas and in the shallows of the Aral, primarily in its freshened zones.

Fishes were the main food for a part of the aquatic birds of the Aral Sea. Living in the deltas and reeds where there was fresh river water were the white pelican *Pelicanus onocrotalus* and curly or Dalmatian pelican *P. crispus*, the grey heron *Ardea cinerea* and purple heron *A. purpurea* that caught fish in shallow water, great bittern *Botaurus stellaris* and a number of other birds. Along the entire coast of the Aral and on islands there were colonies of fish eating birds: the Caspian gull *Larus cahinans*, the Caspian tern *Hydroprogne tschegrava* and the great cormorant *Phalacrocorax carbo*. On islands far from the shore was the great black-headed gull *Larus ichthyaetos*. In addition to fishes, seagulls and terns were able to use small rodents as food.

For a considerable part of the aquatic birds of the Aral Sea, the main foods were aquatic invertebrates to which aquatic plants were sometimes added. Their number included first of all various ducks, most numerous of which were the ferruginous duck *Aythya nyroca* and common pochard *A. ferina*, which were widespread in the lower reaches of rivers and on the eastern seacoast and also the greater flamingo *Phoenicopteriformes roseus*, which stopped here during migration. The whooper swan *Cygnus cygnus* and common swan *C. olor* that stopped on the Aral sea during migration fed predominantly on aquatic plants.

Among predatory birds that lived near the Aral Sea, the white-tailed eagle *Haliaeetus albicilla* and pallas eagle or band-tailed fish-eagle *H. leucoryphus* hunted fishes and medium-sized aquatic birds.

The muskrat *Ondatra zibethicus* was acclimatized in the Aral Sea Basin in the 1930s and rapidly settled the deltas of the Amu Darya and Syr Darya. This rodent is predominantly a plant eater. In spring the muskrat feeds on young stalks and leaves; in summer and autumn it eats roots and rhizomes, in winter only rhizomes. Rarely, when vegetation is lacking, the muskrat eats mollusks, frogs and fish fry. For lodging the muskrat digs burrows in the shores holes and builds lodges. It swims floats and dives well. Having valuable fur, muskrat became important for trapping. This rodent is the natural carrier of serious diseases, including tularemia (rabbit-fever) and paratyphus.

Narrow bands of Tugay forest stretch along the banks of the Syr Darya and Amu Darya, which are surrounded by deserts and semi deserts, and constitute a type of oasis. The main tree species in these forests were poplars *Populus diversifolia* and *P. pruinosa*. Many species lived in the Tugay, including nesting birds such as the pheasant, various reptiles, wild boars *Sus scrofa*, the tolai hare *Lepus tolai*, jackal *Canis aureus*, and others. In the nineteenth century the Turanian tiger *Panthera tigris virgata* still inhabited the Tugay forests, but it was driven to extinction by the 1970s.

3.5 Aquatic Plants

Thirty species of macrophytes were known in the aquatic plant communities of the Aral Sea. There were 17 species of flowering plants within the hydrophyte community[3]: yellow floating heart *Nymphoides peltata*, watermilfoil *Myriophyllum spicatum*, marine naiad *Najas marina*, pondgrasses – *Potamogeton crispus*, *P. filiformis*, *P. lucens*, *P. macrocarpus*, *P. nodosus*, *P. pectinatus*, *P. perfoliatus*, *P. pusillus*, ditch grasses – *Ruppia cirrhosa*, *R. maritima*, horned pondweeds – *Zannichellia palustris*, *Z. pedunculata*, eelgrasses – *Zostera marina* and *Z. noltii*. In these communities there were six species of charophytes (green algae): *Chara aculeolata*, *Ch. polyacantha*, *Ch. tomentosa*, *Lamprothamnium papulosum*, *Nitella hyaline* and *Nitellopsis obtusae*. Besides coastal waters, hydrophytic communities often were found in communities formed by seven species of helophytes[4]: flowering rush *Butomus umbellatus*, common reed *Phragmites australis*, arrowhead *Sagittaria trifolia*, club-rushes *Scirpus kasachstanicus*, *S. tabernaemontani* and *S. trigueter*, cattail *Typha angustifolia*.

Alenitsyn (1875) noted the extreme monotony and poverty of vegetation and flora of aquatic and coastal-aquatic plants in the main water zone during early studies of the Aral Sea. Everywhere only two species and two plant communities dominated: reeds in coastal shallow waters and eelgrass at depths of up to 11 m on silty-sand bottoms. Apart from these, in the central part on muddy bottom tangles of charophytes were found at depths of 11–22 m, and in the shallows tangles of *Myriophyllum* sp. and *Potamogeton perfoliatus* (Alenitsyn 1874, 1875; Borshchov 1865, 1877; herbarium BIN RAS). To which taxonomic group belonged deepwater Charophyta remained unclear, because the species found by V.D. Alenitsyn (1875) was not identified. L. Berg (Berg 1908) in his monograph named the charophyte found by him *Tolypella aralica*. Unfortunately, M.I. Golenkin, who gave it a name, never published a description of this species. Thus *T. aralica* is just a *nomen nudum*[5] (Gollerbach 1950). In all further works on the Aral Sea under the name *T. aralica* and *tolipella* were meant various species of charophytes.

By the 1960s experts had identified a variety of the flora of the Aral Sea including 24 species of higher plants, 6 species of charophytes and about 40 other species of macroalgae (Behning 1935; Bervald 1964; Dengina 1954, 1959b; Dobrokhotova 1971; Husainova 1960; Yablonskaya 1964; herbarium BIN RAS). Aquatic vegetation formed two zones: one of helophytes and other of hydrophytes. Helophytes formed clump and border tangles located as continuous or discontinuous bands 1–100 m wide. On the southern and eastern coasts, they were more sizeable than in the north and west. Everywhere reed-beds of *Phragmites australis*

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[3] Plants that complete their entire life cycle submerged, or with only their flowers above the waterline.

[4] Plants rooted in the bottom, but with leaves above the waterline.

[5] A name of a new taxon published without a description or diagnosis or reference to a description or diagnosis.

dominated. The maximum height of cane reached 4.5 m. Density of reed-beds reached 300 specimens/m^2, the average phytomass was 0.8 kg/m^2 of fresh weight, while in the deltas it reached up to 23 kg/m^2 of fresh weight and 9.8 kg/m^2 of dry weight. During the year cane produced 2.8 million tons of organic matter. In the northern part of the Aral Sea beyond the reed zone often was a zone of bulrush *Scirpus kasachstanicu*, forming at depths of 1.5–3.5 m tall thickets up to 4 m (length of the leaves up to 2.5 m) with density up to 25 specimens/m^2 and phytomass up to 1.85 kg/m^2 of dry weight (Behning 1935; Bervald 1964; Dobrokhotova 1971; Yablonskaya 1964). Other helophytes found in the waters of the Aral Sea didn't form large thickets.

Communities of hydrophytes were more developed in the northern part of the Aral Sea and they presented diverse associations that formed vast underwater meadows. *Zostera noltii* dominated at the seaward side and in open bays at depths of 3–11 m on sandy bottoms forming continuous or discontinuous thickets. Its productivity was so high that the layer of leaves thrown on the shore reached 0.8–1 m thick and 2–3 m wide for a considerable distance along the shoreline. Extensive deepwater thickets of Charophyta found at the beginning of the twentieth century were absent by the mid 1950s. In their place were found dense accumulations of algae *Vaucheria dichotoma*. In freshened bays the basis of macrophytobenthos was higher flowering plants forming small by area but diverse associations of 1–3 species. In saline closed bays and inlets chatophytes dominated. The biomass of dominant species was: *Potamogeton pectinatus* – 1.24–3.16 kg/m^2, *Myriophyllum* sp. – 0.86 kg/m^2, *Zostera noltii* – 0.1 kg/m^2, Charophyta – an average 1.5 kg/m^2 of dry weight (Bervald 1964; Dobrokhotova 1971; Yablonskaya 1964).

In the 1950s and 1960s of the twentieth century, the gross phytomass of submerged macrophytobenthos of the Aral Sea was three times higher than in the Caspian Sea. In general, at a depth of 2–60 m it was about nine million tons of crude and 1.3 million tons by dry weight. More than 70 % of the gross phytomass was produced by Charophyta, 13 % – *Vaucheria*, 9 % – *Zostera noltii* while other hydrophytes produced less than 1 %. Productivity of thickets of helophytes was two times lower than that of hydrophytes and macroalgae (Bervald 1964; Yablonskaya 1964).

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Chapter 4
Changes of the Aral Sea Level

Sergey Krivinogov

Abstract This chapter reviews the available data on the Aral Sea level changes and presents the current thinking on the sea's recessions and transgressions prior to its modern desiccation. The geomorphologic, sedimentologic, paleoenvironmental, archaeologic and historiographic evidence is reconsidered and combined on the basis of calibrated ^{14}C ages. The geomorphologic data appear contradictory and require re-examination. Lithology and paleoenvironmental proxies of the sediment cores provide much consolidated information, as they record lake level changes in sediment constitution by deep and shallow water facies and layers of gypsum and mirabilite, which are of special importance for determination of low levels. High levels are recorded in several on-shore outcrops. The new archaeological data from the now dry bottom of the Aral Sea and its surrounding zone in combination with the historiographic records provide a robust model for level changes during the last two millennia. Discovery of tree stumps in different parts of the bottom indicate low stands of the lake as well. During the last two millennia, there were two deep natural regressions of ca. 2.1–1.3 and 1.1–0.3 ka (1,000 years) BP (Before Present) followed by the modern anthropogenic one. The lake level dropped to ca. 29 m asl. Their separating transgressions were up to 52–54 m asl. The middle to early Holocene record of level changes is probably incomplete. Currently the middle Holocene regressions are documented for the periods of ca. 5.5–6.3, 4.5–5.0 and 3.3–4.3 ka BP. The early Holocene history of the Aral shows a long period of a shallow lake.

Keywords Lithology • Stratigraphy • Paleogeography • Archaeology • Historiography • Aral Sea • Lake level changes • Transgressions • Regressions

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4.1 Introduction

The idea that the Aral Sea is a notably changeable body of water became clear after the pioneering study by Berg (1908) and later developed by Soviet geologists (e.g., Veinbergs and Stelle 1980; Kes 1983; Shnitnikov 1983; Rubanov et al. 1987). Knowledge of those days was summarized in several reviews (Sevastyanov et al. 1991; Aladin and Plotnikov 1995; Tarasov et al. 1996; Letolle and Mainguet 1997; Boomer et al. 2000). Drops and rises of the Aral level have been considered geomorphologically, sedimentologically, paleontologically, archaeologically and historiographically. In general, the following important theses arose from the initial studies: (1) the Aral Sea is very young and its age is approximately 10–12 ka; (2), the typical mollusk *Cerastoderma* spp. (former *Cardium edule* L.) penetrated into the Aral Sea from the Caspian Sea at ca. 5 ka BP (BP = before present), (3) The highest level of the Aral was in the middle Holocene, and its deepest regression was ca. 1.6 ka BP.

New data obtained by international teams[1] in the first decade of the twenty-first century (e.g., Nourgaliev et al. 2003; Boroffka et al. 2006; Oberhansli et al. 2007; Reinhardt et al. 2008; Boomer et al. 2009; Krivonogov et al. 2010a, b) considerably improved this common knowledge; however a synthesis of the older and newer data has not been done yet. This chapter provides a critical review of the knowledge, adds a portion of the newest data and gives an integrated interpretation of the Aral Sea level changes. All sites discussed in the chapter are shown in Fig. 4.1.

4.2 Terraces

Geomorphologically, changes of the Aral Sea levels are recorded in eight erosional and accumulative terraces and shore bars ranging from 72 to 31 m asl (above sea level) (Fig. 4.2a). However, this scheme is “idealized” and does not reflect a variety of views, especially on the high lake levels, i.e., above 53 m asl, which is a conventional stable level for the middle of the twentieth century.[2]

Berg (1908) found only one 4 m high terrace contoured at 54 m asl, which is commonly recognizing as the “new Aral” terrace. Yanshin (1953) additionally recorded terraces at 60, 62, 64 and 72 m asl, and attributed them to one recent transgression. Neotectonic movements explained the difference in their heights.

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[1] Projects: EU INTAS-Aral Sea (2002–2005) and USA-Russia CRDF-RFBR (2008–2010).

[2] Researchers used different altitudinal estimates of the Aral Sea level. The conventional levels were 50.75 m in 1903 (Berg 1908), 52 m in 1911–1931 (Berg 1932) and 53 m in 1960 (official nautical maps). These differences include sizeable corrections by topographic leveling and perennial fluctuations of the lake. The amplitude of mean annual levels was 78 cm for the period of 1911–1931 and 3.09 m for the period of 1874–1931 (Berg 1932). Therefore, both heights and altitudes of terraces provided by individual authors may vary considerably.

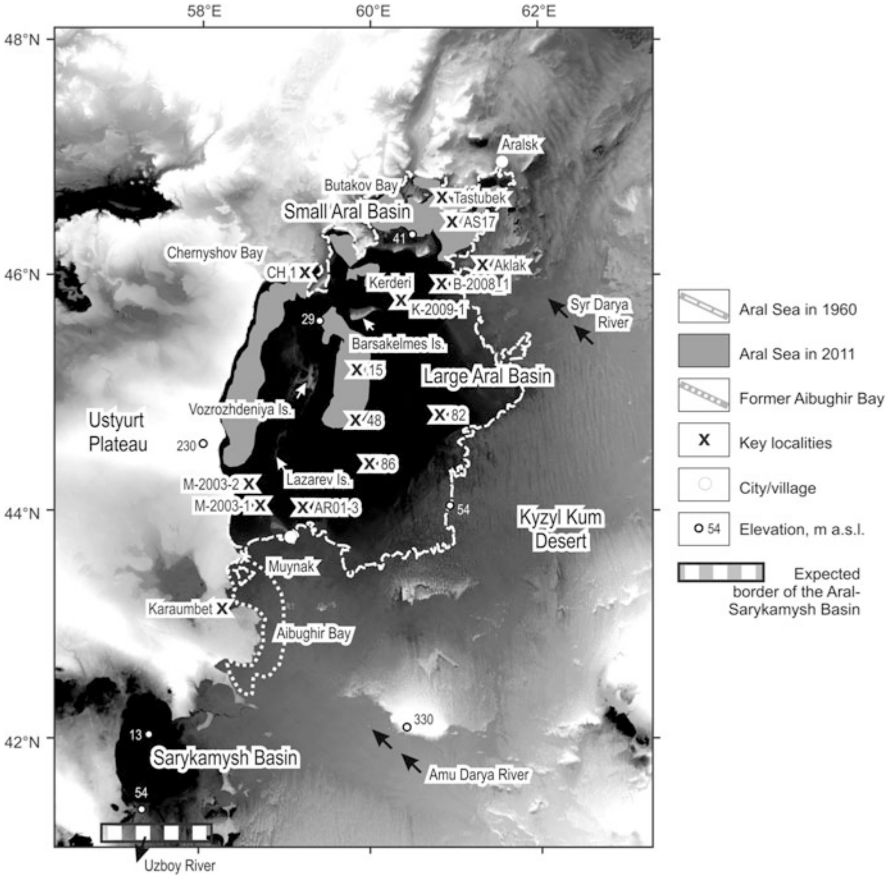

Fig. 4.1 Location map and the SRTM Digital Elevation Model topography of the Aral Sea region

Lymarev (as summarized in Lymarev (1967)) found four terraces from 1 to 10 m above the Aral level, i.e., up to 63 m asl. Epifanov (1961) described two lower and three higher terraces. The lower ones are “late Aral” and “ancient Aral” at ca. (approximately) 54 and 56 m asl, respectively. The higher terraces are 8–10, 12–17 and 22–27 m high, i.e., 61–63, 65–70 and 72–77 m asl (Fig. 4.2b). Locations of the higher terraces are additionally listed in Kiryukhin et al. (1966). According to Gorodetskaya (1978), all the described terraces form hypsometric levels traceable over the whole Aral-Sarykamysh region and representing different stages of the basin evolution. For instance, the hypsometric level above 80–85 m asl represents the late Pliocene lacustrine stage.

Occurrences of the Aral at the highest levels of 58–70 m suggest a topographic border between the Aral and Caspian Seas, which does not exist in modern relief (Fig. 4.1). Khondkarian (1977) and Fedorov (1980) hypothesized such a border. In contrast, Veinbergs (1986) did not find any lake terraces higher than “ancient Aral”,

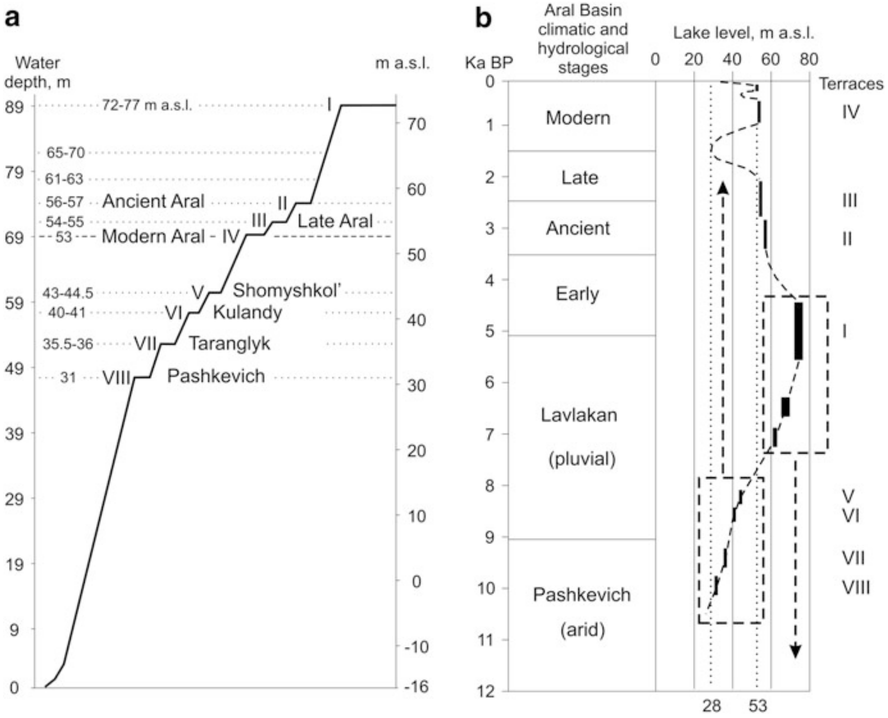

Fig. 4.2 A summary of the common knowledge about the Aral Sea level changes. Modified from Boomer et al. (2000). (**a**) Lake terraces. (**b**) Timing of the events recorded in the terraces. Dashed frames indicate groups of events, whose ages look to be incorrectly defined as discussed in Sect. 4.2. *Arrows* show their probable shifts in age (older and younger)

56–57 m asl, along the northeastern, northern, eastern and southern shores. He suspected that high terraces described by the above-cited authors in fact are surfaces of denudation of Paleogene and Neogene rocks surrounding Lake Aral. The ideas of Veinbergs found support from recent detailed field surveys as well as tachymetric and DGPS-derived altitude measurements in several sites of the northern and southwestern shores of the lake (Reinhardt et al. 2008).

A crucial argument for the high lake terraces is the presence of shells of the Aral Sea mollusks *Cerastoderma* and *Dreissena*, in their sediments or on their surfaces (e.g., Epifanov 1961; Kirukhin et al. 1966). However, some authors raised doubts about such findings on the surface and attributed them to wind transport (e.g., Yanshin 1953; Veinbergs 1986).

The relation of the high terraces to the coastal processes of the Aral Sea is questionable based on their ages. Commonly, the 72 m terrace is dated to the middle Holocene and correlated to the Lavlakan pluvial epoch, which approximately matches the Atlantic climatic phase (Boomer et al. 2000). Alternatively, terraces higher than 56 m asl may be older than the Holocene and have no relation to the Aral. Thus, Pshenin et al. (1984) described an outcrop of a 15–17 m, 68–70 m asl, terrace of the north-western coast, which contains alien pebbles transported from the Mugodzhar Hills situated northward of the Aral Sea. As the basal clays beneath have a radiocarbon age of 24,820 ± 820 (IGAN-372), the authors concluded that powerful water-flows from the West Siberian proglacial lake in the late Pleistocene time formed this terrace.

Archaeological data restrict the age of the "ancient Aral" terrace, at 56–57 m asl, to a Neolithic date of around 5 ka BP, which made it possible to place the older 72 m terrace within the Holocene (Boomer et al. 2000). However, Boroffka et al. (2005a, b, 2006) clearly showed wide distribution of Paleolithic sites, 50–35 ka BP, at 60–70 m, and these areas have never been inundated by the Aral since then (Reinhardt et al. 2008).

Lower "late Aral" and "ancient Aral" terraces (Fig. 4.2) were much less disputed until Reinhardt et al. (2008) asserted that there are no lake terraces above 54–55 m asl, which matches the idea of Berg (1908). Radiocarbon dating of the terraces contradicts their conventional order: 745 ± 80 and 730 ± 80 BP for the "ancient Aral" and 2,860 ± 80, 1,320 ± 120[3] BP for the "late Aral" terraces (Veinbergs 1986). Therefore, the problem of Aral terraces remains unresolved and expert reanalysis of their locations addressed earlier by Yanshin, Epifanov, Kiryukhin, Veinbergs and other scientists is needed.

Shore bars situated on the former bottom of the Aral Sea below 53 m asl indicate lower levels of 35.5–36, 40–41 and 43–44.5 m asl (Veinbergs et al. 1972). The 31 m "Paskevich" level actually was not found in bottom relief, but was suggested from the altitudes of highly mineralized layers in bottom sediments (Veinbergs and Stelle 1980). These authors hypothetically dated the Paskevich basin as late Pleistocene – early Holocene and considered formation of all these shore bars during one phase of lake transgression. This point of view is reflected in the reviews (Fig. 4.2); however, its correctness is questionable. Why are such old landforms well preserved and were not covered by a thick layer of sediments? Just a casual visual examination of satellite images of the modern dry bottom of the Aral shows many shore bars, which reflect the gradual retreat of the lake in modern times. Therefore, any recent transgression or regression could leave the pattern of shore bars described by Veinbergs and others.

4.3 Sediments

4.3.1 Sediment Cores

Dozens of short, up to 1 m, and more than 100 longer, up to 4.5 m, cores of bottom sediments have been obtained over the Aral Sea over the period from

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[3] Veinbergs (1986) refers this date to M.E. Gorodetskaya; however, Gorodetskaya (1978) published only the date of 920 ± 120 obtained in VSEGEI from shell material. Veinbergs believed the date was probably younger than the real age of the terrace.

the 1940s into the 1990s. The cores were studied lithologically and geochemically (Brodskaya 1952; Khrustalev et al. 1977; Rubanov et al. 1987; Zhamoida et al. 1997), paleontologically for pollen and spores (Maev et al. 1983) and for diatoms (Zhakovschikova 1981; Aleshinskaya 1991) and isotopically (Nikolaev 1987, 1991; Nikolaev et al. 1989). In general, the sediments consist of the following parts (bottom to top): (i) brown clays of non-lacustrine origin, a substratum; (ii) light gray coarsely laminated clays, silts and sands with gypsum, which reflect conditions of changeable small lakes and salt-marshes; and (iii) greenish-gray clays and silts and gray sands of the Aral Sea (Nikolaev 1991). The last part is rich with marine fauna, whose most characteristic components are shells of the mollusk *Cerastoderma* spp. The lake sediments and paleontological data reflect several changes of the lake from deep-water (clayey silts) to shallow-water (sands with shells). Other evidence of a shallow lake are layers of salts (calcite, gypsum and mirabilite) and peat.

Variations in the sedimentation during lake level fluctuations are well illustrated by lithological studies of the surficial layer. Mapping by Brodskaya (1952) and Zhamoida et al. (1997) show changes in facial structures, which reflects the modern recession of the lake. In the sediment sequences, sulphate and carbonate deposits in the central part of the Aral Sea mainly define low water level events, as does gypsum or mirabilite near the borders (Le Callonnec et al. 2005).

The sediments were dated by the radiocarbon method (Kuptsov et al. 1982; Maev et al. 1983; Kuptsov 1985; Parunin et al. 1985; Maev and Karpychev 1999). However, a major part of about 70 dates (summarized in Krivonogov et al. 2010b) obtained from bulk sediment samples of organics and carbonates are stratigraphically inconsistent. They were found unsuitable for sediment correlation (Rubanov et al. 1987; Ferronskii et al. 2003) and only a few of them originated from plant remains and mollusk shells were used (Table 4.1, sites A and B; Fig. 4.3). Finally, only two well-dated sediment cores no. 15 and 86 from the Large Aral Basin (Fig. 4.1) were comprehensively studied and used for paleolimnological and paleoclimatic reconstructions (Maev et al. 1983; Sevastyanov et al. 1991; Maev and Karpychev 1999; Ferronskii et al. 2003). However, their correlation in Sevastyanov et al. (1991) and Tarasov et al. (1996) was done before obtaining the core no. 86 ^{14}C dataset (Maev and Karpychev 1999). Figure 4.4 corrects for this problem.

The sediment structure in both cores suggests variable lake conditions from deep to shallow. The age vs. depth plots of the cores show two major stages of sedimentation: faster in the upper part and slower beneath (Fig. 4.3). The linear approximation of probable ages shown in the figure is too simple and does not reflect the complicated facial structure of the sediments. The sedimentation rate may vary from one to another layer, and hidden breaks could occur. However, the model presented gives us a chance to correlate layers and to date important lake level changes. Fortunately, exact littoral and beach facies provide good material for dating, which makes it possible to correlate the lake recessionary events. It is worth noting that the shallow lake facies in the cores from distant sites may be diachronous.

Table 4.1 Radiocarbon dates from Aral Sea sediments

Depth, m	^{14}C age, BP	Lab code	Material	δ^{13}C, ‰	Calibrated age, BP[a]
A. Core 15 (Maev et al. 1983)					
1.0–1.03	1590 ± 140	MGU-778	Mollusk shells		1550 ± 280
1.2–1.28	3610 ± 140	MGU-742	Mollusk shells		3930 ± 365
1.48–1.55	4850 ± 90	MGU-741	Mollusk shells		5600 ± 155
1.56–1.64	4960 ± 100	MGU-740	Mollusk shells		5750 ± 170
B. Core 86, reference dates only (Maev and Karpychev 1999)					
1.25–1.3	1510 ± 150	IVP-285	Plant remains		1430 ± 310
2.05–2.21	3450 ± 80	IVP-273	Plant remains		3750 ± 175
2.6–2.87	4810 ± 180	IVP-260	Mollusk shells		5480 ± 445
310–324	5610 ± 220	IVP-268	Mollusk shells		6410 ± 495[b]
310–324	5750 ± 250	IVP-297	Plant organics		6630 ± 535[b]
342–345	6090 ± 150	IVP-258	Mollusk shells		6970 ± 345
C. Core Ar-8 (Nourgaliev et al. 2003)[c]					
0.45			Algal TOC[d]		450 ± 100
1.0			Algal TOC		480 ± 120
3.85			Algal TOC		660 ± 65
4.5			Algal TOC		1100 ± 125
5.55			Algal TOC		1500 ± 125
5.95			Algal TOC		1470 ± 110
D. Core Ar-9 (Nourgaliev et al. 2003)[c]					
4.95			Algal TOC		1150 ± 135
5.9			Algal TOC		1310 ± 90
E. Cores CH 1 and 2 (Austin et al. 2007; Sorrel et al. 2006, 2007)					
0.55	110	POZ-4753	Algal TOC		Modern
1.24	4320 ± 80	POZ-4750	Algal TOC		Rejected
4.65	820 ± 30	POZ-13511	TOC		730 ± 50
5.93	1650 ± 30	POZ-4756	Algal TOC		Rejected
6.04	1230 ± 30	POZ-4758	Algal TOC		1130 ± 60
6.17	1660 ± 30	POZ-4759	Algal TOC		Rejected
6.34	1160 ± 110	POZ-12279	Algal TOC		1100 ± 195
6.93 (7.2)[e]	1400 ± 30	POZ-4762	Algal TOC		1300 ± 35
7.63	1600 ± 40	POZ-4764	Algal TOC		Rejected
7.73 (7.88)[e]	1480 ± 30	POZ-9662	Mollusk shells		1360 ± 50
8.28 (8.6)[e]	1520 ± 25	POZ-4760	Algal TOC		1380 ± 40
F. Core C2/2004 (Píšková et al. 2009)					
0.075	Modern	POZ-	Mollusk shells		
1.12–1.15	775 ± 30	POZ-	Mollusk shells		700 ± 30
1.25–1.26	915 ± 30	POZ-	Mollusk shells		840 ± 80
2.04	1400 ± 30	POZ-	Algal filaments		1320 ± 35
2.07–2.08	1415 ± 30	POZ-	Mollusk shells		1330 ± 40
2.54–2.56	3080 ± 70	POZ-	Mollusk shells		Rejected

(continued)

Table 4.1 (continued)

Depth, m	^{14}C age, BP	Lab code	Material	δ^{13}C, ‰	Calibrated age, BP[a]
2.9–2.98	1820 ± 40	POZ-	Algal filaments		1780 ± 85
3.16–3.18	4875 ± 35	POZ-	Mollusk shells		5620 ± 40
G. Core M-2003-1 (Krivonogov et al. 2010a, b)					
2.6–2.7	1010 ± 30	AA-59339	Shell of *Dreissena*	+1.0	940 ± 40
3.1–3.2	1490 ± 30	AA-59340	Shell of *Cerastoderma*	+1.1	1360 ± 55
4.0–4.1	1330 ± 40	AA-61833	Shell of *Cerastoderma*	+1.1	1240 ± 65
4.2–4.3	1580 ± 40	AA-61834	Shell of *Cerastoderma*	+0.9	1470 ± 85
4.3–4.4	1680 ± 40	AA-61835	Shell of *Cerastoderma*	+0.2	1610 ± 95
6.2–6.3	4790 ± 40	AA-59342	Shell of *Cerastoderma*	−0.9	5530 ± 70
6.9–7.0	4840 ± 40	AA-59343	Shell of *Cerastoderma*	+0.3	5560 ± 90
8.0–8.1	5390 ± 40	AA-59344	Shell of *Cerastoderma*	+0.6	6230 ± 55
H. Core M-2003-2 (Krivonogov et al. 2010a, b)					
2.8–2.92	1190 ± 60	AA-83691	Shells of ostracods and gastropods	+0.9	1090 ± 110
7.2–7.52	6690 ± 80	AA-83690	Shells of ostracods	−2.7	7550 ± 115
16.6–16.72	8740 ± 95	AA-83689	Shells of ostracods	−3.3	Rejected
18.8–18.92	8550 ± 95	AA-83688	Shells of ostracods and gastropods	−3.2	Rejected
I. Core B-2008-1 (Krivonogov et al. 2010a, b)					
0.25–0.27	390 ± 35	AA-83393	Shell of *Cerastoderma*	+2.7	470 ± 45
0.31–0.32	1160 ± 35	AA-83394	Shells of *Caspiohydrobia*	+1.0	1110 ± 65
0.69	4240 ± 45	AA-83396	Shell of *Cerastoderma*	+1.5	4750 ± 125
1.0–1.1	4230 ± 35	AA-83397	Shells of *Cerastoderma*	+1.5	4780 ± 85
1.18	4200 ± 40	AA-83398	Shells of *Cerastoderma*	+0.5	4690 ± 75
5.6–5.7	8030 ± 130	AA-86200	Terrestrial plant remains	−25.4	8930 ± 355
5.7–5.8	9590 ± 120	AA-86199	Terrestrial plant remains	−25.8	10930 ± 285
6.34	19,900 ± 140	AA-83399	Shell of a gastropod	−1.6	23,800 ± 435
J. Core K-2009-1 (Krivonogov et al. 2013)					
0.78	510 ± 45	AA-90634	Plant remains	−27.6	530 ± 35
1.34	410 ± 45	AA-90635	Plant remains (root?)	−25.6	480 ± 50
1.79	310 ± 40	AA90636	Plant remains	−24.6	390 ± 90
1.89	4150 ± 35	AA90637	Shells of *Caspiohydrobia*	2.9	4700 ± 130
2.0	4230 ± 55	AA90638	Shell of *Cerastoderma* (in sity)	0.9	4720 ± 150
2.2	340 ± 40	AA90639	Plant remains (root?)	−26.0	400 ± 90
2.8	360 ± 40	AA90640	Plant remains	−25.1	410 ± 95
7.5	9200 ± 50	AA90641	Shells of *Caspiohydrobia*	2.6	10370 ± 125
K. Aklak (Krivonogov et al. 2010a, b)					
2.5	1,510 ± 35	AA-83390	Shell of *Cerastoderma*	+1.1	1,370 ± 55
2[f]	160 ± 35	AA-83391	Pieces of wood/grass	−20.2	140 ± 140
3[f]	165 ± 35	AA-83391	Grass stem	−27.2	140 ± 140

(continued)

Table 4.1 (continued)

Depth, m	^{14}C age, BP	Lab code	Material	$\delta^{13}C$, ‰	Calibrated age, BP[a]
L. Karaumbet (Reinhardt et al. 2008; Krivonogov et al. 2010a, b)					
0.45–0.5	300 ± 30	POZ	Shells of *Cerastoderma*	[c]	400 ± 60
2.0–2.1	1810 ± 30	POZ	Shells of *Cerastoderma*	[c]	1760 ± 70
2.1	1720 ± 30	AA-59338	Shells of *Cerastoderma*	−0.3	1630 ± 75

[a] Intcal09 (Reimer et al. 2009)
[b] Paired dates indicating negligible age difference between mollusk shells and plant organics
[c] From Fig. 1 in Nourgaliev et al. (2003)
[d] *TOC* total organic carbon
[e] Different depth specified by Sorrel et al. (2006, 2007) and by Austin et al. (2007) for the same samples
[f] The sample was collected in the floodplain sediments about 1 km downstream on the Syr Darya River from the Ak-Lak outcrop

Three layers of shallow water sediments occur in the upper parts of both cores (Fig. 4.4). Their radiocarbon and tentatively interpolated ages show synchronism of low lake levels, which took place at ca. 1.5–1.4, 0.8–0.65 and 0.3–0.2 ka cal. (cal. = calibrated) BP (Table 4.2). In these intervals, the lake level fell to 26–27 m asl. Core 86 has one more distinct layer of beach sediments dated at ca. 7.0–6.6 ka cal. BP, which however is absent in core 15.

Le Callonnec et al. (2005) investigated a 4.4 m long core 48 obtained by Rubanov et al. (1987) in the central part of the Aral Sea at a water depth of 25 m, i.e., ca. 26–27 m asl (Fig. 4.1). The low water levels are represented in the core by five calcium carbonate-rich layers at 51–55, 110–115, 128–130, 150–155 and 210–215 cm, one gypsum-rich layer at 300–310 cm and by the basal sand. Careful geochemical study allowed Le Callonnec et al. (2005) to attribute fluctuations of the lake level to changes in river inflow; however, their timing of events is based on the tentative correlation of core 48 with cores 15 and 86, which is not well founded because core 48 has neither radiocarbon dates nor prominently correlative strata.

Krivonogov et al. (2010a, b) investigated three new cores: M-2003-1, M-2003-2 (Muynak) and B-2008-1 (Barsakelmes) obtained at the heights of 50, 36 and 39 m asl, respectively (Fig. 4.1). Two boreholes, M-2003-2 and B-2008-1, penetrated through the whole lake sediments and entered into the substrate of brown colored dense clays of non-lacustrine origin.[4]

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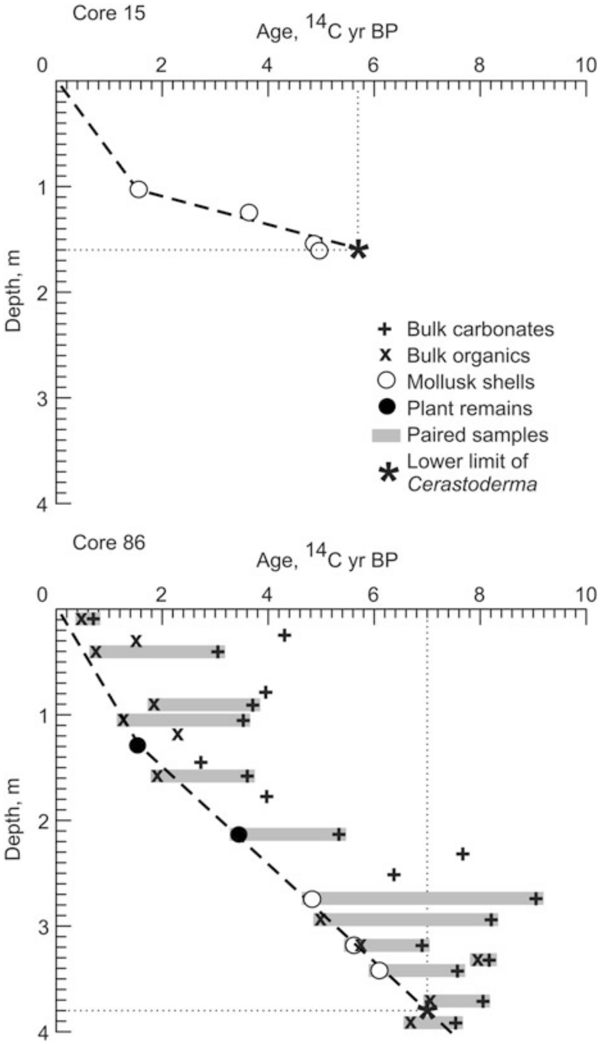
[4] Core M-2003-1 was obtained with a help of a Forestry Suppliers Inc. regular auger. Only the lower, non-contaminated, part of every portion of sediments was collected. Upper 7 m of the core B-2008-1 were obtained with the help of a Livingston-type piston corer, which provides undisturbed sediment columns. Lower part of the core B-2008-1 and the whole core M-2003-2 were obtained with the help of a checking sampler, which is a pipe with a vertical slit. Due to this, the lowermost lots of the cores were contaminated by younger materials during the hoisting of the downhole instrument. This was recently verified by the ^{14}C dating and the previously published stratigraphic columns of the cores B-2008-1 and M-2003-2 (Krivonogov et al. 2010a; Guskov et al. 2011) are corrected (Krivonogov et al. 2010b and this chapter).

Fig. 4.3 Age-to-depth plots for the sediments of cores 15 and 86 (Modified from Maev and Karpychev 1999; Ferronskii et al. 2003)



The lake sediments show alternation of deep and shallow water facies (Fig. 4.5) similar to those in cores 15, 48 and 86. Correlation of the sediments is accurately done by the use of radiocarbon dates, which mostly belong to the shallow water sandy facies enriched by mollusk and ostracod shells (Table 4.1, sites G-I).

The oldest date of 19,900 ± 140 ^{14}C BP (23,800 ± 435 cal. BP) was obtained from a large, 3 cm long, thin-wall Lymnaeidae-type gastropod, which was unluckily broken by the cutter during the core splitting procedure. The shell is from the topmost part of the substratum clays and its age is the likely age minima of the pre-Aral Sea environment. The oldest age of the Aral sediments is 9,590 ± 120 ^{14}C BP (10,930 ± 285 cal. BP). Recessions of the Aral occurred at ca. 11–8, 7.5, 6.3–5.5,

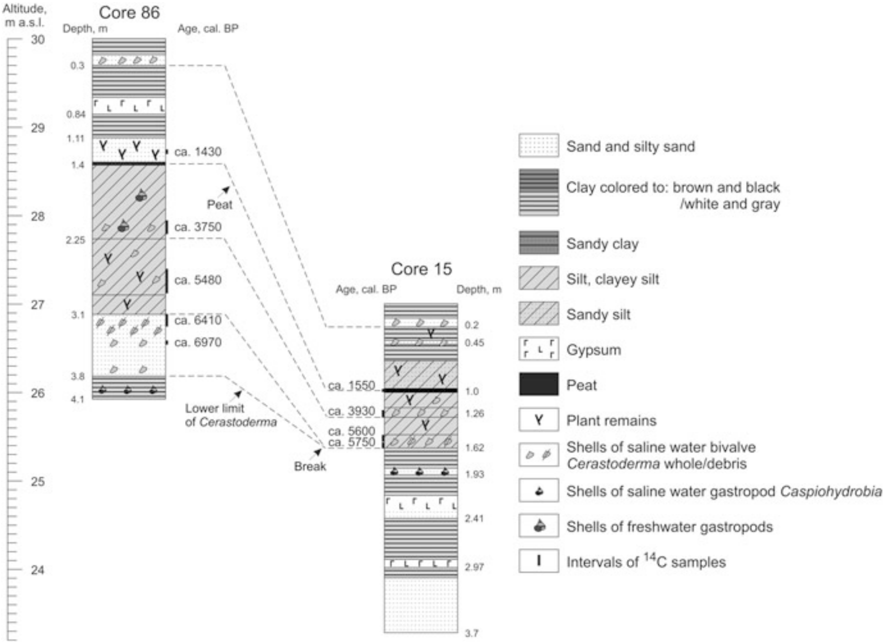


Fig. 4.4 Stratigraphy of cores 15 and 86 and their correlation to the calibrated ^{14}C ages (Based on a summary of the data from Maev et al. 1983; Sevastyanov et al. 1991; Tarasov et al. 1996; Maev and Karpychev 1999 and Ferronskii et al. 2003)

Table 4.2 Age of sediment layers in cores 15 and 86 representing low lake levels

Core 15				Core 86			
Depth, m	Age, ka cal. BP	Sediments	Lake level, m asl	Depth, m	Sediments	Age, ka cal. BP	Lake level, m asl
0.16–0.21	0.2–0.3[a]	Sand with shells	~27	0.17–0.3	Sand with shells	0.2–0.3[a]	~30
0.43–0.45	0.65–0.7[a]	Sand with shells	~27	0.66–0.84	Gypsum	0.7–0.8[a]	~29.5
0.98–1.0	1.5[b]	Peat	26	1.39–1.41	Peat	1.4[b]	~ 28.5
				3.1–3.77	Beach sands with shells	6.6-7.0	26

[a] Interpolated
[b] Based on ^{14}C date

4.8, 1.6–1.3 and 0.5 ka cal. BP. The oldest date of *Cerastoderma* shell is 5,390 ± 40 ^{14}C BP (6,230 ± 55 cal. BP).

Boomer et al. (2009) briefly reported one more newly obtained core AR01-3 drilled in the southern part of the Large Aral at ca. 38.5 m asl (Table 4.1). A *Cerastoderma* shell taken at a depth of 54–60 cm returned a ^{14}C age of 4,420 ± 55

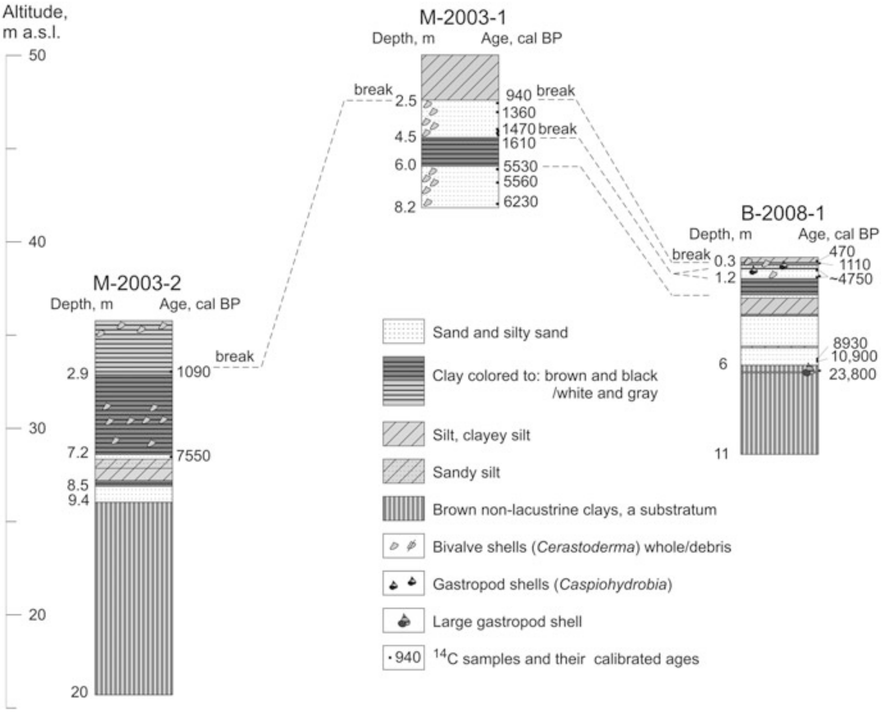


Fig. 4.5 Stratigraphy of cores M-2003-1, M-2003-2 and B- 2008–1 and their correlation to the calibrated ^{14}C ages (A summary of the data from Krivonogov et al. 2010a, b)

BP, which suggests very slow sedimentation. The authors suggest this date to be reworked, while core B-2008-1 taken at about the same height in the northern part of the Large Aral has similar age marks (Krivonogov et al. 2010a, b, Table 4.1, site I), and therefore may represent the same event of the lake level change.

Sediments of the Small Aral Basin were characterized by two ca. 1.5 m long cores that showed alternation of dark gray mineral and black organic rich clays (Boomer et al. 2003). Only one ^{14}C date of 380 ± 40 (0.3–0.5 ka cal. BP) was obtained in the organic rich layer of the core AS17, ca. 27 m asl, (4.1) from the *Phragmites* stem at the sediment depth of 125–130 cm. The date indicates a high sedimentation rate and three organic rich layers with remnants of the near-shore reed (*Phragmites*) indicate several lowerings of the Small Aral in the latest stages of its development.

Sediments of the deep-water northwestern part of the Large Aral were cored to a depth of 1.5–11 m in the Chernyshov Bay; a total of 28 cores were obtained (Figs. 4.1 and 4.6a; Nourgaliev et al. 2003; Sorrel et al. 2006, 2007; Austin et al. 2007; Píšková et al. 2009). The sediments are coarsely laminated and consist of considerable biogenic mud and terrigenous clays and silts (Fig. 4.6b). Alternation of biogenic and terrigenous layers may reflect environmental variations.

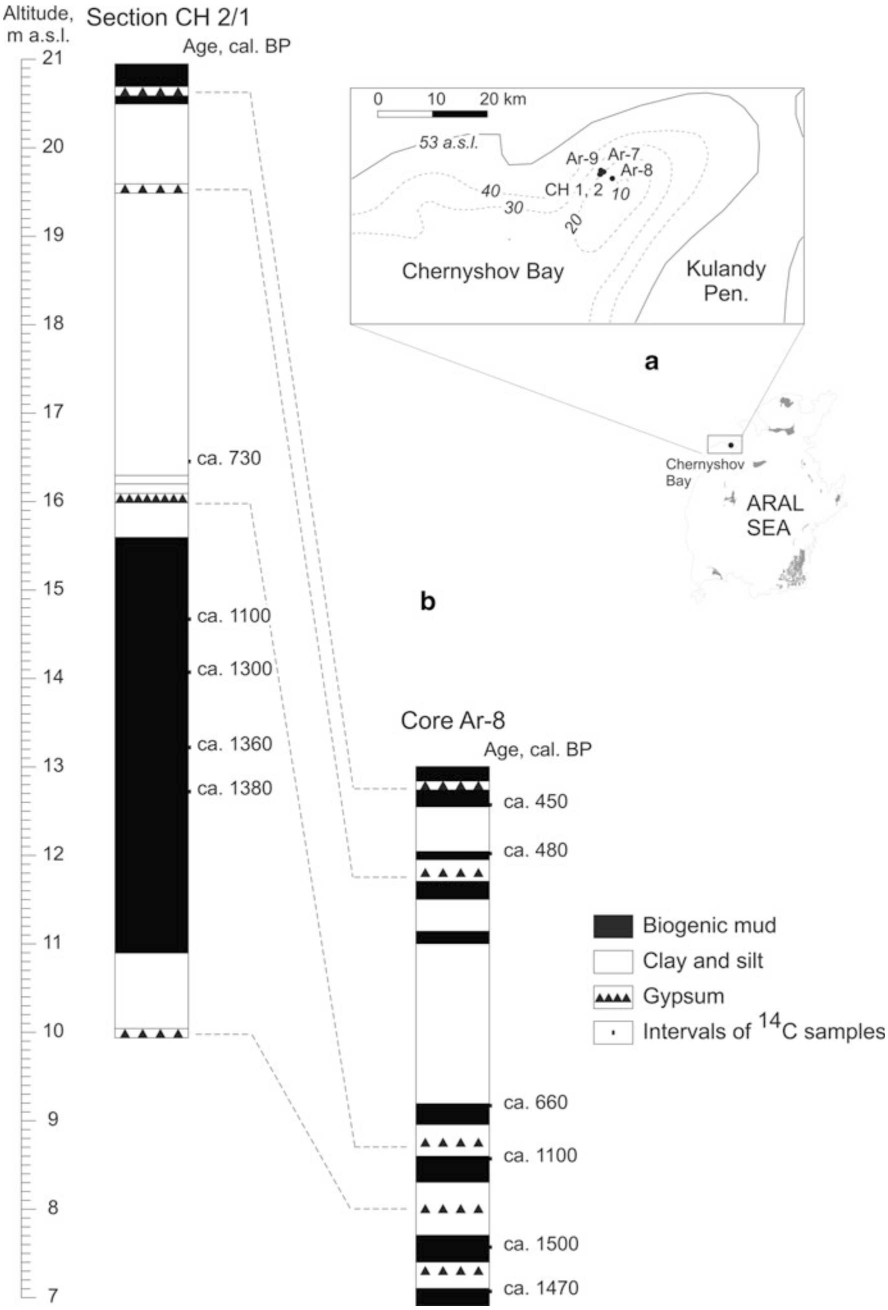


Fig. 4.6 (**a**) A detailed map showing the position of the cores obtained in the Chernyshov Bay. (**b**) Stratigraphy of cores CH-2/1 and Ar-8 and their correlation to the calibrated ^{14}C ages (Based on a summary of the data from Nourgaliev et al. 2003; Sorrel et al. 2006, 2007; Austin et al. 2007; Oberhansli et al. 2007)

However, their sequences in the reference cores CH 1, 2 and Ar-8 drilled at different water depth, 21 and 13 m asl, respectively, are ill matched. Gypsum-rich layers are more reliably correlative as a precipitation of gypsum marks progressive salinization of the lake (Sorrel et al. 2006; Oberhansli et al. 2007).

Radiocarbon dating of biogenic mud layers showed a very young age for the sediments of the Chernyshov Bay (Table 4.1, sites C–E) and their very fast accumulation at an average rate of 4–6 mm per year. The organics of the mud is mostly filamentous green algae *Vaucheria* sp. (Sorrel et al. 2006) and, therefore, the dates look reliable; however, several dates were rejected because of probable contamination by older carbon (Austin et al. 2007). Fast accumulation of the biogenic mud may be attributed to the intensive growth of the algae. Nevertheless, the intervals of clay and silt accumulation in core Ar-8 show an even higher, up to 15 mm per year, sedimentation rate. Thus, fast sedimentation is a specific feature of the northwestern deep part of the Aral Sea.

The correlative gypsum-rich layers indicate increased salinization and, therefore, declines of the lake levels at ca. 1, 4, 0.8, 0.5 ka cal. BP and also recently.

4.3.2 *Outcrops*

The structure of a limited number of outcrops highlights a problem of determining high stands of the Aral. Sediments of the 60–65 m asl Tastubek Peninsula of the northern shore of the Aral were investigated in a gully situated southward of Tastubek Village (4.1; Reinhardt et al. 2008). A 3.5 m high section consists of sandy, silty and clayey sediments of continental origin including paleosoils and wind erosion horizons. No evidence of a lacustrine layer was found. Probable age of the sediments has an upper limit of ca. 30 ka BP according to the mesolithic artifacts found in the nearest vicinities (Boroffka et al. 2005a). This suggests that the Aral Sea did not rise to a high level during the formation of the sediments and afterward.

A high stand of the lake at 52 m asl is recorded in the Aklak outcrop situated on the left bank of the Aklak reservoir recently constructed on the Syr Darya River near its mouth (Fig. 4.1). The outcrop shows very shallow water littoral sand facies of Aral sediments covered by the deltaic series of the Syr Darya (Fig. 4.7a). The lake sediments contain an abundance of shells *Cerastoderma* and *Dreissena*, having a ^{14}C date of 1510 ± 35 BP (Table 4.1, site K), which suggests a transgression at ca. 1.4 ka cal. BP. The deltaic sediments showed very recent ages of 140 ± 140 cal. BP, which suggests an interruption in the sediment record of the modern Syr Darya mouth (Krivonogov et al. 2010a, b).

Evidence of two high levels of the Aral is recorded in the Karaumbet outcrop, which is situated about 70 km southward from the middle twentieth century southern bank of the Aral Sea (Fig. 4.1). The Karaumbet Basin (39 m asl), is a sinking tectonic structure along the eastern scarp of the Ust-Urt Plateau separated

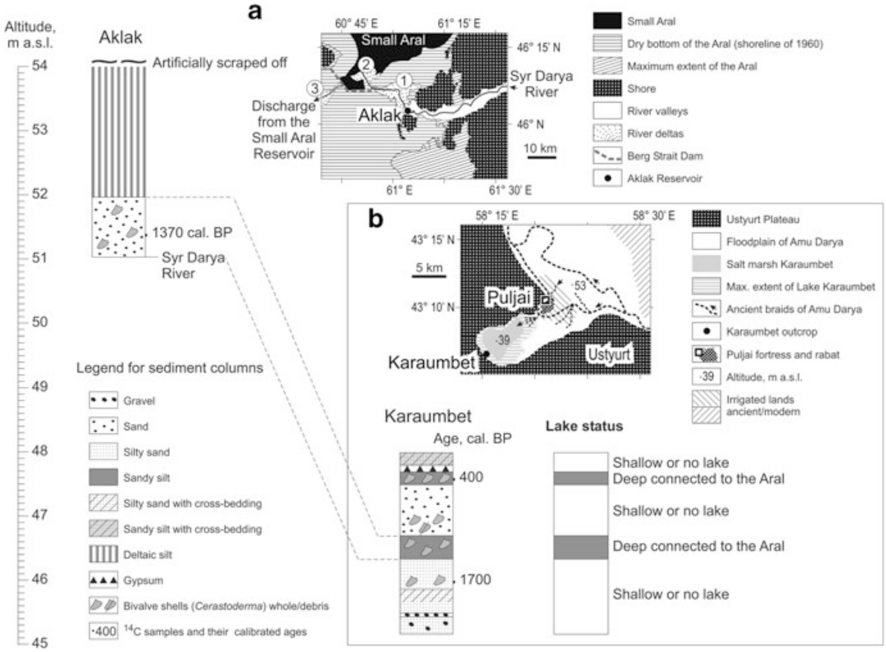


Fig. 4.7 High stands of the Aral recorded in the outcrops of Aklak (**a**) and Karaumbet (**b**) (Modified from Krivonogov et al. 2010a, b; Reinhardt et al. 2008)

from the Aral Basin during its low stands. In the periods of high stands, the Karaumbet connected with the Aral via the shallow Aibughir Bay.

The outcrop is a wall of a 2 m deep gully cut by surface water in the sloped bottom of the Karaumbet Basin at ca. 45 m asl. The sediments consist mostly of sub-aerial fluvial and aeolian series, whereas the lacustrine facies are subordinate (Fig. 4.7b). The typical Aral Sea shells *Cerastoderma* and *Dreissena* are in-situ in the lake sediments and apparently reworked in the non-lacustrine ones. The outcrop shows two layers of sandy silt lake sediments with shells, which represent the highest stands of the Aral (Reinhardt et al. 2008). The dates (Table 4.1, site L) allow us to correlate the older layer with the Aklak event, i.e., ca. 1.4 ka cal. BP, and date the younger layer ca. 0.4 ka cal. BP.

4.4 Paleoenvironmental Proxies

A variety of records obtained from the Aral Sea sediments give us information about climate and lake level changes. In this section we discuss only those records, which are related to lake levels. They characterize two environmental settings: the

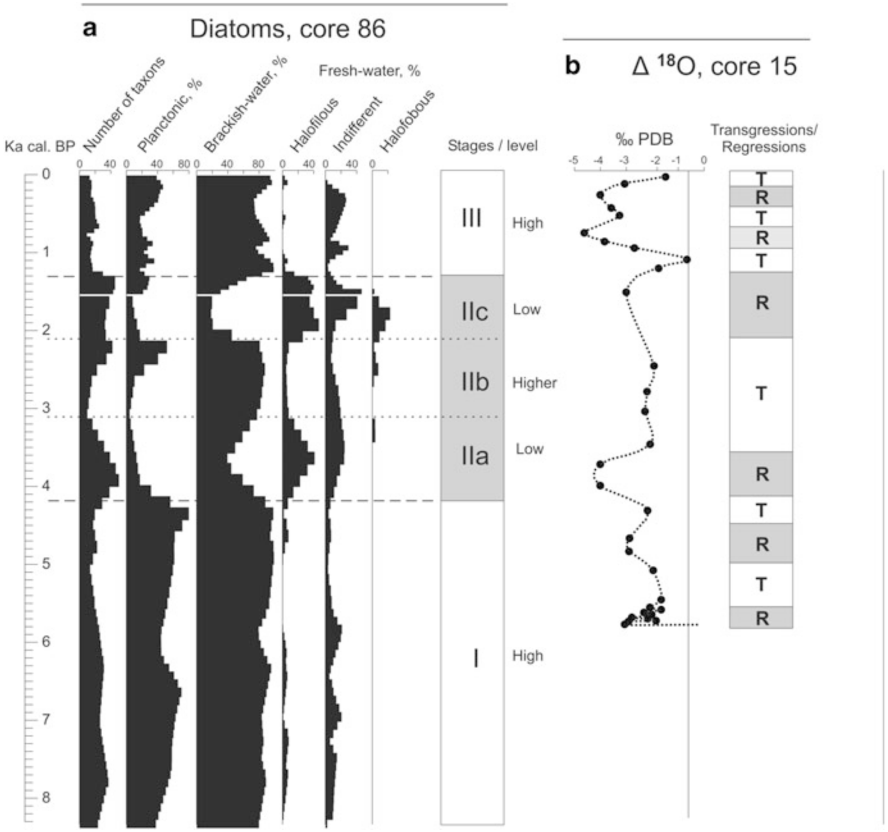


Fig. 4.8 Paleoenvironmental proxies indicating Aral Sea level changes. (**a**) Diatom data from core 86 (Aleshinskaya 1991). (**b**) ^{18}O data from core 15 (Nikolaev 1991)

rather shallow central part of the basin, cores 15 and 86, and the deep-water Chernyshov Bay, cores CH 1and 2 and C2/2004 (Fig. 4.1).

Diatom data from core 86 show three stages of the lake development (Aleshinskaya 1991, Fig. 4.8a) with prominent boundaries at a depth of 225 and 111 cm (Fig. 4.4). Stages I and III represent brackish and saline-water basins, which were typical to the recent Aral of nineteenth to twentieth centuries. Stage II represents desalinization of the basin, which is indicated by the dominance of fresh-water diatoms at ca. 4.2–1.3 ka cal. BP (Fig. 4.8a). Aleshinskaya (1991) explained this phenomenon by the decrease of the lake level and progradation of the Amu Darya Delta. The diatom data match the sedimentological evidence of shallow-water and deltaic conditions in the central part of the Aral Sea (Rubanov et al. 1987). In detail, Stage II includes two peaks of the fresh-water diatoms, which may represent deep regressions of the Aral at ca. 4.2–3.2 and 2.1–1.3 ka cal. BP.

Oxygen isotopes were investigated in several cores in the central part of the basin (Nikolaev 1987, 1991; Nikolaev et al. 1989). The geochronologically referenced record was obtained from core 15 (Fig. 4.8b). Its interpretation is based on the suggestion that increases of ^{18}O in the bottom sediment carbonates reflect regressions (Nikolaev et al. 1989), which therefore occurred at ca. 5.8–5.5, 5.0–4.5, 4.1–3.5, 2.1–1.3, 0.9–0.7 and 0.2–0.4 ka cal. BP.

Cores CH 1 and 2 from the Chernyshov Bay provided data on the level changes in the part of the Aral, which was not dried out during the last 1.5–2 ka. The dinoflagellate cyst and chlorococcalean algae records suggest low level and saline basins at ca. 2.1–1.6, 1.1–0.7, 0.6–0.3 and 0.05–0 ka cal. BP (Sorrel et al. 2006). Additionally, the authors concluded that a very high lake level occurred at ca. 0.7–0.6 ka cal. BP. This explains abundant reworked dinocysts, which could be re-deposited from the shore sediments of Paleogene and Neogene age by wave erosion.

Diatom-inferred salinity indicates low levels at ca. 1.6, 0.8–0.7 and 0.2–0 ka cal. BP (Austin et al. 2007) and increases in salinity coincide with the peaks of total organic carbon. The authors constrained the record by ca. 1.6 ka because of an abrupt transition in the diatom flora and magnetic susceptibility (Sorrel et al. 2006), which suggest a hiatus within the material at a depth of 10.3 m.

Píšková et al. (2009) published the diatom data of a C2/2004 core retrieved by D. Nourgaliev (Nourgaliev et al. 2007) in the Chernyshov Bay at a distance of 25 km SE from the core CH 1, 2 locality at a water depth of ~3 m (ca. 27 m asl.).[5] Changes of the diatom assemblages showed low lake level stages at ca. 2.0–1.75, 1.1–1.0, 0.6–0.55 and 0.1–0 ka cal. BP and high level stages at ca. 1.5–1.1, 0.8–0.65 and 0.4–0.1 ka cal. BP.

The ostracod data from the Small Aral sediments suggest a considerably decreased lake level at ca. 0.5–0.3 ka cal. BP (Boomer et al. 2003, 2009). The level was estimated to have fallen as low as 27–29 m asl., which is the first paleontologic evidence of the Middle Age catastrophic regression.

In addition, Filippov and Riedel (2009) analyzed the ecology of mollusk fauna and stable isotope compositions in mollusk shells in ten short half-meter cores obtained by Zhamoida et al. (1997) in the eastern part of the Aral. Sediment age is controlled by two ^{14}C dates: fruits of water plant *Ruppia* sp. found in core 82 (altitude 33 m asl.) at a depth of 34 and 35 cm gave ages of 690 ± 35 (KIA-18247) and 710 ± 40 (KIA-18248), respectively. Despite lacking age control, which does not allow fixing inconsistencies in sedimentation, the authors suggest considerable variations of the lake level during the last millennium with minimums at ca. 0.85 and 0.5 and maximums at 0.65 and 0.35 ka cal. BP.

Boomer et al. (2009) summarized the recently obtained microfaunal data and proposed a scheme of the Aral Sea level changes during the last ca. 2000 years, which suggests low Aral levels during ca. 2–1.6, 1.1–0.65, 0.5–0.35 and 0.2–0 ka cal. BP.

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[5] Unfortunately, the referenced paper (Nourgaliev et al. 2007) has no mention of core C2/2004, thus, its exact location is unknown.

4.5 Tree Stumps

Stumps of the *Saxaul* tree were reported in several places across the bottom of the Aral Sea. Their careful investigation would allow us to estimate limits of the past regressions and their duration (by tree rings). However, few of them were dated and, unfortunately, the investigators did not record coordinates and altitude positions of their findings, which decrease the value of this data. In any case, the territory where the *Saxaul* grew is rather dry and therefore the stumps cannot serve as precise markers of levels.

A stump on the strand of the Lazarev Island (Fig. 4.1) investigated by Maev et al. (1983) has ^{14}C age of 970 ± 140 (MGU-734), i.e., ca. 0.9 ka cal. BP. The position of this finding could not be lower than 47 m asl., which marks the Aral level of that time (Kravtsova 2001). Aladin and Plotnikov (1995) and Boomer et al. (2000) briefly mention a *Saxaul* stump of 287 ± 5 ^{14}C age. According to S. Stine[6] (pers. comm.), there are two ^{14}C dated stumps: one sample from the southern part of Butakov Bay is 280 ± 70 (CAMS-2504), ca. 0.4 ka cal. BP, and another one from the exposed bottom northward of the Barsakelmes Island (Fig. 4.1) is 170 ± 70 (CAMS-2503), ca. 0.3 ka cal. BP. According to N. Aladin (pers. comm.), the last site was a forest of *Saxaul* trees currently represented by hundreds of stumps.

Six poorly preserved stumps representing a small *Saxaul* grove were found in the vicinities of the Kerderi 1 (Fig. 4.1) archaeological site at the altitude of ca. 34 m asl. (Krivonogov et al. 2013). The finding is related to human activity, as the geomorphological survey and excavation of the sampled stump show (see Sect. 4.6). The grove was situated near an artificial pond-like basin. A cultural layer with pieces of bricks and an animal bone was found at a depth of ca. 30 cm. The stumps are 10–25 cm in diameter, and one of them was collected for ^{14}C dating (Fig. 4.9). Its upper part, which stood above ground level, is strongly foliated along tree-rings and contaminated by roots of modern plants; therefore we dated the better preserved lower part of the stump, which returned an age of 470 ± 35 (AA-93688), i.e., 0.5 ka cal. BP.

4.6 Archaeological Data

Sites of ancient cultures are widespread around the Aral, which many geologists and geomorphologists considered as an opportunity to date lake level changes (e.g., Yanshin 1953; Kes 1969, 1983; Rubanov et al. 1987; Sevastyanov et al. 1991). The distribution of the sites of different ages has been summarized in several publications (e.g., Tolstov 1962; Vinogradov 1968; Levina 1998). In respect to

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[6] Scott Stine, California State University, received these two samples from Ian Boomer in 1991 and dated them. The samples were collected by Nick Aladin.

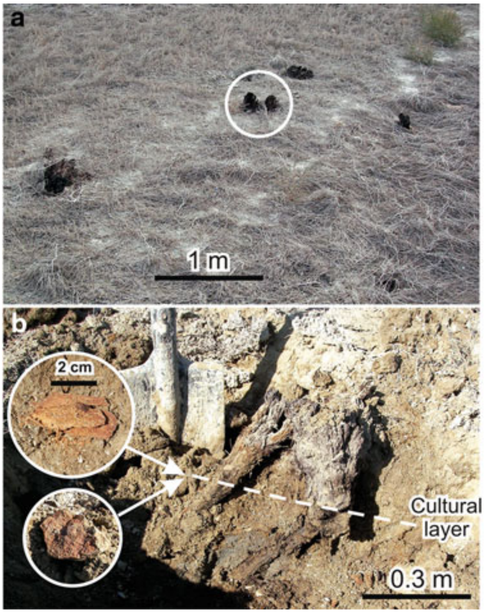

Fig. 4.9 Stumps of the Saxaul trees at the Kerderi-1 locality. (**a**) General view. (**b**) A stump excavated for the ^{14}C dating. The picture shows the position of cultural layer and findings of pieces of a bone and a brick in it (*in circles*) (Photos by S.K. Krivonogov)

the lake levels, Yanshin (1953) and Vinogradov (1981) mentioned the lack of Mesolithic sites around the Aral Sea contrary to the abundance of Neolithic ones, and suggested that this indicated the settling of ancient man closer to the Aral since ca. 10–9 ka BP. This was interpreted as a change from climatically unfavorable conditions of poor water supply to favorable ones, which matches a transition from the Pashkevich low to the Lavlakan high phases of the Aral in terms of the ideas of Veinbergs and Stelle (1980). The Neolithic findings constrain the period of the Lavlakan phase to ca. 9–5 ka BP (Mamedov 1991a).

Nevertheless, the major part of the available archaeological materials characterizes settlement processes away from the Aral shores and mostly represents the development of river deltas, which may reflect variations in climate, river courses and irrigation. Deeper investigation has shown the presence of archaeological sites of different ages, from the Late Paleolithic, ca. 50–30 ka, to modern, near the Aral (Shirinov et al. 2004; Baipakov et al. 2004; Boroffka et al. 2005b), which have never been covered by its water except those situated below 54 m asl. (Boroffka et al. 2005a, 2006). This refutes the concept of a “high”, up to 72–73 m asl, Aral.

A site, which was obviously covered by the Aral Sea is Puljai situated near the eastern edge of the Ustyurt Plateau (Fig. 4.7b). The monument consists of a fortress having a higher position on a cape of the Ustyurt cliff and of a civil settlement (rabat). Rabat occupies a deltaic plain of the Amu Darya at an altitude of ca. 53 m asl. It consists of several manors placed at a distance of 50–90 m along one of the river channels, which flowed into the terminal Karaumbet Lake. Its adobe brick

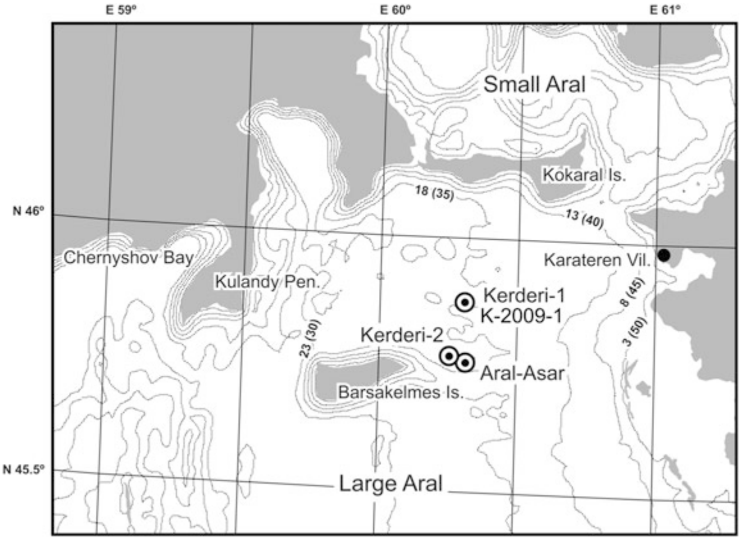

Fig. 4.10 A detailed map showing the positions of the archaeological sites on the dry bottom of the Aral Sea. Topographic situation of ca. 1960. Isobaths are labeled by their depth and altitude asl (*in parentheses*)

buildings now look like clayey mounds because their ruins were flooded by the Aral Sea. That it was flooded is clear from a cover of *Cerastoderma* and *Dreissena* shells, which are abundant on the tops of the ruins. The artifacts date the Rabat to twelfth – end of fourteenth centuries AD, i.e., ca. 800–500 year BP (Shirinov et al. 2004; Boroffka et al. 2005a, b, 2006). Therefore, the transgression occurred later than 500 BP, and it probably was the highest during the last millennium.

The Kerderi monuments situated on the bottom of the Aral Sea to the east-northeast of the Barsakelmes Island are clear evidence of a deep regression (Figs. 4.10, 4.11 and 4.12). They were found by local hunters and excavated by Kazakh archaeologists in the early 2000s (Smagulov 2001, 2002; Catalogue of Monuments of the Kazakhstan Republic History and Culture 2007; Sorokin and Fofonov 2009). The sites include mausoleums Kerderi-1 and Kerderi-2 and the settlement Aral-Asar. The sites occupy areas with altitudes of ca. 34 m asl (Table 4.3), which suggests deep regression similar to the modern one.

Baipakov et al. (2007) suggest a very short period of several decades for the Kerderi – Aral-Asar civilization, which was ended by a sudden rise of the Aral Sea. However, the authors describe a rather developed industrial and agricultural community. The findings from Aral-Asar, which probably appeared as a settlement on the Great Silk Road, indicate extensive livestock and plant agriculture, and trade. The settlement has a necropolis, and its citizens were rich enough to construct two amazing mausoleums ornamented by terracotta, blue-colored

Fig. 4.11 Photographs of the archaeological sites Kerderi-1 (**a**) and Kerderi-2 (**b**). The detailed photo of "b" shows wood excavated by archaeologists from a grave. This wood was used for ^{14}C dating (Photos by S.K. Krivonogov)

ceramics and mosaics, which are architecture and decoration analogues of sacred buildings in Samarkand and other cities of Khorasan, Middle Iran and Azerbaijan (Sorokin and Fofonov 2009). The Kerderi-1 and Kerderi-2 mausoleums were constructed on the weak silty sediments of the Aral Sea, which required reinforced basements. Their basements were made from the Paleogene sandstone slabs, for which the nearest source is the Kok-Aral Peninsula, ca. 50 km northward (Smagulov 2001). Thus, the Middle Age people populating the dried Aral Sea bottom had to have enough time to settle and economically develop the area and also construct various amenities.

Extensive plant agriculture is evidenced by specific large pots used for storage of rice or wheat and millstones, which are abundant in the Aral-Asar settlement, and by paddies and irrigation channels constructed in the vicinities of Aral Asar (Catalogue of Monuments of the Kazakhstan Republic History and Culture 2007) and Kerderi-1 (Krivonogov et al. 2013) (Fig. 4.12). The agriculture implies a sufficient amount of fresh water, which was taken from the Syr Darya (Krivonogov 2009; see Sect. 4.8).

Various authors interpret the archeological age of these sites differently. The Kerdery-1 mausoleum and mosque is dated to the twelveth-fourteenth by Smagulov (2002), to the fourteenth-sixteenth or fourteenth to early fifteenth by Boroffka et al. (2005a, 2006), and to the XIII–XIV centuries AD by Boomer et al.(2009). The Kerdery-2 mausoleum has been assigned an age of late thirteenth to middle fourteenth (Catalogue of Monuments of the Kazakhstan Republic History and Culture 2007) or fourteenth-fifteenth centuries AD (Sorokin and Fofonov 2009). The Aral-Asar settlement is dated by coins as middle fourteenth century AD

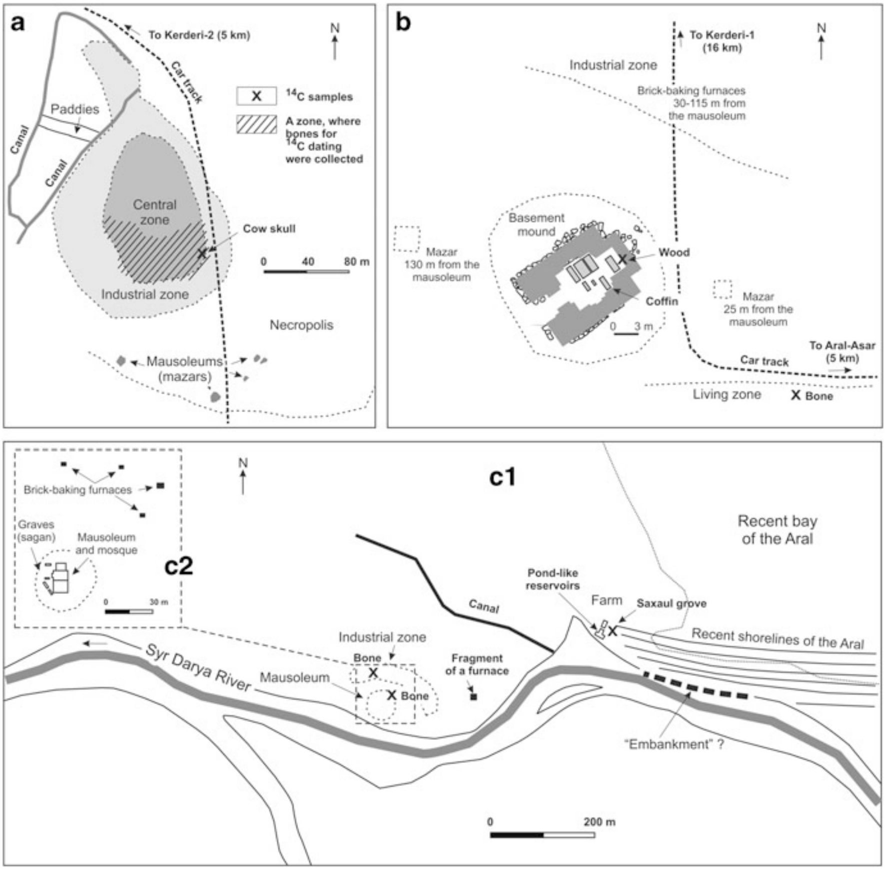

Fig. 4.12 Sketches of the Aral-Asar (**a**), Kerderi-2 (**b**) and Kerderi-1 (*C1* and *C2*) localities (The modified data by Smagulov 2002; Catalogue of Monuments of the Kazakhstan Republic History and Culture 2007; Krivonogov et al. 2013). The drawings show general topography and location of archaeological sites and of ^{14}C dated samples

Table 4.3 Location of the Kerderi monuments

		Altitude, m asl	
Monument	Coordinates, dd	Measured by investigators	From the nautical chart-based DEM
Kerderi-1	N 45.86381 E 60.31314	34[a]	34
Kerderi-2	N 45.72346 E 60.26193	29[b]	33.6
Aral-Asar	N 45.70883 E 60.31687	33[b]	34.8

[a] Boroffka et al. (2005a, b)

[b] Catalogue of Monuments of the Kazakhstan Republic History and Culture (2007)

Table 4.4 Radiocarbon dates from the Kerderi archaeological monuments (Krivonogov et al. 2010b, 2013)

^{14}C age, BP	Lab code	Material	δ^{13}C, ‰	Calibrated age, BP[a]
Kerderi-1				
470 ± 35	AA-93688	Saxaul-tree wood[b]	−23.1	510 ± 35
620 ± 45	AA-93685	Domestic animal bone[c]	−22,1	600 ± 60
640 ± 45	AA-93686	Domestic animal bone[d]	−15.7	610 ± 60
860 ± 35	AA-93687	Shell of *Cerastoderma*[e]	−0.7	750 ± 55
1600 ± 65	SOAN-8176	Cannon-bone of an ancient man[f]		1490 ± 140
Kerderi-2				
580 ± 35	SOAN-8175	Domestic animal bone[g]		590 ± 60
600 ± 65	SOAN-7688	Thin wood stick[h]		600 ± 75
820 ± 55	SOAN-7687	Thick wooden plank[h]		740 ± 65
Aral-Asar				
540 ± 45	SOAN-8174	Caw skull		580 ± 70
630 ± 35	SOAN-8173-1	Domestic animal bone[i]		610 ± 55
910 ± 80	SOAN-7686	Domestic animal bones[j]		820 ± 135
1050 ± 90	SOAN-8173-3	Domestic animal bone[i]		970 ± 205
1750 ± 95	SOAN-8173-2	Domestic animal bone[i]		1690 ± 185

[a] Intcal09

[b] The sample was collected from a stump of the saxaul tree on the farm eastward of the mausoleum

[c] The sample was collected within the industrial zone northward of the mausoleum

[d] The sample was collected in the cultural layer under the saxaul tree on the farm eastward of the mausoleum

[e] The sample was collected from the sediments below the cultural layer in the same excavation as "d"

[f] The sample was collected on the northern slope of the mound of the mausoleum. Probably the bone was washed out from a grave of the sagan surrounding the mausoleum

[g] The sample was collected within the living zone of the mausoleum

[h] The material was collected in the north-eastern part of the mausoleum near a grave, which was robbed before the archaeological excavations in 2055 (Catalogue of Monuments of the Kazakhstan Republic History and Culture 2007)

[i] The samples SOAN-8173-(1, 2 and 3) were selected from a collection of bones used for paleontological identification. The bones were collected in the southern part of the Aral-Asar settlement (Fig. 4.15a). They belong to domestic animals: cow, horse, and sheep/goat (Krivonogov et al. 2010b)

[j] The sample consists of material from several bones

(Catalogue of Monuments of the Kazakhstan Republic History and Culture 2007). All of these datings, constrain the Medieval "Kerderi" regression to ca. 0.8–0.4 ka BP.

The radiocarbon dating of different materials of the sites (Krivonogov et al. 2010b, 2013; Table 4.4, Fig. 4.12) showed two clusters of ages, which suggests two phases of low levels of the Aral at ca. 1.9–1.4 and 1.0–0.5 ka cal. BP with a higher level in between (Fig. 4.13).

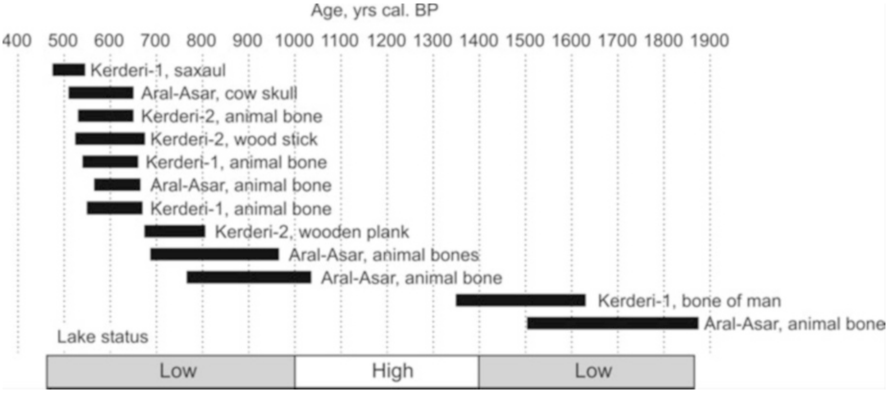

Fig. 4.13 Distribution of the calibrated ages (*black bars*) of the samples dated in the Aral-Asar, Kerderi-1 and Kerderi-2 localities. These data suggest two low level phases of the Aral separated by a high level phase (*lake status bar*)

4.7 Historical Data

The Aral Sea (Kurder, Khoresm or Jend Lake) has been mentioned in geographic treatises, chronicles and other documents since ancient times. Available manuscripts were carefully analyzed by Bartold (1902), whose findings were used by Berg (1908) and by subsequent researchers in their reconstructions of Aral history. However, most of these documents are poor witnesses of Aral Sea changes. More or less reliable information, however, appeared beginning in the middle Ages.

A famous example, often cited in geological literature, is attributed to Genghis Khan whose troops conquered Urgench City, the capital of Northern Khorasan, in 1221 AD. During the campaign, an earthen dam protecting the city from flooding by the Amur Darya River was destroyed and the river turned from flowing to the Aral to the Sarykamysh Basin. Many scientists believe that this event was a major contributor to the Medieval recession of the Aral. However, our dating of the Kerdery sites suggests an earlier onset of the regression at ca. 1 ka cal. BP.

Hafizi-Abru, a chronicler and geographer of the Tamerlane court, wrote in 1417 AD that the Aral Sea "does not exist now" and that the Amu Darya flows to the Caspian Sea (Bartold 1902). Berg (1908, p. 268) considered this evidence of an extremely low Aral as exaggerated and for decades it was dismissed. In light of modern data, the witness of Hafizi-Abru coincides with the main period of the Kerdery sites development.

The subsequent rise of the Aral Sea is evidenced by the Khiva khan Abulgazi, who noted that the Amu Darya turned to the Aral Sea 30 years before his birth, i.e., in about 1573 AD (Bartold 1902). By the end of the sixteenth century, the Aral Sea became fully filled. In "Kniga glagolemaya Bolshoi Chertezh" (Book of the Great

Map, 1627), which was a description to the first map of the “entire Moscow state”, the Aral was called “the Blue Sea” with a latitudinal length of 250 versts[7] (Berg 1908). S. Remezov depicted it as a big lake on the maps in 1697 (Berg 1908) and by A. Bekovich-Cherkasskii in 1715 AD (Shafranovskii and Knyazhetskaya 1952).

The actual dimensions of the Aral Sea were geodetically measured by Russian topographers led by Commander A. Butakov in 1848–1849 AD (Butakoff 1853). On the map, its extent looks similar to the size of the sea in the 1960s or even a bit larger, as the map depicts the Aibughir Bay extending about 100 km to the south (4.1).

Berg (1908) summarized the data on the changes of the Aral level since 1790 AD, the record of which was continued later on (e.g., Shermatov et al. 2004). This record shows the level fluctuated within ca. a 3 m range only (see footnote 2 above), which indicates a metastable transgressive state of the lake during the last 190 years.

4.8 Braids of the Syr Darya

The extensive and long (ca. 400 km) Syr Darya Delta possesses several very prominent ancient river courses with well-preserved channels named Karadarya, Inkardarya, Janadarya and Kuvandarya (Fig. 4.14a). They probably functioned in different periods of the Holocene; however, when they were active is not well known (Mamedov 1991b).

Nikolaev (1991) was the first, who found the paleochannels of the Syr Darya on the Aral Sea bottom northward of the Barsakelmes Island and in the middle part of the sea and showed them in a paleogeographic map. The channels were attributed to the 1.6 ka BP drop of the sea (1.5–1.4 ka cal. BP, see Sect. 4.3). Krivonogov (2009) mapped braids with the help of satellite imagery in which the ancient river bed and side channels of the Syr Darya are clearly seen for a distance of more than 100 km (Fig. 4.14a). There are two braids to the north and to the south of the Barsakelmes Island.

The northern braid starts at about 50 km eastward near the village where the present Syr Darya sharply turns to the north. To the west of Oktyabr, the ancient river branches into three channels. The northern channel reaches the Akkol Bay to the south of the village of Karateren and goes further on the Aral’s dried bottom for a distance of about 40 km, forming a clearly seen delta. The middle channel reaches the Karashokhat Cape, ending with a little delta, corresponding to the maximum water level of about 53 m asl. The southern channel continues far off to the west; the Kerdery sites are situated along this riverbed.

The delta of the southern channel covers an area of 22 by 22 km to the north of the Barsakelmes Island. The western edge of the delta touches the opposite side of

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[7] One verst is approximately 1.6 km.

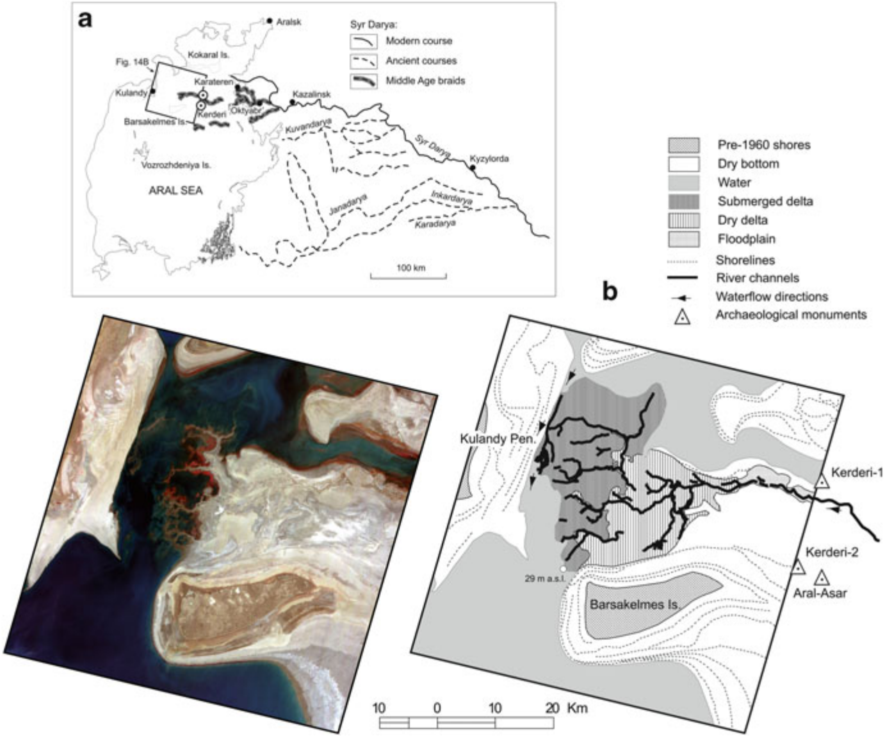

Fig. 4.14 (**a**) The Syr Darya Delta, its main river courses and the Middle Age braids. (**b**) The ASTER satellite image of 2004 (*left panel*) showing a part of the Aral Sea bottom between the Kulandy Peninsula and Barsakelmes Island and its interpretation (*right panel*) showing the medieval delta of the Syr Darya (Krivonogov 2009)

the Aral Sea, namely the Kulandy Peninsula. The edge of the delta has an altitude of about 29 m asl, which marks the medieval drop of the Aral of ca. 0.6 ka cal. BP (Fig. 4.14b).

The delta system of the northern channel is less than those of the southern one, and its surface is complicated with a smaller delta, reflecting a sea transgression. This gives grounds to suggest that the northern channel is younger than the southern one, whereas the middle channel may represent high stands occurring before or after the Kerderi low stand.

Drilling of the riverbeds was performed on a smaller braid of the southern channel near the Kerderi-1 monument, borehole K-2009-1 (Krivonogov et al. 2013; Fig. 4.10). Sandy and silty river sediments were identified at a depth of 0.4–1.8 m in between the lacustrine layers marked by *Cerastoderma*. They are enriched by plant remains (mostly stems and roots of *Phragmites*), which yielded ^{14}C dates of ca. 0.5–0.4 ka cal. BP (Table 4.1, site J). Penetration of roots deeper into the sediments explains dates of ca. 0.4 ka cal. BP at a depth of 2.2 and 2.8 m beneath the lacustrine sediments with *Cerastoderma* dated to ca. 4.7 ka cal. BP. Therefore, the temporal coincidence of the Syr Darya braids and archaeological sites on the bottom of the Aral is obvious.

A similar braid situated to the south of Barsakelmes Island (Fig. 4.14a) has not been dated yet. Good preservation of the channel landforms suggests that it is similar in age to the Kerderi braid. This implies that both braids fed the Aral Sea simultaneously, which provides evidence of quite high-flow of the Syr Darya during the Middle Ages drop of the Aral Sea.

4.9 Level Changes: A Synthesis

Figure 4.15 summarizes all available data about Aral Sea level changes during the Holocene. Gray bars indicate considerable drops of the level, which are confirmed by at least two datasets. The drops of the early, middle and late Holocene are evidenced in different degree and the changes of the last two millennia have the best grounds. Their intervals constrained by different datasets are not identical, which can be explained by incompleteness of the employed sedimentary records, obstacles in radiocarbon dating and its interpretation, and by different responses of certain lake ecosystem components to environmental changes. Therefore, the limits indicated of regressions are not conclusive and are subject to updating in light of new facts.

Thus, during the last two millennia, there were two deep natural regressions of ca. 2.1–1.3 and 1.1–0.3 ka BP followed by the modern anthropogenic one. All three regressions were of similar scale: the level dropped to ca. 29 m asl. Their separating transgressions are well evidenced by the Aklak outcrop inferring the level of ca. 52 m asl, and by the recent (historically documented) high-stand of the Aral at the altitude of ca. 53 m. The highest level of the last transgression could be up to 54 m asl, as the flooded ruins of the Puljai settlement indicate. According to the current data, the regressions look to be longer than the transgressions, but this conclusion requires careful investigation in the future. In any case, it is evident that during the last 2,000 years the Aral Sea experienced several desiccations and the related deaths of its biota, which subsequently naturally recovered.

The middle to early Holocene record of level changes is probably incomplete due to the lack of geological data. Currently the middle Holocene regressions are documented for the periods of ca. 5.5–6.3, 4.5–5.0 and 3.3–4.3 ka BP. The early Holocene history of the Aral is obscure, but the newly obtained data (Fig. 4.15b) confirm a long-lasting period of a shallow lake suggested earlier (Nikolaev 1991).

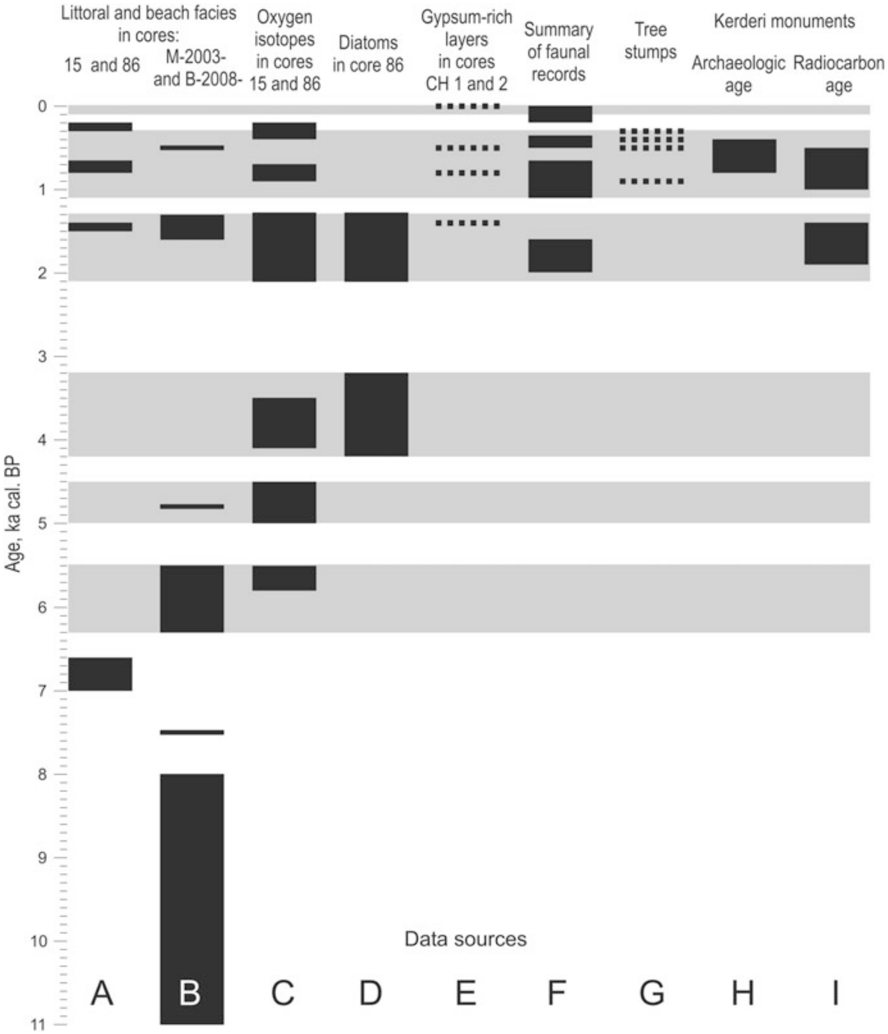

Fig. 4.15 Intervals of low levels of the Aral Sea (*gray bars*) during the Holocene inferred from the available datasets (*black rectangles*). Data sources: *A* – Maev et al. (1983), Sevastyanov et al. (1991), Maev and Karpychev (1999), and Ferronskii et al. (2003). *B* – Krivonogov et al. (2010a, b). *C* – Nikolaev (1991). *D* – Aleshinskaya (1991). *E* – Sorrel et al. (2006, 2007) and Austin et al. 2007. *F* – Boomer et al. (2009). *G* – Maev et al. (1983), Boomer et al. (2000), and Krivonogov et al. (2013). *H* – Smagulov (2002), Boroffka et al. (2005a, 2006), Boomer et al. (2009), Catalogue of Monuments of the Kazakhstan Republic History and Culture (2007), and Sorokin and Fofonov (2009). *I* – Krivonogov et al. (2010b, 2013)

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Part II
Modern Recession of Aral

Chapter 5
Aral Sea Basin Water Resources and the Changing Aral Water Balance

Philip Micklin

Abstract This chapter deals with two related water issues: the water resources of the Aral Sea Basin and the Aral Sea's water balance. The Aral Sea's size is dependent on the water resources in its basin and how much these are depleted by human usage. The chief water resources are the large basin rivers Amu Darya and Syr Darya and groundwater. The author discusses the size and character of these and their sufficiency for meeting human demand. Contrary to popular belief, the Aral Sea Basin is reasonably well endowed with water resources. But the high level of consumptive use, overwhelmingly for irrigated agriculture, has resulted in severe water shortage problems (see Chap. 8). Since the Aral Sea is a terminal (closed basin) lake with no outflow lying amidst deserts, its water balance is basically composed of river inflow on the gain side and evaporation from its surface on the loss side. Precipitation on the sea's surface contributes only about 10 % to the positive side of the balance. Net groundwater input is difficult to determine with any accuracy and likely had minimal influence until recent decades when, owing to major drops in river inflow, its impact on the water balance has grown. The Aral's water balance was very stable from 1911 until 1960. However, since then it has been consistently negative (losses more than gains) owing to very substantial reductions in river inflow caused by large consumptive losses to irrigation. This was particularly pronounced for the decadal periods 1971–1980 and 1981–1990. More river flow reached the sea over the period 1991–2000 and its water balance, although remaining negative. However, the water balance situation deteriorated during the subsequent decade (2001–2010) owing to recurring droughts. The decidedly negative water balance has led to rapid and continuing shrinkage of the sea. (See also Chaps. 9 and 11).

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5.1 Aral Sea Basin Water Resources

Water resources of the Aral Sea Basin may be divided into national and interstate, (also known as transnational). The former consist of rivers, lakes, usable groundwater, and return flows from uses situated entirely within the bounds of one or another of the basin states that do not directly affect the other states. The latter are the same hydrologic entities that cross or form national borders or directly affect water resources in other basin nations (World Bank and the ICWC 1996, p. 14). In the Aral Sea Basin, interstate water resources are by far larger and more important than national water resources and will be the focus of attention here. The key transnational water resources of the Aral Sea Basin are the two major rivers (Amu Darya and Syr Darya)[1] with an aggregated drainage area of 2.1 million km^2 and the Aral Sea into which these rivers flow.

5.1.1 Amu Darya and Syr Darya

The most important river within the Aral Sea Basin is the Amu Darya. Originating among the glaciers and snowfields of the Pamir Mountains of Tajikistan, Kyrgyzstan and Afghanistan, it flows 2,500 km from the mountains across the Kara-Kum desert and into the Aral Sea (CAWATERinfo 2012a). During this journey, the river, or its major tributaries (Kafirnigan, Surhandarya, Sherabad, and Kunduz) flow along the borders and across four states: Tajikistan, Afghanistan, Turkmenistan, and Uzbekistan, entering, leaving, and reentering the last two states several times (Fig. 1.2). Average annual flow from the drainage basin is around 79 km^3. This includes not only the flow of the Amu Darya and its tributaries but several "terminal" rivers[2] (Zeravshan, Murgab, Tedjen) that disappear in the deserts (Micklin 2000, p. 6; Mamatkanov 1996). Maximum flow is during the summer and minimum in January and February.

The Amu Darya is an "exotic" river, which, in the hydrologic sense used here, means that all its flow originates in the well-watered Pamir mountains, but that this flow is substantially diminished by evaporation, transpiration from phreatophytic vegetation (deep-rooted plants that draw water from the zone of saturation) growing

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[1] Darya in the Turkic languages of Central Asia means river.

[2] Terminal rivers are not tributary to a body of water (river, lake, or sea). They are common in arid regions where they arise in humid mountainous zones and flow into deserts where evaporation rates are so high they lose all their water.

along its banks, and bed filtration as the river passes across the Kara–Kum desert to the Aral Sea. Owing to its "exotic" nature, even prior to the development of modern, large-scale irrigation, average inflow of the river to the Aral Sea decreased to around 40 km^3 from the 62 km^3 coming out of the mountains. Tajikistan contributes 74 % of flow generated in the Amu Darya river basin, followed by Afghanistan and Iran, (13.6 %), with Afghanistan far and away contributing the largest share of these two countries, Uzbekistan (8.6 %), Kyrgyzstan (2.1 %) and Turkmenistan (1.8 %) (CAWATERinfo 2012a, b).

The Syr Darya is the longest river in Central Asia at 3,019 km. The source of the river is the Tian Shan Mountains located to the north of the Pamirs. As is the case for the Amu Darya, glaciers and snowmelt also chiefly feed it, with the latter being of greatest importance. The river (or its main tributaries the Naryn and Karadarya) flows from Kyrgyzstan into Uzbekistan, then across a narrow strip of Tajikistan that protrudes, thumb like, into Uzbekistan, and finally across Kazakhstan and into the Aral Sea. Average annual flow of the Syr Darya, at 37 km^3, is considerably less than that of the Amu Darya, but second to it among the rivers of Central Asia. Maximum flow is in the spring-summer period beginning in April with June having the greatest discharge. Kyrgyzstan contributes 75.2 % of river flow, Uzbekistan 15.2 %, Kazakhstan 6.9 %, and Tajikistan 2.7 % (CAWATERinfo 2012a). Like the Amu Darya, the Syr Darya is exotic. Prior to the modern age of irrigation, flow diminution was substantial during its long journey across the Kyzyl-Kum Desert with less than half (around 15 km^3 on an average annual basis) of the water exiting the mountains reaching the Aral Sea.

Together, the two rivers (and the terminal rivers in the basin of the Amu Darya) provide, on an annual average basis, an estimated 116 km^3. A reasonably recent study sees somewhat less basin wide surface flow (Diagnostic study…no date). According to it, "the arithmetic mean of the total run-off in the Aral Sea Basin for the entire period of observations (1911–2000) is 112.6 km^3/year, inclusive of 77.09 km^3/year for the Amu Darya and 34.08 km^3/year for the Syr Darya." This study goes on to state "the hydrograph for the Amu Darya basin indicates three 19-year cycles from 1934 to 1992, while that of the Syr Darya basin indicates six 12-year cycles from 1928 to 1997."

Groundwater contributes additional water to river flow. Total renewable groundwater resources in the Aral Sea Basin may be 44 km^3/year with, perhaps, 16 km^3/year (36 %) usable (Micklin 2000, pp. 6–7).[3] Groundwater is a significant contributor to the flow of the Amu Darya and the Syr Darya in those rivers' headwaters whereas in the desert regions along the middle and lower courses, the rivers are net contributors to groundwater reserves via exfiltration from their beds. As a result, it is difficult to ascertain the net addition groundwater makes to

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[3] Usable is defined is that portion of the total resource that has sufficiently low salinity and depth from the surface that it is usable for drinking and economic purposes at a reasonable cost.

available water resources above and beyond its contribution to river flow. During Soviet times, Central Asian water experts estimated usable groundwater that was not connected with river flow at 17 km^3/year in the Aral Sea Basin (Micklin 1991, p. 99). Using this figure total basin water resources that are potentially usable (river flow + groundwater that is not connected to river flow) equals on an average annual basis about 133 km^3 (116 + 17).

At 133 km^3/year average annual water resources of the Aral Sea Basin are substantial. On a per capita basis (assuming a mid 2009 basin population of 55 million), they equal 2,418 m^3/person, whereas on a per unit area basis (assuming a basin area of 2.2 million km^2) they equal 60,455 m^3/km^2. However, such per capita and per unit area figures are meaningless. They do not take into account the sharp spatial discontinuities of the region in terms of where flow is generated and where people live and use water most heavily. On this basis, we may divide the basin into two basic zones. First are the upstream mountains where the flow is generated, which are sparsely inhabited and whose water use is far less than the available supply. This zone occupies only 20 % of the basin but generates 90 % of the flow for the Amu Darya and Syr Darya (Mamatkanov 1996). Second are the downstream arid plains (covering 80 % of the basin) where most of the population lives, where most of the water is used, and whose indigenous water resources are far less than use. The deficit in the plains is, of course, covered by outflows from the well-watered mountains.

Tajikistan and Kyrgyzstan occupy the core of the mountain zone of the basin and are “water rich”. The former supplies 51.5 % of average annual basin river flow of 116 km^3 and the latter 25.2 % for an aggregate contribution of 76.7 % (CAWATERinfo 2012a). Water withdrawals for the two countries together in 2010 were only 14.7 % (16.3 km^3) of the amount generated (CAWATERINFO 2012d). Consequently, these states are large net donors to basin water supplies. Afghanistan and Iran, but primarily the former, provide 9.3 % of Aral Sea Basin river flow. Their withdrawals are much less, probably not more than 1–2 % of the total, which also places them in the category of net upstream donors (World Bank and the ICWC 1996, p. 14).

The picture is exactly opposite for the downstream states of Uzbekistan, Kazakhstan, and Turkmenistan. They are large net consumers of basin water resources. Lying mainly on the arid plains of the Central Asian deserts, they contribute, as a group, only 14 % of Aral Sea Basin river flow. Possessing substantial irrigated areas, these states withdrew 93 km^3 in 2010 or 80 % of the total flow generated in the basin (CAWATERINFO 2012d). Uzbekistan contributes only 10.6 % of basin flow but its withdrawals in 2010 were 52 % of total flow generated. Turkmenistan contributes essentially no flow (most of the discharge of the Tedjen and Murgab rivers that enter Turkmenistan territory comes from Iran), but that nation’s withdrawals accounted for 22 % of flow generated in 2010. Kazakhstan contributes 2.2 % of aggregate basin flow, but 6.7 % of the flow for the Syr Darya River, and its withdrawals were 5.7 % of basin flow in 2010.

5.1.2 Sufficiency of Renewable Water Resources

A key question for management of water resources in the Aral Sea Basin and the future of the Aral Sea is the sufficiency of the resource to meet demand. On an average annual basis, an upper limit estimate of renewable water resources in the Aral Sea Basin is about 133 km^3 – 116 km^3 from the flow in the basins of the Amu Darya and Syr Darya, and 17 km^3 for groundwater not connected to river flow. Water withdrawals in 1960 are estimated to have been 61 km^3, in 1970 – 95 km^3, in 1980 – 125 km^3 in 1990 – 114 km^3, in 2000 – 96 km^3, and in 2010 – 109 km^3 (CAWATERinfo 2010b, Table 6; CAWATERINFO 2012d). The maximum withdrawals were attained in 1980 and minimum withdrawals in the severe drought years of 2000 and 2008 (89 km^3). These withdrawal figures are for the five former Soviet Republics (Kazakhstan, Uzbekistan, Kyrgyzstan Tadjikistan and Turkmenistan) and do not include withdrawals in Afghanistan and Iran (although these would be very small compared to the aggregate figures). They also should be viewed as reasonable estimates rather than precise measurements.

A portion of the flow withdrawn (estimated at near 24 km^3/year for 1990–1994) is returned to river channels, albeit with degraded quality, and is available for use downstream (ICAS 1996, Chap. 6). A large volume of withdrawn flow (estimated at 16 km^3/year for 1990–1994) ends up in desert depressions forming lakes from which it evaporates. This also is potentially usable for irrigation purposes, although the salinity of some return flow is too high for such use. Thus, total return flows are probably near 40 km^3 on an average annual basis. ICAS (1996) estimated that 36–38 km^3 (90–95 %) of this is potentially available for reuse. Including these reserves gives a total upper limit of near 170 km^3/year for the usable water resources in the basin. This is significantly more water than has been withdrawn, even in the peak use years of the early 1980s, and might suggest, at first glance, that there is plenty of water to go around for all basin countries and users, now and in the future.

Unfortunately the situation is more complicated and less sanguine. First, there are losses of flow that are unavoidable, or at least difficult and costly to reduce. The most important of these are filtration from the riverbed to surrounding land (exfiltration), evaporation from the river's surface and even more importantly reservoirs that have been created along the river, and transpiration from riparian vegetation. Such losses may run to 16 km^3 in average flow years along the Amu Darya and Syr Darya (ICAS 1996, Chap. 7, Tables 7.1 and 7.2). Losses to riparian vegetation owes primarily to water loving plants (phreatophytes) such as salt cedar, also known as tamarisk, (*gallica Linnaeus*), willow (*Salix*), and cottonwood (Populus) that grow along natural and artificial watercourses in arid regions. These plants have deep roots and can draw huge amounts of water from significant depths. This water is subsequently lost through their leaves or other parts adapted to transpiring water to the atmosphere.

Typical losses from these species in the Western U.S. are 14,300–16,800 m^3/ha for salt cedar, 13,400 m^3/ha for willow, and 15,800–23,200 m^3/ha for cottonwood

(Van der leaden 1990, pp. 117–124). Losses would be close to these in the climatically similar Aral Sea Basin. For comparison to a key irrigated crop in arid regions, cotton, in desert regions of the U.S. has water consumption rates from 7,000 to above more than 10,500 m^3/ha.

Secondly, river flow is uneven on an intra-and inter-annual basis. Thus, there are seasons and years when flows are much more than usage and other seasons and years when they are much less. Large dams and reservoirs are used to maximize the seasonal and multiyear availability of water by storing it during high flow periods (spring and early summer) and years for use during summer low flow periods of high demand and low flow years (Micklin 1991, pp. 4–7). However, it is neither economically feasible nor environmentally wise to totally regulate rivers, particularly those as large as the Amu Darya and Syr Darya. Economically, the marginal cost of total or near total regulation (i.e., storage of all or nearly all spring-early summer flow in every year for later release) would entail constructing costly additional storage capacity that is only filled for short periods. Such an approach would also mean that for substantial periods during the high flow season river beds below the dams would be dry or nearly dry for significant distances (to the next major tributary or next reservoir) with extremely serious negative environmental and sanitary consequences (Collier et al. 1996; Micklin 1996). Thus, not all the seasonal surplus flow, and especially the surplus flow in high water years, can be stored for times when flow is low and demand is high.

During the Soviet era large seasonal and multiyear storage dams were built on the Amu and Syr rivers and their major tributaries to increase water resource availability during low flow periods. The aggregate, usable storage capacity in the entire Aral Sea Basin at the end of the Soviet era in 1991 was about 44 km^3 (17 in the basin of the Amu Darya and 27 in the basin of the Syr Darya) (ICAS 1996, Chap. 6).[4] The largest storage facilities are the Toktogul (gross capacity of 19.5 and useable capacity of 14 km^3) on the Naryn River, the major tributary of the Syr Darya, and the Nurek (gross capacity of 10.5 and useable capacity of 4.5 km^3) on the Vaksh, the main tributary of the Amu Darya (Dukhovnyy 1993, p. 260; Askochenskiy 1967, p. 112; WARMAP Project 1997, p. 8).

The construction of large dams in the Aral Sea Basin essentially halted after the breakup of the Soviet Union owing to the new Central Asian nations lack of funds and construction expertise. Uzbekistan and Turkmenistan have or are completing a few moderate sized dams to serve irrigation purposes (Economic Commission for Europe 2007, Annex 1, pp. 46–55). On the other hand, both Kyrgyzstan and Tadjikistan, the upstream states where most of the river flow is generated are intent on constructing additional large dams for power generation purposes. Tajikistan has

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[4] The full water storage volume of a reservoir is termed gross capacity whereas that portion of it that can be drained and refilled is known as useable capacity. The difference is termed dead storage.

restarted work on the Rogun Dam on the Vaksh River above the Nurek structure on which preliminary efforts began during the Soviet era (Wikipedia 2012). If completed (a very large "if") this would be the highest dam in the world at 335 m. The downstream states (Kazakhstan, Turkmenistan, and Uzbekistan), particularly the last, are opposed to more large dams upstream of them on the Syr and Amu rivers, which they perceive as detrimental to their irrigation interest as they would be operated for maximum winter power production meaning less water would be available in the warm season for irrigation.

Storage has allowed the increase of the ensured yield of water (a measure of the flow available for use) in a 90 % flow year, occurring, on average, once in 10 years, to 52 km^3 on the Amu Darya and to 27 km^3 on the Syr Darya for a total of 79 km^3. A 90 % flow year is a probabilistic concept. It is a flow year, which analysis of a long record of annual flows, at least 30 years, indicates is likely to be exceeded 90 % of the time. Such probabilities are derived from the fitting of a theoretical probability curve to the flow record or plotting of the actual flow record on probability paper. The amount of water that is available in low flow years is, in fact, most crucial for water resource management. It is more indicative of the state of water resources in arid regions such as the Aral Sea Basin than the average annual figure, which is biased by the high flow years, much of whose flow neither can be stored nor used.

Examining water availability in low flow years, which usually occur in cycles in arid regions rather than being randomly distributed, the situation looks much less sanguine than the average annual flow scenario presented above. Taking the 79 km^3 figure for a 90 % flow year and subtracting "unavoidable" losses of 16 km^3, only 64 km^3 remain as the usable resource. Assuming the maximum usable irrigation return flows of 38 km^3 and groundwater additions of 17 km^3, would give a total available resource of 119 km^3. This figure is slightly exceeded by withdrawals characteristic of the early 1980s although above more recent figures such as the 109 km^3 estimate for 2010. Furthermore, to reach the 119 km^3 figure assumes two critical preconditions. First, storage of nearly all spring high flows for later use, and filling of the multiyear reservoirs to capacity at the beginning of the "dry" period. Second, full use would need to be made of usable groundwater and of return flows that do not reach rivers. In 1992, for example, estimates are that around 12 km^3 of the former (71 %) were used, and only 6 km^3 (38 %) of the latter (ICAS 1996, Chap. 7, Table 7.2).

In reality, during low flow years, withdrawals from the Amu and Syr river systems in the downstream net consuming countries of Uzbekistan, Kazakhstan, and Turkmenistan are, of necessity, substantially reduced (as are return flows). Furthermore, it is these years that cause heightened tensions among the states of the basin as the "down streamers" try to maximize their share of water coming from the "upstreamers" (Tajikistan and Kyrgyzstan). The former also apply pressure on the latter, which is strongly resisted, to increase the amount of water delivered downstream by reducing their usage and releasing more water from reservoirs on their territory.

5.2 Aral Water Balance Changes 1911–2010

The Aral Sea as a terminal (closed basin) lake has an average annual water balance that may be represented by the following equation where the gain side of the balance is on the left of the equals sign and the loss side on the right (Micklin 1991, p. 104; Bortnik and Chistyaevaya 1990, pp. 34–35; Vikulina 1979, pp. 21–25):

$$Q_r + Q_u + (Qc \ast F)/10^6 + (P \ast F)/10^6 = (E \ast F)/10^6 \pm (\Delta H \ast F)/10^6,$$

where

Q_r is average annual river inflow in km^3; Q_u is average annual net groundwater inflow (inflow of groundwater to the lake minus outflow of water through the bottom and sides of the lake) in km^3; Q_c is average annual condensation of water vapor on the lake surface in millimetres (mm); F is the average annual area of the lake in km^2; 10^6 is a proportionality constant of mm/km to keep the equation parameterised; P is average annual precipitation on the lake surface in millimetres; E is average annual evaporation from the lake surface in millimetres; and ΔH is the average annual change in level in millimetres.

During Soviet times, net groundwater inflow and condensation were usually ignored because they were considered of minor size compared to the other gain components and impossible to measure accurately. However, as river inflow to the sea rapidly decreased after 1960, net groundwater input has become a significant part of the gain side of the water balance.

As the modern recession of the Aral has unfolded since 1960, the sea's water balance has been dramatically altered. Figures 3.1 and 3.2 are an attempt to illustrate these changes. The format used is based on the water balance equation shown above with two simplifications for easier understanding. First, all figures are given in cubic kilometers. Second, precipitation on the sea's surface has been subtracted from evaporation on it to create a net evaporation parameter. Because of the growing relative importance of groundwater inflow to the sea's water balance as the sea has shrunk, an estimate of this parameter, however imprecise, is included, which was not the case with the most detailed and accurate water balance estimate produced for the Aral by Bortnik and Chistyayeva (1990, pp. 34–43) at the end of the Soviet period. It must be emphasized that the water balance figures shown in Figs. 3.1 and 3.2 are reasonable estimates based on the best available data and calculations, but do not in any way represent exact measurements of any of the water balance parameters.

5.2.1 Water Balance 1911–1960

The period 1911–1960 was characterized by water balance stability. As noted earlier, the lake's level was measured by the gage installed at Aralsk located at the extreme north end of the sea beginning in 1884 (but consistent, regular observations were not started until 1911). Average annual Lake level from 1911 to 1960 varied only 0.9 m, with a low of 52.5 m in 1920 and a high of 53.4 m in 1960 (Cawaterinfo 2012c; Asarin and Bortnik 1987). Regular measurements of a number of key hydrometeorological variables necessary to calculate water balance parameters, including air and water temperature, water salinity, humidity, precipitation, and wind speed began in 1929, when a hydrometeorological station was installed near Aralsk (Bortnik and Chistyaevaya 1990, pp. 10–12). Between then and 1961, eight other facilities were erected at other locations around the sea to not only measure levels but also hydrometeorological parameters.

River flow measurements on the lower Syr Darya at Kazalinsk began in 1912 and on the lower Amu Darya at Chatly in 1913 (Uzglavgidromet 1994–2003). However, both sites had problems with missing data for some months and the Syr even had 2 years with no data collection (1923 and 1933). Hence reasonably reliable estimates of river flow to the Aral for the "quasi-stationary" period of water balance equilibrium (1911–1960) are only available from 1926, with the accuracy increasing with time. Measurements were made some distance upstream from the river mouths (at Kazalinsk on the Syr Darya and at Chatly, 240 km from the mouth, on the Amu Darya) and then corrected for estimated losses in the deltas, chiefly to evaporation from open water surfaces and transpiration from water loving (phreatophytic) vegetation (Bortnik and Chistyaevaya 1990, pp. 35–36).

In the book edited by the last two experts, the estimated average annual loss of flow in the Amu delta below Chatly for 1911–1960 is 6–10 km^3/year. Losses in any given year were heavily dependent on the flow volume reaching the head of the delta. In low flow years, deltaic losses were estimated to range from 0.5 to 2.0 km^3, whereas in high flow years they could reach 15–20 km^3 (Shiklomanov 1979, p. 229). Flow loss in the Syr Darya Delta below Kazalinsk has been estimated from 0 to as much as 1.5 km^3, again depending on the amount of flow reaching the delta.

Measurements of precipitation at the nine shore and island stations were used in the most authoritative available set of water balance calculations (Bortnik and Chistyaevaya 1990, pp. 36–38). Determining sea surface evaporation was a more difficult task. Some meteorological stations had equipment for direct measurement of water surface evaporation (tanks with 20 m^2 surface areas), but the data received were too scattered or unreliable to be of much use (Gorelkin and Nikitin 1985). Hence, the study edited by Bortnik and Chistyayeva placed reliance on a modification of a semi-empirical formula developed by N.P. Goptarev. This method manipulated measurements of water surface (or ice) temperature, sea surface salinity and roughness, air temperature and humidity near the sea surface, and wind speed, to determine monthly values of evaporation.

Figure 5.1 and Table 5.1 show that for the period 1911–1960 the water balance was near equilibrium. Estimated average annual river inflow was 56 km^3 and net evaporation 57 km^3 (evaporation from the sea's surface of 1,000 mm minus precipitation on the surface of 138 mm for a net loss of 862 mm) (Bortnik and Chistyaevaya 1990, Table 4.1, p. 36). Net groundwater inflow was disregarded because of its small impact on the water balance. This author's admittedly imprecise estimate of this parameter is 2 km^3/year. Soviet experts' estimates ranged from

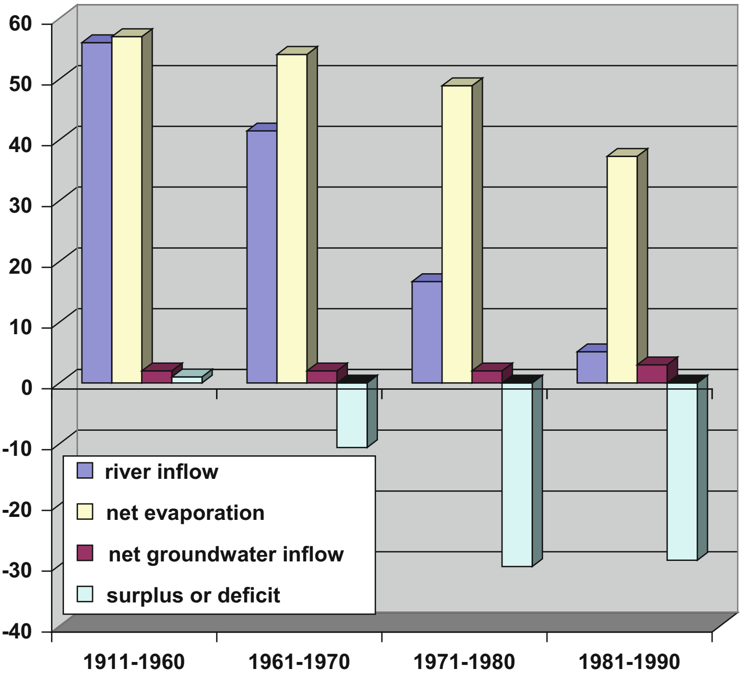

Fig. 5.1 Estimated water balances for the Aral Sea, 1911–1990

Table 5.1 Estimated water balances for the Aral Sea, 1911–1990

Period	Average river inflow (km^3)	Average net evaporation (km^3)	Average net groundwater inflow (km^3)	Average deficit or surplus (km^3)
1911–1960	+56	−57	+2	+1
1961–1970	+41.5	−54.1	+2	−10.6
1971–1980	+16.7	−48.9	+2	−30.2
1981–1990	+5.1	−37.3	+3	−29.2

Sources: Asarin and Bortnik (1987), Micklin (1990–2012) and Uzglavgidromet (1994)

[a] River inflow = flow of Syr Darya and Amu Darya to the Aral Sea

[b] Net evaporation = evaporation from the sea surface minus precipitation on it

[c] Net groundwater flow = groundwater inflow to sea minus outflow from sea

[d] Surplus or deficit = river inflow to sea plus net groundwater inflow to sea minus net evaporation from sea

−1.3 to 3.4 km^3 (Bortnik and Chistyaevaya 1990, p. 38). The overall water balance was slightly positive with a surplus of 1 km^3.

Even though the water balance was in essential equilibrium for the 1911–1960 period, there was substantial annual variation for the key parameters of river inflow and evaporation. River discharge to the sea for the period 1926–1960 (for which continuous data exist) varied from a high of 65 km^3 in 1934 to a low of 43 km^3 in 1947, whereas evaporation ranged from a high of 77 km^3 in 1948 to a low of 44 km^3 in 1950 (Asarin and Bortnik 1987).

Irrigated agriculture was widespread in the Aral Sea Basin during the 1911–1960 period. The irrigated area in 1913 has been estimated at around 3 million ha, growing to around 4.5 million ha by 1960 (Micklin 2000, Table 3, p. 28; Dukhovnyy 1993, Table 8, p. 56). Consumptive withdrawals (water that is withdrawn but not returned) from rivers, chiefly the Amu and Syr and their tributaries, in the Aral Sea Basin, due overwhelmingly to irrigation reached an estimated average of 40 km^3 for the period 1951–1960 (Bortnik and Chistyaevaya 1990, p. 35). Construction on the gigantic Kara-Kum Canal started in 1954. It began to draw water from the Amu Darya in 1956 to meet the water needs of Turkmenistan (mainly for irrigation). All of the water diverted into it was lost to the river as irrigation drainage flows ended up in the Kara-Kum desert and evaporated.

New reservoirs were also built that contributed to water losses owing to their filling and filtration losses through their bottom and sides. However, these were one-time events in the case of the former and short-term losses (periods of years) in the case of the latter. More serious was increased evaporation from the surfaces of the reservoirs. For example the Kayrakkum Reservoir on the Syr, with a volume of 4.2 km^3, filled between 1956 and 1959. With an area of area of 510 km^2, and an evaporation loss averaging 1,376 mm/year (determined from observations at a 20 m^2 evaporating basin for the period 1962–1980), the annual volumetric loss since filling has been around 0.7 km^3/year (Avakyan et al. 1987, Appendix 1, p. 308; Gorelkin and Nikitin 1985.)

A legitimate question is why didn't consumptive withdrawals and reservoir creation have a significant negative impact on the water balance, leading to reduced inflow to the Aral and a drop in lake levels by the 1951–1960 period? Two factors primarily explain this seeming contradiction. First, losses to irrigation (see Chap. 8) were largely compensated by reduced evaporation, reduced transpiration from water-loving plants (phreatophytes), and reduced filtration along the lower reaches and especially in the deltas of the Amu Darya and Syr Darya, primarily owing to the truncation of spring floods that diminished flood plain inundation and the area of deltaic wetlands and lakes (Micklin 1991, p. 45). Second, the decade 1951–1960 experienced heavier than normal river flow out of the mountain source regions (Asarin and Bortnik 1987, estimate the flow into the Aral for this period at 57 km^3/year) that likely "masked" the effects on discharge to the sea of growing irrigation withdrawals and new, large reservoirs. This situation changed in the next decade.

5.2.2 Water Balance Changes 1961–1970

The subsequent 10-year period (1961–1970) saw the beginnings of the modern recession (Fig. 5.1 and Table 5.1). Calculations based on water balance data provided to the author by Asarin and Bortnik (1987) show river discharge to the

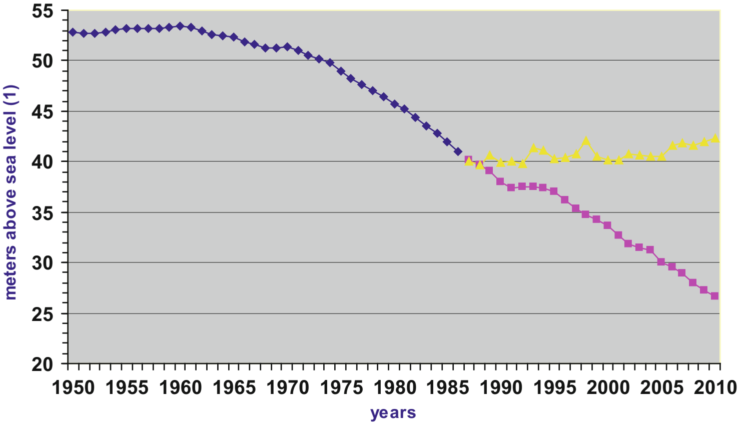

Fig. 5.2 Water level of the Aral Sea, 1950–2010 (Measured in reference to the Baltic Sea level gage at Kronstadt Russia on the Gulf of Finland, which is approximately 20 cm above sea level) *blue line* is entire Aral; *yellow line* is Small Aral, *purple line* is Large Aral (Sources: Asarin and Bortnik (1987), Uzglavgidromet (1994–2012), and Cretaux 2012)

sea averaged 41.5 km^3/year and net evaporation (evaporation layer of 991 mm minus precipitation layer of 132 mm) 54.1 km^3/year over these years. The author of this chapter's estimate of net groundwater input is 2 km^3/year, giving a deficit of 10.6 km^3/year. Water balance estimates for this period are likely the most accurate for the entire time from 1911 to 2010. The key reason is that inflow from the Amu Darya, accounting for about 75 % of the inflow to the sea during this period, was based on direct measurements at the settlement Temirbay only 25 km from the mouth, where observations started in 1955 (Bortnik and Chistyaevaya 1990, p. 35).

Over the 10 years, average annual sea level declined from 53.3 to 51.4 m, a drop of 1.9 m. The decadal decline occurred relatively gently averaging 0.2 m/year (Fig. 5.2). Indeed, average sea level even went up slightly in 1969 and 1970 owing to unusually high flow from the mountain source regions in the former year, when discharge to the sea reached 71 km^3 – the highest recorded since accurate record keeping began in 1926. Flow was so great on the Syr that the newly completed Chardarya dam could not handle the volume and it was necessary to divert flow into the Arnasay lowland nearby forming a large lake of the same name that persists because of irrigation drainage and irregular diversions from the Syr.

The Aral received considerably less inflow during the other years, ranging from a low of 28 km^3 in 1965 to a high of 50 km^3 in 1964. The area of the sea shrank from 67,400 to 60,900 km^2, a 6,500 km^2 (10 %) loss whereas the volume dropped from 1,081 to 962 km^3, a 119 km^3 (11 %) reduction. River flow through the deltas of the Amu and Syr had one positive impact on the quantity of water reaching the sea: they reduced deltaic losses to an estimated average level of 3.9 km^3 from the 7.8 km^3 for the much higher flow period 1951–1960 (Ratkovich 1993, Table 8.4, p. 324).

It should be noted that the water balance of a shrinking water body, such as the Aral, has a powerful negative feedback component (i.e. one that promotes a system to return to stability) in that as the surface area shrinks, volumetric evaporative losses decrease, leading ultimately to a new equilibrium.

The causes of the level drop were both natural and anthropogenic. The study edited by Bortnik and Chistyayeva (1990, Table 4.4, p. 43) assigns 59 % of the drop to natural factors and 41 % to human influences for this period. The chief natural factor was the start of a lengthy series of low flow years owing to reduced precipitation in the mountain zones of river flow formation. A second less important influence was some increase in the per-unit-area surface net evaporation, which averaged 860 mm for the 10-year period compared to 801 mm for the preceding decade (Asarin and Bortnik 1987).

Shiklomonov (1979, Table 30, p. 235), an expert on human impacts on river flow, on the other hand, saw the human influence on inflow to the Aral as considerably stronger for the period 1961–1970. He estimated little reduction in annual flow generation from source regions compared to the preceding 10-year period (a drop from 112 to 110 km^3) and contended that 90 % of the decline in average inflow from 54.5 km^3 for 1926 to 1960 to 40.9 km^3 for 1961 to 1970 owed to human activities and only 10 % to natural factors. Another group of experts also support this view (Shapiro et al. 1985). Comparing 1916–1960 to 1961–1970, they estimated a drop in average annual source region flow formation only from 117 to 112 km^3 (4 %), flow to the heads of the two deltas (Syr and Amu) falling from 63 to 46 km^3 (27 %), losses in the deltas declining from 7 to 3 km^3 (57 %) and the resultant inflow to the Aral dropping from 56 to 43 km^3 (23 %).

Further development of irrigation was the key human dynamic. The estimated annual average consumptive use of water in the Aral Sea Basin for this period, overwhelming for irrigation, grew to 55–57 km^3, a 38 % increase over the 1951–1960 figure, as the irrigated area rose over 5 million ha (Bortnik and Chistyaevaya 1990, p. 35; Dukhovnyy 1993, Table 8, p. 56). The average withdrawal for irrigation grew by 35 %, from 12,450 m^3/ha in 1960 to 16,860 m^3/ha in 1970 (Diagnostic Report, no date, Table 10). Contributing to this was irrigation of new areas in the Golodnaya (Hungry) Steppe in Uzbekistan that required more water per hectare to fill pore spaces and leach excessive salt from the soil, increased dumping of drainage water into the desert where it formed terminal evaporative lakes rather than being partially returned to its source rivers, and growing diversion of water into the Kara-Kum Canal.

New reservoirs also went into operation during this period. Chardarya on the Syr, filled in 1967–1968, is the largest with a volume of 5.7 km^3 and surface area of 900 km^2. Its annual evaporative layer is estimated at 1.2 m, giving an average annual loss of a little more than 1 km^3 (Gorelkin and Nikitin 1985). All these factors contributed to the decreased flow of the Syr Darya and Amu Darya and their lessened input to the Aral Sea (Micklin 1991, p. 46). The capacity of the natural system to compensate for increasing irrigation water withdrawals, as explained above, was exhausted and the long and steady human induced recession of the Aral that continues today began.

5.2.3 Water Balance Changes 1971–1980

The sea's water balance became considerably more negative in the next decade (1971–1980) as shown on Fig. 5.1 and in Table 5.1. Average yearly river inflow, measured at Temirbay, fell to 16.7 km^3 – a nearly 60 % decrease from the previous decade (Asarin and Bortnik 1987). The maximum and minimum annual discharges occurred in neighboring years: 1973 (48 km^3) for the former and 1974 (7.5 km^3) for the latter. The second half of this period saw especially low inflow to the Aral, averaging only 14 km^3, versus 25 km^3 for the preceding 5 years. Average net evaporation also decreased owing to a shrinking surface area, but only by 9 %. The same groundwater input of 2 km^3 as for the previous period is assumed. The water balance deficit rose to 30.2 km^3, an increase of 63 %. Consequently, sea level fell rapidly from 51.1 to 45.8 m, an overall decline of 5.3 m at an annual rate of 0.53 m (Fig. 5.2). Sea surface area shrank from 60,200 to 51,400 km^2, a reduction of 8,800 km^2 (15 %) whereas volume dropped by 31 % from 940 to 648 km^3. The small decline in net evaporation reflects the loss of parts of the sea where the bottom had a relatively steep slope so that the decrease in surface area per meter of sea level drop was modest. This also explains the larger relative reduction in volume versus area.

As in the previous decade, diminution of flow and the consequent level drop owed to both natural and human factors. The low river flow cycle that began in the 1960s continued through the 1970s. In the absence of growing human impacts, sea level likely would have only dropped about 1.2 m (Bortnik and Chistyaevaya 1990, Table 4.4, p. 43). It actually declined 5.15 m, indicating that lessened flows from source regions contributed about 23 % of the decline and anthropogenic factors about 77 %. Consumptive use, almost all owing to irrigation, rose to an estimated 64–66 km^3/year as the irrigated area grew to more than 6.9 million ha, irrigation continued to be expanded into steppe and desert regions, and more irrigation drainage water was sent into terminal lakes. The two largest of these were Arnasay near the Chardarya reservoir on the Syr Darya and the Sarykamysh depression located west of the lower course of the Amu Darya.

Two very large reservoirs, the Nurek on the Vakhsh, the major right bank tributary of the Amu Darya, and the Toktogul, on the Naryn, the largest tributary of the Syr Darya, were completed during this period. The former, filled in 1972, had a volume of 10.5 km^3 and the latter, filled in 1973, a volume of 19.5 km^3. Their filling caused losses of more than 30 km^3 to the discharge of the two rivers over the 10-year period and had a major impact on inflow to the Aral. The two reservoirs, which are located in deep valleys in the mountains, have relatively small areas (100 km^2 for the Nurek and 285 km^2 for the Toktogul) for their volumes and, given the cooler annual temperature cycle, a modest layer of evaporation from their surfaces. Hence, they contribute little to evaporative losses from the rivers compared to the shallow downstream plains reservoirs with much higher evaporation rates and considerably larger areas.

5.2.4 Water Balance Changes 1980–1989

The 10-year period 1981–1990 was another dire decade for the Aral's water balance. River inflow to the sea was very low, averaging only about 5 km^3/year – 76 % lower than the previous decade (Asarin and Bortnik 1987; Uzglavdiromet, 1994–2003; Micklin 1990–2012). For most of the period, Amu Darya flows were measured at the village of Kyzyldzhar, which was located about 70 km up river from the gauge at Temirbay (closed in 1982), and about halfway between that village and the earlier used measuring point at Chatly (Bortnik and Chistyaevaya 1990, p. 35). Flows at Kyzyldzhar were then adjusted for average annual downstream losses estimated by Ratkovich (1993, Table 88, p. 334) at 2.5 k^3/year. Owing to upstream movement of the lowest gauging point, the inflow figure for the Amu is not as accurate as for the preceding two decadal periods when flow data from Termirbay were available. The measuring point on the Syr remained at Kazalinsk. Ratkovich (1993, Table 88, p.334) cites average annual losses in the Syr delta of 1.2 km^3. According to Uzglavgidromet (The Main Administration of Hydrometeorology of Uzbekistan) the Amu Darya contributed 2.8 km^3 and the Syr Darya 1.1 km^3 on an average annual basis for the period (Uzglavgidromet 1994–2003; Micklin 1990–2012).

Uzglavgidromet estimated that there was no inflow to the sea from either river in 1982–1983 and in 1985–1986. Maximum discharge of 16 km^3 was in 1986. As the sea shrank, annual net evaporation also dropped to 37 km^3, 25 % below the figure for 1971–1980. Net groundwater input is assumed at 3 km^3/year – slightly higher than for previous time periods – based on the assumption that the dropping sea level increased the groundwater hydraulic gradient and led to more inflow. The resultant water balance deficit was 29.2 km^3.

The Aral Sea separated into two water bodies between 1987 and 1989 as the Berg Strait connecting the Small and Large Sea closed. However, a channel (more akin to a river) of considerable width continued to connect them. The Syr Darya shifted its course slightly northward and entered into the Small Sea just north of the connecting channel. The flow of the Syr into the Small Sea stabilized its level and even gave it a somewhat positive water balance with the surplus water flowing from the higher level Small Sea toward the lower level Large Sea. This flow was especially strong during the spring/early summer (late March – late July) high flow phase on the Syr Darya and typically dwindled to near zero from late November until early March. The Level of the Small Sea declined from 45.2 in 1981 to 39.6 m in 1990 whereas the Large Sea fell from 45.2 to 38 m, a rate of 0.72 m/year, over the same period (Fig. 5.2). The overall area of the sea shank from 50,400 to 40,600 km^2 (20 %) and the volume decreased from 648 to 318 km^3 (51 %).

Irrigation continued as the dominant factor in the Aral's recession during this period. Annual water withdrawals for irrigation are estimated at 104 out of total withdrawals for all purposes of 125 km^3 for 1980 and 91 out of 114 km^3 for 1990, as the irrigated area rose from 6.56 to 7.77 million ha (CAWATERINFO 2012d). Peak usage was reached in 1980 with some decline toward the end of the decade in spite of a larger area irrigated because of a significant decline in per hectare water use. Annual average consumptive use has been estimated at 70–75 km^3/year for 1981–1985 (Bortnik and Chistyaevaya 1990, p. 35). Withdrawals from the Amu Darya into the Kara-Kum Canal continued to grow, reaching 12 km^3 in 1987 (Micklin 1991, p. 46.). From 1956 through 1987, the canal accounted for 236 km^3 of water loss to the Amu.

Also contributing to diminished inflow to the Aral was the construction of the Tyuyamuyun reservoir, situated at the head of the Amu Delta, with a volume of 7.3 km^3 that was filled in 1984 (Avakyan et al. 1987, Appendix 1, p. 311). With an area of 780 km^2 and an estimated annual average evaporation layer of near 1600 mm, its average annual evaporation loss is around 1.25 km^3 (Gorelkin and Nikitin 1985, Fig. 8, p. 22).

5.2.5 Water Balance Changes 1991–2000

The estimated Aral water balance for 1991–2000 is shown on Fig. 5.3 and in Table 5.2. For this and the next decade (2001–2010) the author of this chapter has calculated separate water balances for the Small Aral Sea and the Large Aral Sea. The reasoning is that these became separate water bodies with their own distinctive hydrologic characteristics by the end of the 1980s. For several reasons, the water balance parameters are not nearly as accurate as those for the 1961–1990 period. First, is the lack of reliable hydrometeorological data for the sea for these two periods owing to the closing of most of the hydromet stations around the sea in the 1980s as the sea receded (Bortnik and Chistyaevaya 1990, Tables 1.2, p. 11 and 2.1, p. 12). By the early 1990s only two of the nine stations continued in service. These were Aralskoye morye (Aral Sea) located near the city of Aralsk on the Small Aral and Aktumsyk on the Ust-Urt Plateau near the western shore of the Large Aral. Even though Aralskoye morye remained open, its observations became less representative of seaside conditions as the shallow Gulf of Saryshaganak on which it lies rapidly shrank. By 1990, the station was 45 km from the shoreline. Aktumsyk, on the other hand, remained relevant as its location near the shore of the Western Basin of the Large Aral with its steep shoreline gradient allowed it to continue providing data of near shore meteorological conditions as well as reasonably accurate, level readings from gauges maintained in the sea itself (Micklin 2005). Both the Aralskoye morye and Aktumsyk stations continue to operate today and the latter in 2004–2005 was re-equipped with modern meteorological instrumentation provided by USAID (United States Agency for International Development).

A second problem is that estimates of inflow to the Large Aral from the Amu Darya became less reliable as the shallow Eastern Basin rapidly shrank and the distance from the nearest gauging station (Kyzylzhar) and the shore rapidly increased. Estimating water losses between there and the sea became very difficult, as they not only consisted, as earlier, of those owing to natural factors but also

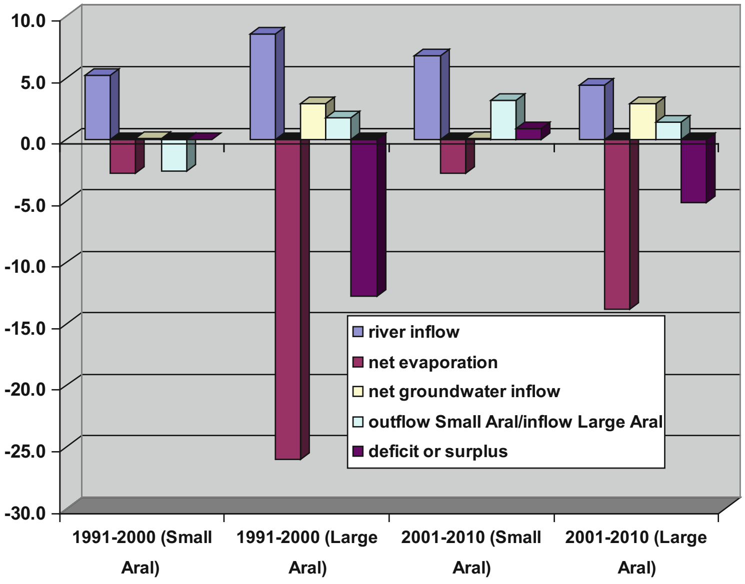

Fig. 5.3 Estimated water balances for the Aral Sea 1991–2010

Table 5.2 Estimated water balances for the Aral Sea 1991–2010

Water body and period	Average river inflow (km^3)[a]	Average net evaporation (km^3)[b]	Average net groundwater inflow (km^3)[c]	Outflow Small Aral inflow Large Aral (km^3)[d]	Average deficit or surplus (km^3)[e]
Small Aral 1991–2000	+5.2	−2.7	+0.1	−2.6	0.0
Large Aral 1991–2000	+8.6	−2.6	+2.9	+1.8	−12.7
Small Aral 2001–2010	+6.8	−2.8	+0.1	−3.2	+0.9
Large Aral 2001–2010	+4.4	−13.8	+2.9	+1.4	−5.1

Source: Micklin (1990–2012)

[a] River inflow = flow of Syr Dar'ya and Amu Dar'ya to the Aral Sea

[b] Net evaporation = evaporation from the sea surface minus precipitation on it

[c] Net groundwater flow = groundwater inflow to sea minus outflow from sea

[d] Outflow Small Aral/inflow Large Aral = discharge from Small Aral southward toward Eastern Basin of Large Aral and estimated volume of water reaching Eastern Basin of Large Aral

[e] Surplus or deficit = river inflow to sea plus net groundwater inflow to sea minus net evaporation from sea

growing man-made diversions to maintain wetlands and lakes (e.g., Lake Sudochye), shallow reservoirs (e.g., Mezhdurechiye), and former gulfs (Adzhibay, Rybatskiy, Muynak, Zhilterbas) for ecological and economic reasons (Micklin 2007).

Attempting to estimate water losses for the residual Amu Darya as it flowed across the sandy, barren, and dry bottom of the Aral was very difficult if not impossible.

Finally, there is the problem to estimate the flow from the Small Aral to the Large Aral via the channel formed in the former Berg strait that connected them. The flow was not measured by any standard hydrologic method, although there were sporadic observations as to the width and approximate speed of the current, including by Aladin and Plotnikov, associate editors of this book (Aladin et al. 1995). Furthermore, much of the water passing through this channel was subsequently lost to evaporation from the series of large, shallow lakes formed along the route to the Eastern Basin of the Large Aral Sea and to transpiration from hydrophytes (the most common being reeds) growing in and along the shoreline of these lakes.

In spite of these caveats, the author of this chapter believes it is possible to provide a reasonably clear picture of the approximate size and trends of water balance parameters for the 20-year period 1991–2010. For this he has relied on information from a variety of primary and secondary sources, including that gathered during a number of short-term and long-term visits to the Aral Sea and countries of the Aral Sea Basin (Uzglavgidromet 1994–2003; Micklin 1996–1997, 2005, 2007). A series of annual flows for the Amu Darya at the Takhiatash Dam, representing flow to the lower Amu Delta and the Large Aral Sea and for the Syr Darya Delta at Kazalinsk, representing flow to the Syr Darya Delta and Small Aral Sea, for the period 1992–2011 have also been of great value in creating an annual inflow series for the Amu Darya and Syr Darya. These stations are some distance up river from the seas. Hence, flows measured at each must be adjusted for estimated downstream losses. Estimated inflow to the Small Sea from the Syr is much more accurate than estimates for the Amu owing to more and better data and lesser distances to the water body from measurement points, thus requiring smaller relative corrections.

The author has created an Excel based annualized physical water balance model of the Aral Sea for 1987–2011 (Micklin 1990–2012). This has been used to calculate the level, area, and volume for the Small and Large Aral seas on January 1 of each year from 1988 to 2011. Key input data have been (1) Soviet and post Soviet data on river inflow to the sea (corrected for estimated losses between the gauging stations and the sea) and on sea levels, (2) estimates of flow from the Small to Large Aral taken from published sources and also derived as residuals from the water balance of the Small Aral, (3) estimates of the layer of net evaporation based on published sources giving surface evaporation from and precipitation on the Small and Large Aral Seas, (5) the author's estimates of net groundwater inflow based on published sources, (6) sea bathymetry data taken from Bortnik and Chistyayeva (1990, Table 1.1, p. 8) and from the 1:500,000 scale bathymetric map of the Aral Sea (Aral Sea 1981), (7) NASA MODIS satellite imagery of the Aral used to determine when the Amu's flow reached the Eastern Large Aral in the years 2001–2010, and (8) very importantly, the satellite radar altimetry derived sea level data set provided the author by Dr. Jean-Francois Cretaux of the Laboratory for the study of Geophysics and Ocean Topography in Toulouse, France.[5] (See Chap. 11 written by Dr. Cretaux).

The period 1991–2000 saw higher river flows for both the Syr Darya and Amu Darya from the mountain source regions than had been experienced since the 1950s (Zholdaseva 1999). Average annual inflow to the entire sea is estimated at 13.8 km^3, 3.5 fold greater than for 1981–1990 (Micklin 1990–2012; Micklin 2005). Syr Darya average discharge to the Small Sea is set at 5.2 km^3/year. Maximum annual inflow on the Syr was in 1994 (8.5 km^3). Minimum discharge was in 2000 (0.3 km^3). Net annual average evaporation (E of 960 mm – P of 120 mm) was 2.7 km^3 and groundwater input assumed to be 0.1 km^3. The Small Sea experienced a positive water balance for this period, which resulted in average annual outflow of 2.6 km^3 toward the Eastern Basin of the Large Aral.

The average annual level of the Small Sea was about 40 m in 1991 and 40.2 m in 2000, for a difference of only 0.2 m. In the former year the area (on January 1) was calculated to be 3022 km^2 and the volume 20.9 km^3 (Micklin 1990–2012). In the latter year the corresponding figures were 3,138 km^2 and 21.2 km^3. However, there were variations in this parameter over the decade as local authorities blocked the connecting channel with a low earthen dike to improve ecological and fishery conditions by raising and stabilizing the level that also resulted in lower salinities. The first earthen dike was constructed in 1992. In ensuing years, it periodically breached, lowering water levels, but then was repaired, raising them again. In April 1999 the level reached more than 43 m above sea level (asl) and during a storm on April 20 the dike was completely destroyed with the loss of two lives (Micklin 2010).

Estimated average annual inflow to the Large Aral from the Amu Darya for 1991–2000 is estimated at 8.6 km^3, more than double the 4 km^3 of the previous 10 years. Maximum inflow was in 1996 at 21 km^3, followed closely by 1994 (17 km^3) and 1998 (16 km^3). The minimum flow year was 2000 (a severe drought began in the middle of this year – see Agrawala et al. 2001) at 0.3 km^3 with 1995 in second at 2 km^3. Inflows for the first 5 years averaged around 12 km^3. They were considerably greater than for the last 5 years that averaged around 5 km^3. Average net groundwater input is assumed at 2.9 km^3. Average annual inflow from the Small Aral is calculated at 1.8 km^3 (this figure is 0.8 km^3 lower than outflow from the Small Aral to account for substantial evaporation, transpiration, and infiltration losses from the series of shallow lakes that constitute its route to the Large Aral). Thus the positive side of the water balance was 13.3 km^3. This was not nearly enough to balance the average loss over the period to net evaporation of 26 km^3/year and resulted in an annual deficit of 12.7 km^3.

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[5] Aral Sea levels since late 1992 have been determined most accurately and regularly by Jean Francois Cretaux of the Laboratory for the study of Geophysics and Ocean Topography (Laboratoire d' Etudes en Geophysique et Oceanographie Spatiales) in Toulouse, France using radar altimetry data from the Poseiden/Jason/Topex satellites. He has been able to determine sea level every ten days with an accuracy of ±12 cm at the 95 % confidence level (two standard deviations).

Owing to the large water balance deficit, the level of the Large Aral (calculated on January 1) fell from 37.4 to 32.8 m, between 1991 and 2000 (Fig. 5.2). The area shrank from 32,976 to 25,533 km^2, a loss of 7,443 km^2 (23 %) whereas volume decreased from 276 to 169 km^3 (39 %) (Micklin 1990–2012).

Irrigation, as in previous periods, was the dominant factor in the Aral's recession. Annual water withdrawals for irrigation are estimated at 91 out of total withdrawals for all purposes of 114 km^3 for 1990 and 75 out of 96 km^3 for 2000 (Cawaterinfo 2012d). Over this period, the irrigated area rose from 7.77 to 8.43 million ha. The drop in withdrawals for irrigation while the irrigated area rose reflects a drop in average withdrawals from 11,711 m^3/ha in 1990 to 8,897 in 2000. This resulted from a reduction of the irrigated area devoted to cotton and rice, higher water use crops, and expansion of the area of irrigated winter wheat, a lower water use crop (Micklin 2000, pp. 36–42). It was also a result of 2000 being a severe drought year, which forced water withdrawal limitations on irrigators.

Diversions from the Amu Darya into the Kara-Kum Canal continued to be an important source of water loss to the Aral Sea. No new large reservoirs were put into operation during this period.

5.2.6 Water Balance Changes 2000–2010

During these years the Small and Large Aral seas continued to develop as essentially separate water bodies. There was continued outflow during the Syr Darya's spring high-flow period from the former to the latter via a channel until mid 2005 and from then until 2010 owing to releases from a dam built to regulate the outflow (more details below). But as time passed, this connection became longer and more tenuous as the Eastern Basin of the Large Sea rapidly shrank and more water traveling south evaporated and infiltrated from the shallow lakes formed and transpired from the hydrophytic vegetation on their shores.

The water balance of the Small Aral, as in the prior decadal period, was positive (Fig. 5.3 and Table 5.2). Annual average river inflow is estimated at 6.8 km^3 – 31 % more than during the previous decade. River inflow data used for 2001–2005 are considered highly accurate as they are based on measurements made at the Ak-Lak gauge near the village of Karateren that is only 15 km from the shoreline of the Small Sea. These were reduced by 10 % to account for losses in the new delta of the Syr Darya that formed as the sea receded. River flow data for 2006–2010 are less precise. They are based on flows to the Aral Sea and Syr Darya Delta (assumedly measured at the Kazalinsk gauging station) published on the CAwaterinfo website (Cawaterinfo 2012e, f). These flows are for the vegetation (April-September) and non-vegetation periods (October – March), which constitutes the hydrologic as opposed to calendar year. The author annualized these data. He then compared flows for the overlapping years 1997–2005 at Ak-Lak and Kazalinsk, which showed an average difference for the 9-year period of 19 % less flow at the former than latter location. Based on this, the flows for years 2006–2010 at Kazalinsk were reduced by 19 % to create a synthetic flow series for these years at Ak-Lak. These Ak-Lak figures were then reduced by 10 % the same as was done for the data for 2001–2005 to create a consistent inflow series to the Small Aral.

For the 10-year period, the lowest inflow was in 2001 at 3.23 km^3. Three consecutive years were essentially tied for high inflow (2003, 2004, and 2005), which in order registered 9.07 9.31, and 9.25 km^3. The gain side of the water balance (river discharge of 6.8 km^3 plus 0.1 km^3 of groundwater input) averaged 6.9 km^3. Average net evaporation is calculated at 2.8 km^3, giving an overall surplus averaging 4.1 km^3, which resulted in a average annual water balance gain of 0.9 km^3 and outflow toward the Large Aral averaging 3.2 km^3.

The key event for the Small Aral water balance during this period was construction of a dike across the former Berg Strait that blocked the flow from the Small to Large Aral. The structure was completed in August 2005 and raised the level of the Aral approximately 2 m by late March 2006. Since that date, the dike has maintained levels ranging from 41.2 to 42.4 m (measured above the Kronstadt gauge on the Baltic Sea) (Cretaux 2012). At the nominal level of 42 m the Small Sea has an area around 3,600 km^2 and volume of 27 km^3 compared to a level of 40 m, area of 3100 km^2, and volume 21 km^3 when the gates were closed. Water releases are made through a regulating structure of nine movable gates into the channel and shallow lakes that lead to the Large Aral. The project (discussed in detail in Chap. 15) was very ecologically beneficial for the Small Aral and economically helpful to the people living around this water body. However, it did reduce outflow from the Small Aral toward the Eastern Basin of the Large Sea by about 0.4 km^3 owing to increasing the surface area by about 500 km^2 that led to increased evaporative losses, thereby, contributing, although in a minor way, to the continuing desiccation of that water body.

In stark contrast to the Small Aral, the water balance of the Large Aral for 2001–2010 was decidedly negative (Fig. 5.3 and Table 5.2). The author estimates river inflow to the sea to have averaged about 4.4 km^3/year. There was no surface inflow from the Amu (and large irrigation drainage water collectors in the lower Amu Delta that discharge directly toward the sea) in 2001 as the severe drought that began in the previous year, continued to impact the Amu's drainage basin, greatly diminishing outflow from the source regions in the Pamir Mountains. The volume of water reaching the lower Amu Delta (measured at the Takhiatash Dam) was less than 0.5 km^3 (CAwaterinfo 2012g, h). Hence, only a trickle of water was discharged below the dam, which is the last point for major water distribution to irrigation canals in the Lower Amu Darya Delta, and none came anywhere near reaching the Eastern Basin of the Large Aral Sea.

The subsequent 4 years (2002 through 2005) saw recovery from the drought with releases below Takhiatash of, respectively, 6.7, 11.5, 5.9, and 17.6 km^3. Although precise estimates are impossible the author, based on visual analysis of MODIS 250 m resolution satellite imagery, his water balance model, and Cretaux's radar altimetry measurements of levels of the Large Aral, estimates that inflows to the Eastern Basin of the Large Aral averaged around 6.5 km^3/year for this period (MODIS 2002–2005; Micklin 1990–2012; Cretaux 2012).

In late 2006, dry conditions returned to the Amu Darya Basin and 2007 and 2008 were very dry years. Flow conditions improved somewhat in 2009. Measurements of flow releases below the Takhiatash Dam for these years averaged only 2.8 km^3 (CAwaterinfo 2012g, h). The author estimates that only 3.3 km^3 reached the Eastern Basin of the Large Aral during this 4 year period (Bulletin ICWC 2006–2010; MODIS 2006–2010; Micklin 1990–2012). During these years most of the Amu flow that was released below the Takhiatash Dam was held in the wetlands, lakes, and shallow reservoirs of the lower delta rather than being released to flow toward the sea. Equally important was the simple fact that the distance to the Eastern Basin shoreline grew rapidly as that shallow water body shrank so that much of the water released toward it evaporated or disappeared into the sandy, salt covered, barren, dry bottom. But Amu Darya flows significantly increased during the second half of 2009 and continued through 2010. Flows to the lower Syr Darya Delta and Aral Sea measured at the Takhiatash Dam were 20 km^3 in 2010, third highest for the 20 year period 1992–2011. This led to a considerable inflow to the Eastern Aral Basin estimated at around 15 km^3 that increased its area from 857 to 5,211 km^2 and its volume from 0.64 to 8.4 km^3 between September 2009 and November 2010 (Cawaterinfo 2012i, Tables 3 and 4).

Average net groundwater input, is again assumed at 2.9 km^3. Average annual inflow from the Small Aral is calculated at 1.4 km^3, only 39 % of the outflow from the Small Aral, reflecting the increasing losses of water enroute to the Eastern Basin of the Large Aral as the distance between the two water bodies continued to grow. Adding average annual river inflow of 4.4 km^3, gives a total for the positive side of the water balance of 8.7 km^3. This was not nearly enough to balance the average estimated loss to net evaporation of 13.8 km^3/year and resulted in an average deficit of 5.1 km^3/year. However, as mentioned earlier, owing to evaporation from a shrinking water body being a powerful negative feedback mechanism, the deficit was considerably lower than in the preceding decadal period as the Aral's water balance moved closer to stability. Indeed, over the period, estimated annual evaporation dropped from 22 (in 2001) to 8 (in 2010) km^3, a nearly three fourfold decrease (Micklin, 1990–2012). The reason for this was the rapid shrinkage of the Shallow Eastern Basin of the Large Aral, which accounted for nearly all of the area decrease. The total area of the Large Sea (on January 1 of the year) shrank from 22.3 thousand to 7.9 thousand km^2, while the level dropped from 32 to 27 m, a decline of 5 m (Fig. 5.2). The volume decreased 51 % from 147 to 72 km^3.

During this period, the Large Aral changed from a single water body to two lakes, the deep Western Basin and shallow Eastern Basin, connected by an increasingly long, narrow channel that developed between the Kulandy Peninsula and the former Vozrozhendeniya Island – that itself became a peninsula connected to the mainland to the south in June-Aug, 2001 (MODIS 2001).

Irrigation, again, was the dominant factor in the Aral's recession (see Chap. 8 for more details). Annual water withdrawals for irrigation rose from 75 to 91.6 km^3 between 2000 and 2010 while the irrigated area dropped from 8.43 to 8.2 million ha (Cawaterinfo 2012d). Although we lack reliable figures, diversions from the Amu Darya into the Kara-Kum Canal likely grew during this period and continued to be a significant source of loss of flow to the Aral Sea. No new large reservoirs were put into operation during this period, although Tajikistan renewed work on the giant Rogun hydropower station (volume $= 11.8\ \text{km}^3$; reservoir area $= 160\ \text{km}^2$) on the Vaksh, the main tributary of the Amu Darya in the latter part of the decade. Work on this station was initiated in the 1980s under the Soviets but was suspended when that nation collapsed (Avakyan et al. 1987, Appendix 1, p. 310). In the ensuing years, floods destroyed much of the preliminary work that Soviet engineers had done, so Tajikistan has had to redo much of the earlier construction work.

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Chapter 6
The New Aquatic Biology of the Aral Sea

Igor S. Plotnikov, Nikolay V. Aladin, Zaualkhan K. Ermakhanov, and Lyubov V. Zhakova

Abstract Regression of the Aral Sea began in 1961. At first changes in the fauna were primarily the result of fish and invertebrates introductions. In the 1970s regression accelerated. The main factor influencing fauna is increasing water salinity. In 1970s–1980s invertebrate fauna went through two crises. Freshwater species and brackish water species of freshwater origin became extinct first. Then Ponto-Caspian species disappeared. Marine species and euryhaline species of marine origin survived, as well as species of inland saline waters fauna. By the end of the 1990s the Large Aral became a complex of hyperhaline lakes. Its fauna was passing through the third crisis period. Incapable of active osmoregulation, hydrobionts of marine origin, and the majority of osmoregulators disappeared. A number of species of hyperhaline fauna were naturally introduced into the Large Aral. Salinization of the Aral Sea has resulted in depletion of parasitic fauna. All freshwater and brackish-water ectoparasites and significant part of helminthes began to disappear. Together with the disappearance of hosts, the parasites associated with them in their life cycle had to disappear. Regulation of the Syr Darya and Amu Darya and decreasing of their flow altered living conditions of the Aral Sea fishes, especially their reproduction. In 1971 there were the first signs of negative effects of salinity on adult fishes. By the middle of the 1970s natural reproduction of fishes was completely destroyed. Commercial fish catches decreased. By 1981 the fishery was lost. In 1979–1987 flounder-gloss was introduced and in 1991–2000 it was the only commercial fish. After the flow of the Syr Darya again reached the Small Aral, aboriginal fishes began migrating back to the sea from lacustrine systems and the river. This allowed the achievement of

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commercial numbers of food fishes. Since the end of the 1990s the Large Aral Sea is a lake without fishes. Regression and salinization of the Aral Sea caused destruction and disappearance of the majority of vegetational biocenoses.

Keywords Aral Sea • Fauna • Invertebrates • Fishes • Parasites • Aquatic plants • Alien species • Acclimatization • Zooplankton • Zoobenthos • Salinization

6.1 Invertebrates

6.1.1 Free-Living Invertebrates

The hydrological regime of the Aral Sea has been changing since 1960 and this has led to a progressive level decline and increase in salinity. Since that time the main factor affecting the biota of this saline lake became the changing water salinity. During the period 1961–1970 the Aral Sea desiccation and increase of its salinity occurred very slowly. Over these 10 years salinity increased only by 1.5 g/l, and by 1971 it reached 11.5 g/l (Fig. 6.1). At this early stage of the Aral Sea's modern regression, changes in the species composition of its fauna were mostly the result of the introduction of new fishes and invertebrate species (Table 6.1) and to a lesser extent were the result of increasing salinity.

The Shrimp *Palaemon elegans* accidentally introduced in 1956–1958 during a failed acclimatization of mullets became naturalized in the Aral and was the cause of declining numbers and eventually the extinction of the amphipod *Dikerogammarus aralensis* (Mordukhai-Boltovskoi 1972; Andreev 1989; Aladin and Potts 1992). Benthic invertebrates, including the amphipod, provided by weight one-third of the food for these shrimp (Malinovskaya 1961). In addition, shrimp and amphipod habitats coincided and with the explosive growth of shrimp numbers the amphipod population declined rapidly. From 1963 to 1966 it decreased by about 10 times. From 1966 to 1972 amphipod remained in the western part of the Large Sea, while in 1973 (Fig. 6.2) it did not disappear completely (Andreev 1989). Increasing salinity of the sea could not have caused the disappearance of the amphipod as in saline kultuks (shallow bays) of the eastern coast and in the waters of the Akpetkinskiy archipelago it lived at salinities up to 50 g/l (Husainova 1960; Dengina 1959). The reasons for the amphipod's disappearance were biotic factors, including eating of it by shrimp and fish, and competition from other introduced species (Aladin and Kotov 1989).

To speed up the settling and naturalization of mysids *Paramysis lacustris* and *P. intermedia*, successfully introduced to the Aral Sea in the 1958–1960s, in 1964 they were transferred from Karateren Bay of the Small Sea into the freshened Sarbas Bay of the Large Aral near the Amu Darya Delta. Next year mysids were found in the Abbas Bay. Here and in other bays of the southern Aral Sea mysids acclimatized and quickly formed large populations (Bekmurzaev 1965, 1970; Kortunova 1970).

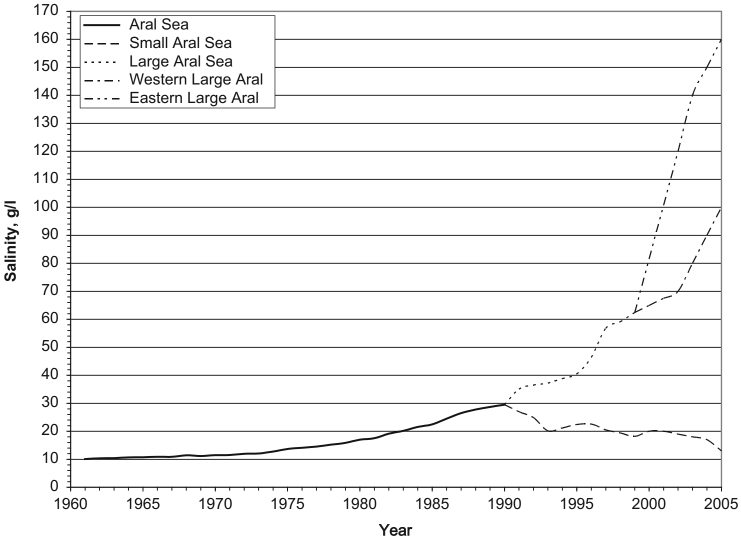

Fig. 6.1 The changing salinity of the Aral Sea (1960–2005)

If during the first years after the introduction of mysids the largest in number *P. lacustris* predominated in the Aral Sea, then in the second half of the 1960s they disappeared almost completely and their place was taken by the originally not numerous *P. intermedia*. This species became the most numerous and widespread species of mysids in the Aral Sea. It settled the entire coastal zone up to a depth of 6–7 m except for saline areas. Such a strong decrease in the number of *P. lacustris* was caused by habitat conditions in the new biotope that were sufficiently favorable for this species of mysids in contrast to *P. intermedia*, or this was due to the pressure from Aral Sea fishes. It is likely that the larger and less mobile *P. lacustris* was more accessible than *P. intermedia* as food for fish and was consumed more intensively. As a result, *P. lacustris* remained only in the north of the Aral Sea, mainly in Karateren Bay (Bekmurzaev 1970; Karpevich and Bokova 1970; Kortunova 1970).

In 1965 a third species of mysids *P. ullskyi* (Table 6.1) was found in the Aral Sea. It was not specifically introduced into the Aral Sea. This species was found only near the delta of the Syr Darya, and not in the Gulf of Karateren, where the other species of mysids were placed, and remained the smallest in number (Karpevich 1975). Presumably this mysid entered here independently from the Kayrakkum and Farkhad reservoirs on the upper Syr Darya, where it together with other species of mysids was introduced in 1963 (Akhrorov 1968; Kortunova 1970).

By the end of the 1960s, mysids had settled almost all the Aral Sea except for the Akpetkinskiy archipelago but they were numerous only in areas with low salinity – estuarine expanses just in front of the Amu Darya and Syr Darya deltas. Besides this mysids appeared in the Syr Darya and settled many of the connected

Table 6.1 Alien free-living invertebrates in the Aral Sea (Aladin et al. 2004, with changes)

Species	Source	Year of introduction	Status	Status in the 1990–2000s	Way	Impact
Ciliophora						
Fabrea salina Henneguy[a]	Aral region	1990s–2000s	N	N	N	0
Frontonia marina Fabre-Domergue[a]	Aral region	1990s–2000s	N	N	N	0
Branchiopoda						
Artemia parthenogenetica (Linnaeus)[a]	Aral region	1996	N	N	N	+
Ostracoda						
Eucypris inflata G.O. Sars[a]	Aral region	1990s–2000s	N	N	N	0
Cyprinotus salinus (Brady)	Aral region	1980s	N	N	N	0
Mysidacea						
Paramysis ullskyi (Czerniavsky)	Syr Dar'a	1965?	R	–	N	+
Decapoda						
Rhithropanopeus harrisii tridentata (Maitland)	Sea of Azov	1965, 1966	N	N	A+	+
Copepoda						
Calanipeda aquaedulcis Kritschagin	Sea of Azov	1965, 1966–1970	N	N	A	+
Heterocope caspia Sars	?	1971	–	–	A	0
Acartia clausi Giesbrecht	?	1985, 1986	–	–	A	0
Apocyclops dengizicus (Lepeschkin)	Aral region	2004	N	N	N	0
Polychaeta						
Hediste diversicolor (Müller)	Sea of Azov	1960–1961	N	N	A	+
Bivalvia						
Abra ovata (Philippi)	Sea of Azov	1960, 1961, 1963	N	N	A	+
Monodacna colorata (Eichwald)	?	1964, 1965	–	–	A	0
Mytilus galloprovincialis Lamarck	Sea of Azov	1984–1986	–	–	A	0
Mya arenaria Linnaeus	Sea of Azov	1984–1986	–	–	A	0

Way of introduction: *A* acclimatization, *A+* incidentally at planned introduction, *N* naturally
Status: *R* rare, *N* numerous
Impact: + positive, *0* no effect
[a]Only in the Large Aral

to it deltaic lakes. It is possible that they got there not from the Aral Sea but from upstream reservoirs where they were also introduced (Kortunova 1970; Karpevich 1975).

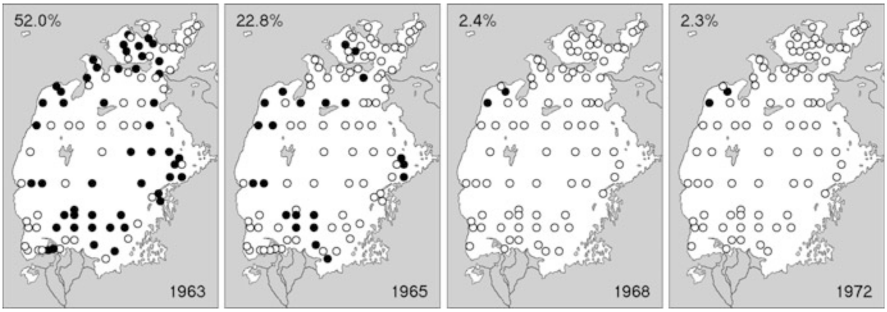

Fig. 6.2 Occurrence of amphipod *Dikerogammarus aralensis*. (○ – stations of standard sampling where this species was found; ● – stations of standard sampling where this species was not found)

The Mediterranean-Atlantic euryhaline polychaete worm *Hediste diversicolor* (= *Nereis diversicolor*) (Table 6.1) was purposely introduced into the Aral Sea in 1960–1961. This worm (about 100,000 individuals) was taken from Berdyansk limans (estuaries) of the Sea of Azov and was placed near the Syr Darya Delta in the freshened Dzhida Bay of the Small Sea. This polychaete worm quickly naturalized in the Small Aral Sea and by 1968 fully colonized it. Settling occurred due to transfer of pelagic larvae by permanent and local wind-driven currents. In 1965 *H. diversicolor* penetrated into the Large Aral, where the direction of its future settlement (Fig. 6.3) was determined by the predominant anticyclonic (clockwise) current (Karpevich 1975; Bortnik and Chistyaevaya 1990). In 1968 the worm was registered in benthic samples collected in Sarbas Bay, and in 1973–1974 it had spread around the Aral Sea (Fig. 6.3), repopulating various types of bottom grounds and depths to 20 m and more.

This worm became an important food for young predatory fish and adult nonpredatory fish (Gavrilov 1970; Kortunova 1970; Bekmurzaev 1970; Karpevich 1975; Mordukhai-Boltovskoi 1972; Markova and Proskurina 1974; Proskurina 1976, 1979; Andreeva 1989). It is possible that this introduced species, along with the increased salinity caused the diminution of the number of Chironomidae and Oligochaeta in the Aral Sea.

Not all species of mollusks in the Aral Sea fauna are valuable food for fish. Among the most abundant bivalves the most preferred by fish was *Hypanis minima*, whereas *Cerastoderma* because of its thick shell and limited habitat area and older age *Dreissena* were not valuable food. However, benthophage fishes used them as food to a small extent. Only barbel ate large bivalves. In contrast to them the recommended for introduction into the Aral Sea Mediterranean-Atlantic bivalve *Syndosmya segmentum* (Table 6.1) is able to eat small plant detritus and having a thin-walled shell is itself a valuable and accessible food for benthophage fishes (Karpevich 1960, 1975; Yablonskaya 1960).

This bivalve mollusk was brought from the Gulf of Taganrog and Berdyansk limans of the Sea of Azov and introduced into the Aral Sea in 1960, 1961 and 1963. The first attempt at introduction in 1960 into the freshened Dzhida Bay of the Small

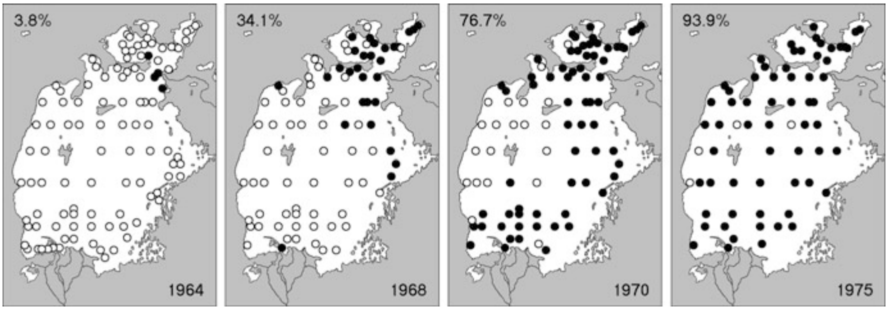

Fig. 6.3 Occurrence of polychaete worm *Hediste diversicolor*

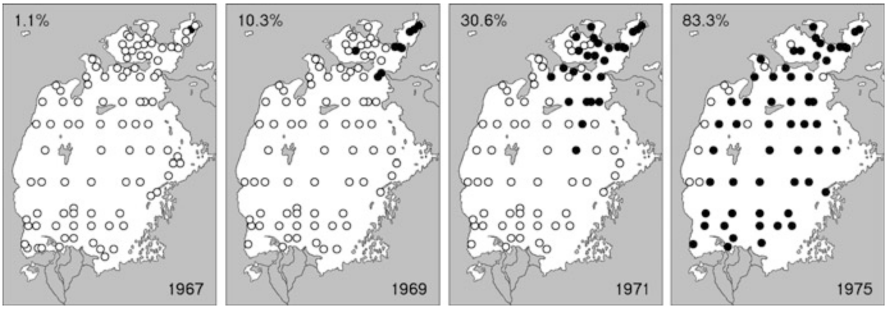

Fig. 6.4 Occurrence of bivalve mollusk *Syndosmya segmentum*

Aral Sea was unsuccessful, probably due to the low salinity here. In 1961 and 1963 these mollusks were successfully introduced in Saryshaganak Gulf with a salinity of 10.2 g/l. In 1967, for the first time, this mollusk was found in samples of zoobenthos and by the mid 1970s it had settled all the Aral Sea (Kortunova 1970; Karpevich 1975; Andreeva 1978) (Fig. 6.4). As a result, *S. segmentum* had become the major component of the benthic fauna, and its larvae formed the basis of meroplankton[1] that earlier were almost completely composed of bivalve mollusks' larvae. Due to its high euryhalinity *S. segmentum* survived the further salinization of the Aral Sea and replaced in this role the mollusks *Dreissena* and *Hypanis* whose numbers were greatly reduced by 1970 and which later entirely disappeared. The attempts made in 1964 and 1965 to introduce the earlier recommended for introduction marine bivalve mollusk *Monodacna colorata* (Table 6.1) failed (Husainova 1971).

The introduction of highly productive planktonic crustaceans began in the mid-1960s. This was done not only to restore crustacean zooplankton affected by introduced additional consumers of it – Baltic herring (introduced purposely but without sufficient study) and atherine (introduced by accident) but also to increase

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[1] Organisms that are planktonic for only a part of their life cycles, usually the larval stages.

its productivity. For this purpose a list of high-productivity euryhaline Copepoda were chosen (*Calanipeda aquaedulcis* and *Heterocope caspia)* for introduction that A.F. Karpevich had recommended (Table 6.1) (Gunko and Aldakimova 1963; Bondarenko 1974; Karpevich 1975). In 1965 *C. aquaedulcis* was transported from the Kuban River limans to the south of the Large Aral Sea and placed in Muynak and Karakultuk bays with salinity about 8 g/l, in Sarbas Bay with salinity of 6 g/l, as well as in the freshened Abbas Bay at the mouth of Amu Darya. In 1966 this crustacean was introduced only into Muynak and Sarbas bays. In 1970 *C. aquaedulcis* was transported from Taganrog Bay of the Sea of Azov into Muynak and Sarbas bays (Karpevich 1975).

In 1970, for the first time, single individuals of *C. aquaedulcis* were found in zooplankton of the Aral Sea, 5 years after the first attempt at introduction of this crustacean into Muynak and Sarbas bays (Kazakhbaev 1974). They were also found in samples from the open sea (Kortunova et al. 1972). In summer that same year these crustaceans settled the entire area of freshened bays and in autumn they appeared in the southern part of brackish water areas of bays on the south of the sea with a salinity of 9–11 g/l. By the autumn of 1971 *C. aquaedulcis* was found throughout the south of the Aral Sea, including Akpetkinskiy archipelago with salinities from 15 to 18 g/l.

During 1971–1972 *C. aquaedulcis* rapidly increased its numbers, settling all the Aral Sea (Fig. 6.5) and became one of the dominant species of zooplankton (Daribaev 1967; Kazakhbaev 1972, 1974; Karpevich 1975; Andreev 1978, 1980, 1989). Thanks to its high fertility – six generations per year – *C. aquaedulcis* by 1974 quickly and completely replaced the freshwater dominant *Arctodiaptomus salinus,* which had very low fertility and had been greatly reduced due to extermination by introduced planktophages (Fig. 6.6) (Falomeeva and Kazakhbaev 1981).

Apparently *Calanipeda aquaedulcis*, this time as a competitor, caused the disappearance of the cladoceran *Moina mongolica.* It disappeared in 1973 (Fig. 6.7) as happened at the same time with *Arctodiaptomus salinus*. Increased salinity could not possibly be the cause of *M. mongolica's* disappearance because this widely euryhaline hydrobiont can survive with salinity above 80 g/l (Aladin 1996). An attempt to introduce the copepod crustacean *Heterocope caspia* undertaken in 1971 when *C. aquaedulcis* had settled the entire sea was a failure – this crustacean was not able to survive in the Aral Sea (Aladin et al. 2004).

In connection with the introduction of *C. aquaedulcis* into the Aral Sea in 1970, the planktonic larvae of the crab *Rhithropanopeus harrisii tridentata* were also accidentally introduced along with this crustacean (Table 6.1). Its planktonic larvae were discovered by control inspection of samples taken from the shipping packages of the crustaceans (Mordukhai-Boltovskoi 1972; Karpevich 1975). Introduction of this crab was accidental and was considered undesirable even in the 1930s (Zenkevich and Birstein 1937). The crab was first discovered in the sea in 1976 in Adzhibay Bay. By the end of the 1970s it became a common species in the southwest of the Large Aral. In the late 1970s individual crabs were found in Chernyshov Bay (Andreev and Andreeva 1988) and in 1981 the crab was found

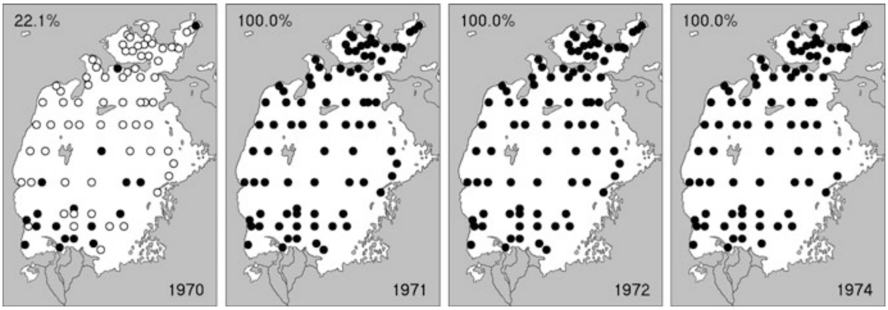

Fig. 6.5 Occurrence of copepod *Calanipeda aquaedulcis*

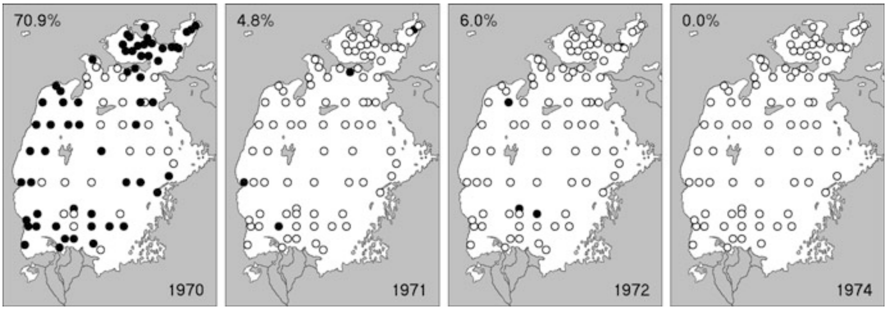

Fig. 6.6 Occurrence of copepod *Arctodiaptomus salinus*

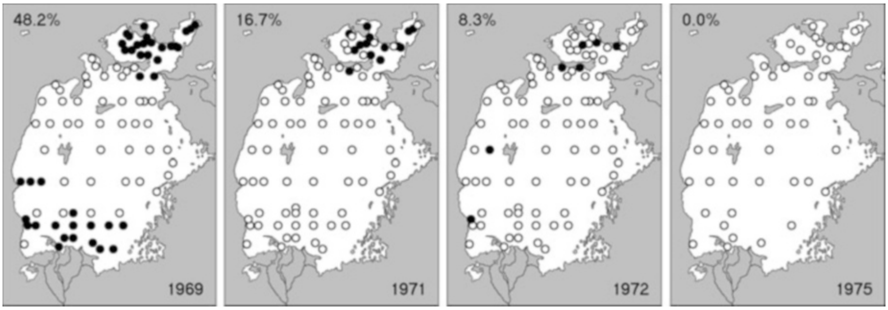

Fig. 6.7 Occurrence of cladoceran *Moina mongolica*

near Barsakelmes island (Aladin 1989). In 1989 the crab was one of numerous species of benthic fauna of the Large Sea but did not appear in the Small Aral Sea (Andreev et al. 1990).

The following is one possible explanation for the absence of crab in the Small Aral. There was a relatively small number of crab pelagic larvae introduced into the Large Aral Sea. As a result diffusion from the south of the Large Aral in the direction of Berg Strait was much slower than the diffusion of *C. aquaedulcis*. Apparently, at that time when the crab appeared in the north part of the Large Aral there was a stable flow of water to the Large Aral Sea through the Berg Strait. This prevented the transfer of crab larvae to the Small Aral. However, it remains unclear exactly what prevented migration of adult crabs in this direction. Perhaps they did not have time to do it before the Berg Strait dried and later their migration was hindered by a strong flow of water southward in the channel that later formed connecting the Small Aral and Large Aral.

The marine euryhaline species of invertebrates introduced in the 1960s, which are valuable as food for commercial fish, not only expanded the food base, but also in the future replaced those native species that were reduced in numbers or completely disappeared due to the increasing salinity of the Aral Sea.

Existing data on the occurrence and abundance of specific species of free-living invertebrates in the Aral Sea, as a rule, is limited by their small numbers or easily identifiable species, to the most widespread species or taxonomic groups: Oligochaeta, Cyclopoida, Chironomidae, etc., without distinguishing genera. Besides this there is a total lack of similar data on Nematoda, Turbellaria, Bryozoa and some other groups of aquatic invertebrates. Nevertheless even in the absence of such information for certain groups of free-living invertebrates it is possible to reconstruct the probable disappearance sequence of species representing these groups in the Aral Sea to the beginning of its salinization. This reconstruction could be based on the existing experimental data on the salinity tolerance of individual species and on the information about their initial distribution in the Aral Sea. In the case of a group of crustaceans, like ostracods, these changes can be observed through the presence of remnants of certain species in thanatotcenoses formed in various years on the dried former sea bottom owing to the level drop and the sea's recession.

Studies of the ostracod species composition of the Aral Sea in thanatotcenoses formed in 1960, 1965 and 1970 showed that visible changes in the fauna of these crustaceans did not happen in this period (Aladin 1991). In all these thanatotcenoses were represented shells of *Lymnocythere inopinata*, *Cyclocypris laevis*, *Plesiocypridopsis newtoni*, *Amnicythere cymbula*, *Tyrrhenocythere amnicola donetziensis*, *Limnocythere (Galolimnocythere) aralensis* and *Cyprideis torosa*. From this it follows that all these species at that time still lived in the sea. Although other species of ostracods from those found in the Aral Sea in the reporting period by E.I. Shornikov (1974), were not detected in the studied thanatotcenoses, it does not mean their extinction. Their remnants could not be found due to the relative scarcity of these species.

Throughout the period 1961–1971 the species composition of larval Chironomidae fauna in the Aral Sea remained unchanged (Andreeva 1989). However, in 1963 an abrupt and very fast decrease in their overall abundance and, consequently, biomass began, and by 1971 they were reduced several fold. Their occurrence also fell (Fig. 6.8). There is not sufficient reason to consider the low increase in salinity as the main and only reason for this process, especially since the majority of Chironomidae species represented here also lived in the salinized sea

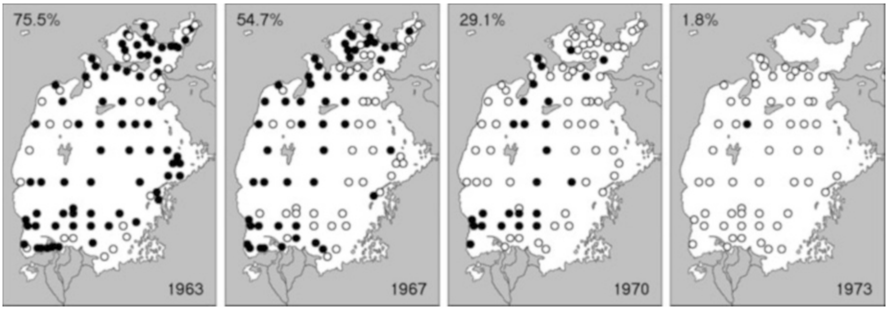

Fig. 6.8 Occurrence of larval Chironomidae

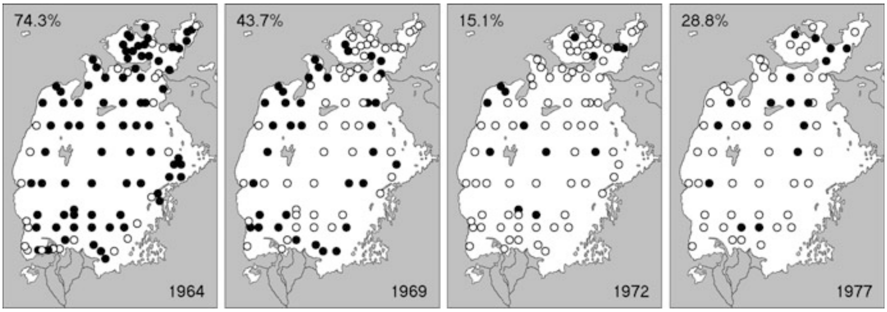

Fig. 6.9 Occurrence of bivalve mollusks *Dreissena* spp.

areas at 20 g/l and higher (Dengina 1959; Andreeva 1989). Apparently, a large role in this was played by the introduced polychaete *Hediste diversicolor* that became a competitor of chironomids, as well as feeding on them. A.F. Karpevich (1960, 1975) expected what happened, proving the expediency of this worm's introduction into the Aral Sea.

Still, a small increase in salinity of the Aral Sea caused a reduction in the total habitat for the bivalves from the genus *Dreissena* and a very significant reduction in their total number beginning after 1964 (Fig. 6.9). As a result by 1967 total numbers of these mollusks decreased by 40-fold. A decline of bivalve larvae abundance in plankton observed from 1967 to 1969 reflected this reduction of the number of *Dreissena* spp. in zoobenthos (Andreeva 1989). Related to this, it should be noted that the given slight salinization was unfavorable only for the two brackish-water forms of these mollusks that were dominant in the Aral Sea: *D. polymorpha aralensis* and *D. p obtusecarinata* but not for more resistant to salinity *D. caspia pallasi* which were present in smaller numbers (Dengina 1959; Andreeva 1989).

As a result of the Aral Sea regression by the end of the 1960s, the number and area of the gastropod *Theodoxus pallasi* (Fig. 6.10) was reduced, first of all due to reduction in the area of solid bottom preferred by them because of decreasing levels and shoreline retreat (Andreeva 1978).

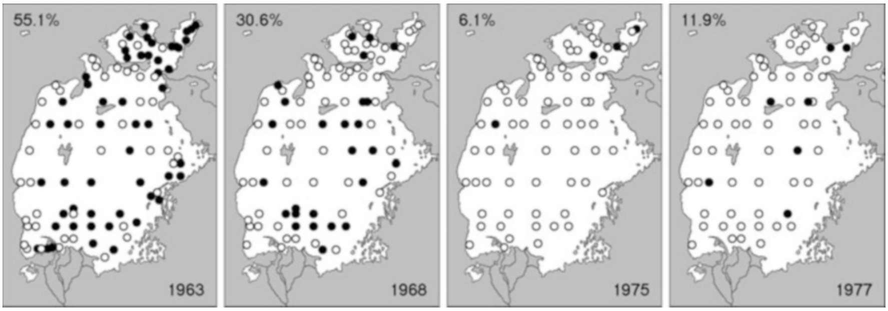

Fig. 6.10 Occurrence of gastropod *Theodoxus pallasi*

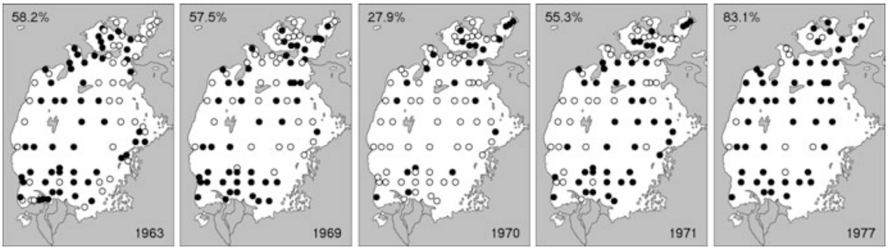

Fig. 6.11 Occurrence of bivalve mollusks *Cerastoderma* spp.

In the Aral Sea the bivalves *Cerastoderma rhomboides rhomboides* and *C. isthmicum* earlier were considered as one species *Cardium edule* that previously had been present in relatively small numbers compared with the bivalves *Dreissena* spp. and *Hypanis* spp. These two species of *Cerastoderma* prefer different salinity, and therefore they lived in different parts of the sea. If C. *r. rhomboides* inhabited waters of the main part of the Aral Sea, then *C. isthmicum* inhabited only the salinized areas ("kultuks" of the Akpetkinskiy archipelago and bays of the Large Sea east coast), where this mollusk reached the maximum number at salinities of 24–28 g/l (Dengina 1959; Starobogatov 1974; Andreeva 1989). The increase in salinity of the sea led to reduction in habitat area and abundance of *C. r. rhomboides*, which survived for some time until its extinction only in the less saline areas of the sea, and, conversely, increasing salinity allowed *C. isthmicum* to get out from the zone of high salinity and settle all over the Aral Sea, replacing *C. r. rhomboides* (Andreeva 1989) (Fig. 6.11).

In the 1970s the rate of Aral Sea desiccation and salinity rise increased (Fig. 6.1). After 1974 the discharge of the Amu Darya and Syr Darya decreased sharply increasing the sea's water balance deficit, and accelerating its regression. If to 1971 changes occurring in free-living invertebrate fauna of the sea were primarily the result of planned and incidental introductions of new species of invertebrates and fish, then since that time the main factor influencing the fauna of the Aral Sea has been continued growth in the salinity of its waters.

In the Aral Sea with its highly metamorphosed water, the zone of critical or first barrier salinity occurs at the range from 8 to 13 g/l (Aladin 1983, 1989; Plotnikov and Aladin 2011). This salinity is the junction zone of two major types of aquatic faunas – marine and freshwater; it also corresponds to brackish waters (Khlebovich 1974). In 1971–1976 invertebrate fauna of the Aral Sea passed through the first crisis period caused by salinization over the upper limit of 12–13 g/l of the first barrier salinity (Plotnikov et al. 1991). The Aral Sea ceased to be a brackish water body. Exceeding this limit of water salinity became an obstacle for further existence of freshwater origin species.

During this first crisis period drastic changes occurred in the free-living invertebrate fauna of the Aral Sea. The most species-rich, freshwater component of this fauna that was widely represented in the brackish part of the open sea before the crisis disappeared.

Those species of zooplankton that first disappeared gained entry to the Aral Sea in river water and inhabited the most freshened waters. They were followed by species, which developed under low salinity. Species that lived in the Aral at its normal salinity were the last to begin to disappear (Andreev 1989).

Only eight of 21 species of rotifers that earlier lived in the open areas of the Aral Sea remained after the first crisis. From them only a few species of the genus *Synchaeta* were common and numerous. The remaining species of rotifers were present in very small numbers or were found only locally. The most common among them were *Brachionus plicatilis*, *B. caliciflorus* and *Notholca squamula* (Andreev 1983, 1989).

Freshwater cladocerans *Alona rectangula* and *Ceriodaphnia reticulata* in the early 1960s were very much reduced in numbers in the Aral Sea as a result of the introduction of plankton feeders in the late 1950s. With increasing salinity *C. reticulata* ceased to be found in the plankton samples taken after 1970 and *A. rectangula* disappeared by 1974 (Fig. 6.12). As a result, by 1975 of seven species of Cladocera in the Aral Sea fauna only four representatives of the Ponto-Caspian fauna *Evadne anonyx*, *Podonevadne camptonyx*, *P angusta* and *Cercopagis pengoi aralensis* remained.

The sharp decline in the abundance of Cyclopoida copepods in the Aral Sea due to increasing salinity began in 1973. As a result only 16 species from 22 species of Copepoda survived the first crisis period. Instead of freshwater *Mesocyclops leuckarti* the most numerous species of Cyclopoida became euryhaline *Halicyclops rotundipes aralensis*. At the same time the total abundance of Harpacticoida species began to decrease (Fig. 6.13) due to the gradual disappearance of the least euryhaline species. By 1976 *Cletocamptus retrogressus* and *C. confluens* disappeared but other more euryhaline Harpacticoida species survived the first crisis period (Andreev 1989).

The abundance of bivalve mollusks from the genus *Hypanis*, already declining in the 1960s, continued to decline under the influence of increasing salinity and loss of their natural habitat (Fig. 6.14) (Andreeva and Andreev 1987; Andreev 1989). All three subspecies of these mollusks: *Hypanis vitrea bergi*, *H. minima minima* and *H. m. sidorovi* disappeared completely after 1977 (Andreev and Andreeva 1981; Andreev 1989).

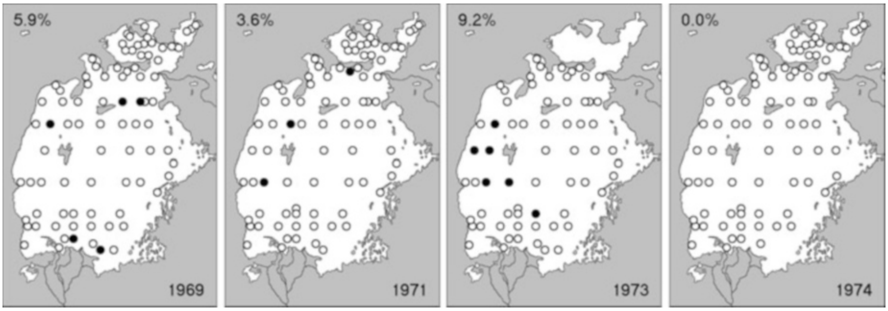

Fig. 6.12 Occurrence of freshwater Cladocera

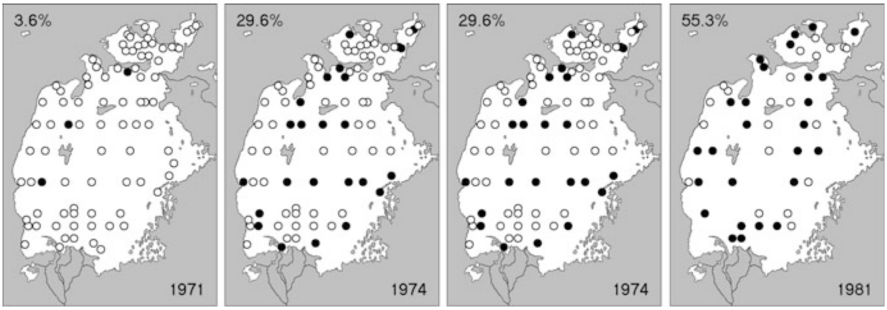

Fig. 6.13 Occurrence of Harpactocoida

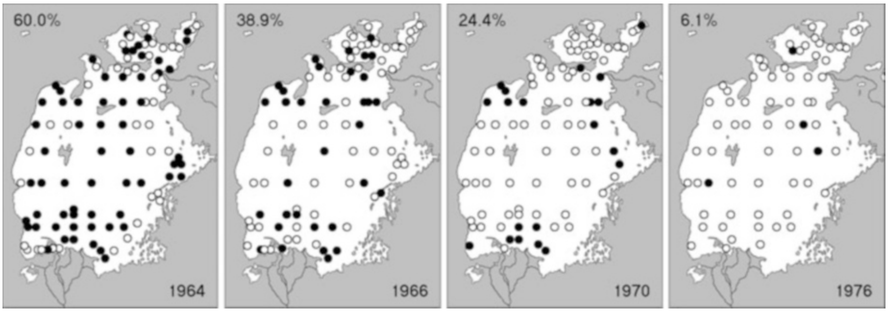

Fig. 6.14 Occurrence of bivalve mollusks *Hypanis* spp.

Further increase in salinity affected the sea forms of *Dreissena* inhabiting the sea differently. It was unfavorable to *Dreissena polymorpha aralensis* and *D. p. obtusicarinata*, but favorable to *D. caspia pallasi* that is capable of tolerating salinities up to 17–20 g/l (Dengina 1959; Andreeva 1989). For this reason, as well as reduction in the number of the bivalve *Hypanis* spp., in 1974–1976 there was some stabilization of the total natural habitat area and abundance of *Dreissena* (Fig. 6.9).

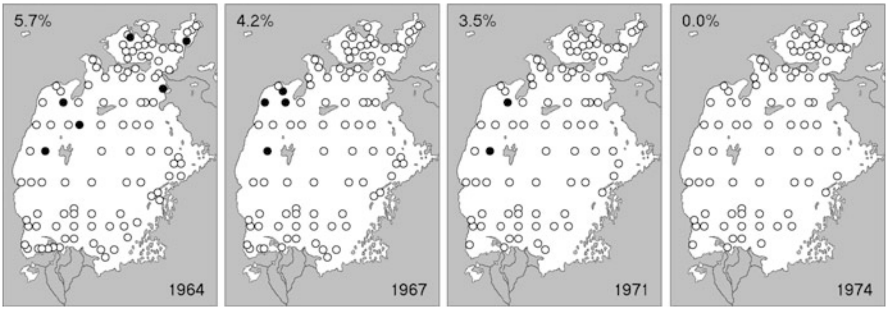

Fig. 6.15 Occurrence of Oligochaeta

The continued growth of salinity led to the further reduction in the area and reduction of the number of the bivalve *Cerastoderma rhomboides rhomboides* that began in the 1960s, and conversely it was favorable for *C. isthmicum*. Since 1971 due to the continued salinity growth the mollusk *C. isthmicum* began active colonizing throughout saline areas on the east of the Aral Sea (Fig. 6.11). Its numbers began to increase. After 1978 when salinity reached 15 g/l (Fig. 6.1), *C. rhomboides rhomboides* was no longer found in the Aral Sea, and *C. isthmicum* took its place and even became a species more numerous than its predecessor (Andreeva and Andreev 1987; Andreeva 1989).

Rising of the Salinity above 12–14 g/l favored the recently introduced euryhaline bivalve mollusk *Syndosmya segmentum*. Settling of these bivalves around the Aral Sea was completed in general by 1976 (Fig. 6.4). Later they composed over 50 % of the total zoobenthos biomass. Owing to the increased salinity, the abundance of the halophilic gastropods *Caspiohydrobia* spp. began to grow (Andreeva 1989).

Since 1973, when the salinity of the sea reached 12 g/l, the rare Oligochaeta were no longer found (Fig. 6.15). In this case we cannot exclude that in addition to the increased salinity the introduced polychaete worm *Hediste diversicolor* was as in the case of Chironomidae the cause of Oligochaeta disappearance from the Aral Sea fauna. By 1974 most of larval Chironomidae species had already disappeared from the main parts of the sea (Fig. 6.8) and only *Chironomus salinarius* and *Ch. halophilus* remained in the salinized bays of the east coast (Andreeva 1989). There these halophilic chironomids withstood salinity of more than 36 g/l (Dengina 1959).

The study of the species composition of ostracods in thanatocenoses in 1975 showed that the fauna of these crustaceans underwent the first changes during the first crisis period (Aladin 1991). No longer are found shells of *Limnocythere inopinata*, *Cyclocypris laevis* and *Plesiocypridopsis newtoni*. Other ostracods were extremely scarce, and only shells of *Cyprideis torosa* were found with the same frequency.

By 1974 the polychaete *Hediste diversicolor* had settled all the Aral Sea and became one of the main components in the benthic fauna (Andreeva 1989). By 1980, the leading forms of zoobenthos were *Syndosmya segmentum*, *Cerastoderma*

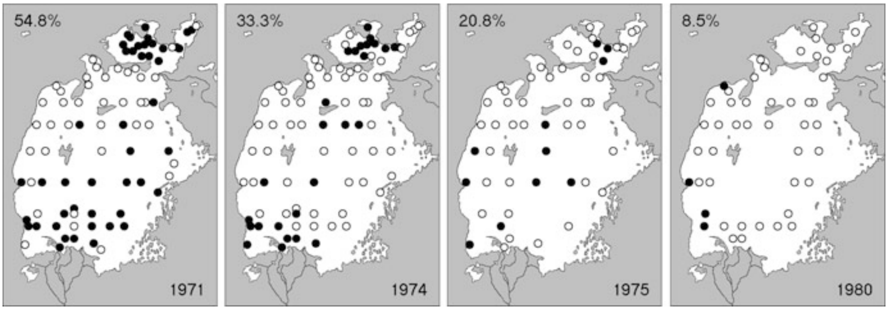

Fig. 6.16 Occurrence of cladoceran *Cercopagis pengoi aralensis*

isthmicum, *H. diversicolor*, *a* euryhaline Mediterranean-Atlantic species, and *Caspiohydrobia* spp., a halophilic species inhabiting saline continental waters (Proskurina 1979; Andreev 1983, 1989; Andreeva and Andreev 1987).

As a result of this first crisis, freshwater and brackish water species of freshwater origin disappeared from the free-living invertebrate fauna of the Aral Sea. This provided an advantage to Caspian and marine (Mediterranean and Atlantic) euryhaline species and halophilic species from continental waters (Andreev and Semakina 1978; Andreev 1989).

Despite the continuing steady salinity growth, the first crisis period for the free-living invertebrate fauna of the Aral Sea transitioned into a period of relative stability between 1977 and 1985. One may note that this stabilization did not mean the absolute absence of change since at the beginning and the end of this period there were, after all, some changes in the composition of this fauna.

After 1977 when the salinity had reached 15 g/l, all species of mysids were absent from the Aral Sea and were preserved only in the rivers Amu Darya and Syr Darya and their deltas. At the same time bivalves *Cerastoderma rhomboides rhomboides* and three endemic bivalve mollusk subspecies *Hypanis vitrea bergi*, *H. minima minima* and *H. m. sidorovi* disappeared completely (Andreev and Andreeva 1981; Andreeva 1989).

In the period from 1977 to 1979 the most common species of Cladocera was *Pododevadne camptonyx*. *Evadne anonyx* was more rare and occurred in lower numbers. The copepod cladoceran *Cercopagis pengoi aralensis*, which had the most limited distribution in the Aral Sea and was most sensitive to further salinity growth survived in the least saline regions until 1980 (Fig. 6.16) (Balymbetov 1972). The most abundant species of Copepoda was a recent invader *Calanipeda aquaedulcis*. To it in summer were added numerous larvae of bivalves *Syndosmya segmentum* and *Cerastoderma isthmicum*, which intensively reproduces in this season. The Euryhaline halophilous copepod *Halicyclops rotundipes aralensis* also was found throughout the sea, but overall its abundance was low. The cyclops *Acanthocyclops bisetosus* was sometimes observed among the zooplankton.

The Caspian cladoceran crustacean *Podonevadne trigona* was for the first time found among the Aral zooplankton in 1981 (Mordukhai-Boltovskoi 1974). Perhaps it was not distinguished from other species of *Podonevadne* with which it may have been mixed. More likely this crustacean did not attract the attention of researchers because of its extreme rarity until its abundance increased. It remains unknown whether it was incidentally introduced from the Ponto-Caspian to the Aral Sea in the 1950–1960s connected with the introduction of fishes, or it was an indigenous species (Aladin and Andreev 1981, 1984; Andreev 1989).

By 1987 salinity of the Aral Sea rose to 27 g/l (Fig. 6.1). This salinity corresponds to the lower boundary of the second barrier salinity (27–32 g/l) (Plotnikov and Aladin 2011). Crossing this boundary free-living invertebrate fauna of the Aral Sea entered the period of the second crisis during which occurred the next reduction of species diversity (Plotnikov et al. 1991).

As a result of this crisis disappeared the Ponto-Caspian species still remaining in the Aral represented in its free-living invertebrate fauna only by cladocerans of the family Podonidae. Already in 1988 when the salinity reached 28 g/l *Evadne anonyx* disappeared. By 1990 all species of the genus *Podonevadne* disappeared.

After the second crisis period of the native species in the zooplankton of the sea remained only the rotifers *Synchaeta* spp., *Notholca squamula*, *N. acuminata*, *Keratella quadrata*, *Brachionus plicatilis*, *B. quadridentatus* and perhaps a few very small in number species of copepods (Calanipeda aquaedulcis and Halicyclops rotundipes aralensis), as well as several species of Harpacticoida: in particular *Schizopera aralensis* and *Halectinosoma abrau*.

In the benthic fauna only the bivalve mollusk *Cerastoderma isthmicum*, gastropods *Caspiohydrobia* spp. and ostracod *Cyprideis torosa* survived this crisis among aboriginal species. Among introduced species only the polychaete *Hediste diversicolor*, bivalve mollusk *Syndosmya segmentum*, crab *Rhithropanopeus harrisii tridentata* and shrimp Palaemon elegans remained. After the second crisis period in the free-living invertebrate fauna of the Aral Sea were marine species and euryhaline species of marine origin as well as representatives of euryhaline halophilic fauna of inland saline waters.

The last attempts to introduce euryhaline marine invertebrates in the Aral Sea (Table 6.1) were taken in the mid-1980s. In 1986–1987 an attempt was made to introduce from the Sea of Azov two species of bivalves – *Mytilus galloprovinciali*, and *Mya arenaria*. They were released in the Large Aral near Barsakelmes Island. Both the introductions were not successful. Introduction of the former failed because of the lack of solid substrates in the Aral Sea required for attachment of mussels (Aladin 1991). In addition, both mollusks were released in shallow water, which due to the continuing fall in sea level dried completely in a few months. If *M. arenaria* had not been released into shallow water then, possibly, the introduction of this bivalve would have been successful. In 1985 and 1986 an attempt was made to introduce the marine copepod *Acartia clausi*, which also could not be naturalized in the Aral Sea. In this case, the reason for the failure may have been that the appropriate ecological niche was already occupied by *Calanipeda aquaedulcis*, which by this time had become the dominant crustacean in the zooplankton (Aladin et al. 2004).

The second crisis period was followed by a new period of relative stability. It should be noted that associated with the fall of the Aral level, water exchange with Butakov Bay and Saryshaganak Gulf was hindered and the salinity of them began to grow faster than in the open waters of the Aral Sea. Therefore the second crisis period and the subsequent stabilization came about in these two water bodies earlier.

Soon after the separation of the Aral Sea into two parts (Small Aral on the north and Large Aral on the south) when the decrease in salinity in the former began (but before construction of the first dam regulating flow between them) (Fig. 6.1) reappeared from dormant eggs *Podonevadne camptonyx* crustaceans of the Podonidae family that had gone extinct in the 1980s. In 1999 in the benthos again were found larvae of Chironomidae not found since 1974 (Aladin et al. 2000).

It remains unknown whether bryozoans were preserved in the sea, because after the 1960s such research was not conducted. Two freshwater species – *Bowerbankia imbricata aralensis* and *Plumatella fungosa* found in freshened areas could be preserved in the delta of the Syr Darya. The third species – *Victorella bergi* could have survived the salinity and remain in the Small Aral. This pearlwort was found in the Aral Sea not only at a salinity of 10 g/l but in kultuks at high salinities (Dengina 1959).

Salinity in the separated Large Aral grew rapidly and by the end of the 1990s its transformation into a group of residual hypersaline lakes was complete. During this transformation in the mid-1990s came another period of crisis associated with the transition of the sea's salinity above the barrier salinity of 47–52 g/l. Widely euryhaline hydrobionts of marine origin incapable of active osmoregulation are disappearing from the fauna of the Aral Sea and the disappearance of some osmoregulators has started. The continued fast increase in salinity of the Large Aral (Fig. 6.1) led to a rapid change in the composition of all its biota. By the end of the 1990s the Large Aral Sea became a hypersaline lake with fauna characteristic of the new environmental conditions.

By 1997 with salinity at 57 g/l the dominant zooplankton crustacean *Calanipeda aquaedulcis* and rotifers *Synchaeta* spp. disappeared. Most of the not so numerous species of rotifers, aboriginal harpacticoids, cyclops *Halicyclops rotundipes aralensis*, shrimp *Palaemon* elegans and the crab *Rhithropanopeus harrisii tridentata* also disappeared. By 2001 as salinity reached 67 g/l the composition of zoobenthos significantly changed. The polychaete *Hediste diversicolor* and mollusk *Cerastoderma isthmicum* disappeared. By 2002 the mollusk *Syndosmya segmentum* suffered the same fate. According to some researchers, in the bottom fauna of the western Large Aral at that time still remained live gastropods *Caspiohydrobia* spp. and ostracods *Cyprideis torosa* (Zavialov et al. 2006). However, in 2004 we could not find live *Caspiohydrobia* spp. and *Cyprideis torosa* at salinities of 100–105 g/l in the samples we gathered. We found only empty shells of mollusks and ostracods with the mummified remains of soft bodies. During this period crustacean ostracods *Cyprinotus salinus* disappeared, it was not aboriginal but an invasive species (Table 6.1) that appeared in the Aral Sea in the 1980s.

A number of invertebrates, absent in the Aral Sea, that live in saline water bodies of the Aral Sea region colonized the hypersaline Large Aral by natural means. These introductions occurred without human help primarily through the introduction of their dormant stages. In 1996 the cladoceran *Moina mongolica* returned to the Large Aral; it disappeared in 1973 as a result of displacement by introduced planktonic crustaceans. In 1996 *Artemia parthenogenetica* settled here and became the new dominant zooplankton species. In 2004 in the Western Large Aral appeared halophilous copepod *Apocyclops dengizicus* (Mirabdullayev et al. 2004, 2007). Two formerly minor native species of rotifers *Hexarthra fennica* and *Brachionus plicatilis* became widespread. During summer months the halophilous infusoria *Fabrea salina* is common among the zooplankton. In the Large Aral the haline tolerant halophilous ostracod *Eucypris insflata* settled as well as the aboriginal *Cyprideis torosa* (Aladin and Plotnikov 2008). *E. inflata* is found in thanatotcenoses since 2005. In the bottom fauna of the Western Large Aral there are numerous halophilic larvae of *Chironomus salinarius* (Mirabdullayev et al. 2007), native Turbellaria *Mecynostomum agile* that is found to be widely euryhaline and large ciliate *Frontonia marina* (Aladin and Plotnikov 2008). Besides them in the zoobenthos there are foraminifera and ematodes (Mokievsky 2009). In the more saline Eastern Large Aral, apparently, only *Artemia parthenogenetica* is found (Aladin and Plotnikov 2008).

6.1.2 Parasitic Invertebrates

Beginning in the 1960s, salinization of the Aral Sea resulted in drastic and rapid changes in its parasite fauna that resulted in the first place in the impoverishment of species composition.

Under the direct influence of salinity already in the 1960s initiated the disappearance of freshwater and brackish-water parasitic protozoans, leeches, parasitic crustaceans and a large part of helminths. Salinization of brackish bays and reduction of the areas occupied by freshwater mollusks led to the reduction of the infestation of Aral Sea fishes with trematodes. Rising salinity affected adversely their free-living stages. Salinization of the sea affected the different species of trematodes to varying degrees that depended on the sensitivity of the initial intermediate hosts – mollusks – to it. In the first place infestation by larval trematodes connected in their development with mollusks of the family Planorbidae living at a salinity of 1 g/l fell. This is especially true for *Posthodiplostomum cuticola*. In the past infestation with it reached 80 %, but by the end of the 1960s it was observed only in freshwater areas, and the extensiveness of infestation did not exceeded 5 %. The changed conditions were also unfavorable for many other species of trematodes. Infestation of fish with *Diplostomum* metacercariae still remained high in the late 1960s. The first intermediate hosts are mollusks of the family Lymnaeaidae that are able to withstand slight salinization. Infestation with these parasites occurs not only in fresh water but at salinities up to 7 g/l. A common parasite was still *Asymphylodora kubanicum*, its first intermediate hosts (mollusks *Cerastoderma* spp. and *Caspiohydrobia* spp.) are associated with salinized sea areas. The circle of this parasite's final hosts expanded owing to introduced fishes and the aboriginal zander. The last increased in numbers due to enrichment of the food base with gobies and atherine, and was reinfected by eating infested fish especially gobies. A similar situation occurred with *Aspidogaster limacoides*. The growth of the zander population contributed to the growth of its infection with *Bucephalus polymorphus* (Osmanov et al. 1976).

Infestation of Aral Sea fish with cestodes dropped by the end of the 1960s. This, in particular, was due to a decrease of planktonic crustaceans' abundance and appearance of dead ends in their life cycles. By the late 1960s plerocercoids of ligulids *Ligula intestinalis* and *Digramma interrupta* were not found. There has been a strong decline in fish infection with cysticerci of *Paradilepis scolecina*. If in 1930 sabrefish and shemaya were 60–80 % infested, by 1971 their infection did not exceed 10 % (Dogiel and Bykhovsky 1934). The intensity of infection also decreased. In addition to these causes, a drop in infection was related to a decline in the number of fish-eating birds (Osmanov et al. 1976). The infection of catfish, the final host of *Proteocephalus osculatus*, with this parasite has decreased but to a lesser degree. Catfish live where there are many young fish – a reservoir of hosts – that contributes to its high infestation with *P. osculatus* (Osmanov et al. 1976).

Changes in the hydrologic regime of the Aral Sea and its ecosystems differentially affected the distribution of various species of nematodes. Reduction of infestation of fish by the nematode *Raphidascaris acus* in the late 1960s is explained by the decrease in the number of pike, which is its final host. The nematode *Cystoopsis acipenseri*, a sturgeon parasite in the late 1960s, has not been found since its intermediate host *Dikerogammarus aralensis* disappeared from the Aral Sea fauna (Andreeva 1989; Aladin and Kotov 1989). Infestation by the larval nematodes *Contracoecum spiculigerum* (= *C. siluri-glanidis*) and *C. microcephalum* (= *C. squalii*) remained high, despite the decrease in the number of intermediate hosts (Osmanov et al. 1976). The causes of this phenomenon were discussed above.

Reduction of infestation by monogeneans also occurred. This owed both to the influence of salinization on stenohaline species and to the decreasing abundance of hosts for host-specific species.

In the late 1960s the total infestation of Aral Sea fish remained high (96–100 %). Everywhere there was strong infestation by monogeneans (40–77 %), trematodes (59–91 %) and nematodes (58–86 %). The most heavily infested fish were in freshwater areas (particularly in Abbas Gulf near the Amu Darya Delta). Changes in the parasite fauna of the Aral Sea that took place during the 1960s, related both to the progressing salinization and the effects of acclimatization, and are as follows (Osmanov et al. 1976):

1. Because of the reduction in river inflow and progressive salinization favorable habitat for freshwater species, and as a result, their abundance fell.
2. The decrease in the number of hosts led to a decrease in the abundance of parasitic species.

3. Under new conditions a number of species – many monogeneans, *Ichthyophthirius multifiliis*, *Asymphylodora kubanicum*, *Diplosthomum spathaceum*, nematodes *Contracoecum* spp., *Camallanus* spp. – remained abundant. Along with this, changes occurred related to alteration of food links in a number of groups of Aral Sea fish, particularly in ship sturgeon and Aral barbel, shemaya, and sabrefish connected to the switch to predation.

Remnants of native fish fauna survived in the Aral Sea to the 1980s in freshened estuarine areas and in the mouths of the Amu Darya and Syr Darya in the form of older fish (Aladin and Kotov 1989). In 1977–1980, 30 species of parasites of these fish were recorded, even though nine species were never found but were inferred to be present. Monogeneans accounted for 20 of these species. There was only one species of protozoans; glochidia of bivalves *Anodonta* were absent. The parasitic crustacean *Achtheres percarum* was discovered in zander. It had not previously been encountered, and was introduced, apparently, in the 1960s during acclimatization of copepod *Calanipeda aquaedulcis* (Osmanov and Yusupov 1985).

During the period under examination, most species of invertebrates as intermediate hosts of parasites of fish disappeared or would disappear from the fauna of the Aral Sea the (Osmanov and Yusupov 1985; Andreev 1989; Andreeva 1989; Aladin and Kotov. 1989). Therefore, it is quite natural that 24 species of parasites listed for the end of the 1970s have direct development (ciliates, monogeneans, parasitic crustaceans). All of them previously were characterized as euryhaline: ciliate *Trichodina* sp. and monogenean *Gyrogactylus rarus* in stickleback, several species of monogeneans, *Dactylogyrus*, *Silurodiscoides*, *Ancyrocephalus paradoxus*, *Nitzschia sturionis*, all previously recorded species of monogenean *Diplozoon*, nematode *Camallanus lacustris*, and parasitic crustaceans *Ergasilus sieboldi and Achtheres percarum* (Osmanov 1967, 1971; Osmanov and Yusupov 1985). Cestodes, trematodes, and nematodes were represented by 13 species that were previously widespread in the Aral (Osmanov et al. 1976; Osmanov 1971; Osmanov and Yusupov 1985). Seven of them have fish as final hosts. All rheophilic and freshwater parasites and the surviving group of euryhaline able to withstand salinity up to 12–14 g/l disappeared from the parasite fauna of the Aral by the end of the 1970s (Osmanov and Yusupov 1985).

Infestation of Aral Sea fish species with cestodes still remained low; it has decreased sharply since the late 1960s. The main cause was related to salinization and happened in the past period of impoverishment of the native fauna of Copepoda and its replacement by acclimatized *Calanipeda aquaedulcis*, apparently not involved in the circulation of cestodes. Cestodes that remained in the Aral Sea longer than others have simpler life cycles (*Bothriocephalus gowkongensis* = *B. opsarichthydis*, *Proteocephalus osculatus*) and their final hosts are fish (Osmanov and Yusupov 1985).

The most numerous trematodes in the late 1970s remained *Asymphylodora kubanicum*, *Bunocotyle polymorphus* and possibly *B. cingulata* in the stickleback, the mature stage of which parasitize fish (Osmanov and Yusupov 1985). In *A. kubanicum*, besides those already mentioned, *Cerastoderma* spp. and

Caspiohydrobia spp., perhaps the first intermediate host also became *Syndosmya segmentum* (Latysheva 1939), acclimatized and widespread in the Aral Sea. *Dreissena* is one of the hosts of *B. polymorphus* (Ginetsinskaya 1958). Both trematodes of Miracidia hatch from eggs in the digestive tract of mollusks. The larvae of most species of euryhaline Diplostomatidae *Diplosthomum spathaceum* and *Tylodelphys clavata* still were observed, but not in all species of fish and in small quantities. Salinity of the sea adversely affects their free-swimming larvae and the intermediate host – mollusks of genus *Lymnaea* (Osmanov and Yusupov 1985; Arystanov 1976). *Aspidogaster limacoides* disappeared due to salinization of the Aral Sea together with its intermediate hosts – brackish-water mollusks *Hypanis* spp. (Osmanov and Yusupov 1985; Andreeva 1989; Aladin and Kotov 1989).

Infestation of Aral Sea fish with nematodes has decreased sharply. The earlier common nematode *Raphidascaris acus* disappeared as rising salinity decreased the numbers of pike and intermediate hosts (oligochaetes, larvae of midges). Infestation of fish with the nematodes *Contracoecum spiculigerum* and *C. truncatus* sharply dropped because of a decrease in the number of native Copepoda (Osmanov and Yusupov 1985). The incidence of parasitic crustaceans decreased 44-fold (Osmanov and Yusupov 1985). They were close to disappearing from the Aral Sea fauna.

Although research conducted in 1977–1980 did not include all species of Aral Sea fish, nevertheless, it is possible to draw some conclusions about the situation in the 1990s.

Fresh and brackish water fish should have disappeared from the Aral Sea in the early 1980s when salinity reached 18 g/l and more (Osmanov and Yusupov 1985; Aladin and Kotov 1989). With further salinization freshwater mollusks, still surviving in river mouths under the influence of freshwater runoff, should also have disappeared. The remaining copepods were only *Calanipeda aquaedulcis* and in fewer number *Halicyclops rotundipes aralensis*, *Acanthocyclops* sp. There was a strong decrease in the numbers of fish-eating birds. As a result parasites connected in their life cycles with freshwater and brackish-water hydrobionts (i.e., the majority of still remaining in the late 1970s elements of the Aral Sea parasitic fauna) had to disappear, with the disappearance of their hosts. The disappearance of the monogenean *Nitzschia sturionis* was not due to the direct impact of salinity on the parasite, which is a specific parasite of marine sturgeon that is able to withstand high salinity (in *Acipenser sturio*), but due to disappearance of ship sturgeon that took place both because of the salinization of the sea and because of the disappearance of spawning grounds in rivers.

It seems quite possible that some parasites could remain in the Aral Sea at salinities up to 14 g/l and higher. In the first place we can mention here the trematode *Asymphylodora kubanicum*, as a widely specific parasite without free-living stages in its life cycle. Its first intermediate hosts became the dominant macrozoobenthos over the entire sea (Andreev 1989). For this reason, it cannot be excluded that *A. kubanicum* could be found in fish that feed on mollusks (gobies, flounder, and possibly silversides) at salinities above 25 g/l, although earlier, this parasite was not found in these species (Osmanov et al. 1976).

It cannot be excluded, although it seems to be less likely, that the trematode *Bunocotyle cingulata,* survived in the stickleback. The circle of its first intermediate hosts (mollusks) in the Aral Sea is unknown. Also, it is not known what salinity can be withstood by cercariae, and whether copepods surviving in the Aral can serve as second intermediate hosts. It is also possible that *Gyrodactylus bubyri*, a specific parasite of the bubyr goby, tolerant of increased salinity, could remain. Unfortunately, the lack of data on the salinity tolerance of this monogenean does not allow prediction of its survival with sufficient certainty.

Ten species of parasites were found in the Aral Sea stickleback, indigenous euryhaline inhabitant of the Aral Sea (Dogiel and Bykhovsky 1934; Osmanov 1971). Of them, seven species – trematodes *Diplostomum spathaceum*, *Bunocotyle cingulata*, metacercariae of family Echinostomatidae, cestode *Proteocephalus cernuae* and cysticerci of Dilepididae, nematodes *Contracoecum spiculigerum*, *C. microcephalum* – are widely-specific, and only three species (ciliate *Trichodina* sp., monogenean *Gyrodactylus rarus*, cestode *Schistocephalus pungitii*) are specific parasites of sticklebacks (Schulman and Schulman-Albova 1953; Osmanov 1971). Although what species of *Trichodina* were in Aral stickleback is not clear, probably they are euryhaline species (Osmanov and Yusupov 1985). It is likely that it is the specific for sticklebacks species *Trichodina latispina* (Schulman and Schulman-Albova 1953) known from other water bodies including Lake Balkhash (Dogiel and Bykhovsky 1939). The parasitic copepod *Thersitina gasterostei*, found in sticklebacks everywhere, was not found in the Aral Sea. Of these specific species are euryhaline *Trichodina latispina* and *G. rarus*, and not found in the Aral Sea *G. arquatus*, *G. bychowsky*, *Th. gasterostei*. It is shown experimentally that they are able to survive, as does the stickleback, the transition from fresh water to salinities of 26 g/l and back (Isakov and Schulman 1956). As the Aral Sea grows more saline and freshened areas are lost, all freshwater parasites of stickleback should disappear. We can expect that in the Aral stickleback representatives of the euryhaline complex *G. rarus* and *Trichodina* sp. survived. It is not excluded that *B. cingulata* could remain in the stickleback, just as in in other surviving fishes.

Parasite fauna of the flounder-gloss in the Aral Sea has never been investigated. It is unknown what parasites were introduced together with it into the Aral Sea from the Sea of Azov. In accordance with this, there are possible only some considerations about the probable parasite fauna composition of flounder in the Aral Sea. In the Black and Azov Seas there is 100 % infestation of flounder-gloss with the cestode *Bothriocephalus scorpi* and plerocercoids, which are also found in *Pomathoschistus* gobies (Naidenova 1970). It may be that this parasite has been introduced into the Aral Sea together with flounder. It cannot be excluded that it has the nematode *Cucullanellus minutus*. As for the other species of parasites of flounder-gloss it is very doubtful that they are in the Aral Sea (Osmanov 1940).

One may expect that in the second half of the 1980s in the Aral Sea probably survived, albeit with different probabilities, the following species of fish parasites: ciliate *Trichodina* sp., monogeneans *Gyrodactylus bubyri*, *G. rarus*, trematodes *Asymphylodora kubanicum*, *Bunocotyle cingulata*, cestode *Bothriocephalus scorpii* and nematode *Cucullanellus minutus*.

Table 6.2 Introduced fish species in the Aral Sea (Aladin et al. 2004, with changes)

Species	Years of introduction	Source	Way	Status	Impact	Status in the 2000s
Channidae						
Snakehead *Channa argus warpachowskii* Berg	1960s	Kara-Kum canal	A+	C	0	C
Pleuronectidae						
Black Sea flounder *Platichthys flesus* (Linnaeus)	1979–1987	Sea of Azov	A	N, C	+	N, C

Way of introduction: *A* acclimatization, *A+* incidentally at planned introduction
Status: *N* numerous, *C* commercial
Impact: + positive, *0* no effect

Unfortunately, any data on the current state of the Small Aral Sea parasite fauna is completely absent. This is a consequence of the fact that since the late 1980s no parasitological research was conducted. The same is true for the Large Aral Sea. But in this case there is a high probability that in this complex of residual hypersaline water bodies all parasitic fauna was lost together with the former fish fauna and fauna of free-living invertebrates.

6.2 Fishes and the Fishery

In the 1960s in the deltaic areas of the Syr Darya and Amu Darya, representatives of fresh-water fishes from China were introduced and acclimatized (Karpevich 1975), including the predatory snakehead *Channa argus* earlier introduced into the Kara-Kum Canal (Table 6.2). Snakehead became commercially important. In the early 1960s, freshened deltaic bays and lakes were considered the best places for spawning (Bervald 1964) and here 65–70 % of the main commercial fishes were reproducing. Since the 1960s the main factor influencing the hydrological regime of the Aral Sea became human activity. Regulation of the Syr Darya and Amu Darya and increasing withdrawal of their flow caused the gradual but steady fall of the Aral Sea level, salinization of its water and drying of deltas. All these changes significantly altered the historically formed living conditions of the Aral Sea fishes, especially conditions of their reproduction. For semi-anadromous fishes it was expressed in the shallowing or even full disappearance of spawning areas in the deltas of the rivers, and for anadromous fishes in the interruption of migration routes upstream to places of natural reproduction (Ermakhanov et al. 2012).

The Aral Sea level decline even though by only 1.5–2 m to the mid 1960s was nevertheless responsible for a perceptible decrease in the spawning area. Reproduction of bream, zander, roach and shemaya – the main fish species – decreased accordingly. Northern Aral fishes in mass began to spawn in places that earlier were considered unusual for this activity. In years with heavy and average flow, when the Syr Darya was connected with lakes, reproduction of fishes occurred in these lakes, and then grown up juveniles migrated down to the sea. In low-water years such as 1974–1975 when connection of the river with lakes was interrupted, the spawning occurred directly in the river. In this case the fate of larvae migrating down to the sea was not propitious because in the mouth of the Syr Darya there was a sharp shift of salinity (Ermakhanov et al. 2012).

In the late1970s and early 1980s, as a result of the blocking of the Syr Darya by a dam located near the settlement Aklak (20 km from the mouth) the discharge of fresh water to the sea ceased. Freshened bays disappeared. The most important of these (Karashalan and Karateren) separated from the sea and subsequently dried up (Ermakhanov et al. 2012).

Since 1975, because of the Aral Sea level fall, marine spawning areas, as such, are absent. The ichthyofauna of coastal zone, as studies of juvenile yield counts in 1971–1975 showed, consisted only of atherine, gobies, and sometimes of noncommercial nine-spined stickle-back (Ermakhanov et al. 2012).

Catastrophic deterioration of conditions of natural reproduction in the Aral Sea also sharply impacted the state of commercial fish populations. The first signs of the negative impact of salinization on the ichthyofauna occurred in the mid 1960s as salinity reached 12–14 g/l. In shallow spawning areas salinity increased faster than in the open sea and already in 1965–1967 it exceeded 14 g/l. This level harmfully affected development of roe of fishes of freshwater origin. At the end of the 1960s conditions in spawning grounds for semi-anadromous fishes sharply worsened (Ermakhanov et al. 2012).

Beginning in 1971 when average salinity in the open sea reached 12 g/l, there were the first signs of negative effects of salinity on adult fishes. For many fish species, the rate of growth slowed and their numbers sharply fell. By the middle of the 1970s when the average salinity of the sea exceeded 14 g/l, natural reproduction of Aral fishes was completely destroyed. As a result, in the second half of the 1970s in the populations of many fish species recruitment of new members was absent. As a result, from 1961 until 1976 commercial fish catches across the Aral Sea (Table 6.3) decreased more than by four times (Ermakhanov et al. 2012).

By 1981 when salinity exceeded 18 g/l, the Aral Sea had completely lost its fishery. The ichthyofauna (Table 6.4) consisted of nine-spined stickle-back from the aboriginal species as well as gobies, atherine and Baltic herring from species that were introduced and acclimatized. Aboriginal commercial fishes survived only in the Syr Darya and Amu Darya rivers and flood plain deltaic lakes. Single cases of the catching of older commercial fishes occurred only in the mouths of these rivers (Ermakhanov et al. 2012).

Since the mid 1970s, based on forecasts of the hydrological and hydrochemical regimes of the Aral Sea, researchers of the Aral branch of KazNIIRKH (Kazakh Research Institute of the Fishing Industry) carried out selection of euryhaline and halophilic fish species. They experimented with Caspian sturgeon, Kura salmon (*Salmo trutta caspius*), Far East coho (*Oncorhynchus kisutch*), Azov-Black Sea flounder-gloss (*Platichthys flesus luscus*) and flounder-turbot (*Psetta maeotica*).

Table 6.3 Dynamics of fish catches in the Aral Sea 1961–1980 in metric tons (before separation of the Small and Large Aral seas)

	Year										
Fish	1961	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
Bream	8,920	600	640	790	1,100	1,608	1,975	1,381	528.9	66.8	6
Carp	9,940	1,390	1,000	990	1,050	1,346	328	219.5	100.9	–	373.5
Roach	6,950	2,360	1,350	1,380	1,980	2,277	1,423	418.6	213.9	242.8	68.6
Shemaya	440	10	11	2	5	–	–	–	–	–	–
Barbel	1,220	330	344	260	316	361.2	306	134.6	27.8	0.4	–
Zander	2,740	8,290	12	10,680	6,630	5,351	4,474	3,500	2,696	1,689	2,479
Pike	650	120	10	40	360	128.8	30	9.5	44.9	–	–
Wells	920	430	110	320	450	248.5	61	20.6	30.1	–	2.2
Asp	900	1,010	1,000	1,460	2,740	554.3	207	195.4	7.9	–	–
Snakehead	–	–	50	180	500	72.5	38	34.8	158.8	–	–
Grass carp	–	40	10	20	50	306.9	101	58.8	148.1	–	–
Silver carp	–	10	13	–	10	485.8	14	29.1	48.6	–	–
Others	1,480	370	200	850	210	422.9	68	4	39	9.3	5.5
Total	34,160	14,960	16,730	16,970	15,500	13,462	9,027	6,007	4,045	2,009	2,935

Table 6.4 Species composition of the Aral Sea ichthyofauna since the 1960s

Species	Years 1960–1979	 1980–1990	 1991–2004	Status
Acipenseridae				
Ship sturgeon	+	–	–	C-, E
Acipenser nudiventris Lovetsky				
Stellate sturgeon	+	–	–	
Acipenser stellatus Pallas				
Salmonidae				
Aral trout	+	–	–	C-, E
Salmo trutta aralensis Berg				
Esocidae				
Pike	+	–	+	C-
Esox lucius Linnaeus				
Clupeidae				
Baltic herring	+	+	+	
Clupea harengus membras (Linnaeus)				
Cyprinidae				
Aral roach	+	–	+	C
Rutilus rutilus aralensis Berg				
Orfe	+	–	+	C-
Leuciscus idus oxianus (Kessler)				
Asp, zherekh	+	–	+	C
Aspius aspius iblioides (Kessler)				
Rudd	+	–	+	C-
Scardinius erythropthalmus (Linnaeus)				
Turkestan barbel	+	–	–	C-, RB
Barbus capito conocephalus Kessler				
Aral barbel	+	–	+	C-, RB
Barbus brachycephalus brachycephalus Kessler				
Bream	+	–	+	C
Abramis brama orientalis Berg				
White-eye bream	+	–	+	C-
Abramis sapa aralensis Tjapkin				
Aral shemaya	+	–	+	C-
Chalcalburnus chalcoides aralensis (Berg)				
Sabrefish	+	–	+	C-
Pelecus cultratus (Linnaeus)				
Crucian carp	+	–	+	C-
Carassius carassius gibelio Bloch				
Carp	+	–	+	C
Cyprinus carpio aralensis Spitshakow				
Grass carp	+	–	+	I, C-
Ctenopharyngodon idella (Valenciennes)				
Silver carp	+	–	+	I, C-
Hypophtalmichthys molitrix (Valenciennes)				

(continued)

Table 6.4 (continued)

Species	Years			Status
	1960–1979	1980–1990	1991–2004	
Bighead carp *Aristichtys nobilis* (Richardson)	+	–	+	I, C-
Black carp *Mylopharyngodon piceus* (Richardson)	+	–	–	I, C-
Siluridae				
Wels *Silurus glanis* Linnaeus	+	–	+	C-
Atherinidae				
Caspian atherine *Atherina boyeri caspia* (Eichwald)	+	+	+	I, NC
Gasterosteidae				
Nine-spined stickleback *Pungitius platygaster aralensis* (Kessler)	+	+	+	NC
Percidae				
Pike perch, zander *Stizostedion lucioperca* (Linnaeus)	+	–	+	C
Perch *Perca fluviatilis* Linnaeus	+	–	+	C-
Ruff *Gymnocephalus cernuus* (Linnaeus)	+	–	–	NC
Channidae				
Snakehead *Channa argus warpachowskii* Berg	+	–	+	I, C-
Gobiidae				
Bubyr goby, transcaucasian goby *Pomatoschistus caucasicus* Berg [= *Knipowitschia caucasica* (Berg)]	+	+	+	I, NC
Sand goby *Neogobius fluviatilis pallasi* (Berg)	+	+	+	I, NC
Round goby *Neogobius melanostomus affinis* (Eichwald)	+	+	+	I, NC
Syrman goby *Neogobius syrman eurystomus* (Kessler)	+	+	+	I, NC
Tubenose goby *Proterorhinus marmoratus* (Pallas)	+	+	+	I, NC
Bighead goby *Neogobius kessleri gorlap* Iljin	+	+	+	I, NC
Pleuronectidae				
Black Sea flounder *Platichthys flesus luscus* (Pallas)	+	+	+	I, C

Note: + present; – absent

Status: *C* commercial; *C-* commercial but low stocks; *NC* not commercial; *I* introduced; *RB* in Red Book; *E* extinct now

Table 6.5 Dynamics of catches of flounder-gloss in the Small Aral Sea for 1991–2004 in metric tons (period between separation of the Small and Large Aral Seas and construction of the Kokaral Dam)

Years											
1991	1992	1993	1996	1997	1998	1999	2000	2001	2002	2003	2004
50	100	85	650	720	945	1,050	1,155	1,225	1,260	1,350	1,230

Data source: Yearly fish catch data: Unpublished, Kazakhstan Research Institute of Fisheries, Aralsk, Kazakhstan

The most promising were experiments with flounder-gloss, which are characterized by remarkably large ecological flexibility and the ability to reproduce at salinities from 17 to 60 g/l (Ermakhanov et al. 2012).

In order to preserve the fishery of the Aral Sea under conditions of increasing salinization in line with the biological substantiation that was developed, from 1979 to 1987, 14,280 flounder-gloss were introduced to the Aral Sea from the Sea of Azov (Lim 1986). Flounder-gloss has acclimatized successfully in the Aral Sea. In the early 1990s, it was settled across the entire sea and had commercially useful concentrations in water with salinities from 15–20 to 50 g/l. Acclimatized flounder-gloss was the only commercial fish species in the Aral Sea (Table 6.5) from 1991 to 2000 (Ermakhanov et al. 2012).

At the end of 1989, as a result of the continuing level drop, the Aral Sea separated into two parts: the southern Large Sea and the northern Small Sea. After partition of the Aral Sea, the change of hydrological-hydrochemical regime in the Large and Small Seas became independent of each other.

Salinity in the Large Aral Sea continued increasing and in the second half of the 1990s this water body became hyperhaline. So, by the end of the 1990s salinity of the Large Aral reached 60–70 g/l and, as a result, acclimatized flounder in this part of the sea were completely lost. Since then the Large Aral Sea is a lake without fishes (Ermakhanov et al. 2012).

Beginning in 1988, after a long interval, the flow of the Syr Darya again reached the Small Aral Sea. As a result of this, a freshened zone appeared in the mouth zone where aboriginal commercial fish fauna migrated from lacustrine systems and the Syr Darya (Ermakhanov et al. 2012). Lessening of water withdrawals for irrigated agriculture allowed the provision of a relatively stable annual runoff to the Small Aral Sea of 6–8 km^3. Construction of the first Kok-Aral earthen dike in 1992 to block the flow from the Small to Large Aral seas allowed accumulating most of the Syr Darya flow in the Small Sea. In 2005 a new Kok-Aral dam was built.

Freshening of the Small Aral Sea began and the zone with salinity from 1–10 g/l increased to 60,000 ha. Water level stabilization and gradual salinity decrease have allowed the return of generative-freshwater commercial fish fauna to the Small Aral Sea by migration from lacustrine systems of the lower Syr Darya. Representatives of aboriginal ichthyofauna (Aral roach, bream, carp, zander, asp, etc.) began to be found in the Small Aral Sea for the first time in many years (Ermakhanov et al. 2012).

Table 6.6 Dynamics of fish catches in the Small Aral Sea 2005–2008 in metric tons (after construction of Kok-Aral dam)

		Fish species							
Year	Total	Flounder	Bream	Zander	Carp	Roach	Asp	Sabrefish	Others
2005	695	303	57	30	181	–	–	–	124
2006	1,360	700	120	70	190	250	30	–	–
2007	1,910	640	410	260	260	370	80	40	–
2008	1,490	410	360	170	170	340	90	–	–
2009	1,885	615	470	185	125	410	80	–	–
2010	2,810	715	835	245	115	765	70	65	–

Data source: Yearly fish catch data: Unpublished, Kazakhstan Research Institute of Fisheries, Aralsk, Kazakhstan

Unfortunately during the period of annual high flows on the Syr Darya (late spring-early summer) the water flowing from the freshened areas of the Small Sea through the water discharge gates of the Kok-Aral dam to the Large Sea, because of the absence of protective facilities, contains many aboriginal commercial fishes, which die in mass during summer in the shallow lakes and ponds between the Small and Large Aral Seas. The area of the freshened zone considerably increased, as did the area inhabited by aboriginal commercial fish species. The fish fauna expanded their zone of spawning and feeding to almost the entire area of the Small Aral Sea with the exception of Butakov bay where the salinity has remained higher (Ermakhanov et al. 2012).

The relative stabilization of the hydrological regime and, above all, freshening of the Small Aral Sea promoted the achievement of commercial numbers of a number of valuable food fishes: carp, bream, zander, asp, etc. However, at the same time, the relative commercial importance of flounder-gloss (Tables 6.5 and 6.6) is decreasing (Ermakhanov et al. 2012).

6.3 Aquatic Plants

Regression and salinization of the Aral Sea caused the destruction of the majority of vegetational biocenoses. Freshwater and freshwater-brackish water complexes of submerged higher plants were not able to endure these changes. Over the course of several years disappeared thickets of freshwater pondweeds, and then thickets of the watermilfoil Myriophyllum spicatum and the fennel-leaved pondweed Potamogeton pectinatus began to disappear. Over 10 years to the end of the 1970s, there was a strong depletion of the species composition, and under the influence of salinity, a few euryhaline species became dominant. By this time, reed-beds were reduced by half. At first they were arranged on a large area of dried bottom without extending into the water, and in the 1980s they disappeared completely. Earlier studies of salinized bays of the Aral Sea showed that reeds develop normally at salinity up to 18.5 but at 24 g/l they die. Thickets of the bulrush Scirpus kasachstanicus disappear at 16 g/l. New formed, fast salinizing shallow habitats were being rapidly overgrown by halophilic species of the horned pondweed Zanichellia, ditch grass Ruppia and charophyte Lamprothamnium papulosum. With the increase in salinity above 25–26 g/l thickets of these species also were disappearing (Dengina 1954, 1959; Husainova 1960). By the end of the 1980s there were only species of Ruppia as they are able to tolerate salinity of 50 g/l.

In the Large Aral, which had been transformed into a hypersaline water body, microphytobenthos (diatoms and the community of blue-green algae) dominated. Among macrophytobenthos only species of green filamentous algae of the genera Cladophora and Vaucheria were found. From higher plants sterile specimens of Ruppia sp. were found (Zavialov et al. 2003; Zhakova, unpublished data).

The role played by microphytobenthos in the Small Aral Sea is also great. In the 1990s, the bulk of production of macrophytobenthos belonged to the macroalgae Chaetomorpha linum, Cladophora glomerata and Cl. fracta. Macrophyte communities were formed of four species of flowering plants – common reed Phragmites australis, Ruppia cirrhosa, Ruppia maritima, eelgrass Zostera noltii, and two species of charophytes – Lamprothamnium papulosum and Chara aculeolata (= Ch. intermedia). In shallow bays on muddy bottoms at depths of 0.7–1.2 m communities of R. cirrhosa dominated. On sandy grounds at depths of 1.2–4.5 m communities formed by Z. noltii predominated. Everything that could be attached to was overgrown with green algae (Zhakova 1995; Orlova and Rusakova 1995). Communities of the charophyte Lamprothamnium papulosum were very rare. In waters near the Syr Darya Delta reed-beds began to form.

At present, the salinity of the Small Aral Sea continues to gradually decrease and this water body is being settled by widespread halophilic, cosmopolitan and highly polymorphic species of hydrophytes and helophytes penetrating from other continental brackish water bodies of the near Aral region.

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Chapter 7
The Present State of the South Aral Sea Area

Polat Reimov and Dilorom Fayzieva

Abstract The Aral Sea was once the world's fourth largest inland body of water in terms of surface area. A lake basin, fed by two rivers, the Amu Darya and the Syr Darya, it supported a diverse ecosystem and an economically valuable fishery. Intensive agricultural activity related to cotton production with high water demands during the Soviet era caused excessive water diversion for irrigation purposes from the rivers. As a result, since the early 1970s, the shores of the sea have been steadily receding. The disappearance of the Aral Sea has caused several severe environmental and economic impacts. The fishery is no longer viable. The seabed became exposed leading to the airborne dispersal of salts and pesticide residues. The river delta flora and fauna have deteriorated such that fewer species exist. The decreasing level of the Aral Sea was accompanied by a rise of salinity, which resulted in the degradation of the ecosystems in the Aral Sea area as well as those of the fertile delta lands. The exposed seabed has turned into a desert, which at the present time is a source of tons of salty dust, blown away by the wind and carried along for thousands of kilometers. The quality of river water and other sources for drinking water have deteriorated. Environmental degradation in the Aral Sea area, especially in the south part in Karakalpakstan has resulted in decline of the socio-economic and public health situation.

Keywords Aral Sea area • Karakalpakstan • Environment • Climate • Fauna • Flora • Water ecosystems • Anthropogenic impact • Ambient air quality • Water quality • Population health

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7.1 Introduction

Not so long ago (1960) the Aral Sea was the fourth largest lake in the world according to surface area and was famous for its rich natural resources, particularly its fishery. The zone around the sea was a biologically rich natural environment. In 1960, the area of the Aral Sea was 68.9 thousand km^2 and the water volume was 1,083 km^3. Two rivers, the Amu Darya and Syr Darya, supplied the sea with water. The population of the region had built a successful economy that met their vital needs over the historical past, while at the same time preserving the region's unique flora and fauna.

The Aral Sea was very rich with fish. The fish fauna of the Aral Sea constituted 20 types. The major types of fish were an acantha, an aspius, a carp, a bream, and a catfish. Thirty-eight kinds of fish inhabited the reservoirs of Priaralye (the near Aral region). At times, 30,000 tons of fish were caught annually in the Aral Sea.

A number of kinds of hoofed animals such as Bukhara deer, goitered gazelle (djeyran), Ust-Urt argali (listed in the Red Book of Uzbekistan), and also a wild boar and a saiga inhabited extensive territories of Priaralye. In Uzbekistan saigas live on the Ust-Urt Plateau, located within the Republic of Karakalpakstan. The aggregate number of saigas gathering for wintering and reproduction reached 1.0 million in 1988. The floristic structure of the delta of the river Amu Darya consisted of 638 kinds of higher plants.

Unfortunately all of these have been left in the past. At present, the world has almost lost the unique Aral Sea. Millions of people living in the zone of ecological catastrophe not only lost their employment and income, but also were subjected to a high risk of growth disorders due to a sharp deterioration of the environment. There have been dramatic changes in the flora and fauna of the region, which has lost tens of species of animals and hundreds of species of unique plants. In the Aral Sea region emerged a complex set of ecological, socio-economic and demographic problems of unprecedented scale. An understanding of this issue has been confirmed in the UN reports on human development in Central Asia, where it was noted that desiccation of the Aral Sea has not only regional but also global significance.

One of the largest terminal lakes in the world has nearly disappeared within the last 45–50 years. There has been no previous case, when within a single generation the death of a whole sea has been witnessed. The sea quickly dried out due to intensive evaporation. Like shagreen-leather the sea continues to shrink causing all-round deterioration of environmental conditions and aggravation of the crisis. Today its volume has decreased more than 13 times and the area of the sea – more than 7 times. The water level has fallen to 26 m, the coastline has receded hundreds of kilometers. Salinity has risen to 120 g/l in the Western Basin of the large Aral Sea and up to 280 g/l in the Eastern Basin. Consequences of this ecological disaster have affected living conditions of millions of people inhabiting the Aral Sea Basin. Negative environmental changes, including the effects of global warming, are magnified and also more persistent in this zone.

Seasonal droughts have amplified. The Aral Sea disaster has aggravated the continentality of climate, having strengthened dryness and heat in summertime, and led to longer and colder winters. The number of days with temperatures above 40 °C has grown twofold in Priaralye, whereas in other territory of Uzbekistan it only increased 1.5 times on average. The subsequent climate change will lead to a 10–15 % increase in evaporation from water bodies and to 10–20 % rise in transpiration from plants. These two processes will cause, on average, an increase in irrevocable water consumption of 18 %, and accordingly lead to a growth in water withdrawals.

According to the forecasts of experts, air temperature in the region can increase 1.5–3 °C by 2035–2050. The greatest rise in air temperature is expected in Priaralye. An extensive territory of white salt fields mixed with sand has become a new desert, the so-called Aral-Kum, with an area of more than 5.0 million hectares on the dried bottom of the sea. Dust and salt storms regularly arise here carrying millions of tons of salt and dust hundreds of kilometers.

Now in Southern Priaralye many small lakes have become shallow or dried up, leading to the disappearance of about 90 % of existing riparian (Tugay) forest, destruction of reeds over an area of 800,000 ha, and death of their faunal inhabitants. The forests along the rivers were lost due to the lack of the moisture. Hundreds of lakes in the Amu Darya Delta have disappeared. Desertification of Priaralye is accompanied by the loss of land resources as well as the deterioration of natural pastures and hay-fields. Soil salinization is occurring more actively, covering new areas. As a result of anthropogenic desertification, the biological productivity of soils has been reduced tenfold.

Priaralye already has lost over half of its gene pool of flora and fauna. Kulan, arkhar, striped hyena, and cheetah disappeared from the fauna. An extremely difficult situation has emerged with population of saigas. Today, their population is practically on the verge of complete extinction. The Red Book of Uzbekistan lists 11 species of fish, 12 species of mammals, 26 species of birds, 11 species of plants and 2 species of reptiles that are endangered or threatened.

Reduction of pastures and decrease of land use efficiency have contributed to the loss of more than 100,000 jobs in the areas directly adjacent to the Aral Sea. As emphasized by I.A. Karimov, President of the Republic of Uzbekistan, in a number of sessions of the United Nations General Assembly, the Aral crisis has become one of “the severest environmental and humanitarian catastrophes in the history of mankind; tens million of people living in the zone around the sea area are exposed to it”.

7.2 Geography of the Area

The Republic of Karakalapkstan occupies the northwestern part of the sand desert Kyzyl-Kum, southeastern part of the Ust-Urt Plateau, the Amu Darya Delta and the southern part of the Aral Sea. The northwestern part of the Kyzyl-Kum Desert represents a vast flat plain (75–100 m high) sloping towards the Aral Sea and covered predominantly with ridge-like, hilly sand dunes. There are isolated mountain massifs and low mountains (the highest at 473 m is Sultanuizdag in the east). In the Amu Darya River Delta, there are many branches, small lakes, Tugay thickets, and saline and waterlogged expanses. There are more irrigated lands and canals in the left-bank part of the Amu Darya Delta. The Ust-Urt Plateau breaks abruptly at the Aral Sea and Amu Darya Delta forming terraces. The southeastern end of Ust-Urt is located at the Sarykamysh Depression.

The climate is sharply continental. Dry, hot summers and relatively cold, snowless winters are characteristic. The mean temperature for January in the south is −4.90 °C and in the north −7.60 °C. Precipitation is meager – about 80–110 mm and falls mainly in winter and spring. The annual average number of frostless days is 194–215. The soils in the Amu Darya valley and delta are sierozem (grey-brownish) meadow soils, in the Kyzyl-Kum Desert sandy sierozems are found, on the Ust-Urt gray-brown soils, takirs (crusted clay), alkaline and individual sandy teritories are encountered. The sandy expanses of the Kyzyl-Kum Desert are thinly covered with grass/bush vegetation (djuzgun, cherkez, boyalish, keyreuk, sedge, xerophilous cereals, wormwood, various ephemerals and ephemeroids, etc.) and with arboreal species, chiefly saksaul. The Amu Darya Delta is rich with Tugay vegetation (poplar – turanga, willow, djida, tamarisk, liquorice, reed, yantak, akbash, etc.). On the Ust-Urt, gypsophilious vegetation predominates (biyurgun, wormwood, ephemerals and ephemeroids, keyreuk, boyalish, xerophilious cereals, etc.).

The desert is inhabited by reptiles (lizards, snakes), rodents (ground squirrels, jerboas), large mammals (djeyrans, saigas, wolves, foxes), birds (saksaul jay, golden eagle, beauty bustards, larks), Arachnida (scorpions, etc.). The wild life of the Tugay is more rich: pheasants, ducks, geese, cormorants, sandpipers, bald-coots, swans, gulls; mammals: jackals, reed lynxes, wolves, foxes, badgers, hares, wild boars, weasels, etc. Muskrats and nutrias have been introduced and acclimatized.

Karakalpakstan is rich in mineral wealth. Most prospected are deposits of raw materials for the construction industry, especially marble and granite. There are also large deposits of titanium/magnetic ores, mineral salts, sulphates, magnesium, talc, alabaster, and phosphorites. Large gas and oil fields have been discovered on the Ust-Urt Plateau.

7.3 Environmental Issues

The current tendencies in sustainable development require complex and continuous attention to all environmental issues. The problem of conservation of biodiversity on the planet and monitoring of it have become especially important when it comes to ecosystems formed and developing under extreme conditions (Rafikov 1998; Kust 1999; Bakhiev et al. 2001; Reimov et al. 2001).

The anthropogenic changes and disturbances of the environment in recent years are on a grand scale. In a number of cases, they can be compared to large natural disasters. The negative impacts of anthropogenic activity gradually build to critical values. Then there may appear a whole complex of effects that are ruinous for the environment. The other specific feature of these impacts is a situation when the negative outcomes of anthropogenic interference may appear in areas considerably distant from where they originated. It is extremely difficult and expensive to fight such man-made disasters. It is more rational to prevent such negative impacts caused by economic activity. But for this to be possible, continuous or periodic observations of the status of the environment must be maintained (Mamutov 2002).

The territory of the South Aral Sea area is situated on the Turan Lowlands of the Asian continent and represents a unique site for nature study. The flora alone in the lower reaches of the Amu Darya River consist of 635 species of higher plants of 304 genera in 75 families. The most diverse are the families of Chenopodiaceae, Asteraceae, Polygonaceae, Boraginaceae, Cyperaceae, Caryophyllaceae, and Tamaricaeae. Within the South Aral Sea flora, 176 endemic species are distinguished (including the Karakalpak endemics which constitute 10 species), 15 survivors and 33 congeners of wild plants. The floral make-up of the dried bottom of the Aral Sea includes 62 species, representatives of 47 genera and 18 families (Bakhiev 1985; Bakhiev et al. 2001; Mamutov 1991).

Land ecosystems of the South Aral Sea area are characterized as highly vulnerable and delicate. They respond even to slight changes in the environment, which later may lead to irreversible changes in ecosystems often accompanied by complete loss of scientific and economic value. Intra-zonal landscapes are subject to maximum transformation. What are the most reliable criteria for evaluating the condition of ecosystems, which are under extraordinary dynamic environmental pressure? Which of the factors should be decisive in management and maintenance of balance in delicate ecosystems? And the evaluation must have not only qualitative, but quantitative criteria as well (Kust 1999; Mamutov 2002).

Thus, to conserve and recover the resource potential of vegetation in the South Aral Sea area it will be necessary to work out special actions, which could facilitate stabilization of its condition and at the same time it will be necessary to maintain monitoring. The environment and prospects of socio-economic development of this region will depend on how soon and successfully this problem will be solved.

Mainly Tugay, meadow, psammophilious and gallophilious types of plants represent the current vegetation of Karakaplakstan. Due to changes in habitat, environmental disturbances are observed in formation processes and in the behavior of Tugay vegetation associations. In all distinguished associations, various stages of desertification are observed. The anthropogenic impact has resulted in a 90 % decrease in Tugay forest areas (Populus ariana, Elaeagnus angustifolia, Salix songarica) over the last 60 years. At the current rate of exploitation of Tugay forests, they will come under threat within the coming 10–15 years. Only in the last 10 years, the area, occupied by vegetation associations which are capable of existence in flood plain habitat (provided that they are flooded every year) has decreased from 35 % to 30 %. At the same time the number of associations confined to saline and desertified areas of the flood plain and delta has increased from 25 % to 70 %. Thickets of giant reeds in the Amu Darya Delta once occupied over 600,000 ha. By the mid 1980s, this area had decreased sixfold. And the yield of green grass, which in the 1960s reached 300–400 centners/ha, by the 1980s had decreased to 40–120 centners/ha. The areas of liquorice associations, which were once widely present in the Amu Darya Delta, have decreased from 12,000 to 1,500 ha. The areas of hay fields and pastures and their yield were also subject to a considerable decrease. For example, of 420,000 ha of hay fields that existed in 1960, by the late 1980s only 70–75,000 ha remained. Their yield on fields which are subject to irregular flooding decreased from 15 to 40 centners/ha to 3–16 centners/ha, and on unflooded desertifying areas to 0.7–0.8 centners/ha (dry hay), i.e. 22 times less. The area of pasturelands in the flood plain and delta has decreased from 348,000 to 125,000 ha.

Meadow-type vegetation depends on excessively wet and temporarily flooded depressions in the Amu Darya Delta. Their base consists of the association of *Phragmites australis*, *Calamagrostis dubia*, *Typha angustfolia*, *T. laxmanii*, *T. minima* with productivity between 20 and 90 t/ha. For the last 30 years, the area of meadows in Karakalpakstan has decreased from 600,000 to 70,000 ha. The psammophilious type of vegetation (plants having adaptations to resist damage from wind-blown sands) mainly are represented by *Haloxylon persicum*, *H. aphyilum*, *Salsola arbuscula*, *S. richteri*, *Agropyron fragile*, *Oligosporus arenarius*, *Ceratoides ewersanniana*, *Astragalus ammodendron*, *Ammodendron conolly*, *A. floribundum*, *A. eichwaldii*, *A. karelinii*, *Aristida karelinii* and by various kinds of Calligonum. The current condition of this type of vegetation is characterized by thin populations and wide spread derivative, low-yield associations that have low value in terms of fodder, due to various kinds of anthropogenic impacts (Bakhiev 1985; Bakhiev et al. 2001; Mamutov 1991).

The halophilious type of vegetation (plants able to tolerate high soil salinity) is represented by various kinds of *Halocnemum strobilaceum*, *Climacoptera crassa*, *C. lanata*, *C. aralensis*, *Suaeda salsa*, *Salsola paulseni*, *Halostachys caspica*, *Kalidium caspicum*, *Limomium suffruticosum*, *Nitraria schoberi*, and *Limonium ruthenicum*. This type of vegetation is widely spread over the territory of Karakalpakstan and is confined to soils of various salinity levels. Contrary to the tendency towards a decrease in area of Tugay, meadow and psammophilious vegetation, the halophilious type is expanding its natural habitat occupying more and more territory. At present, the association of halophytes occupies 40 % of Karakalpakstan’s territory.

One of the major aspects of the problem of nature conservation is conservation of vegetation, the most dynamic component of landscape, which is of huge biospheric significance. Until recently, most reserves were created in order to conserve the genetic resources of specific (mainly rare and threatened) biologic species. At present, there is a necessity to protect larger ecosystems, biocenoses (a group of interacting organisms that live in a particular habitat) and even individual physical/geographic regions with their multi-component landscapes.

To conserve the unique forest/bush associations of Tugay vegetation communities, which preserve the environmental balance and aesthetic asset of Tugay bush associations, it will be necessary to establish reserves in the lower reaches and delta of the Amu Darya. However, it seems that the most critical and effective action on conservation of the existing Tugay forests and on their partial recovery would be establishment of a single reserve on the whole territory of the flood plain of the Amu Darya River in its lower reaches in those areas where Tugay is present with the additional proviso that the adjacent river-side zones are also shallow flooded (Mamutov 2002). The suggested territory for establishment of a reserve, beside Tugay, includes also the main types of delta landscapes in inter-channel areas: intra-delta ridge-like sandy territories, meadow-lands of various water-supply levels, lacustrine depressions, alkaline land complexes, and fragments of quasi-zonal associations on takyr (salt flat) soils.

In view of the fact that the national reserves are regional research and organizational centers for nature conservation, establishment of Tugay reserves in the lower reaches of the Amu Darya River and the currently existing delta is quite promising (Mamutov 2002). Beside identification and conservation of the genetic resources, it will be possible to organize here monitoring of the behavior of Tugay and meadow ecosystems and to carry out research on the fundamentals of management of such ecosystems. On the territory, which is suggested for the reserve, Tugay of various ages is represented – from newly forming to established associations that have adapted to desert conditions. Under reserve conditions it will be necessary to identify the stages of development of forest/bush vegetation, its stepped- phase replacement due to a limited level of surface flows and recovery after restoration of a regular irrigation regime and to identify the impact of regulation of river flow on the make-up and productivity of Tugay and meadow associations. Based on the major problems of modern nature utilization, such an approach will facilitate the forecast of changes in vegetation and how to control them.

7.4 Impact of Ecological Crisis on Water Ecosystems

Owing to a complex of factors, issues related to reasonable use of water resources became one of the most serious problems for the region. When defining approaches to their solution, it is necessary to take into consideration that water owing to its importance for people, nature and society is an irreplaceable substance of vital importance. Impairment of the natural complex, the basic element of which is the hydrological system, inevitably leads to ecological disasters on a huge scale that far outweigh the benefits from individual projects. The desiccation of of the Aral Sea confirms all that has been stated above and occurred due to an unreasonable, one-sided, predatory attitude toward water resources.

The intensively increasing shortage of river and drinking water in the Aral Sea area necessitates raising the issue of seeking ways and methods of rational use of water resources to a high priority. Irrigation is a powerful force destabilizing the natural environment of the region. All changes in flow behavior that occur in the Aral Sea Basin are integrated in the Amu Darya estuary, as it is the final link in the hydrographic network. Any changes occurring in the river behavior immediately, either directly or indirectly, affect the estuary processes in the delta ecosystems.

The current hydrographic network of the South Aral Sea area consists of the main channel of the river, branches, circulating and stagnant lake water bodies, as well as numerous irrigation canals, their branches, as well as the collector/drainage network. The water management complex being the major factor of environmental well being became the most difficult and science-intensive sector. The experience of Karakalpakstan shows what an important role belongs to land reclamation both in raising the productivity of and in maintaining stable agriculture. This is especially important for the Republic of Karakalpakstan where the major part of irrigated lands needs various kinds of actions in land reclamation and irrigation.

It is a well-established fact that there has been and is a rise in the mineralization level of all categories of surface and groundwater and deterioration of its chemical composition within the lower reaches of the Amu Darya. And it has been demonstrated that the main cause of this process is irrigated farming as a result of which ever larger amounts of return flow, including highly mineralized collector/drainage waters are discharged into the river and canals. Inflow of soluble salts from irrigated lands to irrigation canals occurs with collector/drainage flows and by underground routes. The sources of these salts are saline soils together with groundwater that saturates them.

A network of irrigation canals covers the territory of the Republic of Karakalpakstan. Irrigation is carried out primarily from main canal systems (Suenly, Kizketken, Bostan, and Pakhtaarna) the source of which is the Amu Darya River. The left-bank canal Pakhtaarna takes in water from the Tyuyamyunsk Reservoir (up to 65 m^3/s) and irrigates the lands of the southern districts Turtkul, Beruny, and Ellikkala.. Upstream of Takhiatash dam the left-bank Suenly canal (up to 100 m^3/s) and the right-bank Kizketken canal (180 m^3/s) take in water, which irrigates the lands of the northern districts Khodjeyly, Shumanay, Kanlikul, Kungrad, Nukus, Kegeyly, Chimbay, Karauzyak and Takhtakupir.

Based on the conditions of its formation, the groundwater in the Republic of Karakalpakstan can be divided into two zones: (1) irrigation – the feeding source is surface water courses related to irrigation and (2) non-irrigation – where the behavior of groundwater depends mainly on natural factors. The influence of the river and irrigation canals on the rise in groundwater levels extends to a distance of 5–10 km and more. Although the depth of occurrence near the river is 1–2.5 m, after a considerable distance it drops to 15–20 m. The mineralization level of groundwater also rises with distance from the river. Within the influence zone of the Amu Darya River and canals it is 0.7–1.6 g/l with a composition that is hydro-carbonate/sulphate/sodium/potassium. As the distance from the river increases, the groundwater mineralization level rises to 5.5 g/l, the chemical composition changes to chloride/sulfate/potassium/sodium.

The hydro-chemical behavior of groundwater under natural conditions is determined by a complex of natural factors, which affect formation of flows of these waters in each individual district. The common feature for them is the fact that from formation zones down to district discharge points, a rise is observed in the mineralization level and transformation of the chemical type of these waters from hydro-carbonate and sulfate/hydro-carbonate into sulfate/chloride and chloride takes place.

In the Republic of Karakalpakstan, construction of collector/drainage networks was started only in 1962. In 1968, effluents from lands started to be diverted from all districts. The collector/drainage network was constructed mainly on the existing and newly developed lands that needed reclamation. The land reclamation system of the right-bank of the Amu Darya River covers the territories of Kegeyly, Chimbay, Bozatau, Karauzyak, and Takhtakupir districts, which have a combined, irrigated area of 83,800 ha. The main collector/drainage systems are KS-1, KS-3 and KS-4. Collector KS-3, over 100 km long, serves an area of 144,000 ha. With the retreat of the sea, all drainage water of the collector is accumulated in lake-like depressions. The KS-4 collector is constructed in the former Koksu branch of the river. The area covered by the collector is located within Takhtakupir district, the total area of which is 72,800 ha.

The land reclamation system of the left bank of the Amu Darya Delta covers the territories of Khodjeyly, Shumanay, Kanlikul and Kungrad districts. The main collector systems are the Kungrad collector ditch, which is the main left-bank collector. The Kungrad collector diverts drainage waters into Lake Sudochye. The collector is formed by confluence of the main left-bank collector and the right branch of the Kungrad collector ditch. The main left-bank collector is the continuation of the Khodjeyly collector. It receives drainage from 40,000 ha of irrigated lands.

Regulation of the Amu Darya has resulted in changes to the salinity regime of the Takhiatash Dam section of the river and its dependent water bodies. Deterioration of water quality in winter and spring between the Takhiatash Dam and estuary occurs due to a rise in mineralization levels of 1.2–2.5 g/l and chlorine ions to 600–800 mg/L. The changes in mineralization of the Amu Darya have a reverse negative relationship with the changes in water flow in the upper reaches. For example, during high water periods the mineralization level drops to 450–600 mg/l whereas during low water periods it rises to 1,200–1,600 mg/l. Year by year, the mineralization level of river water increases downstream, as the water flow drops to 8–12 km^3 near Takhiatash.

The Amu Darya has two periods of intra annual flooding: during spring from melting of snow and during summer from melting of mountain glaciers. These floods supplied the freshest water to the river. The distribution of salinity along the river entirely depends on farm work schedules. The major features of functioning of water ecosystems of the South Aral Sea area are the specific nature of behavior and stocks of mineral forms of biogenic elements which act as one of the triggering mechanisms of eutrophication and pollution. It is impossible to determine the speed of anthropogenic eutrophication only by the magnitude of the biogenic burden on a water body. It to a considerable extent depends on the processes in the water body: accumulation of bottom sediments of biogenic substances, the speed of their turnover, qualitative make-up of aquatic life, etc. Accumulation of biogenic substances entering water ecosystems together with agricultural effluents help activate autotrophic groups of organisms that keenly respond to nitric and phosphoric compounds, which results in formation of a certain specific behavior characteristic for eutrophic water bodies.

Growing aridity and decreasing fresh water inflow became the major factors transforming the water ecosystems, including their chemical composition. A rise in mineralization levels of water, transformation of all categories of waters into chloride/sulphate types (often sulphate/chloride, specific for this province), with the background of excessive concentrations of nitric and phosphoric compounds have resulted in development of limnic (fresh water ecosystems) with specific hydro-chemical behavior. A rise in salinity of water and a change in its composition in themselves are not inhibiting factors in development of aquatic fauna of water bodies. However, an excess of biogenic compounds creates an unfavourable complex of abiotic conditions such as oxygen deficiency and stressed gas regimes.

The noticeable deterioration in irrigation water quality has led to a number of negative consequences that were not observed earlier, including deteriorating soil desalinization conditions, increasing inflow of salts with irrigation waters to irrigated lands, and deteriorating quality of canal-side lenses of fresh waters that are used for potable water supply. Mineralization levels of water in collector/drainage ditches are increasing starting from the head parts towards the tail parts and range from 1.2 to 13.4 g/l. The collector/drainage network is one of the factors in lowering the depth of groundwater and its mineralization levels. In the head part of the main canals and alongside their channels, fresh waters (up to 1.5 g/l) form with the width of 1 to 1.5 km and low mineralization (1.0–3.0 g/l). On irrigated lands groundwater has high mineralization levels.

7.5 Lakes in the South Aral Sea Area

In the lower reaches of the Amu Darya River there were over a hundred lakes, many of which contained fresh water fit for water supply, watering of animals, irrigation and industrial use, as well as habitat for water fowl. Fish, muskrat, nutria inhabited a number of fresh-water and low-salinity lakes and rich reed thickets grew on them. Some lakes were situated amidst picturesque landscapes.

The current condition of water bodies of the Republic of Karakalpakstan fully depends on the water level in the Amu Darya River. Due to irrational utilization of water resources for agricultural needs in the region many water bodies dried up and most water bodies lost their direct uses (fishing, musk rat breeding, drinking water supply, recreation, etc.). At present, the general natural condition in combination with local conditions is creating a complex determining the hydrologic and hydrochemical behavior of lakes. This allows classification of water bodies into three groups in terms of water inflows. First are those fed exclusively by river water (the inter-fluvial lake systems, that include the lakes Domalak and Makpalkul and the former bays of the Aral Sea: Sarbas and Muynak). Second are those fed by collector/drainage and return waters (the Lakes Sudochye and Akchakul and Djiltirbas Bay). Third are those fed by mixed inflows of collector/drainage, river and underground waters (the Lakes Dautkul, Karateren, Ayazkala, and Ashikul).

Water body surface areas vary from several to hundreds of hectares. Small lakes predominate. Their depths are up to 8 m. Yearly variations of water level in water bodies, as mentioned above, entirely depend on water levels in rivers. In drought years (e.g., 2000/2001), some water bodies in peripheral areas of the delta completely dry due to water shortage. Deep lakes such as Karateren and Ayazkala are partly fed by groundwater; therefore, their levels vary relatively little. Most water bodies in the lower reaches of the Amu Darya River are fed mainly by runoff from irrigation systems, and by collector/drainage waters.

Coastal water bodies have considerable fishery significance. They are excellent spawning places for major food fishes and nesting places for waterfowl. However, yearly withdrawal of river water for various needs and a decrease in yearly flow of the Amu Darya River have resulted in deterioration of environmental conditions in water bodies.

Most water bodies contain a considerable amount of biogenic substances, which ensure high biologic productivity in them. During the year, the concentrations of biogenic substances, especially of nitrogen nitrates and dissolved mineral phosphorus are subject to specific changes. Their highest concentrations are observed in spring, and the lowest in summer and in early autumn. In summer time, concentrations of nitrogen nitrates often drop to analytical zero. In autumn and winter, with the decrease in consumption by phytoplankton and due to nitrification processes nitrogen nitrate again builds up in lakes to 2.10 mg/l.

As mentioned above, within the existing irrigation systems in the lower reaches of the Amu Darya River, most of the topographical depressions are used as the local water receptors for discharge and collector waters. The territory, on which such water bodies are located, is made up of impermeable loamy-fine sediment. Mineralization in them is diverse. Water bodies are commonly found that are located not far from each other, but have mineralizations different in quantity and quality of dissolved salts. At present, these water bodies are mainly used for fishing (Lakes Karateren, Aktuba, Akshakul, Kirkkiz, Ayazkal, and Ashikul).

The mineralization and chemical composition of water bodies that are fed by mixed inflow are quite diverse. Due to a lack of outflow and century-long exploitation as water receptors, large amounts of soluble salts have accumulated in them. Water bodies with a chloride/sulfate nature are common. In autumn and winter, water is mineralized at a relatively high level (2–8 g/l), and during periods of intensive irrigation at a lower level (1.5–2.8 g/l). During the year, the chemical composition of both chloride and sulfate ions remains stable.

As mentioned above, the behavior of biogenic substances is characterized by many positive and negative factors and, therefore, it is quite complex. The concentration of biogenic substances in water bodies depends on the amount of externally received biogenic elements together with inflow water, from erosion of surrounding soils, attached to wind-blown dust, and from human economic activity.

It may be deduced from the above material that development of gas behavior in water bodies is affected by numerous factors, including the reduction of water movement in comparison to river flow, wind-activated periodic mixing, photosynthetic processes that are intensive during warm periods of the year, the formation and mineralization of organic substances, etc. Under their influence, dissolved oxygen (DO) in water bodies of the lower reaches of the Amu Darya River varies between 3–4 and 13–14 mg/l. The presence of hydrogen sulfide (H_2S) is also observed in the bottom layer of water. The level of pH in lakes ranges from 6.8 to 8.8. The highest levels are observed in water bodies during summer and autumn periods, and the lowest in winter.

Therefore, the on-going changes in the hydrographic network, instability of the Amu Darya hydrologic behavior, as well as agricultural activity do not exclude evolution of specific genetic groups of water bodies. In the lower reaches of the Amu Darya River, within different landscapes, the combination of specific physical/geographic conditions of formation of the chemical composition of water bodies is possible. Thus, according to hydro-chemical behavior, the water bodies of the Amu Darya River lower reaches and delta show that their chemical composition is variable both in terms of time and territory and is formed under the influence of various factors, among which the most important are the water supply level of the river, climate, geography, lithologic composition of soils and rocks, mixing of waters belonging to different genetic categories, soil and groundwater salinity, intra-water body processes (physical/chemical, bio-chemical and biologic), as well as economic activity.

7.6 Anthropogenic Impact on the Environment in the South Aral Sea Area

The extreme environmental situation in the Aral Sea area is caused first of all by changes in the water supply level. Intensification of use of water resources for the needs of development of irrigated agriculture has resulted in changes in the region. Major vegetative changes took place in the region: degradation of the Aral Sea area environment (loss of the Aral Sea, degradation of natural pasturelands; a decrease in their potentials, replacement of vegetation associations by desert vegetation associations), anthropogenic desertification, intensification of salt accumulation, aeolian salt drift, deterioration of climatic conditions, and intensification of climatic discomfort. Reed thickets were destroyed on an area of 800,000 ha, surviving Tugay thickets on an area of 1.3 million ha are on the verge of extinction, hay fields have decreased by 500,000 ha, yields of natural pasturelands have decreased by five million feed units, and over 50 lakes have dried up. Vegetation and wild life have become impoverished: the formerly rich ecosystems have been severely damaged with the loss of the genetic potential of endemic fauna and flora. At present, only 38 species have survived out of 178 animal species that previously inhabited this area. The sea, which provided 45,000 metric tons of high-quality fish has entirely lost its fishery potential (UNESCO 1998, 2001).

A decrease in the water supply level of the territory, increase in land salinity and general aridization became the most significant factors in transformation of the environment. The driving force for these processes in the last 15 years has been the impact of poorly managed water systems (including large water management actions), the fast growth in the scale of land use, and inadequately targeted development of natural resources. First of all, this was expressed by a sharp increase in water withdrawals and disposal of effluent and irrigation drainage waters on land areas instead of their collection and discharge into the Aral Sea that occurred in low water years in the Syr Darya and Amu Darya River Basins.

In spite of actions being taken for development of drinking water supply such as construction of cluster water supply pipes and installation of desalination plants, the issue of water supply for the population with guaranteed quality and in sufficient quantity still remains urgent. For instance, from 1990 to 2009, the percentage of water samples below the sanitary requirements based on chemical indicators reached almost 69 % and by bacteriological standards – 15 %.

The provision of populated areas with sewerage systems is quite inadequate, although under hot climatic conditions this problem requires urgent solution. In Karakalpakstan, there are 83 large enterprises intensively polluting the environment (air, water bodies, soil). Twenty-seven of them have treatment plants, but only six are operational. Under the existing acute shortage of water and the environmental and epidemiological situation, the discharge of huge amounts of untreated wastewaters is a sanitary/environmental offence. For example, the municipal sewerage system of Nukus, the largest city in Karakalpakstan, has generated 31,000 m^3 of wastewater a day for many years (since 1960). All of it is discharged untreated into the Kyzyl-Kum desert.

Assessing the environmental situation in the Aral Sea area, special attention should be paid to such an indicator as pesticide use. The monoculture cropping system forces the use of dozens of highly toxic plant protection chemicals – 11 kg/ha of pesticides are used in the republic (Table 7.1). Due to this, pesticide residues are detected in 1.3–13.5 % of water samples, and the maximum allowable concentration (MAC) is exceeded in 90 % of those samples. The presence of pesticides was detected in 28 % of soil samples whereas in air they are detected in every second sample. In recent years, reports are that most locally manufactured products contain pesticides in concentrations hazardous to human health, including milk, which is intended for child nutrition (Kurbanov et al. 2002).

Based on observations of many years by these authors of pesticide concentration behavior in water media, they note that HO pesticides have high concentrations of hexachlorocyclohexane, and low DDT concentrations. Hexachlorocyclohexane is distinguished for high volatility, less absorption by soil, easy migration, more stability in water; DDT dilutes poorly, is less volatile, is heavily absorbed by soils and is better kept in them. But this is poor consolation as collector/drainage waters and irrigation discharge lakes are polluted to the maximum. The application of DDT has been prohibited in Uzbekistan.

Among the herbicides applied on rice-fields, propanide got into water bodies in considerable amounts (0.1–0.3 mg/L). Other problem contaminants have been yalane (up to 150 mg/l), and saturn (up to 0.01 mg/l). Accumulation of pesticides were also detected in bottom sediments: diurone – 0.64 mg/l, atrazine – 0.16 mg/l and sevin – 0.05 mg/l. Considerable amounts of pesticides are accumulating in aquatic life, including fish. Toxic substances thus get into biologic life cycles.

Table 7.1 Distribution of chemicals used in Karakalpakstan by type (%)

Districts	Herbicides	Insecticides	Defoliants	Fungicides	Chemical composites
Amu Darya	2.2	51.8	42.5	1.52	1.70 (12)
Beruny	7.94	52.2	33.8	3.83	2.11 (13)
Bozatau	20.6	38.6	33.2	1.68	6.0 (3)
Karauzyak	58.0	17.6	21.0	0.59	2.81 (5)
Kegeyly	9.55	37.6	46.9	2.99	2.82(7)
Kungrad	38.5	22.7	35.4	1.62	1.77 (1)
Kanlykul	41.9	22.3	31.3	1.03	3.52 (9)
Takhtakupir	70.1	19.9	8.54	0.33	1.12 (6)
Turtkul	4.18	44.1	42.1	2.90	6.70 (15)
Khodjeyly	7.03	50.0	39.1	1.86	1.96 (01)
Chimbay	43.2	25.0	26.3	1.49	3.97 (4)
Shumanay	7.67	30.2	55.4	2.70	3.07 (8)
Ellikkala	6.48	44.8	38.6	2.59	7.52 (14)
Average for Karakaplakstan	24.4	34.8	35.8	1.86	3.09

Human consumption of contaminated foods is, obviously, unsafe (Kurbanov et al. 2002).

Thus, at present, against the background of an extreme and dry continental climate, as a result of drying of the Aral Sea, anthropogenic desertification, pollution of soils, water, food, and other factors adversely affecting human health, extreme conditions have developed for the population living on the territory of Karakalpakstan. They are reflected in intensive chemical pollution of all parts of the habitable environment, intensification of climatic discomfort (increase in dryness, unfavorable temperature variations, and dust/salt storms), poor quality drinking water, etc.

7.7 Influence of the Environmental Crisis on the Socio-Economic Development of the South Aral Sea Area

The region of concern in this chapter is the Republic of Karakalpakstan, located in the Amu Darya Delta in the southern area of the Aral Sea area, where the most environmentally dangerous situation has developed. Karakalpakstan is an autonomous republic of Uzbekistan (Uzbekistan is the most populous republic in Central Asia with an estimated population of 30 million in 2012). This is the crisis of the Aral Sea, which has developed into a threatening scale for the last decade. As I.A. Karimov, President of Uzbekistan, noted, “The Aral Sea crisis is the largest environmental and humanitarian catastrophe in the modern history of mankind. About 35 million people living in the basin of the sea are impacted by it.”

The cause of the death of the Aral Sea is the intensive development of the irrigation network and withdrawal of a considerable part of the flow of the Amu Darya and Syr Darya rivers predominantly for irrigation needs with large losses of water in the irrigation network(40 % and more) and the use of obsolete and wasteful irrigation techniques. The intensive water withdrawals from the Amu Darya and Syr Darya, the main water courses of Central Asia, have led to severe water shortage on the one hand, 90 % of which is used for irrigation, and the lack of efficient water resources management systems both at the regional level and at the level of each individual country of the region on the other. Water allocation for irrigation needs reached 30–60 % of the total amount of water withdrawn and only about two-third of this amount is discharged back into the Amu Darya and Syr Darya rivers. Return drainage flows into rivers have mineralization levels of up to 16 g/l with high concentrations of various harmful substances. Added to these are poorly treated municipal/domestic, industrial and livestock effluents. As a result, drinking water sources are polluted and the quality of irrigation water has deteriorated.

Taking into account the scale, sizes and consequences of environmental degradation, ensuring sustainable development, and the mechanism of its implementation in individual regions have their own specific characteristics. Theoretically they can be divided into three groups. The first includes the regions' socio-economic development, which takes place most optimally in a balanced environment. The second includes the regions where there are certain problems related to protection of the environment and water use, the impact of which is not great on sustainable development. The third includes the regions' socio-economic development, which is subject to the impact of environmental factors. The Republic of Karakalpakstan belongs to the third group where the environmental situation is very stressed

The drying of the Aral Sea has sharply changed the environment for the worse with negative outcomes for the socio-economic development of the region. Previously, the Aral Sea had not only played the role of the factor influencing the coastal areas but the function that regulated as well the temperature and humidity in the Republic of Karakalpakstan. In recent years, the number of dust-storm days has increased by more than 50 % in the areas adjacent to the dried bottom of the Aral Sea. And the spatial extent and persistence of dust-storms has increased. The contribution of the Aral Sea to the regional humidity transfer has decreased from 5–8 % to 2.5–4 %. The frost-free period has decreased by 10–12 days. The area of lakes and wetlands that earlier was 80,000–100,000 ha, has been cut in half.

By various estimates, from 15 to 75 million tons of salts and dust are blown onto adjacent territories. Salt-dust fallout, 80–90 % of which comes from the dried bottom of the sea and alkaline soils, has almost covered all of the Amu Darya Delta north of Nukus. Areas of reed thicket in shallow waters and wetlands have considerably decreased which has lowered the self-purification capacity of the delta and undermined the development of the population's traditional activity: fishing and trapping for fur. The forage reserve of livestock has been destroyed. The environment developed in the region requires considerable changes in socio-economic development policies and strategies. Taking into consideration the following major trends listed below is necessary for the proper development of areas that are suffering under extreme natural and environmental conditions:

- The long-term nature of tasks to be implemented in nature utilization and the rational utilization of the natural resource potentials, which require development of the socio-economic development strategy for the region for the period 2010–2050.
- The zonal nature of the impact of the environmental crisis, the influence of desertification processes on management processes, and consideration of the specific territorial features must be taken into account while analyzing and forecasting the region's future.
- It will not be possible to implement complex tasks aimed at decreasing the environmental tension and ensuring sustainable development without extensive introduction of modern technologies and equipment, especially in terms of rational utilization of water resources and efficient functioning of the water resources management infrastructure.
- Sustainable development and efficient utilization of natural resource potentials will largely be determined by rational location of productive facilities taking into account environmental restrictions and by intensification of inter-regional integration processes.
- Intensification of market reforms in the region, which is under extreme environmental pressure, can be attained only through government support and extensive encouragement of foreign investments maintained at levels higher than in other regions of Uzbekistan.

The impact of such important factors on the region's economy as the changes in climate, desertification, water supply, rational utilization of mineral resources and raw materials, land/water resources and labor force is great. Therefore, transitioning from their operative management to long-term strategies is an objective necessity. The long-term strategy of sustainable development of the region will serve as the target for the inter-related solution of environmental, economic and social problems and for prompt pre-emptive measures to prevent negative impacts of nature utilization. While affecting these, it will be necessary to take into account not only processes taking place in the Republic of Karakalpakstan itself, but also the intentions of the neighboring countries in the use of Amu Darya and Syr Darya waters for the needs of their socio-economic development as well as their contribution of water to the Aral Sea. Besides water resources, the external threats to sustainable development of the region include also the tendencies in climate change and desertification processes in Central Asia as a whole.

A drop in the living standards of the population has been a regular process of the transition period (the post Soviet period), but it has been aggravated by environmental deterioration in the Aral Sea crisis epicenter. During the transition period, the government has regulated the social processes and as well raised the minimum salary level, pensions, and allowances. In spite of these measures, wages have dropped. Therefore, considering the environmental situation that has developed in

Table 7.2 Environmental factors in the Aral Sea area and related illnesses

Environmental factors	Clinical incidence
Drinking water (mineralization, toxicity, pollution levels, increased mutagenic activity, presence of pesticides, herbicides, heavy metal salts) Helio/Meteo/Geophysic (atmospheric environment, dust/salt storms, solar activity, atmospheric pressure variations, etc.)	Anemia, immunodeficiency, nephrolithic and gallstone diseases, diseases of support-locomotion system and gastrointestinal tract, oncological diseases, endocrine disturbances, disturbances in hereditary systems, embryonic toxicities, terratogenic after-effects, increased infectious sickness. Vascular reactions, aggravation of chronic diseases, immunodeficiency, hormonal dysfunctions, allergic diseases, bronchial/lung pathology diseases
Nutrition (low-value food, food toxicity levels)	Anemia, gastro-intestinal diseases, poisoning, hemotogenic diseases, oncological diseases, endocrine disturbances, toxic hepatitis, after-effects of mutagenic impacts, increased infectious diseases incidence, toxic diarrhea

the Aral Sea area, improvement of social protection for the population is one of the priority aspects of further reformations in the Republic of Karakalpakstan.

7.8 Aral Sea Environmental Factors Affecting Human Health

Among the Aral Sea zone environmental factors affecting human health are desertification of the territory, shortage of good drinking water, intensification of salt emissions and transport from the dried bottom of the Aral Sea, a rise in dryness of the air, sharp temperature drops, wide spread problems of soil salinity, and pollution of the environment (air, water, soils, plants and food) by chemicals. One of the most serious problems is water pollution. Human habitation of the environment is closely dependent on the quality and quantity of existing water resources. Interaction of environmental factors in the Aral Sea area and their impact on human health can be characterized as follows (Table 7.2).

The aggregate of negative factors is causing disturbance of the biologic composition of the environment that influences the health of the population living here. The health of the population is not only deteriorating but also stresses in the functional systems of people in essentially good health are being observed as well, including disturbances in homeostasis and deterioration of adaptation potentials. Under such circumstances, multifaceted research of the medical/environmental environment become especially important, which allows decoding of the mechanisms that mobilize the functional potentials, to determine the criteria of the human health borderline conditions, to identify illness hazards, and to identify the causal factors influencing human health that bring about diseases. All efforts of health services and social protection of the population may result in nothing unless these regularities have been identified.

A comprehensive analysis of the environment and the morbidity rate in the Aral Sea area show that here microbial and chemical factors tend to act in tandem. Social deterioration and contagion of food and water are characteristic for the former that determines a high sickness rate. Degradation of human health by poor quality water, air and food are possible in the case of the latter that is capable of causing infectious diseases.

As a result of the considerable impact of various unfavorable environmental factors in the Aral Sea area, and low quality drinking water first of all, expectant mothers and children are developing disturbances in the balance of macro- and micro-elements negatively affecting the immune, endocrine, hemotogenic, cardiac/respiratory and other systems which under ordinary conditions are flexible and have pronounced potentials. Indicators of theses systems of human health, especially of children, can be considered as markers of unfavorable environmental impacts.

Total morbidity is an integral social indicator of the status of population health, which depends both on the real prevalence of diseases and the extent to which it is reported. The prevalence of diseases is determined by the influence of diverse direct causes against a background of particular features of the human organism and the social-demographic and geographic risk factors. The balance of exo- and endogenic factors has a character, which in different nosologic (classification of diseases) groups is specific for every region. Increasing of the total morbidity rate indicates the impact of ecological factors on the incidence rate of some diseases.

A common indicator of areas with ecologically unfavorable conditions is the presence of damaging factors of the environment combined with extreme geographic conditions (aridity, air-dust level, etc.), low socio-economic status of the population and insufficient development of infrastructure. The Aral Sea area stands out by its specific features among many other regions characterized by unfavorable conditions (Kudyakov et al. 2004). This uniqueness is created by a combination of anthropogenic changes of the landscape with a number of social-economic problems. The major factors creating an unfavorable environment and influencing the morbidity rate are listed below (Iskandarova 1999; Krighton 1999; van der Meer 1999):

- Reduction of the Aral Sea surface by over 50 % (from 1960s).
- Development of dust storms rising from the dried seabed and containing toxic substances and salts.
- Salinity of soil and agriculture fields.
- Deterioration of water supply to the population (shortage of water, contamination and high levels of salts in potable water, etc.).
- Contamination of water, soil and food products (DDT, pesticides, herbicides and defoliants).
- Deterioration of economic and social conditions due to the cotton monoculture, occupational hazards and inadequate planning of population growth.

- Climate change (further aridization).
- Other factors (lack of health education of the population, unhealthy habits, etc.).

The judgment on the effect of unfavorable environmental conditions on the cardio-respiratory status of the population in the environmental disaster zone to the south of the Aral Sea area was determined by analyzing data from examination of various age groups of the native population inhabiting ecologically differing regions. Severin (1995) has concluded that the environment plays a key role in the incidence of diseases of the bronchial and pulmonary system in association with social economic factors and deteriorating living conditions of the population.

Regional and temporal patterns of variation in the incidence of esophageal cancer in the autonomous republic of Karakalpakstan have been analyzed. Karakalpakstan has the highest rates of this disease among the major administrative units of Uzbekistan. Incidence data within districts (data from 1988 to 1989), ethnic groups (data from 1987 to 1989) and for the calendar periods (data from 1973 to 1987) were available for analysis, with corresponding official population estimates. No significant difference was observed between rates in urban and rural environments, although significant regional variation was observed ($P < 0.05$). The highest rate observed was in the Muynak district of Karakalpakstan with world age-standardized rates (ASR) of 125.96 for males and 150.65 for females (Zaridze et al. 1992, 1993). This district is directly adjacent to the dried bottom of the Aral Sea and is heavily affected by dust and salt blown from it.

7.8.1 Air Quality and Population Health

The regional character of air pollution in Central Asia is a result of deforestation, drying of water-swamp lands and especially of the sharp fall of the level of the Aral Sea. A huge territory (42,000 km^2) of desert with a high content of salt has been formed as a result of the Aral Sea desiccation.

Salt and dust transfer from the dried bottom of the Aral Sea is an important factor deteriorating environmental conditions in the region. The largest quantity of salt and dust is transported from the east to the west by duststorms originating from the Aral Sea bottom. It is common knowledge that the lowering of the Aral Sea level has resulted in the formation of a sandy-salt desert, which became the main source of salt and dust. As a result, in Karakalpakstan, the environmental and health situation has been worsened. The governments of Karakalpakstan and the Republic of Uzbekistan are taking measure to mitigate and stabilize the situation. Programs are underway to prevent salt and dust transport and the movement of sand by planting the dried bottom with various types of grass and other plants. Rapid growing ornamentals have been planted in settlements (Khaytbaev 1999).

Nukus is the capital of Karakalpakstan, which is situated in the northern part of the Republic of Uzbekistan close to the Aral Sea. It borders on the new nations of Kazakhstan and Turkmenistan. The climate is extremely continental. The population of Karakalpakstan is nearly 1.5 million and for Nukus more than 250,000. In Nukus, there are construction material and processing industries, an airport and railway junction. The main sources of air pollution are a canning factory, winery, milk processing factory, machinery overhaul plants, meat processing factory, pre-cast concrete and construction company, construction plant operating company, brick factory, lime and graphite-marble factory, car company, and highway construction company.

The laboratory of the Administration on Hydrometeorology of Karakalpakstan, the State Committee on Nature Protection and the Sanitary Epidemiological Service conduct atmospheric air quality monitoring. In Nukus, observations are carried out at two stationary sites three times per day. The program of observation includes sampling and analyzing samples of dust, nitrogen oxides and dioxide, sulphurous gases, phenol, and carbon monoxide and ozone. The Sanitary Epidemiological Service conducts atmospheric air pollution observations at 29 industrial enterprises. There is no Sanitary-Hygienic Zone (Protection Zone) at 47 % of these enterprises. All these enterprises are equipped with gas-dust purification facilities but the effectiveness of purification is not adequate. Air quality observations are conducted by the enterprises. For instance, 652 atmospheric air samples were analyzed on dust content and 1,566 samples on gases (sulphur dioxide, nitrogen oxides, and magnesium fluoride) in 1998. The MPC (maximum permissible concentrations) were exceeded in 63 samples (9.7 %) of dust and in 1.1 % of gases. But the real extent of air pollution cannot be determined because of insufficient observations (Khaytbaev 1999).

According to the Hydrometeorology Administration data for 1998, the air pollution index (API) in Nukus was 3.82, i.e. low. The average yearly concentration of dust in Nukus was 0.1 mg/m^3 and did not exceed the MPC. The maximum single concentration was recorded at 1.2 MPC, i.e. 0.6 mg/m^3 (the MPC for dust is 0.5 mg/m^3). The average yearly concentration for sulfur dioxide was 0.01 mg/m^3. The maximum single concentration was recorded at 0.044 mg/m^3 and did not exceed the MPC. The annual average concentration of carbon monoxide was 3 mg/m^3, that is, at the level of its MPC. The maximum single concentration was 6.0 mg/m^3, i.e. 1.2 MPC. The annual average concentration of ozone exceeded the MPC by nearly 1.5 times and was 0.04 mg/m^3. The maximum single concentration was 0.084 mg/m^3. The annual average concentration of phenol was 0.04 mg/m^3, i.e. 1.3 MPC. The maximum single concentration exceeded the MPC by 1.2 times and was 0.012 mg/m^3.

In recent years, there is a high morbidity from respiratory diseases, diseases of the blood and blood forming organs, nervous system and sense organs, diseases of skin and subcutaneous tissue, and malignant neoplasms in Karakalpakstan. It is probably related to air pollution by dust and chemical pollutants present in the atmosphere. As reported in general incidence information for all countries of the Central Asian region respiratory organ diseases are at the top. They constitute from 30 % to 78 % of the whole morbidity structure in big industrial cities. Permeation of high concentrations of numerous pollutants through respiratory organs resulted in a high prevalence of respiratory diseases among both adults and children. According to the statistical data, the incidence of childhood pneumonia in Karakalpakstan, located close to the Aral Sea, is the highest in the former Soviet Union. Results of research show direct correlation links between high the air pollution level and frequency of such diseases as acute respiratory diseases, pneumonia, chronic bronchitis, pulmonary emphysema, bronchial asthma, congenital abnormalities, and allergic diseases (Iskandarova 1999).

Diseases of the respiratory organs are one of the most typical consequences of air pollution. Sulphuric and sulphide anhydrides, nitrogen oxides and suspended particles are the most common problem. Both long and short-term inhalation affects the human organism. The consequences are reflected in diseases of the respiratory organs and the alimentary canal, in disturbance of reductive-oxidative processes and suppression of fermentative activity, and in reduction of immune-biologic reactivity of the body and functional changes of the central nervous system.

The permanent adverse effects of low concentrations of pollutants on population health are the injury of different organs and systems that reduces organismal resistance. The cardiovascular system and blood also can be affected by air pollution. A discussion of the impact of tobacco smoke on cardiovascular diseases is beyond this chapter's focus; however, tobacco smoke contains substances, which are characteristic for polluted air.

Dust of anthropogenic and natural origin contributes to disease. Dust/salt storms arising from the dried bottom of the Aral Sea are a good example of an anthropogenic source of this problem. Airborne dust is commonplace and dust storms are a well-known natural hazard in dry land regions. Dust is commonly dispersed in the form of an (aerosol), consisting of solid heterogeneous particles suspended in gas media (air). There is much interest in the effect of dust inhalation on health and growing concern that human activities particularly in dry land areas have increased dust hazards.

Experts believe that major environmental and health problems are related to increased levels of atmospheric dust. The exposed bed of the Aral Sea is the most regionally significant airborne dust source. Despite the possible link between dust and health, there is little information about the extent and nature of dust erosion and deposition in the Aral Sea region.

The main source of fine particulates is fuel burning in the energy and transport sources. A significant portion of total suspended particulates comes as wind blown dust aggravated by widespread soil erosion, the process of desertification and the poor condition of city roads.

O'Hara et al. (2000) conducted a study on the dust problem in the Aral Sea Basin. It was carried out in the Turkmenistan part of the basin. The sampling locations were divided into desert rangeland and irrigated agricultural areas and samples were analyzed for total dust deposition, particulate matter deposition (respirable particles <10 μm in diameter $–PM_{10}$), and phosalone content (an orghanophosphate pesticide that has been widely used throughout the region). Total dust deposition was very high at all sites (the highest in the world), but varied across the region in the range of 50–1,679 kg per hectare. The highest deposition rates were at sites located in the desert and lower at sites closer to the Aral Sea.

Twenty three percent of the deposited dust was PM_{10}, in size or smaller, but as a proportion of total deposition, PM_{10} values were greater at sites located close to or in irrigated zones and lowest in the desert. The findings from this study indicate that there are at least two major health risks associated with dust: risks associated with the inhalation of PM_{10} and problems associated with the inhalation and ingestion of organophosphate pesticides.

The preliminary findings of a year-long study on the link between dust exposure and respiratory health amongst children in the Republic of Karakalpakstan, located immediately down wind of the Aral Sea indicated that dust deposition rates across the region are high with sites located on the delta being the worst affected (O'Hara et al. 2001). There is an apparent inverse relationship between total dust exposure and respiratory health (the more dust, the worse the health).

Analysis of grain size indicated that dust deposited at sites located in the delta is predominantly of local origin. Although dust deposition rates away from the delta region are lower, the dust is predominantly of non-local origin and is considerably finer with high levels of PM_{10}. The physical and chemical nature of the dust is more important than the total amount. However, the links are likely to be far more complex, with other confounding factors such as nutritional status and socio-economic disadvantages being of considerable importance as well (O'Hara et al. 2001).

The existing systems of monitoring, control and evaluation of air pollution in the region require further improving for adequately managing air quality. A main problem is the lack of comprehensive information on air quality monitoring, and difficulties to compare the data on air pollution with the European standards. Lack of research on population exposure to air pollutants leads to the inability to assess the health impact, which is necessary for providing effective air quality management and pollution prevention in the region. Hence, the outdated system of ambient air standards needs to be revised and the database needs improvement in terms of determining the impacts on human health, with development of exposure assessment approaches.

7.8.2 Water-Related Public Health Problems in the Aral Sea Area

Shortage of water may be the most urgent environmental problem facing Karakalpakstan, especially in the territories close to the Aral Sea. The inadequate supply of people with good drinking water, extremely insufficient provision with sewer systems, and poor sanitation in populated areas remain the major causes of high rates of illness in the region. Only 38 % of Karakalpakstan's population is served by a piped water supply. The major part of the rural population uses the Amu Darya and associated water bodies for water supply. The quality of this source is deteriorating due to increasing water withdrawals for irrigation. As a result, the excessive decrease in river flow has minimized the self-purification ability of the river. Effluents of collector/drainage waters from the fields of Uzbekistan and Turkmenistan and untreated industrial/domestic wastewaters have even more negatively affected the environment. Therefore, along the whole stretch of the Amu Darya and collector canals in its delta, organic chloride pesticides are being detected and the mineralization levels in the lower reaches during some periods of the year attain 2–3 g/l. Pollutants that exceed the allowable maximum concentrations (MPC) include phenols, copper, chromium (fourfold), oil (fivefold), and pesticides (tenfold). The bacterial contamination of the river water exceeds the standards by tenfold.

The quality of drinking water resources, which is vital for human health is threatened by increasing agricultural, industrial and domestic pollution in the region. The water supply situation for the population of the region is very crucial. The supply of safe drinking water is inadequate in many areas.

In the Amu Darya River Basin, within the territory of the republic of Karakalpakstan, pollution of groundwater is categorized as regional groundwater pollution resulting from intensive use of chemicals in agriculture and affects surface and groundwater over a wide area. In this region, intensive agriculture has contributed to the deterioration of groundwater quality, especially in terms of salinity, increased hardness, nitrate and pesticides content.

According to different sources about 40 % of urban and about 60 % of rural people in Karakalpakstan use water from decentralized water sources for drinking and domestic needs (Binnie & Partners 1996; Iskandarova 1999). Speaking of centralized water sources, it is noteworthy that existing treatment facilities are not adequate to remove all contaminants. As a result, some chemicals are present in almost the same concentrations in both raw and drinking water. The highest risk is associated with the use of drinking water directly from polluted rivers, canals and wells (Binnie & Partners 1996). Despite recent progress, the improvement in the system of water distribution and the provision of safe drinking water needs to be accelerated. Piped water, especially in summer time, doesn’t meet drinking water standards for a number of microbiological and chemical contaminants. The water supply is not always sufficient, even where water pipes are intact, forcing people to use alternative sources of water (Iskandarova 1999).

There are problems with safe drinking water supply in every region of Uzbekistan but the areas with the greatest water concerns are usually localized. More than 1/3 of the country’s population consumes water, which does not meet the national standards. The Republic of Karakalpakstan is experiencing the most significant pressures on the environment, especially on water resources. A particularly complicated situation has arisen in the Aral Sea area in connection with (1) the growth of salinity in open watercourses, (2) high salinity of ground water, (3) uneven distribution of good quality water sources, and (4) the scattered and uneven distribution of rural population (Binnie & Partners 1996).

In some parts of Uzbekistan, freshwater resources are scarce and provision of drinking water is difficult. This is particularly the case in the Republic of Karakalpakstan and Khorezm, Bukhara, Navoi, Kashkadarya and Surkhandarya provinces, where there is little surface water of good quality. The principal water source in Karakalpakstan and Khorezm is the Amu Darya River and its associated irrigation canals (Binnie & Partners 1996). Supply of good quality drinking water in sufficient amount for the population is still the most important component of public health services activity.

The tap water supply to the rural population, which constitutes 60 % of the total population, increased from 51 % in 1985 to 64 % in 1998. Sewage treatment in towns where sewer systems are available reached 51.1 % by 1999 (for Karakalpakstan 31 % and for Khorezm region 38 %). More than half of the towns and rural settlements do not have sewage systems. The percentage of tap water samples tested by the sanitary epidemiological stations that did not meet health standards according to chemical indicators has increased from 22 % in 1985 to 25 % in 1998. However those not meeting bacteriological indicators fell from 18 % to 7 %, which is still high. The highest level of microbiological tap water pollution was revealed in Syr Darya region (17 %), Djizak region (12 %) and Tashkent and Namangan regions (13 %). In the surface waters used by the people, chemical pollution increased from 21 % in 1985 to 30 % in 1998, and bacteriological from 10 % to 10.5 %, (NEHAP 1999).

There are a number of problems as far as water utilization is concerned, which are the most significant due to their specific characteristics. One of these is the supply of safe drinking water, as according to the data of the Ministry of Health of Uzbekistan about five million people still do not have access to sources of safe drinking water. There are problems of discharges of dangerous elements such as resistant organic pollutants and carcinogens as well as the presence of viruses and bacteria in the internal and transboundary waters. Water borne diseases are resulting from the consequences of inadequate water management and water utilization and control both on the national and international levels (NEHAP 1999).

Morbidity rates of the population have increased due to the use of surface water for drinking purposes, and substandard water purification facilities in built-up and rural areas have amplified the problem (NEHAP 1999). Forty years ago, surface and ground water supplies were not contaminated with toxic substances and there was ample potable water for human consumption. However there has been a rapid degradation of water supplies. Contamination by agro-chemicals of 10–50 m deep wells in rural areas is common. In industrial zones, additional organic compounds and metals exacerbate water quality problems, and parasites have been found in urban water distribution systems.

Water supply in Uzbekistan, especially in the rural areas, remains one of the foremost environmental concerns. Until recently, over five million people used water from open, contaminated water bodies for their everyday and household needs. This problem is most pressing in the rural areas where over 60 % of the population does not have a centralized water supply system and only 2 % have a centralized sewage system (NEHAP 1999).

The contamination of open water resources is exacerbated by poor sanitary conditions and water distribution systems built in the 1950–1960s, which do not meet modem requirements for sustainability. These problems are most serious in summer months in the aforementioned regions when bacterial and chemical contamination regularly exceeds safe standards up to 50 % of the time. Overall, bacterial and chemical contamination is a serious environmental problem, which adversely impacts the health status of the population, mortality, and total infection morbidity (Iskandarova 1999).

Active diarrheal surveillance in the city of Nukus in Karakalpakstan over 9½ weeks revealed a mean monthly diarrheal rate of 75.5/1,000 among individuals with piped water on their premises and 179.2/1,000 among those without piped water on the premises (Semenza et al. 1998).

Among all reports on drinking water the most detailed information was presented in the report of Binnie & Partners Consulting Engineers Company, which is based on data from the Japan International Cooperation agency (JICA) study carried out during the period March 1995–February 1996. Water samples were taken from raw water sources (river, canals and wells) as well as from treated water sources (treatment facilities, pipes, and final consumer). Collected water samples were analyzed for such parameters as taste, odor, turbidity, total dissolved solids and for the content of different contaminants such as heavy metals, salts, halogens, pesticides, phenol, oil, bacteria and others.

The results of analysis were compared to WHO drinking water standards, which are accepted as the most detailed, with good scientifically based explanation of health outcomes. Attention was mainly to the samples taken from drinking water sources, which means piped water, treated water and well water. However, as was mentioned above, in many locations people use canal and river water for drinking and domestic needs, therefore in many cases in rural districts the raw water could be considered as a drinking water source. That is why the drinking water quality standards were applied not only to the "real" drinking water sources, but also to some raw water samples (Binnie & Partners 1996).

Such parameters as total dissolved solids (TDS), hardness, fluorides, sulfates, chlorides, sodium, potassium, calcium and magnesium had values that were similar to those found in the corresponding raw waters. The total hardness of all samples of treated waters, with few exceptions, was above the standard. The turbidity of treated well water was within the Uzbekistan standard, but in all except one instance the values were greater than the WHO guidelines. The turbidity of treated canal and river water was in most instances greater than the Uzbekistan standard and hence was very poor. Some unacceptably high values for oil were reported for Kungrad (0.18 mg/l), Chimbay (0.34 mg/l) and Muynak (0.14 mg/l) treated waters in June and July 1995 (Binnie & Partners 1996).

Among the heavy metals, iron concentrations in 1995 were higher than the WHO and Uzbekistan standards in all of the treated water samples examined. The concentration of nickel in July 1995 was high in all of the treated waters with all values reported exceeding 25 μg/l and was above the European standard of 20 μg/l. The high values reported were Nukus (52 μg/l), Urgench (41 μg/l), Kungrad (48 μg/l), Chimbay (39 μg/l) and Muynak (40 μg/l). Lead also was found in small concentrations in some water samples. The other metals copper, zinc, chromium, arsenic and selenium were not present at significant levels in any treated waters.

The pesticide concentrations in treated waters reflect those found in the raw water because the treatment processes used do not remove pesticides effectively. Thus, in the latter part of May 1995, DDT, α-HCH and γ-HCH were found in low, but appreciable concentrations in all the treated waters. The bacteriological quality of water in 1995 complied with the Uzbekistan standard of less than three total coliform colonies per liter for most of the treated water supplies. An exception was Muynak City treated water where values of 960 and 94 coliforms per 1,000 ml are reported for March and April 1995. This fact shows that there is high risk of intestinal infectious diseases among the population using this water for household and drinking needs (Binnie & Partners 1996).

Lack of water resources in the area of the Aral termed the "ecological disaster zone" has resulted in degradation of water bodies and deterioration of water quality in surface and underground sources (Elpiner 1993). The basic source of the centralized potable and household water supply of the population of Khorezm province and the Republic of Karakalpakstan is the Tyuyamyunsk reservoir. Its hydrological status, hydro-chemical and hydro-biological characteristics, including microbiological indicators, completely depend on the flow of the transboundary river Amu Darya. At the same time, over one third of the population of Khoresm and Karakalpakstan drink water from the underground sources of water including open wells and wells with manual pumps (the decentralized sources).

Frequently, water from surface and underground sources in the Aral Sea area does not meet the State standard of Uzbekistan (UzSt 950, 2000), as well as the requirements and recommendations of the WHO on potable water. Much higher values of the indicators of mineralization (more than 1.5 g/l) and the general hardness of water (more than 10 mg-eqv./l), in particular in the decentralized sources of water supply, have increased the risk of formation of stones in the urinary system and gallbladder. Rather high concentrations of sodium in the water, at times exceeding 200 mg/l – the WHO recommended level for potable water – raise the risk of development of hypertension and other diseases accompanied by an increase in arterial pressure. Quite probably this factor among others contributes essentially to rather high values of cardiovascular and renal pathology rates in the Aral Sea area. The majority of diseases of both somatic and infectious character became severer under the influence of more frequent drought periods.

Implementation of hydro technical projects impairing the historically developed pattern of water-use and influencing the balance of water resources (e.g., upstream construction in Tajikistan of the huge Rogun Dam on a major tributary of the Amu Darya with a very large storage reservoir, which is underway) will inevitably lead to exacerbation of problems in providing the population with both irrigation and potable water due to a changed flow regime below the dam in concert with regularly occurring droughts. Reduction of nutrition resources and access to safe potable water, as well as water used for public and personal hygiene, can affect the basic indicators of health care raising the need for improved health care services, in particular due to growth in the rates of intestinal infectious diseases resulting in worsening epidemiological conditions and development of emergency situations. In this case, the countries of Central Asia, where over 50 million people are living, will face dramatic deterioration of an already difficult ecological situation, particularly in terms of sanitary and epidemiological aspects.

It is also necessary to stress that environmental conditions are made worse by climate change with negative consequences for public health services and the sanitary and-epidemiological situation in the region. No doubt, climate change in turn will affect the health status of people in parallel with the various factors connected with water resources. The change of the water ecosystem status resulting from climate change will affect the well-being of communities, including impairment of nutrition and degradation of the food supplyand create new problems for health care services.

Salinity in the water supply systems in the Aral Sea area is due to both natural conditions and poor irrigation management. Saline water for potable and agricultural use has direct and indirect impacts on health, social welfare and the economy. Nonetheless, the health effects associated with known environmental contaminants in the Aral Sea area remain poorly understood and relatively under investigated.

The aforementioned impacts are interrelated in various ways. Firstly, drinking water sources are hydraulically linked with water in the irrigation system, which then leads to the transfer of salts from the irrigation system to drinking water sources. Salt diffusion processes are still poorly understood, thereby hindering efforts to improve the quality of water both for irrigation as well as for drinking purposes. Secondly, saline water used for irrigation purposes decreases yields and crop quality, leading to overall losses in productivity and income. Thirdly, saline water directly and indirectly impacts on welfare among rural populations via socioeconomic effects and ultimately long-term consumption of saline drinking water has deleterious impacts on human health.

Drinking water sources in the study region are connected to agricultural water use. In the rural areas, drinking water is mined from ground water, which is hydraulically linked with irrigation water in the canals and fields. The transportation and diffusion of salts from irrigation systems to ground water and drinking water has significant implications in terms of economic productivity and human health. Analysis of specific non-infectious morbidity dynamics in the Aral Sea area population shows that the growing morbidity of such pathologies as cardiovascular diseases and diseases of the urogenital system were made in the 1990s. These indices were higher than in the rest of Uzbekistan. Probably it is related to the substantial influence of high mineralization and hardness of drinking water and to the functioning of the mentioned human body (Iskandarova 1998). At the present time the health conditions of the population, living in the Aral Sea Area, should be considered in the relationship with the long-term exposure to environmental contamination and, particularly to the pollution of drinking water.

The quality of drinking water in the Aral Sea Area is very poor. The term "drinking water" in Karakalpakstan means not only piped water. People also use well water and quite often canal and river water because of the lack of piped water, especially in rural areas. It was found that such parameters of tap water as total dissolved solids (TDS), hardness, fluorides, sulphates, chlorides, sodium, potassium, calcium and magnesium showed values that were similar to those found in the corresponding raw waters. The total hardness of all samples of treated waters, with a few exceptions, was above the standard. Levels of TDS were high in many samples, and regularly were above the WHO standard of 1.5 g/l (Kudyakov et al. 2000).

According to local physicians' recommendations, four wells were chosen for water sampling as they are used most often as drinking water sources. Sampling of tap water for analysis was also provided. Examination of open well water samples revealed a high level of total hardness ranging from 14.3 to 26.8 mg-esq./l. For tap water total hardness indices were 7.6–14.7 mg-eq/l. The drinking water standards for total hardness were exceeded at all selected sampling points. A significant overall exceeding of the total dissolved solids (TDS) standard (1,000 mg/l), in open wells was detected as well. Measurements ranged from 1,459 to 3,300 mg/l. the TDS of tap water varied from 930 to 1,600 mg/l. Open wells exceeded WHO requirements on sodium (200 mg/l). The level of sodium in open wells ranged from 118 to 610 mg/l and in tap water from 40 to 208 mg/l.

A study on rates of hypertension in relationship to water consumption and the use of different water sources for drinking provides evidence that high levels of sodium have a significant effect on development of the disease among the population in the Aral Sea area (Fayzieva et al. 2002). It is necessary to mention that proving a cause-effect relationship of these diseases to water quality is rather difficult, due to the existence of complicating factors in disease formation and requires further deep studies on the basis of environmental epidemiology, which are important for development of well founded preventive measures in the Aral Sea area.

The spread of infectious disease no doubt depends on changes in ecologic and social conditions and has inter year and seasonal fluctuations. According to the Health Ministry of Uzbekistan, water-borne infections are the most common infectious diseases reported in the region (Iskandarova 1998). Active diarrheal surveillance in the city of Nukus Karakalpakstan during a randomized intervention study over 9.5 weeks revealed a suspected high incidence of diarrheal diseases in Karakalpakstan with a mean monthly diarrheal rate of 75.5/1,000 among individuals with piped water on their premises and 179.2/1,000 among those without piped water on the premises (Semenza et al. 1998). The study on diarrheal diseases in Khorezm investigated existing risk factors, including water sanitation and related hygiene issues for occurrence of diarrheal diseases in the area. Multiple regression analyses revealed that unsafe drinking water storage practices, absence of elementary hygienic practices and unhealthy excreta disposal habits significantly associated with the number of diarrheal episodes per household (Herbst 2006).

The unfavorable sanitary-epidemiological situation with water-borne intestinal infection may also be due to the level of contamination of water bodies, which create favorable conditions for growth and multiplication of pathogenic microorganisms, especially in summer. Being an indicator of anthropogenic contamination of water bodies, they also are of great importance for development of outbreaks of water-borne intestinal infections along with such significant factors as conditions of water-supply and indicators of the sanitary-bacteriologic state of water bodies used by people for household needs and drinking.

However, there is an evident lack of experimental studies in this field. In this connection, the above mentioned data may be the basis for in-depth research using modern approaches of multidisciplinary study of causes and consequences at the ecosystem level, with better methods of laboratory analysis taking into consideration all possible links of the epidemiological process. It would be very useful to study not only characteristics of the infectious agent and the human body but also the character of the environmental impact on the epidemiologic situation. This, in turn, would allow to evaluate properly the ecological and epidemiological situation in the region and to develop a scientific basis for decision-making in order to prevent the appearance of infectious diseases through development of targeted and effective water-protection measures.

The lack of effective sanitation and inadequate water management is the cause of sporadic and major disease outbreaks, which are mainly the result of infection with microbial or other biological agents of the fecal-oral group. Researchers have already demonstrated the role of water in spreading typhoid, dysentery, and enterovirus infections, including viral hepatitis, among the population using surface sources of water for drinking.

Lack of information, the poor quality of water supply equipment, poor sanitation conditions among populations and current economic difficulties – all of them are complex, difficult problems, but require solution for water quality improvement.

7.8.3 Other Public Health Concerns in the Aral Sea Area

7.8.3.1 Ecological Factors and Kidney Stones

Kidney stones (nephrolithiasis, urolithiasis) are the most widespread disease in the world. In addition, morbidity from this disease is increasing every year. This disease appears as a metabolic one and of particular interest for studies of water quality in regard to a possible ecologic impact on the human body in the Aral Sea area. There are many studies confirming the exogenous impact to the development of the disease (Abdisattarov et al. 1985; Riabinskii et al. 1993). According to the statistical data, the disease rate increases in the territories located closer to the Aral Sea in comparison with more distant areas. This is associated with a complex of factors responsible for development of an unfavorable ecological situation in the region.

The effects of environmental hazards on nephrolithiasis onset were studied for region's population that has been exposed to the ecological catastrophe of the Aral Sea. Blood and urine levels of organic acids and trace elements were measured using chromato-mass spectrometry, absorption plasma spectrophotometry and ion-exchange chromatography, respectively, as well as urinary peptide hydrolases activity in 178 patients with nephrolithiasis. The levels of lithogenic substances in the blood and urine were distributed differently in patients living in different ecological zones. The ecologically detrimental zones were denoted as zone “one”- most distant from the Aral, where 96 patients lived, zone “two”-less distant from it with 42 patients and zone “three”-the most ecologically damaged regions of the Aral catastrophe where 40 patients were examined. A reference group of 22 healthy persons was formed. Multivariate statistical analysis revealed factors of risk to develop nephrolithiasis for these zones. High and moderate risk was characteristic for 26 %, 28.5 % and 42.5 % of the patients from zones 1, 2 and 3, respectively. The findings confirm the conception of an essential role for environmental factors in initiation of Aral-region nephrolithiasis (Riabinskii et al. 1993).

Thorough investigation and mathematical analysis of the possible causes of nephrolithiasis development in 360 patients revealed 70 causative factors. The number of factors that affected each patient ranged from 2 to 25. Among the significant environmental factors were the level of foodstuff contamination with pesticides, water quality and the character of nutrition. Environment (climate, food, and drinking water) appears to be most important and responsible for 80 % of the disease. Modern technical progress also contributes through increasing of hypodynamia and stresses. Among the causes that could contribute to nephrolithiasis development, environmental factors obviously have significance (Tynaliev 1995).

The environmental impact on the urologic morbidity rate may be more or less evident in respect to kidney stone diseases as hot and dry climates and the hardness of potable water, in particular, may contribute to increased rates of stones in the kidneys and urinary tract. Kidney stones have a special interest for studying the existence of an environmental effect, in this case the impact of water composition on human health in the Aral Sea Area. There are several important causative factors in this region, including (1) water – high levels of total hardness, contamination and lack of potable water; (2) the climate and geographic peculiarities – aridity, soil salinity, etc.; (3) demographic and socio-economic factors (infrastructure and the health services).

According to the findings of studies on urological morbidity the prevalence of kidney stones in the Aral Sea Area has risen, which is, in particular, due to hardness of water. Most of the studies evaluate the morbidity on the basis of patients’ self-reporting (Mirshina 1996). This approach based on the data of patient visitation to medical facilities does not meet sufficiently high standards to provide real indicators of the causes of kidney stone disease in the Aral Sea Area. At the same time there are some studies based on epidemiologic examination of representative selected parts of the population that were conducted in 1989–1998 (Yuldashov 1998). Prevention actions require the findings of basic and population study of environmental epidemiology. However, to reveal the cause-effect relation of these diseases to environmental factors is rather difficult. As a whole, urologic morbidity in the Aral Sea Area needs further in-depth research and evaluation (Kudyakov et al. 2004).

Rather demonstrative are the results of the potable water study indicating an unfavorable situation in respect to such parameters as total dissolved solids (TDS) and total hardness. It is difficult enough to establish the links between water quality and urolithiasis prevalence; however, among a lot of causes of prevalence of this polyetiologic disease the water factor probably plays an important role. According to Mirshina (1996) and Iskandarova (1999), total hardness of the water used by people for drinking plays an important role in development of urolithiasis.

It should be emphasized that there are controversial data on the effect of water hardness on urolithiasis development. If in some areas the interrelation between the level of water hardness and urolithioasis prevalence was indicated, there are other reports with an the absence of such dependence. Pivovarov and Konashevsky (1989) insist on the reverse dependence: decrease of the number of urolithiasis cases associated with increase of water hardness while higher prevalence of this disease was recorded in the areas with softer water. Clearly, it is impossible to provide a clear explanation of these phenomena. Nevertheless, in our view nutrition is one of the most important factors (predeterminant) for the development of the disease.

7.8.3.2 Anemia in the Aral Sea Area

When one analyzes the possible genesis of anemia, the first thing to consider is that this is a region with a high birth rate and with complicated medical and social problems. Anemia of pregnant women has always been high in Central Asia. Research shows that anemia is observed in most cases when the number of deliveries in anamnesis increases and the interval between deliveries shortens. The nutritional factor is also of some importance as poor female nutrition contributes to anemia. Research carried out in Karakalpakstan also indicates that there is dietary deficiency in protein, fats, iron and vitamins. However, analyses show the same frequency of anemia in women of different social groups – that makes the nutritional factor minor, and high anemia rate among teenage girls also makes the factor of frequent deliveries a secondary cause of anemia in this region.

Research shows the growth of anemia in Karakalpakstan from the early 1980s into the 1990s. The growth began in the early eighties and by 1992 constituted 92 %. It is necessary to take into consideration that that time (1982–1992) was the period of stable social and economic development of the republic and there were few changes in the lifestyle and nutrition of the population. The only factor that has significantly changed is the state of the environment. A high frequency of anemia in pregnant women was detected in other ecologically unfavorable regions, including zones of high pesticides usage and the Chernobyl Atom Power Station. The same frequency of anemia among women of different ages, and social groups as well as clearly high anemia rates in the districts of poor environmental conditions, demonstrates the influence of environmentally unfavorable conditions on anemia development in women of the Aral Sea area (Atanyazova et al. 1998).

The Muynak District located close to the Aral Sea has one of the highest estimated prevalences of anemia among young children in the Central Asian region. Laboratory tests confirm that iron-deficiency anemia is the primary form of anemia in this area. The study on prevalence and correlates of anemia in this district of rapidly changing social and economic conditions was done in 1993 (Herbert et al. 1998).

Questionnaire data and blood samples were collected on a random sample of 433 children ages 1–4 years. The mean hemoglobin level was 9.78 (SD = 1.80) g/dl. According to the WHO criteria, 72.5 % of the children had anemia (26.3 % mild, 38.8 % moderate, and 7.4 % severe). Of the 173 children with complete results for ferritin, iron, and red cell distribution, 95 (55 %) had two or more abnormal test results, indicative of iron deficiency. In both simple and stepwise multiple logistic regression models, only age, history of pica (compulsion to eat non food items), and primary household water source were significantly associated with anemia status ($P < 0.05$). Age-specific anemia rates were 89 %, 79 %, 66 %, and 48 % for 1-, 2-, 3-, and 4-year – olds, respectively. The odds of anemia were 2.4 times greater for children with a history of pica than in those without that history and 2.4 times greater for children whose primary household water source was a communal tap than for those with a private household tap. No significant associations were detected between anemia and the child’s sex, nationality, gestational age, birth-weight, health history, or diet ($P > 0.05$ in all cases). Similarly, no significant associations were detected between the child’s anemia status and parents’ education, employment, socioeconomic status, or income; the mother’s history of anemia or toxemia during pregnancy; or the number of or spacing between siblings (Herbert et al. 1998).

A population based cross-sectional point prevalence survey was designed to determine the prevalence, severity, and causes of anemia, and to identify demographic, socioeconomic, sanitation, dietary, and personal risk factors for anemia in different segments of the general population of Muynak District of Karakalpakstan (1994). Of all the 243 children under 5 years of age, 70.4 % (171) had nutritional anemia and only 2.1 % (5) had the anemia indicative of infection and chronic disease. Fifteen (6.2%) of the children under five had iron deficiency without anemia, and 52 (21.4 %) had depleted retinol levels without anemia, of which 12 had both iron and retinol deficiency simultaneously. Twelve (4.9 %) of the children had no anemia and no retinol or iron deficiency. Of those under 5 years of age who were anemic, 97.2 % had nutritional anemia, with 55 % caused by simultaneous iron and vitamin A deficiency, 14 % caused by iron deficiency alone, and 27.8 % by vitamin A alone. Only 2.8 % of the total anemia was caused by non-nutritional factors in this age group. The rate of anemia declined with age. There were no gender disparities of mean hemoglobin or rate of anemia. Of the 151 children 5–15 years of age, 17.9 % were normal, 26.5 % had nutrient deficiencies of iron, vitamin A or both without anemia, 7.3 % had anemia of infection and chronic disease, while 48.4 % had nutritional anemia caused by vitamin A and iron deficiency. Nutritional causes of anemia were far greater than non-nutritional causes (Morse 1994).

7.9 Joint Efforts for Sustainable Development in the Aral Sea Area

Uzbekistan has undertaken enormous efforts for alleviating the Aral ecological disaster after acquisition of independence in 1991. Creation of the International Fund of saving the Aral Sea (IFAS) in 1993 demonstrated the partnership of Central Asian countries in solving problems of the Aral Sea and Priaralye. From the rostrum of the UN General Assembly at the 48th and 50th sessions, Islam Karimov the President of Uzbekistan spoke of the need for the world community to aid in joint efforts to address Aral Sea issues, which, in his view, are global in nature.

An International Conference was held on 11–12 March of 2008 in Tashkent to attract the attention of international donors to the problems of the Aral Sea and Priaralye, where a "Complex Program of Actions Offered to the International Donors for Realization of Mitigation of the Consequences of Climate Change in the zone of Priaralye" was accepted.

The partnership for Central Asian countries in addressing the Aral Sea problem was manifested in the creation in 1993 of the International Fund for Saving the Aral Sea (IFAS), which were implemented by the Aral Sea Basin Programs (ASBP 1 and 2). The Charitable public fund for preserving the gene pool of Priaralye has been created by the initiative of President Islam Karimov. He also proposed another program titled "Wider Involvement of the World Community for Solving Problems of the Aral Sea Basin" during the meeting of Aral Sea Basin heads of state, which are the founding members of IFAS in April 2009. At this same meeting, President Karimov proposed the concept of the Program of future activities of the participants of IFAS for the period 2011–2015 years and the greater involvement of the international community to address the problems of the Aral Sea.

Many international and interstate projects were implemented in the area. An example is the program for "recultivation of the dried Aral Sea bed" aimed at combating dust and salt transport and localization of its negative impacts on the environment. The project entails the planting of sand-fixing plants (Haloxylon, Salsola, and others).

UNDP (United Nations Development Program) has supported a number of including those listed below:

- Preservation of riparian forests and strengthening of the system of protected areas in the Amu Darya Delta. The project foresees the creation of new protected areas as part of the Biosphere Reserve and Monitoring of Bukhara deer program (the Buhara deer are listed in the international and national Red Data Books of threatened and endangered species).
- Implementation of the Project "Clean Energy" which demonstrates the practical application in remote settlements in Karakalpakstan of photovoltaic stations (PES), designed for providing solar generated energy for domestic uses. More than 50 such stations have already been built.

- Creation of small local reservoirs on the former shoreline of the Aral Sea and in the Amu Darya Delta. The project when completed will substantially restore the biodiversity of the region and improve the socio-economic situation of the population through increased employment, particularly in the development of fisheries and livestock.

The NEAPs (National Environmental Action Plans) and NEHAPs (National Environmental Health Action Plans) support the continuation of the Government programs on the improving of environmental health, living standards, drinking water supply, and sanitation conditions with the focus on rural areas.

One of the highest priorities in creating healthy living conditions is the provision of safe drinking water. The water supplies in all countries of Central Asia are in need of improvement. This problem is especially pressing in the Aral Sea disaster area where there are no local sources of clean, fresh water. Development of sanitation and sewage treatment has a major impact on improving the living conditions and preventing the spread of intestinal diseases.

Currently, only about 50 % of the urban population has access to sewage networks. More than 60 % of discharged sewage goes untreated, and it contaminates waterways and worsens the drinking water supply. The problem is further exacerbated by the poor conditions of and the leakage from pipelines. Sanitation in rural areas is almost non-existent, but the high cost of sewage networks and large treatment plants limits their construction in the near future. Municipal and industrial waste disposal in designated landfills will remain the primary means of waste handling.

A number of projects to improve water supply, sanitation and health in the Aral Sea Area carried out by the authorities of Uzbekistan the with assistance of The World Bank, Asian and Islamic Development Banks, the German Bank of Reconstruction and Development (KfW) are underway. At present, there are a number of projects undertaken by UN agencies and other international and foreign organizations in collaboration with local governmental and nongovernmental organizations. The Third Aral Sea Basin Program (ASBP-3) started in 2011 as a continuation of the efforts on alleviation of the Aral Sea disaster.

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Chapter 8
Irrigation in the Aral Sea Basin

Philip Micklin

Abstract Irrigation is highly developed in the Aral Sea basin. In 2010, irrigation networks covered 8.1 million ha here and accounted for 84 % of all water withdrawals. Irrigation as a highly consumptive user of water is the primary cause of the desiccation of the Aral Sea as it has severely diminished the inflow to the Aral from the Amu Darya and Syr Darya. Irrigation has a long history in the Aral Sea Basin dating back at least 3,000 years. During the Soviet era, irrigation was greatly expanded and water withdrawals for it increased considerably, primarily to grow more cotton. In the post-Soviet period, the area irrigated only increased slightly while water withdrawals for it declined somewhat. The latter has been primarily due to shrinkage of the area planted to high water use crops such as rice and cotton and not to the introduction of more efficient irrigation techniques on a substantial scale. Irrigation systems in the Aral Sea Basin since collapse of the USSR have badly deteriorated owing to lack of proper maintenance of them and insufficient investment in them. And the problems of soil salinization and water logging continue to worsen. There is certainly much that could be done to improve irrigation and use less water for it. This in turn could allow much more water to be supplied to the Aral Sea. But significant improvement of irrigation will require much greater effort and investment along with institutional reforms.

Keywords Irrigation • Soil salinity • Withdrawals • Cotton • Rice • Drainage • Kazakhstan • Uzbekistan • Turkmenistan • Kyrgyzstan • Tadjikistan

As discussed in Chap. 5, expansion of irrigation beyond the point of sustainability by the surface and groundwater resources of the Aral Sea Basin has been the primary cause of the post-1960s desiccation of the Aral Sea. In this chapter we

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delve more deeply into this critical topic, discussing its historical evolution as well as analyzing its modern development.

8.1 Pre-Soviet Period

For peoples of the world’s arid regions, the well-known phrase, “without water there is no life,” is a truism (Lunezheva et al. 1987). Irrigation was the driving force of settlement and civilization in the Aral Sea region since antiquity. Archeological evidence indicates the first settlements on the piedmont plains adjacent to the Kopet Dag Mountains in what is now southern Turkmenistan arose 8,000–10,000 years ago (Kostyukovskiy 1992; Karimov 1997, p. 7). Farmers cultivated wheat and barley, producing a harvest of near 12,000 centners (centner = 0.1 of a metric ton), enough to support 6,000 people. Soviet experts contended these crops were irrigated from small rivers exiting the mountains to the south, which would be one of the earliest examples of irrigation in the world. However, post-Soviet fieldwork by Western specialists at these sites casts doubt on this claim (O’Hara 2000). They contend the climate at the time was more moist than today and may have provided sufficient rainfall to grow crops without irrigation.

Nevertheless, it is clear that by the Bronze Age (2nd millennium, B.C.) farmers practiced irrigation in the oases along the middle and lower course of the Amu Darya and in the deltas of several terminal rivers in the Aral Sea Basin (Murgab in Turkmenistan and Zeravshan in Uzbekistan) (Kostyukovskiy 1992; Kes et al. 1980). Farmers, besides wheat and barley, raised grapes and beans. They dug distributary canals with widths up to 10 m, depths of 2–3 m and discharge capacities of 200–300 m^3/day. The irrigated area may have reached 3,500 ha with water withdrawals of 12–13 million m^3. This implies a water withdrawal rate of 3,400–3,700 m^3/ha, an efficient use of water by modern standards. The population of these settlements may have reached 25,000–30,000. Irrigation in Khorezm, at the head of the Amu Darya Delta, first arose during the latter part of this period.

During the 1st millennium, B.C. (Iron Age), irrigation flourished along the Amu Darya, Zeravshan and Murgab (Kostyukovskiy 1992; Kes et al. 1980). The Khorezm oasis may have had 1.2 million ha under irrigation and a population of 200,000. Farmers of the Merv oasis in the delta of the Murgab irrigated some 500,000 ha, which supported a population of 300,000. The total area with irrigation systems in the Aral Sea Basin was huge, perhaps covering 3.5–3.8 million ha, about half the contemporary irrigated area. However, only a part of this area (probably less than half) was used in any given year. In the chief oases such as Khorezm irrigation technology advanced rapidly. They constructed large canals directly from the main channel of the river in earthen beds that stretched several hundred kilometers along with protective dikes to keep the river from overflowing its banks and flooding crops. The first evidence of irrigation on the lower Syr Darya dates to the middle of the 1st millennium, B.C. – a thousand years later than on the Amu Darya.

However, around the fourth and fifth centuries, A.D., the major irrigation systems of Khorezm were destroyed during a social and economic crisis (Kostyukovskiy 1992; Kes et al. 1980). Irrigation was restored by the seventh century, A.D., but was subsequently partially destroyed during the Arab invasion of 712. Irrigation again flourished during the twelfth and at the beginning of the thirteenth century when Khorezm became the center of a new feudal state whose government saw to the restoration of the canals and protective dikes. They irrigated large tracts of new land and built major canals far into the Kyzyl-Kum desert to unite the irrigated zones of the Amu Darya and Syr Darya. The irrigation experts of the time perfected the method of using diversion dams and storage basins to capture floodwaters for irrigation. The area with irrigation facilities during this period within the area controlled by Khorezm was near 2.5 million ha. Because of improved technology, such as the use of the "chigir" wheel, farmers were able to irrigate more efficiently and continuously than earlier. The "chigar" is a wooden wheel, some 2 m in diameter, with clay buckets arranged around the rim. The wheel is mounted on a horizontal axis in a pit with water in it. Draft animals (horse, donkey, camel) or the force of water can power the wheel to lift water from the pit to the fields. This device was widely used from ancient times until the Soviet transformation of agriculture in Central Asia during the late 1920s and 1930s (Karimov 1997, p. 13).

The Mongol invasion of Central Asia in 1220 led to the nearly complete destruction of irrigation systems along the Amu Darya and Syr Darya. (Kostyukovskiy 1992; Kes et al. 1980) Dikes and dams that controlled the rivers and allowed withdrawal of their waters for irrigation were ruined. The Amu Darya was purposely sent westward or diverted itself in this direction to the Sarykamysh Depression (as it had several times before) depriving the lower delta and Aral Sea of flow. (As noted in Chap. 2, diversion of the Amu Darya 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 the Aral Sea) have periodically occurred during the Holocene geological epoch. These diversions have been caused both by natural events [sedimentation of the bed and subsequent breaching of the rivers left bank during the spring floods] and by human actions such as the destruction of dikes and dams built to keep the river flowing to the Aral as noted above). Until the 1960s, these diversions were the primary cause for the fluctuations of the Aral Sea's level (Kes et al. 1980; Kes and Klyukanova 1990). Subsequently, irrigation facilities were slowly rebuilt and the Amu Darya restored to its former course. By the early nineteenth Century the irrigated area was around 2 million ha, less than it had been prior to the Mongol attack.

The Russian Empire between the 1860s and 1900s, mainly by conquest, brought Central Asia, including the Aral Sea Basin, under its control (Brown et al. 1994, pp. 536–538; Clem 1992). The region was known as "Russian Turkestan" or just "Turkestan" (the land of the Turkic speaking peoples). A major expansion of irrigation began around 1900 focused on construction of new systems within the bounds of the traditional irrigated areas (Tashkent, Bukhara, Khorezm, Fergana and Zeravshan valleys) as well as expansion into desert areas that had never been irrigated, chiefly the Golodnaya (Hungry) Steppe (Fig. 8.1). By 1913, the irrigated

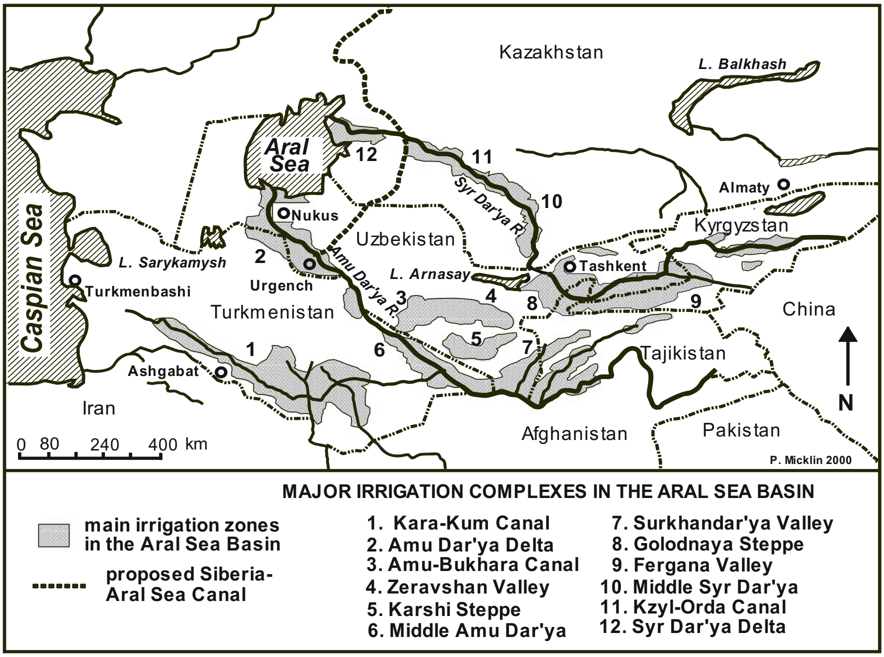

Fig. 8.1 Irrigation development in the Aral Sea Basin

area reached 3.2 million ha (Table 8.1). The newly irrigated lands permitted expansion of cotton sowing to 556,000 ha (17 % of the total irrigated). The major rationale was to meet needs of the growing textile industry in Russia (Clem 1992). However, cotton also displaced traditional food crops in portions of the older irrigated areas. For the Aral Sea Basin, yields of cotton averaged 12 centners/ha.

Irrigation expansion in the early part of the twentieth century mainly occurred in the alluvial fans where rivers exited the mountains and downstream in the river valleys and deltas (Karimov 1995; Pankova et al. 1996, pp. 74–91). This allowed development of the most fertile parts of the piedmont plain and dry sections of river deltas using gravity diversions that did not require construction of head-works facilities (dams, pumping stations, etc.). The main task was building of main delivery canals. In the drier parts of the Amu Darya Delta, farmers used a system of deepened earthen canals with 'Chigar' wheels to lift the water to the fields. These canals simultaneously fulfilled the role of distribution network for irrigation water and collector network for drainage water. Initially, these efforts went well and substantially increased production. But after 10–15 years, the first signs of water logging and secondary soil salinization (from over-irrigation, lack of proper drainage and irrigation of naturally saline soils) appeared in the Golodnaya Steppe, leading to the loss of 60 % of the newly irrigated area here.

Table 8.1 Irrigation data for the Aral Sea Basin for 1913–2010

Year	Irrigated area (million ha)	Withdrawals for irrigation (km^3)	Withdrawals for irrigation (m^3/ha)	Cotton area (million ha)	Cotton % of total irrigated area	Cotton yields (centnars/ha)[a]	Water use for raw cotton (m^3/centnar)[b]
1913	3.2	25.6–43.2	8,000–13,500	0.556	17.4	12	950
1922	1.7	16	9,400	0.100	5.9	7	1,230
1933	3.5	40	11,500	1.800	51.4	5	1,800
1940	3.8	49	13,000	1.369	36.0	14	1,800
1945	no data	no data	15,000	1.110	no data	10	1,350
1950	3.8	57	15,000	1.580	41.6	20	800
1965	4.8	82	17,000	2.287	47.6	23	800
1980	6.3	107.1–126	17,000–20,000	2.869	45.5	29	750
1985	7.0	112–133	16,000–19,000	3.051	43.6	26	700
1990	7.25	109	14,600–17,000	2.907	41.0	8.3	no data
1995	7.94	100	12,594	2.354	29.6	7.3	no data
2000	8.1	75	9,180	2.236	27.6	5.89	no data
2005	8.1	91	11,258	2.537	31.3	6.91	no data
2010	8.2	92	11,169	2.300	28.0	6.39	no data

Sources: Data from 1913 through 1985 taken from Micklin (2000), Table 3, p. 28
Data for 1990 through 2010 from Micklin (2000), Tables 10.2, 10.3 10.4, and 10.5 this chapter and Index Mundi for Uzbekistan, Kazakhstan, Tadjikistan, Kyrgyzstan and Turkmenistan http://www.indexmundi.com/agriculture/?country=uz&commodity=cotton&graph=area-harvested (Accessed 31 January 2012)

[a] Cotton yield data for 1950–1985 probably are significantly exaggerated owing to underreporting of area cropped and over reporting of harvests

[b] Water use for raw cotton is probably significantly underestimated for 1950–1985; see footnote 1

8.2 Soviet Period

During the Civil War (1919–1924) following the Bolshevik seizure of power, irrigation systems were destroyed or idled (Karimov 1995; Pankova et al. 1996, pp. 76–77). The irrigated area decreased from 3.2 million ha in 1913 to 1.7 million in 1922. The cotton area shrank to a little over 100,000 ha and average yields fell to near 7 centners/ha. With the solidification of Soviet power in Central Asia, Moscow ordered the restoration and repair of irrigation systems, which was completed between 1925 and 1928. At this time, although there were significant variations from one place to another, the crop structure for the Aral Sea Basin in terms of the total area sown was grains, 30–40 %, perennial grasses, 30 %, rice, 5–25 %, and cotton no more than 20–25 % (Pankova et al. 1996, p. 78).

The traditional system of irrigated agriculture in the Aral Sea Basin was essentially preserved until the mid 1920s. This system, developed over thousands of years, had survived wars, social collapse, natural catastrophes, and the Tsarist conquest of the region. It had both a land use and administrative component. In terms of the former, some 90 % of the irrigated area consisted of small, individually managed farms of 2–3 ha (Siprozhidnikov 1991). Extended families, some of whom owned the land and some of whom rented the land or worked it as tenants of large landowners for a share of the crop, typically operated these farms. The farms were divided into irrigated fields of 0.3–0.8 ha with permanent low walls lined with trees. Farmers used primitive irrigation technologies based on hand labor supplemented by draft animals. Animal wastes were used as fertilizer. Filtration losses in the irrigation system were as much as 30 %. Irrigation systems were not built according to any overall plan and they lacked control structures, drainage canals and discharge canals to convey runoff from fields.

We might expect such systems to be unsustainable as a result of rapid water logging, soil salinization and falling crop yields. But they obviously weren't. The principles of irrigated farming developed by trial and error over the centuries were sound. The small size of the flooded fields ensured even distribution of the water and the absence of any wasteful runoff. The low walls that surrounded these sectors acted to absorb and accumulate salt, preventing soil salinization. The trees planted along the walls transpired excess water and thereby acted to control water logging as well as lowering wind speeds over the fields, which reduced evaporative losses from the soil. The trees also served as a fuel source. Water was used efficiently. Average withdrawals, including filtration losses on the fields and in delivery canals, are estimated to have been 10,700–11,500 m^3/ha.

The administrative-governance system of irrigation had also evolved over a lengthy period. The basic principle was central government control of water management but local responsibility for operation and maintenance of the water management system (Karimov 1997, pp. 8–11; Karimov 1998). Islamic law (*Sharia*) saw water as social property and did not allow private ownership of it. Local authorities assigned water use rights to farmers and ensured the maintenance of irrigation facilities for distributing water to them. Higher levels of government made sure that local officials fulfilled their responsibilities and handled disputes between regions (e.g., Samarkand and Bukhara on the Zeravshan River) or that couldn't be resolved by local leaders.

The government required water users to both build and maintain the irrigation system. This was managed through a complicated system of obligatory annual work to clean canals of sediments, repair dams and other facilities, and deal with any other maintenance or construction issues that needed attention. Authorities also collected taxes for water used in irrigation and fines from those who didn't appear for their obligatory duties. They used the collected funds to finance construction and maintenance of the irrigation systems.

The irrigation water management system operated through a hierarchy of water technicians/bureaucrats (Karimov 1997, pp. 8–11, 1998). For example, during the nineteenth century in Bukhara Khanate the chief Vizier of the state (known as the *Atalyk*) was in charge of irrigation. The *Mirab* (manager) of the main irrigation canal was subordinate to him and responsible for water distribution from and maintenance of this facility. The *Mirabs* of the main distributary canals were next in the hierarchy and had the same responsibilities for the facilities under their control. The *Mirabs* of the canals for distribution of water to individual fields were at the bottom of the management system. There were also "observers"

(*Panzhbegi* and *Obron*) to ensure that the withdrawals at critical diversion points along the distributary canals were according to the limitations set by higher authorities and personnel known as *Obandozy* who were assigned responsibility to make sure the orders of the *Atalyk* were delivered to the *Mirabs* of the main canals. This system made it possible to determine who was responsible for problems in the system and to punish the guilty (sometimes severely).

The traditional system of irrigated agriculture was adjusted to the environmental constraints of an arid environment and provided strong incentives for farming families to cooperate in the maintenance of irrigation systems as well as to use both land and water carefully (Siprozhidnikov 1991; Karimov 1998). The Soviets could have kept the best aspects of this system while carefully and judiciously introducing more modern technology, where appropriate, and pursuing a program of land reform and redistribution to give land to the landless peasantry. Instead, they chose to institute historically unprecedented changes in irrigated agriculture in the Aral Sea Basin that radically and permanently changed the face of agriculture and peasant life here (An excellent treatment of the devastating changes wrought on farmers and agriculture in Uzbekistan under the Soviets is provided in Thurman 1999).

The primary motivations were two: (1) deeply held beliefs among the Bolshevik leadership and intelligentsia that the traditional (in their view 'feudal') irrigation and agricultural system in Central Asia was primitive, backward, and inefficient, as well as exploitative and oppressive of the peasantry that formed its basis and (2) the need to institute state control of irrigation and agriculture, as well as individual farming, in order to dramatically expand production of cotton (Askochenskiy 1967, pp. 13–20; Siprozhidnikov 1991). Thus, in the view of the Bolsheviks this 'corrupt and worthless' system had to be entirely destroyed and replaced by centrally controlled, modern, large-scale, equipment intensive irrigation on the industrial model with tight government oversight where the peasantry rather than owners/managers of the land and water were simply employees executing the state economic plan. The first steps, instituted by decree in 1925, nationalized all lands and began confiscation of large landholdings for redistribution to small landholders and landless peasants (Karimov 1995). For example, in Uzbekistan, which accounted for the largest share of the irrigated area in the Aral Sea Basin, large landholders controlled more than half the irrigated territory.

Nevertheless, most of the irrigated area remained under private management. Over the next few years, the Soviet government instituted other major changes. Individual farms were amalgamated into larger, supposedly more efficient units (Siprozhidnikov 1991). As a part of this process, and contrary to promises made, the small irrigation fields of 0.3–0.8 ha were combined into larger units, averaging 3.5 ha, resulting in the destruction of the earthen walls separating them and the uprooting of the trees growing on them. The area of irrigation grew, mainly by conversion of lands formerly used for growing trees or kept in fallow within the bounds of irrigation systems. Owing to such actions, water logging and soil salinization significantly worsened. The area devoted to cotton grew rapidly, but because yields were far below pre-Revolutionary levels the harvest remained less than in

1913. Average irrigation water withdrawals in Uzbekistan rose from 10,000 to 13,000 m^3/ha. Water waste and losses in irrigation sharply increased.

As elsewhere in the USSR, massive collectivization of agriculture began in Central Asia in 1929. Soviet authorities forced individual farms to combine into *Kolhozy* (Collective Farms), while *Sovkhozy* (State Farms) were established on newly irrigated lands. Farmers' use of distinct, separate portions of the land was abolished and people were organized into 'teams', working the land in common. The main goal was to reach 'cotton independence' by the end of the first 5-year Plan in 1933 (Pankova et al. 1996; pp. 78–81; Karimov 1995). Cotton plantings grew to over 50 % of the sown area and domestically produced cotton rose from 59 % to 97 % of national needs. However, yields remained below 8 centners/ha while water use per centner skyrocketed to 1,800 m^3 compared to around 1,200 m^3 in the early 1920s (Table 8.1).

The situation improved during the remaining years of the decade as authorities eased the more onerous aspects of collectivization and slowed the pace of its implementation. Renovation of irrigation systems and mechanization of fieldwork slightly lowered water use. By 1940 the irrigated area rose to 3.8 million ha but cotton's percentage of that total fell to 36 %. Average cotton yields in the Aral Sea Basin nearly tripled.

By the end of the decade collectivization was firmly in place. The lasting legacy of this social and economic transformation was destruction of traditional irrigation in the Aral Sea Basin, which converted irrigated agriculture here into a completely state controlled enterprise and set the stage for subsequent developments in irrigation for the rest of the Soviet period.

Even though Central Asia suffered no invasion, the war years (1940–1945) saw deterioration of irrigated agriculture (Pankova et al. 1996, p. 74; Karimov 1995). The irrigated area shrank, cotton plantings dropped nearly 20 % and yields of cotton fell to 10 centers/ha as water use per centner declined sharply. Irrigation more than recovered by 1950 as the irrigated area regained prewar levels, cotton hectarage increased to 1.6 million ha (42 % of the irrigated area), cotton yields doubled to 20 centners/ha, and water use per centner of cotton dropped to 800 m^3.

Irrigation in the Aral Sea Basin underwent steady expansion from 1950 to 1965, reaching nearly 5 million ha (Table 8.1) (Pankova et al. 1996, pp 76–77; Karimov 1995). The Soviet government emphasized expanding irrigation in older irrigated areas such as the Bukhhara Oasis, the Fergana Valley, and the lower Amu Darya and Syr Darya as well as in the zones of more recent irrigation (e.g., Golodnaya and Karshi steppes) (Fig. 8.1). Construction on the Kara-Kum Canal, the largest capacity and longest irrigation canal in the former USSR, started in 1954. Irrigation during this period expanded onto the lower lying portions of the piedmont plains which have poor drainage and are natural accumulators of salt flowing in groundwater from higher territory. This exacerbated the already serious problems of water logging, and soil salinization.

What to do with increasing amounts of saline irrigation drainage water became a serious problem. Much of it was simply dumped into rivers, worsening their water quality. Drainage water also began to flow into desert depressions forming permanent lakes. Today, the largest of these are Sarykamysh in Turkmenistan and Arnasay in Uzbekistan, each of which has grown to several thousand km^2 in area (Fig. 8.1). From 1950 to 1965, irrigation water withdrawals in Uzbekistan, the republic with by far the largest irrigated area, rose 1.25 fold while irrigation drainage flows grew more than threefold.

Construction of very large irrigation systems encompassing hundreds of thousands of hectares (e.g., Golodnaya and Karshi steppes of Uzbekistan) and extending well into the deserts started during these years. These were built on an industrial basis and included social amenities and infrastructure (houses, stores and entertainment and recreational facilities) and communication networks (roads, telephones lines etc.). To facilitate use of larger tractors and other equipment, individual field size was dramatically increased to as much as 100 ha (Siprozhidnikov 1991). These new systems were supposed to improve irrigation conditions and performance. However, they did the opposite. The huge fields were impossible to irrigate evenly, requiring application of excessive quantities of water. This in turn led to soil erosion, rising ground water levels and water logging, secondary salinization, increased water use and lowered yields. Furthermore, some of the areas had naturally saline soils, which required annual applications of water to leach the salts prior to the start of the irrigation season. Another major problem was that the push to expand the irrigated area took precedence over ensuring the proper construction of irrigation systems. Construction brigades frequently disregarded the requirement to install drainage facilities in the drive to bring on-line the maximum newly irrigated area.

The Cotton hectarage grew to 2.3 million or 48 % of the irrigated area by 1965 (Table 8.1) (Pankova et al. 1996, pp. 76–85). Yields slowly increased to 23 centners/ha. During this period, fertilizer use for cotton rose rapidly. Average water withdrawals in the Aral Sea Basin rose to around 17,000 m^3/ha with about 11,000 m^3/ha (64 %) ‘lost’, i.e., not going for plant growth needs. Similar figures for the mid-1920s, prior to the Soviet transformation of irrigated agriculture, are around 10,000 and 5,000, respectively.

The next 20 years, 1965–1985, saw rapid development of irrigation in the Aral Sea Basin, with the irrigated area approaching 7 million ha by the end of the period (Karimov 1995).

The period from 1980 to 1985 was characterized by very rapid growth as irrigators attempted to maintain cotton harvests in the face of declining yields and also expand the irrigated area devoted to grains. The main emphasis was on expanding irrigation in newly irrigated zones, including the Golodnaya, Djizak, Karshi and Kashka Darya steppes, and along the Amu-Bukhara Canal (which was under construction) in Uzbekistan and in the Yavansk Valley in Tajikistan (Fig. 8.1). They also continued extension of the Kara-Kum Canal in Turkmenistan.

This was the era of large (and very large) dam and reservoir construction along the Amu Darya, Syr Darya and their tributaries (Pankova et al. 1996, p. 76; Micklin 1991, pp. 30–32; Dukhovnyy 1993, pp 260–261). The largest of these are the Toktogul, Andizhan, Kayrakkum, Charvak and Chardarya along the former river and its main tributaries, the Naryn, Karadarya, and Chirchik, and the Tyuyamuyun and Nurek on the latter river and its chief tributary, the Vakhsh. The fundamental purpose was flow regulation to provide more water for irrigation (by storing spring high flows for use during summer) and provision of hydropower, much of which would be used for powering irrigation pumps. By the 1980s, they had nearly completely regulated the Syr Darya's flow whereas the flow of the Amu Darya was largely controlled.

The Soviet government devoted much attention to installing collector-drainage networks to cope with the growing problems of rising groundwater levels, water logging and secondary salinization. However, this increased return drainage flows into rivers substantially, worsening their quality. Another major goal was raising the efficiency of irrigation systems. Until 1980, withdrawals increased, reaching a peak somewhere between 17,000 and 20,000 m^3/ha, but by 1985 they fell to around 16,000–19,000 (Table 8.1). Water losses in irrigation systems peaked in the 1970s between 11–12,000 m^3/ha and fell to around 10,000 m^3/ha by 1985 (Pankova et al. 1996, p. 84, Fig. 14). In an attempt to maintain cotton yields, the use of mineral fertilizers and pesticides grew enormously, also contributing to river pollution owing to return flows from irrigated fields. Cotton's percentage of the irrigated area fell slightly to 44 % by 1985. Yields rose to a peak 29 centners/ha in 1980 (in the 1930s, they had been as low as 5) but dropped to 26 centners/ha by 1985. However, the late 1970s and early 1980s were the time of the infamous 'cotton scandals' when harvest and yield data were purposely exaggerated; hence the 1980 figure may be high by as much as 20 % (Thurman 1999, pp. 41 and 46–47)

With the rapid growth of withdrawals for irrigation, the water resources of the Amu Darya and Syr Darya were approaching exhaustion. As a result, little river flow reached the Aral Sea and its level steadily fell. Central Asian political leaders and national and regional water managers in the late 1960s began to push hard for implementation of a grandiose plans to divert huge quantities of water from Siberian rivers (Ob and Irtysh) to Central Asia (see Chap. 16 for a detailed discussion of this project). The major purpose was to provide water to continue expanding irrigation, not replenish the drying Aral. Experts completed the design of this project by the late 1970s. Although there was considerable opposition to the endeavor from nationalist writers, environmentalists, and scientists in Russia, it appeared on the verge of implementation by the early 1980s. However, after Gorbachev assumed leadership in 1985, these plans were vehemently attacked as environmentally dangerous and economically unjustified. The project was put on permanent hold in 1986. Moscow told Central Asians they would and could get along with the water available within the region. Central Asian political leaders and water managers remain bitter about the cancellation of the Siberian project which they believe was promised them by Moscow in exchange for growing ever more cotton.

The decades-long expansion of irrigation in the Aral Sea Basin greatly slowed during the last years of the Soviet regime (1985–1991) (Pankova et al. 1996, pp. 60–82; Karimov 1995). The formerly powerful and rich water management establishment composed of the national Ministry of Water Management in Moscow and its republican affiliates that for decades had successfully lobbied for more irrigation lost its influence. With the open approval of the new Gorbachev regime it was publicly, and often bitterly, attacked for squandering state funds on economically and ecologically questionable water development projects and for destroying the Aral Sea through the massive expansion of irrigation in Central Asia. The fresh water resources of the region, given current irrigation practices, were exhausted and there would be no rescue from Siberian rivers. Hence, it was time to cease initiation of major new projects and concentrate on improving irrigation efficiency and dealing with the very serious problems of soil salinization and water logging in already irrigated zones. Another stated government goal was to provide more water to the Aral Sea.

The new emphasis on irrigation improvement had some success (Pankova et al. 1996, pp. 78–84; Karimov 1995, 1998). Cotton decreased to 40 % of the sown area by 1990 with average basin-wide yields rising slightly to 27 centners/ha (Table 8.1). Beginning in the early 1980s, water withdrawals per hectare steadily declined. Renovation and improvement of irrigation systems played a role in this but the main factor was a series of dry years in the 1980s that forced institution of strict limitations on water use. On the negative side, ground water levels continued on the rise, worsening the problems of water logging, as did the process of soil salinization. By 1989, 3.6 million ha, equaling 50 % of the irrigated area in the Aral Sea Basin, suffered from salinization. The volume of drainage return flows was still growing rapidly and composed over 40 % of irrigation withdrawals. Part of this flow reentered rivers, causing average salinity in the lower Amu Darya and Syr Darya to rise to 2–3 g/l by 1990.

8.3 Post-Soviet (Contemporary) Irrigation

The new states of Central Asia formed from the USSR after its collapse at the end of 1991 inherited an irrigation system developed over a 65 year period under the principles of state ownership and tight control, centralized top down management, which allowed little initiative at the local level, a focus on cotton as the chief crop, and the need for large-scale facilities. As independent entities since 1991 they have dealt with this legacy individually. However, given their common history and the integrated nature of the irrigation systems, they face similar problems in adapting what they inherited to the future. This section provides a description and analysis of irrigation in the Aral Sea Basin over the past two decades, including an evaluation of the potential for solving the most serious irrigation issues faced by the basin nations that were formerly part of the USSR.

Table 8.2 Irrigated areas in the Aral Sea Basin in 1995 (million ha)

Country	Amu Darya Basin	%	Syr Darya Basin	%	Aral Sea Basin	%
Uzbekistan	2.48	53	1.80	55	4.28	54
Turkmenistan	1.74	37	0.00	0	1.74	22
Tajikistan	0.43	9	0.29	9	0.72	9
Kazakhstan	0.00	0	0.74	22	0.74	9
Kyrgyzstan	0.00	0	0.46	14	0.46	6
Total	4.65	100	3.29	100	7.94	100

Source: Adapted from World Bank (1998), Table 2
Afghanistan and Iran are excluded from the calculaltions

Table 8.3 Water withdrawals for Irrigation in the Aral Sea Basin in 1995 (km^3)

Country	Amu Darya Basin	Syr Darya Basin	Aral Sea Basin	% of Aral Sea Basin withdrawals	Specific withdrawal (m^3/ha)	Total basin water withdrawals	Irrigation % of total
Uzbekistan	33.2	19.8	53.0	53.0	12,383	58.0	91
Turkmenistan	22.4	0.0	22.4	22.4	12,874	23.1	97
Tajikistan	7.0	3.3	10.3	10.3	14,306	12.0	86
Kazakhstan	0.0	9.7	9.7	9.7	13,108	11.0	88
Kyrgyzstan	0.0	4.6	4.6	4.6	10,000	5.1	90
Aral Sea Basin	62.6	37.4	100.0	100.0	12,594	109.2	92

Source: Adapted from World Bank (1998), Table 2

8.3.1 Changes in Irrigated Area and Water Withdrawals

The key to improving management of the Aral Sea Basin's water resources (including provision of substantial additional quantities of water for the Aral Sea, the deltas of the Amu Darya and Syr Darya, and for expanding economic uses) is irrigated agriculture. A 1998 World Bank report, based on data provided by the Aral Sea Basin countries that were formerly part of the USSR, cited the irrigated area in the basin in 1995 (excluding Afghanistan and Iran) at 7.94 million ha (World 1998). At that time Uzbekistan had the majority of the irrigated area with Turkmenistan a distant second followed in close order by Tajikistan and Kazakhstan with Kyrgystan somewhat farther back (Table 8.2 and Fig. 8.1). In 1995, irrigation was far and away the chief source of water withdrawals in the basin, accounting for 92 % of the total (Table 8.3). As one would expect, Uzbekistan was also far ahead in water withdrawals followed in order by Turkmenistan, Tajikistan, Kazakhstan, and Kyrgyzstan. The average withdrawal for the Aral Sea Basin was slightly more than 12,500 m^3/ha with Tajikistan the highest at 14,306 m^3/ha, followed by Kazakhstan, Turkmenistan, Uzbekistan and Kyrgyzstan in descending order.

What has happened to the size of the irrigated area and volume of withdrawals since 1995 is not clear, mainly owing to the difficulty of obtaining comprehensive, consistent data for these parameters by country. An authoritative source, the

Scientific Information Center (SIC) of the Interstate Coordinating Commission for Water Resources (ICWC), the intergovernmental agency whose responsibility is to provide reliable information on the water management situation in the Aral Sea Basin, provides a table on their CAWaterinfo website showing a slight decline in the irrigated area to 7.896 million ha by 2000 and then slow growth of the irrigated area to 8.120 million ha by 2004 (Basic Indicators of Water and Land Use in the Aral Sea Basin 2012). Withdrawals for irrigation are cited as 94 out of a total of 106 km^3, for 2000 and 93 out of 104 km^3 for 2004. Based on these figures, irrigation accounted for around 91 % of all withdrawals for each year. Dividing withdrawals for irrigation by the irrigated area gives withdrawals per hectare of 11,904 m^3/ha in 2000 and 11,453 m^3/ha in 2004. The latter figure represents a 9 % reduction from 1995. Victor Dukhovnyy, the head of SIC in a presentation at a major Aral conference in 2008, cited a specific withdrawal figure for the Aral Sea Basin of 12,300 and 11,500 m^3/ha for 2006 and 2007 respectively (Dukhovnyy 2008).

A detailed, comprehensive set of data on the irrigated area and irrigation water withdrawals for different years in the Aral Sea basin by country from 1980 to 2010 is provided in a table on the CAWaterinfo website (Dynamics of General Indicators of the Aral Sea Basin States 2012). This table is periodically updated. Unfortunately the figures presented are not entirely consistent with the data discussed above. Tables 8.4 and 8.5 are adapted and modified from this table. According to these data, the irrigated area for the entire Aral Sea Basin rose from 8.09 to 8.201 million ha from 1995 to 2010, an increase of 1.62 %. Turkmenistan had the largest increase over this period at 11.78 % followed by Tajikistan at 7.36 %. The other states showed small decreases in their irrigated areas. The ranking of countries by irrigated area remained the same over the 15-year period with Uzbekistan far ahead, Turkmenistan a distant second, followed in order by Tajikistan, Kazakhstan and Kyrgyzstan. Uzbekistan's, Kazakhstan's and Kyrgystan's share of the total irrigated area dropped slightly Turkmenistan and Tajikistan increased their portion of the total a small amount. But according to the area irrigated, the picture of the Aral Sea basin in 2010 was essentially the same as in 1995.

Aggregate water withdrawals for irrigation remained essentially unchanged comparing 1995–2010. They were 90.1 km^3 in 1995 and 91.6 km^3 in 2010 and constituted, respectively 80 % and 84 % of total withdrawals. The low figure shown for 2000 of 74.6 km^3 reflects the severe drought that occurred in 2000 and 2001 forcing a considerable reduction in withdrawals. According to the "Dynamics..." (2012) data, there was an even lower withdrawal of 70.8 km^3 in 2008 during another period of serious drought. Throughout this period Uzbekistan far and away accounted for the largest share of withdrawals followed by Turkmenistan, Tajikistan, Kazakhstan and Kyrgyzstan. For the basin as a whole, withdrawals per hectare were nearly the same comparing 1995 (11,165 m^3/ha) and 2010 (11,169 m^3/ha), but showed, as you would expect, significant declines in drought years. Thus, in 2000 these figures were 9,180 and in 2008 equaled 8,638. Comparing 1995 to 2010, all states except Uzbekistan show sizeable drops in withdrawals per hectare. Uzbekistan's withdrawals, on the other hand, grew by nearly 17 %. However, this may not be accurate. The 1995 total withdrawal figure and related per hectare measure for Uzbekistan appears

Table 8.4 Irrigated area in the Aral Sea Basin 1995–2010 (million ha)

Country	1995	%	2000	%	2005	%	2010	%	% change 1995–2010
Uzbekistan	4.466	55.3	4.439	54.6	4.404	54.3	4.373	53.3	−2.1
Turkmenistan	1.672	20.7	1.738	21.4	1.818	22.4	1.869	22.8	11.8
Tajikistan	0.747	9.3	0.750	9.2	0.763	9.4	0.802	9.8	7.4
Kazakhstan	0.758	9.4	0.770	9.5	0.714	8.8	0.750	9.1	−1.1
Kyrgyzstan	0.427	5.3	0.429	5.3	0.411	5.1	0.407	5.0	−4.7
Aral Sea Basin	8.070	100	8.126	100	8.110	100	8.201	100	1.6

Source: Adapted from Dynamics of General Indicators of the Aral Sea Basin States (2012)
Iran and Afghanistan are excluded from the calculations

unrealistically low. If we use the figure from the World Bank study cited above for 1995 (12,383 m^3/ha) and compare it to the 2010 figure from Table 8.5 (11,800 m^3/ha), then Uzbekistan had a 4.7 % decrease in withdrawals.

8.3.2 Improving Water Use Efficiency in Irrigation

There are three major technical approaches to reduce the quantity of water used in irrigation. Taking substantial areas out of this activity would be the quickest to implement. But this is not considered a wise idea as irrigation is the most important economic activity in the Aral Sea basin and major reductions in it would have severe economic and social welfare impacts. Indeed, as shown above, the irrigated area since the mid-1990s has not shrunk but grown, although at a slow pace. A key argument used to justify increasing the irrigated area is the need to expand food production to meet population growth. Hence, significant water savings through reduction of the irrigated area are unlikely for the foreseeable future. The other two methods for saving significant amounts of water in irrigation are improvements in irrigation efficiency, and switching from higher to lower water use crops. Both of these are considered to have substantial promise.

Determining possible savings from raised efficiency entails estimating the minimum water withdrawal required in a given area for optimal (or near optimal) growth of a specific crop mix. The difference between this figure and what is actually withdrawn represents potential gross savings. However, the net additions to usable water resources would be less, as corrections are necessary to take account of reduced drainage water return flows to rivers associated with reduced aggregate withdrawals. Calculating the “minimum”, (or norm in Soviet irrigation parlance still used in Central Asia) is not easy as it depends on the availability of detailed and accurate data on climate, soil conditions, and crops at a scale sufficiently large to reflect the regional variability in the Aral Sea Basin as well as calculating the minimum obtainable losses in the irrigation water delivery system.

Table 8.5 Water withdrawals for Irrigation in the Aral Sea Basin, 1995–2010

State	1995 (km^3)	% of total	withdrawal per ha (m^3)	2000 (km^3)	% of total	withdrawal per ha (m^3)	2005 (km^3)	% of total	withdrawal per ha (m^3)	2010 (km^3)	% of total	withdrawal per ha (m^3)	withdrawal per ha % increase 1995–2010
Uzbekistan	45.2	50.2	10,121	35.7	47.9	8,042	49.9	54.7	11,331	51.6	56.3	11,800	16.59
Turkmenistan	24.1	26.7	14,414	20.0	26.8	11,507	22.7	24.9	12,486	22.5	24.6	12,039	−16.48
Tajikistan	9.6	10.7	12,851	10.2	13.7	13,600	9.7	10.6	12,713	9.3	10.2	11,596	−9.77
Kazakhstan	8.3	9.2	10,950	6.1	8.2	7,922	6.5	7.1	9,104	5.9	6.4	7,867	−28.16
Kyrgyzstan	2.9	3.2	6,792	2.6	3.5	6,061	2.5	2.7	6,083	2.3	2.5	5,651	−16.79
Aral Sea Basin	90.1	100	11,165	74.6	100.0	9,180	91.3	100	11,258	91.6	100.0	11,169	0.04

Source: Adapted from Dynamics of General Indicators of the Aral Sea Basin States (2012)
Afghanistan and Iran are excluded from the calculations

USSR irrigation experts intensively investigated the question of minimum possible withdrawals under Aral Sea basin climatic conditions and cropping patterns. An authoritative figure cited at the end of the Soviet period for the minimum average field application rate obtainable was 8,500 m^3/ha (Polad Zade 1989). Assuming the average losses in the delivery canals could be lowered to 20 % (they remain far higher than this), meaning that 80 % of the water would reach distribution points to the fields, the overall withdrawal would be 10,600 m^3/ha. Subtracting this figure from the basin-wide withdrawal shown in Table 8.3 for 1995 of 12,594 m^3/ha shows possible savings of 1,994 m^3/ha. If we use the withdrawal number for 2010 shown in Table 8.5 of 11,169 m^3/ha savings would be considerably lower at 569 m^3/ha. The 1995 savings figure, assuming an irrigated area of 7.94 million ha, would translate into a basin-wide gross reduction of 15.8 km^3/year. The same calculation made for the 2010 number assuming an irrigated area of 8.2 million ha, would be 4.7 km^3/year. Net savings (corrected for reductions in return flows to rivers) would be less. Taking the 1995 case and assuming return flows to rivers at 24 % of withdrawals, typical for the first half of the 1990s, and that they would be reduced by the same percentage as irrigation withdrawals for 1995 (15.8 %), net savings would equal 12 km^3/year. The same calculation made for 2010 conditions results in net savings of 3.6 km^3/year. The gross figure for 1995 falls within the range of estimated feasible water savings (12.7–18.3 km^3) made by the countries of the region in the mid-1990s and the net figure is slightly less than the lower end of the range (World Bank and the ICWC 1996, pp. 24–25).

The savings noted above are based on implementation of modern technologies for reducing irrigation water usage such as lining delivery canals to reduce water losses owing to exfiltration and more precise leveling of fields using lasers to ensure even distribution of water. Combining these techniques with Western best management practices (BMP) that include irrigation scheduling using computers and specialized software along with real-time monitoring of soil moisture and crop water needs to determine exactly when and how much water to apply, accurate measuring of the exact amount of water being used, genetic engineering of crops to lower water requirements, and precision farming using satellite imagery and GPS [Global Positioning System] technology could lead to substantially greater savings (Texas Water Development 2012). Thus Israel, with similar climatic conditions to the Aral Sea Basin, but technologically sophisticated irrigation practices, had in the mid 1990s an average withdrawal of 5,590 m^3/ha (ICAS 1996, Table 4.1). Such a figure is probably out of reach in the Aral Sea Basin because of the much longer length of water-losing delivery canals and the different crop mix. However, if average water withdrawals for the basin could be lowered to 8,000 m^3/ha, as Victor Dukhovnyy, a leading Central Asian irrigation expert during both the Soviet and post Soviet eras (and currently head of the Scientific Information Center of the Interstate Coordinating Water Management Commission) proposed in 1985, gross savings of 36.5 km^3 and net savings of 27.7 km^3 (27 % of withdrawals) would accrue using the 1995 water withdrawal data (Dukhovnyy 1985). Using the 2010 data, gross savings would be 26 km^3 and net savings 19.8 km^3 (21.6 % of withdrawals).

One means to obtain considerable water savings in irrigation would be to replace a substantial part of the inefficient furrow irrigation systems, which serve 70 % of the irrigated area in the Aral Sea basin, with drip irrigation that uses much less water per hectare irrigated. However, drip systems are very expensive, require a high level of maintenance, and the drip emitters would be subject to severe plugging problems here owing to the high sediment content of water in the Amu Darya and Syr Darya (Jones 2000). Sprinkler irrigation, widely used in the United States, is also a more efficient irrigation method than the use of furrows. But in the extremely arid conditions of the Aral Sea basin, there would be excessive losses to evaporation from the spray before the droplets reached the ground. Partial mitigation of this problem might be possible through the use of "downcomers" that release the spray close to the ground.

In spite of the reality that irrigation in the Aral Sea basin for the foreseeable future will be based heavily on the existing system dominated by the use of furrows, water savings from implementation of aggressive efficiency improvement efforts could well be significantly larger than indicated by the calculations presented above. This owes to the fact that water wastage and inefficient use is likely considerably greater than reported. There is compelling evidence that official figures provided by the basin states for their irrigation withdrawals are underestimated for several reasons (Schapp 1996/1997). The system of measuring deliveries to "cooperative" users (the former collective and state farms), inadequate during Soviet times, has significantly deteriorated. Usage by the variety of 'private' farming types that have developed in the Aral Sea Basin countries since independence (see Chap. 12 for information on these) is even more of a mystery. In the majority of instances, no organized system exists to measure withdrawals.

Frequently, what is reported as farm usage is not based on actual measurement (because measuring equipment is absent or not working) but is an educated guess derived from the established water use "norms" (standards) for the region and farm crop mix left over from Soviet times. It represents the quantity of water that should be delivered to the farm; not what is actually supplied. An Uzbekistan water management expert, relying on careful farm-level studies conducted between 1996 and 2000, clearly and forcefully points out the level of irrigation water wastage:

> A dramatic feature of the current situation in water use in the region is that under conditions of water supply limitation (water quotas), the water deficit is aggravated by extremely irrational water use at the on-farm level. Basic water losses take place in the on-farm irrigation network and in a field. At the same time, over-normative water losses at both levels, on average, amount to approximately 4,440 m^3 per hectare or 37 percent of total water supply at farm boundaries (Sokolov 2006, p. 65).

He went on to note that most of the water losses in the middle and lower reaches of river basins occur in the conveyance systems' unlined canals leading from the farm boundaries to the fields and account for 15–35 % of the water delivered to the farm.

The situation has probably not improved in any major way since and may have deteriorated. A 2009 study of Asian Irrigation by the International Water

Management Institute (IWMI) that was funded by the Asian Development Bank (ADB) concluded that poorly maintained and under funded irrigation systems threaten the future of agriculture in Central Asia (IRIN 2009). Victor Dukhovnyy in his PowerPoint presentation at the International Aral Conference held in Tashkent Uzbekstan in 2008 provided a list of the key problems plaguing irrigation in the Aral sea basin (Dukhovnyy 2008): (1) lack of attention to water conservation; (2) decreased accuracy of water accounting; (3) deterioration of water infrastructure in all chains of [the]water hierarchy that leads to loss of controllability; (4) small investments in reconstruction and modernization; (5) increased number of water users; and (5) lack of financing of operational services and, hence, loss of personnel.

Another factor contributing to underreporting of water usage per hectare is exaggeration of the area irrigated as it represents the lands with completed irrigation facilities but is not reduced for those systems that are under repair, not working, or have been removed from production (for example, because of excessive soil salinization or lack of water). Farms and the agricultural/water management hierarchy have an incentive to over-report the area irrigated and under-report water withdrawals as it makes them look better in terms of efficiency, i.e., water use per hectare.

Implementation of a large-scale program for technical improvement of irrigation in the Aral Sea basin would be a gigantic undertaking and require a long period for completion. For the basin as a whole in 1994, the length of main and inter-farm irrigation channels was around 48,000 km; only 28 % of these were lined to reduce filtration (World Bank and the ICWC 1996). The situation was even worse for on-farm canals: over 268,000 km with 21 % lined. In Uzbekistan in the mid 1990s, 10,000 km of main and inter-farm canals needed lining, and nearly 2 million ha with older irrigation systems, nearly one-half the irrigated area, needed reconstruction (Antonov 1996).

8.3.3 Soil Salinity and Drainage Problems

Soil salinization is one of the most serious problems faced by irrigation in the Aral Sea basin. It not only lowers yields but also increases water use owing to the need to flush (leach) salts from the soil prior to spring planting. A 1996 study reported that 50 % of irrigated lands in the basin suffers from this affliction (Pankova et al. 1996, pp. 85–87). The problem does not appear to have diminished in subsequent years. Reportedly, the share of salinized irrigated lands in Uzbekistan increased from around 48 % to around 64 % between 1990 and 2003 (Schillinger 2003). At the 2008 International Aral Sea conference in Tashkent, Dr. Herath Manthrithilake, head of the Central Asian section of the International Water Management Institute, reported that over 4 million ha or 55 % of irrigated lands in Kazakhstan, Uzbekistan and Turkmenistan were damaged by salinity (Manthrithilake 2008). As a result, cotton and wheat harvests as well as water productivity (yields per cubic meter) in these zones were 20–40 % lower than on non-saline lands. According to a 2001

World Bank study 66 %, 97 %, 80 %, 38 % and 29 % of irrigated lands were salinized to one degree or another in Uzbekistan, Turkmenistan, Kazakhstan, Tadjikistan, and Kyrgyzstan, respectively (World Bank 2001).

Large portions of irrigated lands also suffer from high water tables as a result of the lack of drainage facilities or ones that are inadequate or not working properly. Drainage systems that keep the water table sufficiently deep are exceptionally important for irrigation in dry areas with saline ground water such as are common in the Aral Sea Basin. Field experiments conducted at the end of the Soviet era showed, for example, that in Bukhara Oblast of Uzbekistan, one of that nation's most important irrigated oblasts, it took 26,000 m^3/ha to grow cotton and prevent secondary soil salinization where the depth to groundwater was 1 m or less but only 8,000 m^3/ha when the water table stood at 3 m or more (Micklin 2000, p. 40). In the former case, most of the water was used to flush salts from the upper layers of the soil rather than for irrigating the crop. Again, since the collapse of the USSR, matters have not improved but grown worse. A detailed and excellent 2003 World Bank report stated that:

> Since the collapse of the Soviet Union, both government budgets and farm incomes have fallen dramatically, water management institutions have weakened, and infrastructure maintenance has in many places come to a standstill. Irrigation and drainage (I&D) infrastructure is beginning to fall apart. Canals are silted up or damaged, gates broken or non-existent, and pumps held together by improvised repairs and parts cannibalized from other machinery. Across vast areas, water supply has become erratic, and land salinized and waterlogged (World Bank 2003, p. i).
>
> As drainage systems have deteriorated, vast tracts of land have become either salinized or waterlogged over the last decade, with a corresponding drop in crop yields. Salinization forces farmers to apply ever-greater quantities of water in an attempt to flush the salt out of the soil, making water application even more wasteful than it was before. This raises water tables further, and increases water logging, which further reduces yields and in some areas even damages buildings (World Bank 2003, p. ii).

Of the major irrigation zones, only the Golodnaya Steppe and Khorezm Oasis in Uzbekistan have adequate drainage facilities. Ground water levels are rising nearly everywhere, exacerbating water logging and soil salinization. Disposal of the huge volumes of salinized and polluted (with agricultural chemicals and fertilizers) irrigation drainage water remains a serious problem, although the level of pollution has decreased owing to lower use of toxic chemicals on fields than during Soviet times when these were applied with reckless abandon. These discharges reached 43 km^3 annually by the mid-1990s (ICAS 1996, Chap. 6).

An Uzbekistani expert in 1996 estimated the rehabilitation costs for the older irrigation systems in the Aral Sea Basin at \$3,000–4,000/ha (Djalalov 1996). A World Bank sponsored study of the same vintage indicated renovation of irrigation and drainage systems could run to \$3,000/ha (World Bank and the ICWC 1996, p. 25). This document also estimated that 5.4 million (68 %) of the 7.94 million ha of irrigated lands in 1995 needed reconstruction. At \$3,000/ha this would cost \$16 billion and at \$4,000/ha nearly \$22 billion. Considering inflation, the cost of such rehabilitation today would be considerably greater.

Uzbekistan and Turkmenistan with the largest areas under irrigation and the largest share of the systems needing reconstruction would bear the brunt of the bill. It is extremely doubtful that the states of the basin, individually or collectively, have the funds now, or will in the near or mid-term future, to fund so costly a project. Furthermore, the condition of irrigation systems in the basin has deteriorated since independence as funds for maintenance and repair have plummeted; responsibility for system maintenance has fallen between the cracks or been dumped on farm units who are incapable or unwilling to conduct the necessary work; and the supply of replacement parts and equipment that formerly came from other republics of the USSR has dried up. Hence the size of the job to repair the irrigation infrastructure is increasing with time and is another factor driving the cost upward.

One disturbing result of the deteriorating condition of irrigated lands in the Aral Sea Basin has been a steady decline in the yields of most major irrigated crops (ICAS 1996, Chap. 10, Table 8.2). This owes primarily to salinization and water logging and began toward the end of the Soviet period. It has continued and probably accelerated since formation of the independent states of Central Asia. Between 1990 and 1994 yields of cereals fell 19 % in Uzbekistan, 37 % in Kazakhstan, 23 % in Turkmenistan, 50 % in Kyrgyzstan and 59 % in Tajikistan. Cotton yields declined 7 % in Uzbekistan, 31 % in Kazakhstan, 2 % in Turkmenistan, 24 % in Kyrgyzstan and 31 % in Tajikistan. Vegetable yields rose by 23 % in Turkmenistan, held steady in Uzbekistan but fell between 33 % and 68 % for the other states. Other factors such as poor seed quality, a sharp drop in usage of fertilizers and pesticides, poorly timed agricultural operations and ill-timed harvests, and lack of proper crop rotation also contributed to these declines in yields.

8.3.4 Saving Water by Changing the Crop Mix

Switching the crop mix from high water use crops (rice and cotton) more toward lower (grains, vegetables, melons, fruits, and soybeans) could be a relatively low cost means of reducing water use compared to massive technical rehabilitation. In arid regions such as the Aral Sea Basin, rice may require up to 25,000 m^3/ha and cotton up to 13,000 m^3/ha (Grand Solution 2012). On the other hand, wheat and Sorghum maximally require only 6,500 m^3/ha, soybeans 7,000 m^3/ha, and tomatoes 8,000 m^3/ha. Melons on average need 6,000 m^3/ha (FAO 2012, Table 5). Licorice is a crop native to Central Asia that shows considerable promise. It not only has relatively low water needs but field experiments in the first decade of this century have shown that it has the ability to significantly reduce soil salinity. In heavily saline areas of the Fergana Valley in Uzbekistan, salinity in licorice cropped fields fell from 215 to 185 t/ha and yields of cotton in rotation with licorice rose from 0.3–0.6 to 1.5–1.89 t/ha (Manthrithilake 2008). Similar results were obtained with winter wheat.

In fact, the reason irrigation withdrawals per hectare substantially dropped between 1990 and 1995 primarily owed to cropping changes (Table 8.1). The area devoted to cotton and rice was reduced while the area planted to winter wheat increased. Over this period, Uzbekistan, by far the largest grower of cotton in the Aral Sea basin, shrank its cotton hectarage from 1.83 to 1.491 million ha, a decline of 19 % (Index 2012a). At the same time, the area planted to wheat tripled from 433,000 ha to 1.3 million ha (Index 2012b). Between 1995 and 2011, the pace of decline in cotton hectarage in Uzbekistan greatly slowed with the cotton area falling to 1.34 million ha in 2011, a 10 % decrease. The wheat area for the same time period grew to 1.4 million ha, only an 8 % rise.

Turkmenistan, the second in cotton production, had 623,000 ha under cultivation in 1990. This shrank to 450,000 ha by 1995 (28 % decrease), but then increased to 575,000 ha by 2011, 8 % less than in 1995 (Index 2012c). Wheat area in 1990 was a paltry 60,000 ha but grew rapidly to 437,000 ha by 1995 (a sixfold growth) (Index 2012d). By 2011, the wheat hectarage had doubled to 860,000 ha compared with 1995. The purpose of these changes, however, was not so much water savings but strengthening the national food bases. Significant further reductions in the area planted to cotton is unlikely in either of these countries in the near (or probably even mid-term future) as cotton is an important foreign currency-earning export crop.

In Uzbekistan, the sizable reduction in the area devoted to cotton resulted in a significant reduction of output. In 1990, output of baled cotton was 1.5 million metric tons (mt), by 1995 it had dropped to 1.3 million mt and by 2011 to 981,000 mt (Index 2012e). The 40 % drop in production from 1990 to 2011 is significantly more than the 27 % decline in planted area and indicates a drop in average yield of 33 %. Turkmenistan's 1990 production was 410,523 mt of baled cotton; by 1995 it had shrunk 43 % to 235,227 mt and by 2011 rose 22 % to 286,364 (Index 2012f). From 1990 to 2011, there was a 30 % reduction in production whereas the area planted only decreased by 8 %. Thus the accompanying decline in yields was 73 %. There are, to be sure, year-to-year swings in cotton production owing to changes in climatic and other factors, but the trend since the 1990s is clearly downward in both of these two most important cotton producing countries in the Aral Sea Basin. This is another clear indicator of the general deterioration of irrigated cotton agriculture.

The area given to rice production in the Aral Sea basin also decreased significantly. Kazakhstan, the major rice producer, had 124,000 ha under this crop in 1990. By 1995, rice plantings had fallen to 95,000 (a drop of 23 %) and by 2011 diminished slightly further to 94,000 ha (Index 2012g). Uzbekistan, with the second largest area under rice in the Aral Sea basin, had 145,000 ha planted to this crop in 1990 (Index 2012h). There was little drop in this figure by 1995, but a precipitous decline from 1996 to 2001, with the area falling to 40,000 ha (a 72 % drop). A severe drought afflicted Uzbekistan in 2001 and little water was available in the major rice growing regions in the downstream part of the Amu Darya so they had to make major cutbacks in the area planted to this water intensive crop. The rice hectarage rose in subsequent years, but then again fell reaching 30,000 ha by 2011, only 20 % of what it was in 1990. Certainly the reduction in the area devoted to rice, the most water intensive crop in the Aral Sea basin, has helped reduce aggregate water withdrawals for irrigation and improve the average water use figures for the mix of crops grown here. Given the very high water needs of rice, shrinkage of the planted area also made a significant contribution to reducing water withdrawals from the Syr and Amu rivers. The contraction of the rice growing areas along the lower course of the Syr Darya has been one of the major factors increasing inflow to the Small Aral Sea and allowing its partial rehabilitation (see Chap. 15).

Owing to the major reductions in the area planted to rice, its production has substantially dropped in both Kazakhstan and Uzbekistan. In 1990, the former nation produced 376,000 mt; by 1995 this had fallen to 120,000 mt, a 68 % drop (Index 2012i). However, the harvest rose to 220,000 t by 2011, an 83 % rise over 1995, even though the area planted essentially remained the same. Average yields would have risen by the same percentage. This likely reflects improved growing practices and the taking out of production of the least suitable lands. For Uzbekistan, the 1990 harvest was 351,000 mt (Index 2012j). By 2001 this had contracted to 44,000 mt, an 87 % drop. By 2011, rice production rose to 75,000 t, a 79 % decrease from 1990. The percentage decline in area planted to rice and the production of rice in Uzbekistan were the same in Uzbekistan between 1990 and 2011, indicating that average yields were essentially the same for these 2 years.

A promising program that has been implemented on a pilot basis in the Fergana Valley, location of intensive and productive irrigation, which includes parts of Uzbekistan, Kyrgyzstan, and Tajikistan, utilizes the concept of Integrated Water Resource Management (IWRM). IWRM is an approach to handling water resources that has been around for decades, but has received renewed attention since the 1990s. A useful definition provided by the Technical Committee of the Global Water Partnership is “a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (Wikipedia 2012).”

8.3.5 Other Measures to Improve Irrigation

The Fergana Valley program was initiated in 1999 with the intent to account for all available water sources within the hydrologic basin, take into account the interests of different water using sectors, involve all stakeholders in decision making and to promote efficient water use in order to benefit public welfare and promote environmental stability (Sokolov 2006). According to Victor Dukhovnyy, introduction of IWRM principles to the management of the Southern Fergana Canal reduced water use during the vegetation period from 1.063 km^3 in 2003 to 0.643 km^3 in 2007 (Dukhovnyy 2008).

Adoption of governmental policies and laws promoting irrigation water pricing, privatization of land, and giving rights of self-governance and responsibility for management of on-farm and inter-farm irrigation systems to farmer-irrigators would with out doubt encourage introduction of water saving practices in the

Aral Sea Basin without massive governmental expenditures (Micklin 1996/1997, p. 228, 1997a, b). The governments of Kazakhstan, Tajikistan, and particularly Kyrgyzstan, have taken some serious steps in terms of these reforms. The leaders of Uzbekistan have certainly talked about these subjects but made few moves toward implementing meaningful policies. Turkmenistan has done practically nothing. Among the key problems hindering further advancements along these lines are governmental resistance based on fear of losing social and economic control, opposition from the former collective (now cooperative) farms and local officials, fear of land speculation and exacerbating rural underemployment and unemployment, lack of means to measure water deliveries to farmers, and the impoverished state of the farming economy (Micklin 2000, pp. 54–67).

The major burden for reducing irrigation usage must rest on Uzbekistan as it has the majority of the irrigated area and irrigation withdrawals in the Aral Sea Basin. Turkmenistan which accounts for a significant share of the irrigated area and withdrawals in the Amu Darya Basin could also make substantial contributions to water savings, particularly given that it had the highest per hectare withdrawals of the five Aral Sea Basin states. The remaining states that were part of the USSR (Tajikistan, Kazakhstan and Kyrgyzstan) irrigate much smaller portions of the basin and withdraw considerably less water. Their possible contributions, although not insignificant, would be much smaller. Afghanistan and Iran withdraw little from the basin; their possible contribution to water savings is nil. This may change in the future for Afghanistan as it has the right under international water law to substantially increase its withdrawals from the Amu Darya.

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Chapter 9
Challenges of Transboundary Water Resources Management in Central Asia

Bakhtiyor Mukhammadiev

Abstract Central Asian major river basins link the countries of Afghanistan, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan. Water management in Central Asia continues to be the most important transboundary environmental issue and the biggest problem remains how to allocate water for upstream hydropower production and downstream irrigation. Disagreements between the upstream and downstream states have increased regional tensions and slowed development plans. National responses to existing cooperative opportunities are essentially driven by a policy of national self-sufficiency in energy and water. While it is reasonable to be concerned about water and/or energy security, it is also critical to understand that a policy of self-sufficiency incurs substantial costs for all. As long as self-sufficiency dominates the policy agenda, the benefits of cooperation will not materialize. International water law could provide a rational avenue toward achieving international consensus on both use and allocation of water resources in the basin, with international legal agreements to reinforce the consensus. Incentives to cooperate through the application of the benefit-sharing concept as a development model in the basin would include decreased costs and increased gains in many dimensions of regional cooperation, including the benefits that stem from better agricultural practices and its competitiveness, joint developing of the region's energy resources, and better management of regional environmental risks.

Keywords Central Asia • Water management in Central Asia • Transboundary water resources • International water law • Benefits sharing in international watercourses

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9.1 Introduction

Water management is Central Asia's most important transboundary environmental issue. Today the five Central Asian states struggle to balance their limited water supply with an ongoing contentious regional dispute centering around the use of water for downstream irrigation versus its use for upstream power generation. The biggest problem remains how to allocate water for upstream hydropower production and downstream irrigation in the context of an increasing politicization of transboundary water resources.

The Central Asian states not only inherited many of the problems of past water resources mismanagement under the Soviet regime, but also acquired a daunting variety of new challenges of participation in international affairs. A special case of fragmentation of the highly centralized regional water economy in today's Central Asia is one of the most illustrative examples of this. Implications of this past centralized water management practice for independent national decision-makings, in relation to how transboundary waters are allocated and the benefits thereof distributed among them, are obstacles for the States in diversifying regional water management and prevent basin development in the most optimal way.

Waters of the Syr Darya and Amu Darya – the two large rivers that feed the Aral Sea – are critically important to the livelihoods of millions of people who rely on these rivers' resources for irrigation and energy generation. From its headwaters in the Tian Shan Mountains to the Aral Sea, the Syr Darya River stretches 3,019 km (see Fig. 2.2 in Chap. 2). It drains an area of 782,617 km^2 and its average annual flow is 37 km^3. The Syr Darya is mainly a product of two rivers: the Naryn and the Karadarya, both originating in Kyrgyzstan (UNECE 2011). During its course, the Syr crosses through Uzbekistan, Tajikistan, and Kazakhstan before reaching the Northern Aral Sea, also known as the Small Aral Sea. The 2,540 km-long Amu Darya River, the largest river in Central Asia, is formed by the confluence of the Vakhsh and Pyanj rivers. The average annual runoff of the Amu Darya River is 79 km^3. Tajikistan and Afghanistan are the most upstream countries with Uzbekistan and Turkmenistan in the downstream positions (UNECE 2011).

Expansion of irrigated agriculture on a region-wide scale to facilitate regional economic growth was the general focus of Soviet water polices in Central Asia. A network of more than 32,000 km of canals, 45 dams, and more than 80 reservoirs was built to harness Central Asia's irrigation and hydroelectric potential (Chan 2010).

During the period of Soviet central planning, these rivers' resources were managed centrally under an approach that sought to maximize regional economic growth. Large dams and hydroelectric facilities that were constructed on both rivers in the upstream countries of Kyrgyzstan and Tajikistan were used primarily to supply water-storage and release services to support the expansion of irrigated agriculture in downstream Uzbekistan, Kazakhstan and Turkmenistan. The large storage reservoirs along the Naryn Cascade in Kyrgyzstan and the Vakhsh Cascade in Tajikistan were operated under a water-release regime which scheduled 75 % of the annual discharge from the reservoirs to be made during the summer irrigation period (April-September), with 25 % released in winter (October-March), generally in line with the natural regime of water flow in the rivers caused by seasonal precipitation and snow melt. The electricity generated during summer in excess of the domestic requirements was fed into the integrated regional electricity grid. During winter, Kyrgyzstan and Tajikistan received compensation in the forms of fuel (oil, natural gas, and coal), as well as surplus thermally generated electric power from downstream countries to cover higher winter demand for energy supplies. Such an arrangement was largely value reflective, where the delivery of energy resources in exchange for water-storage and release services was designed to extract maximum value from the water resources.

With the dissolution of the Soviet Union, this arrangement was essentially abandoned. While downstream countries insisted on the pre-independence schedule of water releases from the upstream countries' hydro facilities, deliveries of compensating winter-peak electricity and fuel declined or ceased, or were offered at market prices. Kyrgyzstan and Tajikistan have tried unsuccessfully to persuade their downstream neighbors to value and pay for the water-storage and release services that they provide. In response, Kyrgyzstan and Tajikistan have modified their hydroelectric power generation and water-release schedules to more closely match their domestic energy demand schedules with the bulk of the water now being released during winter. As a result of this, the downstream countries began facing inadequate supplies of water for irrigation in summer, while increased water releases during winter that caused flooding of downstream regions because of the frozen and highly silted riverbeds and irrigation canals (UNDP 2004).

9.2 National Agendas of the Aral Sea Basin States with Respect to Transboundary Waters

Water is an essential input for irrigated agricultural production in each of the region's countries, whose output supported by irrigation accounts for a substantial share of the countries' Gross Domestic Products (GDP). For countries such as Uzbekistan, Tajikistan and Turkmenistan, agricultural products, particularly cotton, constitute a large proportion of their export earnings.

All of Central Asia's cotton producers rely on the Amu Darya and Syr Darya rivers as a source of water for irrigation. Central Asia's cotton industry is part of a major international trade accounting for 6 % of total world production (2010–2011) and contributing 15 % of total world exports. For example, globally, Uzbekistan ranked seventh in production and fifth in export of cotton fiber in 2011 (USDA/FAS 2011).

Water is also important for energy production, contributing more than 90 % of total domestic energy generation in Kyrgyzstan and Tajikistan. It is estimated that only about 10 % of the total regional hydropower potential (524,000 GWh/year) has so far been developed (World Bank 2004).

Appropriate management of water resources is a basic prerequisite for preserving Central Asia's vulnerable environment and unique biodiversity. Water-related environmental problems include increased salinity and water logging due to poor irrigation practices and drainage management. Salinization in the Aral Sea Basin intensifies downstream, because salts wash down the Amu Darya and the Syr Darya rivers in the basin. The upstream countries, Tajikistan and Kyrgyzstan, have very low rates of salinization, while the downstream countries suffer more. Overall, some 47.5 % of the total eight million hectares of irrigated land in Central Asia is affected by salinization to various degrees. Owing to water logging, water tables have risen considerably throughout the basin. For example, the area of irrigated land with a water table of 2 m or less expanded by 35 % between 1990 and 1999 (World Bank 2003).

Central Asia possesses much regionally significant water infrastructure that is located on transboundary rivers. It is only by cooperative efforts the countries could have the necessary resources to manage the regional infrastructure and cover the costs of its operation, maintenance and investment. The total existing storage capacity of the Aral Sea Basin reservoirs is 60 km^3; the total length of the region's irrigation system (includes both on-farm and main and secondary irrigation canals) is 316,350 km; the total number of vertical drainage wells is 865 and the total length of the drainage network is 191,900 km (CAwaterinfo 2013). An inventory of works that the five riparians implemented in 2006 for maintaining the cooperative management of the waters of the Amu Darya and Syr Darya river basins cost some 60.9 million USD. The bulk of the total cost, some 52 million USD (85 %), was spent for river channeling, riverbank protection, flood control measures, maintenance and repair works of the facilities located in transboundary rivers (Dukhovny and Sorokin 2008).

From country specific perspectives, Kyrgyzstan, and to lesser extent Tajikistan, due to their upstream locations on the Syr Darya and Amu Darya rivers, respectively, can control the timing and availability of water releases to the downstream countries of Uzbekistan, Kazakhstan and Turkmenistan (Figs. 9.1 and 9.2). In the absence of an agreement with downstream water users, these upstream countries would prefer to operate the transboundary water facilities located on their territories for electricity generation.

Despite a high demand for irrigation water in Uzbekistan, the country has a limited direct ability to influence the timing and volume of transboundary water inflows from upstream countries. Uzbekistan's best policy option was to participate in the annual barter agreements, although in recent years it has taken a decisive unilateral stance in not agreeing to these. Such a decision to pursue unilateral development was largely pre-determined by the upstream states' policies of energy self-sufficiency. This has largely undermined Uzbekistan's long-term water security, and within a reduced framework of choices, Uzbekistan decided to actively pursue a policy of self-sufficiency in water through the construction of new storage reservoirs on its own territory. To that extent, cooperation with Kyrgyzstan on

Fig. 9.1 Toktogul dam on the Naryn River, Kyrgyzstan (Source: US Embassy in Tashkent)

Fig. 9.2 Nurek dam on the Vakhsh River, Tajikistan (Source: US Embassy in Tashkent)

timely upstream releases and storage capacity are still of utmost importance for Uzbekistan. The purpose of the storage reservoirs is essentially to capture the wintertime releases made from upstream states that operate their storage reservoirs in hydropower regimes. At present, winter releases are largely unavailable for irrigation use and most do not find their way to the Aral Sea because of the ice cover on the river during the winter season. Instead, they cause flooding problems and damages in Uzbekistan and Kazakhstan (UNDP 2004).

As a downstream Syr Darya riparian, Kazakhstan depends not only on upstream Kyrgyzstan but also on the water withdrawal rate in Uzbekistan. As the limitations of the upstream developments became apparent during the 1990s, Kazakhstan looked at a range of alternative options for providing cheap winter electricity to Kyrgyzstan. These plans were effectively shelved, however, when feasibility studies revealed that the electricity generation in Kyrgyzstan was considerably cheaper than any of the Kazakh options. Kazakhstan chose building a Koksaray water storage reservoir on its territory to catch the winter releases. But Kazakhstan also appears to agree with the notion of compensating upstream countries for water storage services, if not paying for water per se. As evidenced by the agreement it already has with Kyrgyzstan on the smaller trans-boundary rivers of Chu and Talas, Kyrgyzstan has the right to compensation from Kazakhstan for part of the costs to ensure safe and reliable operation of transboundary water facilities that serve to benefit both countries. The parties have also decided that costs for operation and technical maintenance of the facilities specified in the Agreement would be shared in proportion to the volume of water received by each party (Agreement 2000). Kazakhstan has also insisted that if it is to help meet the costs of maintaining and developing upstream facilities from which it benefits, then these facilities should be jointly managed. Kyrgyzstan, on the other hand, has rejected this offer on the grounds that it does not wish to surrender its sovereign control over its facilities, which is one of its few sources of regional political influence.

In an attempt to reduce its energy dependence on downstream countries, particularly on Uzbekistan, Tajikistan is currently considering how it can exploit its huge hydropower potential. Tajikistan has been pursuing completion of the Soviet era Rogun hydropower project (HPP) (Fig. 9.3). When the project was first proposed in the late 1970s, it was conceived as a dual-purpose project for irrigation in the basin and for hydropower generation. According to the Soviet era design, the Rogun project, located on the Vakhsh River, a major tributary of the Amu Darya, would have a multi-year regulation capacity and a dam height of 335 m. The reservoir would have a total storage volume of 13 km^3 and installed capacity totaling 3,600 MW. Because the Vakhsh River, as a tributary of the Amu Darya, is a transboundary river, and as such, is beyond exclusive control by a single party, the Rogun project would need significant foreign investment and also would require the Government of Tajikistan to play a key role, in view of the necessity to take full responsibility for environmental, social, resettlement and riparian issues. The downstream countries, especially Uzbekistan, are strongly opposed to the completion of the Rogun project and international donors are also hesitant about financing it without prior consent of the other riparian countries.

While Turkmenistan participates in regional water related politics mainly through its memberships within the existing regional institutions such as the ICWC (Interstate Coordinating Water Management Commission) and IFAS (International Fund for Saving the Aral Sea), the country has generally followed a unilateral development strategy with respect to transboundary waters. This approach is evident in the country's water policies, which include plans to divert agricultural return waters to a natural depression site in the Kara-Kum Desert to create the so-called "Golden Century Lake," increase land under irrigation and extend the Kara Kum and Tuyamuyun canals. Turkmenistan claims that because these waterways are entirely on its territory, interstate consultations are not required.

Fig. 9.3 Rogun dam site on the Vakhsh River, Tajikistan (Source: http://www.flickr.com/photos/32828146@N06/page10/)

Turkmenistan launched a 20-year plan to create a gigantic artificial lake in the Kara-Kum Desert. Seven drainage canals will collect agricultural return waters from the country's five regions to fill the Golden Century Lake. This water will then be dumped into the natural depression of Karashor in the Kara-Kum Desert in northwestern Turkmenistan. The project plan calls for the construction of numerous water collectors, bridges and other facilities to secure the free flow of drainage waters. The construction of the lake has been underway since 2002. The project cost is estimated at 4.5 Billion USD spread over 20 years, but that projection now seems increasingly unrealistic. The completely filled lake would have a surface area of 3,460 km^2 (Stone 2008).

Kara-Kum and Tuyamuyun are the largest and the longest canals in Turkmenistan that withdraw water from the Amu Darya River for irrigation and population water supply purposes. On average, Turkmenistan's territory contributes only 1.9 % to the total Amu Darya River Basin (79.28 km^3/year), but its share under the existing agreements is fixed at 22 km^3/year.

Afghanistan borders Tajikistan, Turkmenistan and Uzbekistan, and shares a number of rivers with these countries, notably the Amu Darya. Concerns have increased in recent years among downstream basin States that renewed Afghan agricultural development will lead to increased water withdrawals from the Amu Darya tributaries located in Afghanistan. Around 8 % (11.6 billion cubic meters) of the Amu Darya's flow is generated on Afghan territory, and Afghanistan is entitled to withdraw up to nine billion cubic meters from the Amu Darya River according to the agreements of 1946 and 1958 that it had signed with the Soviet Union (Agreement 1946; Protocol 1958). At the moment, Afghanistan diverts only about two billion cubic meters to feed irrigation networks in the Afghan portion of the Amu Darya Basin (King and Sturtewag 2010).

9.3 Central Asian Water Agreements

Over the last 20 years, negotiations over water sharing among the Aral Sea Basin States have led to the signing of a number of both multilateral and bilateral agreements. The current treaty based regime in Central Asia is based on the Agreement of 1992 between Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan on "Joint Management of the Use and Protection of Water Resources of Interstate Sources," (Agreement 1992), the Agreement of 1993 between the Republic of Kazakhstan, the Kyrgyz Republic, the Republic of Tajikistan, Turkmenistan and the Republic of Uzbekistan on "Joint Activities to Address the Aral Sea Issues," (Agreement 1993), the Agreement of 1996 between Turkmenistan and Uzbekistan on "Cooperation in Water Management Issues" (Agreement 1996) and the Agreement of 1998 between Kazakhstan, Kyrgyzstan, Tajikistan and Uzbekistan on the "Use of the Water and Energy Resources of the Syr Darya River Basin" (Agreement 1998).

The Almaty Agreement of 1992 was the first agreement that the Aral Sea Basin States reached following their independence in 1991. It formally endorsed States' joint commitment to continue with the inherited from Soviet times "status-quo" regime of water sharing among the countries and established a rule of joint decision-making in the management and protection of transboundary water resources. Under this agreement, the parties agreed to provide strict compliance with established rules of utilization and protection of water resources. Other important provisions of the 1992 Agreement included such clauses as equality of rights for the use of basin water resources, obligations to maintain their rational use and not to cause harm or infringe the interests of the other Parties, joint efforts to address the problems of the Aral Sea, strict maintenance of minimum in-stream flow requirements, particularly during droughts, facilitation of open information exchange and joint scientific-technical research. The Agreement established the Interstate Coordinating Water Management Commission (ICWC), with the mandates, *inter alia*, to act as a basin-wide water policy maker and to develop a long-term program of water supply in the region. During the first half of the 1990s, the basin states made several changes to the structure of the ICWC. At present the ICWC operates through a Ministerial-level Commission, Secretariat, Scientific Information Center and the two River Basin Organizations (RBOs – in Russian BVOs) for each river.

The Scientific Information Center of the ICWC serves as "an intellectual" body to the Commission and advises the member-States on all aspects of water management in the basin and provides technical coordination for joint activities of relevant national institutions. It also facilitates cooperation among parties for the implementation of the IWRM (Integrated Water Resource Management) principles on a basin-wide scale. RBOs are directly responsible for execution of the Commission's agreed polices related to water allocation, quality control and operation of the transboundary facilities located on the Amu Darya and Syr Darya rivers.

The Agreement of 1993 established the Aral Sea Basin institutional framework for joint utilization and protection of the Aral Sea Basin transboundary water resources. It created an Intergovernmental Council for the Aral Sea (ICAS) and International Fund for Saving the Aral Sea (IFAS) that were to lead regional cooperation and manage the Aral Sea Basin Program (ASBP). The previously created Interstate Commission for Water Coordination (ICWC) and the two river basin commissions, BVO "Amu Darya" and BVO "Syr Darya" were made subordinate to the ICAS. Later in 1997, the ICAS and the IFAS were merged into a newly restructured IFAS, with its chairmanship rotating biannually among the Presidents of the five Aral Sea Basin countries. In 2002, the member-states agreed to extend the chairmanship from 2 to 3 years.

The Amu Darya Agreement of 1996 set the legal basis for sharing the waters of the Amu Darya River between the downstream countries of Uzbekistan and Turkmenistan. It established rules of joint utilization of water resources and "compensational practice in the use of water and related land infrastructures located in the territory of one country for the benefit of another country." The Agreement provides that those lands of Turkmenistan lent to Uzbekistan for the latter's use for its water facilities are under "exclusive" ownership of the former (Turkmenistan) but the constructed facilities are property of the latter (Uzbekistan).

To ensure the agreed-upon operating regimes of the facilities and reservoirs of the Naryn-Syr Darya Cascade, and coordinate and make decisions on water releases, production and transit of electricity, and compensation for energy losses on an equivalent basis, the Syr Darya riparians signed the Syr Darya Agreement in March 1998 (USAID 2002). This framework agreement established a rule for irrigation-hydropower trade-offs between upstream and downstream states in the Syr Darya River Basin. The Agreement was specifically designed to integrate riparian interests and competing uses through a balancing process and created the principles of compensation of fuel for water between downstream and upstream countries. Compensation is associated with water release schedules from upstream storage reservoirs in Kyrgyzstan that takes into account both upstream needs for hydropower generation and downstream summer irrigation demand.

From the upstream countries' viewpoint, one of the several problems with these barter agreements between the Syr Darya countries has been that the side payments were not only unreliable, but also too low. Although, the agreed water and energy exchanges have been implemented accordingly, there still has been a shortage of fuel for winter energy generation in the Kyrgyz Republic. Also, downstream countries still report serious irrigation water shortages (2–4 km^3/year), water losses during winter remain high (on average 3 km^3 into the Arnasay Depression), and the upstream storage at Toktogul reservoir in Kyrgyzstan was drawn down despite substantially higher than average inflows of water into the reservoir in the 1990s (USAID 2002).

The Kyrgyz demand, for example, for higher payments from Kazakhstan and Uzbekistan expressed itself in the 2001 "Law of the Kyrgyz Republic on Inter-State Use of Water Bodies, Water Resources and Water Management Installations of the Kyrgyz Republic" (Kyrgyz Interstate Water Law 2001), which declared that water resources created on Kyrgyz territory are the property of that country, and that countries benefiting from water resources flowing from the Kyrgyz territory should therefore pay Kyrgyzstan. Downstream countries' objections to the law led to a softened Kyrgyz stance of demanding that the downstream users share the operation and maintenance (O&M) costs of delivering water rather than paying for water per se.

In addition, the Heads of State met on a number of occasions and signed declarations concerning transboundary waters, environmental cooperation and sustainable development in Central Asia. These declarations include: the Nukus Declaration of the States of Central Asia and International Organizations on the Issues of Sustainable Development in the Aral Sea Basin, signed on 20 September 1995 (Nukus Declaration 1995); the Almaty Declaration of the Heads of States, signed on 28 February 1997 (Almaty Declaration 1997); the Ashgabat Declaration of the Heads of States, signed on 9 April 1999 (Ashgabat Declaration 1999); the Tashkent Statement of the Heads of States, signed on 28 December 2001 (Tashkent Statement 2001); the Dushanbe Declaration of the Heads of States, signed on 6 October 2002 (Dushanbe Declaration 2002); and the Almaty Joint Statement of Heads of States – Founders of the International Fund for Saving the Aral Sea, signed on 28 April 2009 (Almaty Statement 2009).

9.4 International Water law

International water law has developed into one of the distinct branches of international law to govern the non-navigational uses of freshwater resources shared by two or more countries. It underwent a rapid development in response to the dramatically increased utilization of international watercourses and the great emphasis on water resources development. International water law identifies legal rules that determine a watercourse state's "legal entitlement" to the beneficial uses of shared water resources and establishes certain requirements for state behavior with respect to the management and development of international watercourses.

General international law is, in large measure, a catalogue of limitations upon state conduct affecting interests of another state or group of states. Similarly, rules of international water law, by their very nature and basic concepts, limit the exercise of jurisdiction by a state on its own territory over an international watercourse. The nature and extent of limitations imposed upon watercourse states, under international water law, is determined in accordance with the legitimate economic and social needs of each, in such a manner as to achieve the maximum benefit for all with a minimum of detriment to each.

Rules of international water law have emerged and developed as a result of many centuries of international state practice and can be found in international treaties, international customary law and general principles of law. In the absence of a specific legal regime, they together may provide an appropriate framework for negotiations between watercourse states aimed at establishing a cooperative regime over international watercourses or resolving water related interstate disputes.

International water law is concerned with three general substantive obligations placed upon watercourse states. They are the obligation to use an international watercourse in an equitable and reasonable manner (equitable utilization principle), the obligation to take all appropriate measures not to cause significant harm to other watercourse states (no-harm principle), and the obligation to protect ecosystems of international watercourses (UN Watercourses Convention 1997).

Equitable utilization is the allocation of the waters of international watercourses among watercourse states in such a manner as to allow the reasonable use of their waters by each of the riparian states. Although the area of equitable utilization does not provide precise rules for allocation of the waters of international watercourses, it is nevertheless suitable for the formulation of general guiding principles and arriving at equitable and reasonable results as is the requirement of general international law. The application of the equitable utilization principle to the allocation of international watercourses among states is not concerned with what is an equitable use for a state’s activities, but, rather, with what is equitable in relation to other states’ activities using the same watercourse.

The very idea of the principle of equitable utilization is equality of right of the watercourse states to use their equitable share of the waters of an international watercourse. Equality of right in the area of equitable utilization implies that “. . .all states riparian to the international watercourse stand on a parity basis with each other insofar as their right to utilization of the water is concerned.” (Wouters 1997) The nature and extent of their rights is determined in accordance with its respective needs. The term “needs” embraces the economic and social requirements of the watercourse states, which cause them to be, to a greater or a lesser degree, dependent on utilization of the waters of international watercourses.

Equitable utilization is concerned with the examination of the economic and social needs of the watercourse states by an objective consideration of various relevant factors and conflicting elements to their use of the waters and to accomplish the distribution of the waters that should result in achieving the maximum benefit for each and with the minimum detriment to each. Equitable utilization protects beneficial uses only and a right to equitable utilization, under international water law, is recognized only if it relates to the beneficial use of the waters. But this does not mean that the use must be the most beneficial to which the waters could be put, or that the method of utilization is maximally efficient in minimizing the inefficient use of water. Inefficiency stems not from misconduct or wrongdoing but from limitations in technical and financial resources. This implies that it is thus unreasonable to expect and require a developing state to meet the standard of efficiency, for example in utilization of irrigation waters, prevalent in parts of highly developed countries.

According to the principle of equitable utilization, each state has an equal right to an equitable portion of the uses and benefits of a shared watercourse, irrespective of where the watercourse arises or which state’s use is first in time. New upstream uses may be permissible even where existing downstream uses fully consume the waters of an international watercourse. This may be the case, for example, where the benefits of a new use (e.g. providing food and electricity needed to alleviate poverty in the state introducing the new use) substantially outweigh the harm that might result from this introduction (e.g. reduction in the production of agricultural products for export in a state with relatively high living standards). However, the burden is on the state proposing the new use to demonstrate that this is the case. An important consideration in this regard is whether existing users could be compensated for the loss due to the new use through reasonable conservation measures. To accommodate a downstream state's intensive use with upstream state's planned new use, the equitable utilization principle may require the downstream state to increase the efficiency of its water usage or conserve and augment water supplies through such means as treatment of wastewater. Efficiency and conservation would also be required of the upstream state, of course, to minimize the impact of its new use upon established uses downstream.

Under international water law, existing uses have neither absolute protection nor are they entitled to any protection at all. The protection to which they are entitled is determined by application of the equitable utilization principle. Procedurally, after a state demonstrates that it has suffered, or might suffer, significant harm to an existing use of an international watercourse, the burden of proof would shift to the state allegedly causing, or threatening to cause, the harm to prove that its conduct or use of the watercourse was equitable and reasonable vis-à-vis the other state.

International water law holds that a watercourse state can lawfully utilize the waters of international watercourses on its territory for its own needs if its doing so will cause no harm to utilizations in the territories of other co-riparian states. The no-harm principle enjoys sufficient support to qualify as a binding obligation under international water law, which also complements and supports the equitable and reasonable utilization principle. It certainly has a priority over the other individual factors of the equitable utilization but this implies the presumption of an inequitable character of a use that causes significant harm. In other words, it is not the causing of significant harm per se, but the inequitable and unreasonable causing of such harm that is prohibited by international water law.

The no-harm principle is concerned with prohibition of harm or injury to a state's legally protected interests. In other words, the principle protects a watercourse state against the deprivation of its equitable share of the uses and benefits of an international watercourse. The principle might be associated with the doctrine of limited territorial sovereignty, which, by definition, implies that "...the sovereignty of a state over its territory is said to be 'limited' by the obligation not to use that territory in such a way as to cause significant harm to other states." (McCaffrey 2001) 'Harm' may be factual in nature, defined as having physical impacts brought by the upstream new uses upon the downstream state, or legal in nature, as when new uses in a downstream state have no factual impact on an upstream state but may so change the equitable utilization balance that they in effect constrain the scope of future uses the upstream state can make consistent with its obligation under the equitable utilization principle.

In defining the no-harm rule, it also should be noted “harm on the territory of a watercourse state need not necessarily be connected with that state’s use of the waters.” State practice suggests that the no-harm rule is not limited in scope to issues of one watercourse state’s direct use of a watercourse that may cause harm to another state’s use of that watercourse. The principle has obvious connections with the theories of abuse of rights and good neighborliness. The abuse of rights doctrine is treated as one that limits the exercise of rights in bad faith, maliciously, or arbitrarily. When applied in the cases of international watercourses, the doctrine of abuse of rights “. . .serves as a check on a state’s freedom to use its territory in any way it wishes; that freedom would have to be exercised in good faith, and in such a manner as not to cause unreasonable harm to other states” (McCaffrey 2001). As for the doctrine of good neighborliness, it obliges states to pay due regard to activities on their own territories that may possibly cause adverse consequences in other states. According to the doctrine, being a good neighbor means “not only refraining from causing significant physical harm to other states, but also tolerating a certain level of harm originating from the activities in those states.” Summarizing the above, the process of moderation of extreme principles on water allocation could be perceived in international case law. The state’s right to use its territory is not unlimited; it is subject to the rights of other states.

Concerns over the protection of ecosystems of international watercourse are an integral part of international water law and both the principle of equitable utilization and the no-harm rule provide adequate support to the principle. Environmental factors are considered in the indicative list of relevant factors in Article 6(1) of the UN Watercourses Convention for the purposes of establishing an equitable regime of water utilization and also relevant for the proper interpretation and application of the no-harm rule (McCaffrey (2001). In the context of environmental protection, equitable utilization is concerned with impermissible levels of water pollution, which may deprive a watercourse state from its claim to an equitable utilization of the waters. In other words, a certain degree of transboundary water pollution is permissible under international water law provided it does not cause a change to the equitable utilization balance. What it does require is that watercourse states are under obligation to take all appropriate measures, i.e., exercise due diligence, to control and reduce sources of transboundary pollution within their territory and jurisdiction, which may involve, inter alia, continuing obligations of environmental impact assessment, monitoring and precautionary actions to prevent or mitigate transboundary environmental harm.

However, when, despite taking all appropriate measures, or a state acting within its rights, impermissible, or significant, transboundary harm nevertheless results, then, under international water law, states have an obligation to re-negotiate an equitable solution. International water law accepts that unavoidable harm is not prohibited, if the extent of pollution is within the scope of the equitable utilization balance, but when it goes beyond the scope and if a state, whose action causes such transboundary harm, fails to mitigate or compensate for a damage it caused to other watercourse states, utilization of the waters of international watercourse becomes inequitable and unreasonable.

The subject of evolution of international water relations among the Aral Sea Basin States is as unique as for any given river basin of the world. It has its own specific to the region problems that need to be carefully approached with a full knowledge of and respect for the region's long history, culture, customs and common religion in general and current water related social, economic, environmental, politics and greater geopolitics in particular. A failure to take all relevant factors affecting the evolution of water relations in the basin into account will certainly contribute to regional insecurity and increase the risk of raising potential conflicts over water among the Central Asian States.

The intention of the Aral Sea Basin States to develop a mutually beneficial cooperation in the use and protection of shared water resources has been hindered for a number of reasons, including a legal basis for cooperation. The Central Asian water agreements do not cover the entire range of relevant issues and fail to define detailed procedural rules for the preparation and adoption of binding decisions and joint follow-up on commitments assumed by countries. Although the countries of the region attach importance to the rules of international water law, each state uses different approaches to their practical application. The downstream countries, for example, being potentially vulnerable to any actions by the upstream states, insist on the unconditional observance of the rule of no transboundary harm, understandably to protect their existing reasonable and beneficial uses. Upstream nations, on the other hand, believe that they are deprived of their equitable share of the reasonable uses and benefits, and run an excessive risk of causing accidental damage to the downstream countries and are therefore forced to incur disproportionate expenses to prevent possible damages. Despite the declared need to reach agreement on water allocation, the positions of countries over the past two decades have remained unchanged.

9.5 Cooperation Through a 'Benefit-Sharing' Approach

With the region connected through its rivers and lakes, a regional approach to protecting these resources is essential. The quality of water needs to be protected by limiting sources of pollution, improving the treatment of industrial and residential effluents, and protecting mountain and desert ecosystems in terms of their sustainability, biodiversity and survival of endangered species. Sufficient river flow should reach the deltas and the Aral Sea for environmental purposes with the salinity of the water arriving at the deltas and the Sea remaining below the upper limit for use by other beneficial uses of water. Water quality parameters should be such that at any place in the basin safe drinking water can be produced without recourse to expensive technologies and also to permit biodiversity to be sustained or re-established. Society as a whole in each of the basin states has to agree that sufficient water must remain available in the rivers for ecosystems use.

Minimum in-stream requirements need to be developed and enforced for the Syr Darya and Amu Darya rivers, with an emphasis on river flows reaching the deltas and the Aral Sea, especially during drought periods. During times when there are not sufficient flows in the rivers, reserve flows need to be secured, which are separately calculated and independent of country allocations and negotiated between the basin-States on an equity basis. In addition, once negotiated and endorsed, the river flows for environmental purposes need to be fixed and be unconstrained by changes due to drought or wet years in the basin. It is estimated that the required and additional volumes of environmental flows to be secured for the deltas of the Amu Darya and Syr Darya and the Aral Sea for the vegetation and non-vegetation periods are as follows: for the Amu Darya 5.1 and 1.5 km^3 for the vegetation and non-vegetation periods, respectively, and for the Syr Darya 1.8 and 0.6 km^3, respectively (Sorokin et al. 2003).

There are certain benefit-sharing opportunities for the Aral Sea Basin States for using the available transboundary water and energy facilities in agreed and optimized regimes. This would require, according to the World Bank economic analysis, for the basin States to determine the optimal irrigation flow regime of the upstream storage reservoirs based on reliable hydrological data, the frequency of wet and dry years and related adjustments to the flow regime, the range of compensation for water storage services for different hydrological years (normal, dry and wet years); and distribution of the compensation into fixed and variable segments (World bank 2004).

Domestic reforms to enhance efficiency in both the water and energy sectors are part of the overall efforts to improve regional cooperation in transboundary water management. Since water shortages in the region are predominantly a management and incentive problem, not a resource problem, more balance is needed to bring incentive structures to address wasteful management of water resources. Since many of the consequences of wasteful water management are shared with neighboring countries, regionally concerted action by all countries would achieve maximum benefits for everyone. Through establishment of government subsidized pricing mechanisms, increased utilization of available groundwater and agricultural return flows, efficient irrigation and drainage management practices and institutional reforms to promote better governance at the field level, both the upstream and downstream states could collectively save annually 1.75 billion USD (UNDP 2005).

Tensions arising because of conflicts over water allocation are of particular relevance for the Aral Sea Basin case, as they are long-standing with implications of significantly straining broader relations between the basin states and impacting the political economy of the region. Interstate relations hinder regional integration processes and are the major causes for fragmentation of regional markets, major infrastructure projects, telecommunications, labor flows and financial systems. This fragmentation is compromising all of the basin states' economies by denying them the benefits of regional integration that are potentially extremely important (UNDP 2005).

In addition to benefits, or costs prevention, from improved transboundary water management, regional cooperation could generate important economic gains from the reduction in intraregional trade costs, better negotiated cotton prices in international trade forums, cost prevention from some of the risks that the region faces such as HIV/AIDS treatment and TB, and from collective actions to address natural disasters. On all of these issues, regional cooperation can help limit costs and increase benefits. This also holds true for many dimensions of regional cooperation that are not captured, including the benefits that stem from creating a better regional investment climate, developing the region's energy resources, better managing regional environmental risks, or cooperating in education and knowledge sharing (UNDP 2005).

9.6 Challenges Ahead

It appears that the countries of Central Asia are not, at this time, inclined to enter into long-term national commitments that might compromise their independence of action or make them dependent on another country. National sovereignty appears a major issue for all of the states of the Aral Sea Basin. Entering into long-term agreements with each other is viewed by some of the states as long-term dependence on another country, a condition at odds with complete independence of action. No new multilateral agreements on water have been signed in Central Asia since 1998 and none are under development. Major existing agreements such as the 1992 Almaty Agreement and the 1998 Syr Darya Framework Agreement are implemented poorly, largely due to the lack of coordination in national water policies.

International water conventions can provide guidance to the countries in facilitating cooperation. Looking ahead, especially when drafting and negotiating future agreements, factors of a natural character need to be given greater attention and value. For example, the implementation of the 1998 Syr Darya Framework Agreement has revealed that the agreement did not satisfy the requirements of upstream Kyrgyzstan and Tajikistan, where most of the flow of the Syr Darya River is formed, during the normal years of water availability in the basin. On the other hand, the implementation of the agreement during drought years runs against the interests of the downstream states of Uzbekistan and Kazakhstan whereas the overall agreement does not satisfy all of the parties during high water years. Thus, hydrographic, hydrological, climatic and weather conditions were not thoroughly examined and incorporated into the agreement, although they influence certain important characteristics of the Syr Darya River Basin. These factors determine the physical relation of the river to each state and need to be recognized and dealt with in negotiations, particularly if the intent is to enter into long-term and binding water sharing arrangements.

The geography of the Aral Sea Basin also includes the territory of Afghanistan, whose northern part contributes from 10 % to 23 % of the average flow of the Amu Darya River. Afghanistan currently withdraws annually about 1.5–2 km^3, which is only 15 % of its total contribution and it is not a party to any agreement so far but is rightfully entitled, under international water law, to claim increased water utilization of the tributaries of the Amu Darya flowing through its territory. However, that right under international water law should be exercised with due diligence and take into account the needs of the other watercourse states.

Factors of greater regional geopolitics need to be taken into account in determining what should be the equitable allocation of water resources. Transboundary water resources of the Aral Sea Basin cannot be viewed separately from water related energy resources, which together form a larger framework of an interdependent region and always should be considered in an integrated manner. If regional cooperation fails to address the issue of geopolitics and its impact on regional water management, then there may be increased speculation in the water agenda of the Aral Sea Basin and extra-regional economic leverages and political influences placed upon the countries not in favor of the region's sustainable water management and development.

9.7 Conclusions

National responses to existing cooperative opportunities in water management in Central Asia are essentially driven by a policy of national self-sufficiency in energy and water. Upstream countries aim for energy self-sufficiency and those downstream for self-sufficiency in irrigation. While it is reasonable to be concerned about national security and safeguarding national sovereignty, it is also critical to understand that a policy of self-sufficiency incurs substantial costs for all. As long as self-sufficiency dominates the policy agenda, the benefits of cooperation will not materialize.

International water law could provide a rational avenue toward achieving international consensus on both use and allocation of water resources in the basin, with international legal agreements to reinforce the consensus. The benefits from regional cooperation must be compared to the alternative of a continuation into the future of regional non-cooperation. This option implies continued tensions over water allocations, periodic scarcities of water for irrigation with attendant reductions in agricultural output, higher potentials for domestic unrest from shortages of both water and energy, and a continuing failure to address the region's environmental problems. With cooperation, the Aral Sea basin States will be in a better position to attract international capital investment for the large hydropower projects that will, in the long run, support the region's growth through low cost power sources. Cooperation also implies the eventual integration of the countries' economic systems on the basis of comparative advantage, both within the more narrowly defined Central Asian region as well as the wider region, including Afghanistan.

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Chapter 10
Time Series Analysis of Satellite Remote Sensing Data for Monitoring Vegetation and Landscape Dynamics of the Dried Sea Bottom Adjacent to the Lower Amu Darya Delta

Rainer A. Ressl and René R. Colditz

Abstract The Aral Sea region is a rapidly transforming landscape due to the continuous desiccation process. This study describes the vegetation and landscape dynamics in the lower Amu Darya Delta and adjacent parts of the dried sea bottom using MODIS (Moderate Resolution Imaging Spectroradiometer) surface reflectance data and EVI time series for the years 2001–2011. The potential of MODIS time series for monitoring landscape and vegetation dynamics of the dried sea bottom adjacent to the lower Amu Darya Delta was evaluated concerning data availability and spatial and temporal resolution. Two time series with different quality considerations were generated to subsequently characterize the yearly changes in the dried part of the sea bed, a simple layerstack (LS) of observations and quality-filtered and smoothed time series using a double logistic function (DL). The EVI (Enhanced Vegetation Index) values show a small dynamic inter- and intra-annual range. The majority of the EVI values fluctuate between -0.2 and $+0.1$, which indicates generally low vegetation dynamics in the desiccated areas. Looking at the inter-annual behavior of the LS/DL time series plots, the noise of the data and data fluctuations seem to become less for areas which have been dry for a longer period. A regional differentiation of the landscape dynamics between the Eastern and the Western basin of the southern Aral Sea could be observed. The observation points for the Western basin show a more stable behavior of the EVI values in comparison to the samples on the Eastern basin as seasonal or inter-annual flooding is less frequent. A typical pattern as a result of clear vegetation dynamics could not be observed in the EVI, LS and DL time series plots.

Keywords Aral Sea • Time series • EVI • MODIS • Desiccation • Landscape dynamics

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10.1 Introduction

Remote sensing time series have been widely used for land cover and land use monitoring at different regional scales. The Advanced Very High Resolution Radiometer (AVHRR) on board the TIROS-N and NOAA satellites has provided coarse spatial resolution data since 1981 at different levels of processing (Kidwell 1991; Tucker et al. 2005). Since the end of the millennium additional monitoring alternatives are available using data of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), the Système Pour l'Observation de la Terre – Vegetacion (SPOT VGT), Environmental Satellite's (ENVISAT) Advanced Along Track Scanning Radiometer (AATSR) and Medium Resolution Imaging Spectrometer (MERIS) instruments as well as the Moderate resolution Imaging Spectroradiometer (MODIS) on board the Terra (EOS-AM1) and Aqua (EOS- PM1). All systems have a spatial resolution of 1 km except for MERIS with 300 m and MODIS with bands of 250 and 500 m spatial resolution but more and better-calibrated bands than AVHRR. The high temporal resolutions of these imaging sensors have shown to be useful for describing the temporal dynamics of seasonal changes in vegetation and land use (Hansen et al. 2000; Ginzburg et al. 2010).

Thenkabail et al. (2005) showed the usefulness of temporally continuous MODIS data for land cover and land use classification in different river basins. Ressl et al. (1996, 1998) have demonstrated the applicability of multi-temporal AVHRR data to monitor and quantify the desiccation process of the Aral Sea and subsequently the use of these data for crop phenology monitoring and crop water consumption estimation. However, studies using this sensor were limited because of the coarse spatial resolution, 1.1 km for local area coverage and 4 km for global area coverage, and spectral resolution with only five bands. With the launch of the Aqua and Terra-MODIS satellites essential improvements have been made concerning the spatial and spectral resolution, the availability of the data and of derived products in comparison with the NOAA-AVHRR satellite generations. The instruments acquire each day since 2000 (Terra) and 2002 (Aqua) multiple images over the study area and therefore provide a favorable data source for multi-temporal studies and time series analysis. Their improved spatial resolution up to 250 m and 36 spectral bands allow for better product calibration and provide unique opportunities for regional to global studies. The MODIS data processing system operationally corrects for radiometric, geometric, and atmospheric issues and offers a large suite of value-added and modeled products (Justice et al. 2002). In addition, the facilitated access to data and to standardized products such as the Normalized Difference Vegetation Index (NDVI), the Enhanced Vegetation Index (EVI), Land Surface Temperature (LST) and Leaf Area Index (LAI), etc. enabled an enhanced monitoring of the desiccation process of the Aral Sea and associated changes and landscape dynamics in the surrounding newly-formed dry lands (Micklin 2004, 2007).

Landsat TM data with 30 m spatial resolution and seven bands may seem to be an interesting alternative but the small satellite swath width of only 180 km requires mosaicing of multiple passes and may result in only 2–3 cloud-free coverages per year. Newer satellite constellations providing multiple satellites in orbit, such as the Rapideye system (5 satellites) or the DMC multi-nation satellite constellation combine high spatial resolution with a much more enhanced temporal resolution. These constellations provide excellent optical data to monitor dynamic processes, but are commercial systems.

Detailed studies concerning vegetation and landscape dynamics as well as the botanical diversity of the deltaic plains in the lower Amu Darya River Delta were carried out by Ptichnikov (2002) and Novikova (1996a, 1997) on the basis of intensive field work but also using Landsat TM data to provide a synergistic view of the ecological situation.

More recent studies in the Amu Darya Delta include the landscape dynamics, ecosystem and crop monitoring studies of Loew et al. (2012) and Conrad et al. (2007). The former applied multi-temporal MODIS time series of the years 2000, 2004 and 2008 to monitor landscape dynamics for these time intervals and the latter to derive land cover and land use information and to quantify spatio-temporal water use patterns.

The main goal of this study is to investigate the usefulness of non-commercial satellite data time series to monitor general landscape dynamics of the recently dried seabed of the Aral Sea and adjacent areas in the lower Amu Darya Delta. In particular the worth of MODIS time series is evaluated and related to the following issues:

- Qualitative analysis of the inter-annual development of the annually dried seabed
- Qualitative analysis of the intra-annual landscape dynamics using MODIS EVI products
- Plant succession dynamics monitoring on newly dried seabed with respect to different time series length (years)
- Analysis of data availability of MODIS time series with respect to data quality

10.2 Study Area

The southern Aral Sea region was selected as the study area to evaluate the usefulness of MODIS satellite time series to monitor landscape dynamics and plant succession states. The desiccation process of the Aral Sea is most prominent in the lower Amu Darya Delta region adjacent to the southern extensions of the remaining water bodies of the large Aral Sea, which can be divided into the Western and Eastern basin. Every year large extents of the former water body are exposed as newly dry seabed. Numerous studies have documented this dynamic process through satellite data (Ressl 1996; Micklin 2007) but few studies have investigated the rate of plant succession and the general landscape dynamics on these very recent dried-up seabed areas. Studies on areas, that have fallen dry since the early 1960s when the desiccation process started, are manifold. Novikova (1996b) provides an extensive overview on landscape dynamics within these desiccated zones and on plant succession states and their associated ecology in the lower Amu Darya Delta.

The landscape of the dry seabed is very diverse and usually presents a complex mixture of sandy and saline soils. Plants actively colonize these slowly developing ecosystems, where the basis for the plant colonization primarily consists of flora of the Aral Sea terraces and the surrounding mainland of the Aral Sea. These highly salt-tolerant halophytes show different strategies towards the regulation of the high salt content of the solonchak soils.

The continuous process of the succession of the pioneer plants is an important factor for the stabilization of soils. Due to the vast newly dried seabed of the southern Aral Sea, every year large areas are exposed to the frequent strong winds and storms in the region. Thus, this salt desert, occasionally also referred to as the “Aralkum”, has become the main source for salt and dust storms in the last decades threatening the health of the population living in the Amu Darya Delta. The yearly estimates of the salt and dust load range from 40 to 150 million tons per year, resulting in a major highly negative impact on the fertility of important agricultural production sites (Glazovskiy 1990).

Reducing the desertification process and stabilizing the surface against wind erosion is not an easy task. The natural process of plant colonization through halophytes and xerophytes is slow and can last decades before becoming effective. Phytomelioration has been increasingly discussed as a means to fight and reduce desertification in the region. Widespread plantations of adapted desert vegetation, such as the white and black saxaul (Haloxylon aphyllum) are appraised as favorable to stabilize the desiccated seafloor. Studies on the natural process of plant succession on the former seabed show that in the first years after drying, exogenic factors such as geomorphological and edaphic processes are dominating the ecosystem and landscape dynamics (Breckle et al. 2012).

10.3 Data and Preprocessing

In this study we employed the vegetation index product (MOD13Q1) with 250 m spatial resolution and a compositing period of 16 days that is derived from Terra and Aqua satellite data (Huete et al. 2002; Solano et al. 2010). Data were downloaded for the period 2001–2011 from the Land Processes Distributed Active Archive Center (LP DAAC). Besides several ancillary layers such as quality, and angular information this product contains the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI). It should be noted that Terra and Aqua composites are generated in phased production, i.e., the first composite of Terra uses the best observation between January 1st and 16th and Aqua between January 9th and 24th. Higher-level products such as MOD13 are offered in the form of a global grid where the Aral Sea region is entirely located in tile h22v04. Data were transformed to the Transverse Mercator projection centered at 60°E and WGS84 datum using the

MODIS Reprojection Tool (MRT). For visual interpretation cloud-free daily surface reflectance composites at 250 m spatial resolution were obtained for each year for dates between mid-August and mid-September (Vermote et al. 2002; MOD09GQ).

10.4 Methods

10.4.1 Desiccation Range Definition

In order to apply MODIS data time series for the above-mentioned topics firstly the yearly size of the Eastern and Western basins of the Aral Sea (both water bodies together composing the large Aral Sea) had to be determined. In order to extract the maximum dried area for each year, the minimum water extents of the water bodies for each year were derived. The results are "desiccation fringes", which represent the extent of the maximum desiccation process between the 2 years. Time series data of the last 11 years (2001–2011) were evaluated.

To derive the yearly minimum water extensions, so called "land-water masks" were calculated on a yearly basis using cloud-free MODIS surface reflectance data for the months of August and September, which usually reflect the smallest water body size at the end of the summer season after the highest evaporation impact. In addition, MODIS EVI products were used, because the water body can be better distinguished due to the lower index values in comparison to land and vegetation. Clear water bodies can usually be defined easily by this approach but the transition zones between water and land are more difficult as a result of the mixed signal between land and water. This is especially problematic for the Eastern basin due to the very shallow characteristic of this water body with very small water depths. This problem is less present in the Western basin due to a much steeper bathymetry and therefore EVI threshold values could be defined more easily for the land-water discrimination. Thus, a mixed approach was applied for the extraction of the water body of the Eastern basin, where the transition zones were defined visually and afterwards digitized manually complementing the masks for the deeper water bodies.

Secondly, after the derivation of the yearly water masks, four representative ground points were visually selected along the shorelines of the Western and Eastern basin within each annual desiccation fringe. Subsequently, these points were characterized using MODIS data products and associated time series plots. In order to provide a minimum 3 year observation period for the dried seabed, 2008 was selected as the final year.

10.4.2 Time Series Generation

A time series is a temporally ordered sequence of observations, commonly sampled at discrete intervals (Chatfield 2004). In remote sensing there are three broad categories of time series generation approaches: stacking, filtering and quality analysis with interpolation (Colditz et al. 2008a). The simplest approach stacks a number of co-registered satellite images. Since the Earth surface is often obscured by clouds and other atmospheric constituents or images have missing data, a number of images are used to form a composite using rules such as the maximum value (Holben 1986; Roy 2000) and the observation closest to nadir (Huete et al. 2002). In fact, since the early 1980s maximum value compositing has been used for time series generation of NOAA-AVHRR data. Techniques needed to be developed for cross-calibration between AVHRR satellites (Tucker et al. 2005). Filtering aims at eliminating remaining clouds and smoothing the time series. Common approaches include Harmonic Analysis for Time Series (HANTS, Roerink et al. 2000), an iterative approach that compares the original to a smoothed time series obtained by Fourier transformation and eliminates observations lower than a user-defined threshold, and Timesat (Jönsson and Eklundh 2004) that smoothes time series by Savitzky-Golay filtering, and Asymmetric Gaussian and Double logistic functions.

More recent sensor data and processing chains to derive value-added products, e.g. for MODIS, provide additional detailed information on the quality of each observation. The Quality Assessment Science Data Set (QA-SDS) indicates for each pixel the information about cloudiness, general processing state and other product-specific limitations (Roy et al. 2002). The Time Series Generator (TiSeG) analyzes the QA-SDS for all land products and calculates data availability indices according to user-defined quality specifications (Colditz et al. 2008a). The user may choose from a number of generic temporal interpolation methods or flag pixels with low data quality.

Time series of NDVI and EVI were generated combining TiSeG (version 1.3, Colditz et al. 2008a) and Timesat (version 3.1 beta, Jönsson and Eklundh 2004). Eight-day time series (2003–2011) were produced assuming alternation between 16-day composites of Terra and Aqua. Although alternation is not necessarily given, the potential error only relates to time translation but not amplitude and only the latter is of importance in this study. Two time series of different quality were generated: a simple stack of observations without data quality analysis and filtering (in the following denoted as layerstack, LS) and a filtered time series excluding pixels obscured by clouds or shadow with TiSeG and smoothed by a double logistic function in Timesat (in the following abbreviated with DL). Timesat was used with the following parameters: (1) median filter spike method with value 2, (2) forcing to one season, and (3) three iterations for upper envelope fitting with adaption strength 2. LS and DL time series for the years 2001 and 2002, when only Terra data were available, were produced apart from the combined Terra/Aqua time series. The resulting 16-day composite time series was linearly interpolated to match the 8-day intervals to simplify further analysis.

10.5 Results and Discussion

10.5.1 Data Quality and Availability for Time Series Generation

Several studies have highlighted the use of MODIS quality information (Roy et al. 2002; Neteler 2005; Lunetta et al. 2006; Gao et al. 2008). Colditz et al. (2008a) compared various quality specifications and concluded that a strict quality (excluding many observations) may not be able to retain general time series characteristics due to an insufficient number of valid observations for temporal interpolation. A comparison between MODIS data versions (collections) concluded that using the current MODIS collection together with the pixel-level data quality information yields better and temporally more stable time series than the previous data collection (Colditz et al. 2008b). More automated time series generation techniques using MODIS quality information have been recently proposed for the vegetation index (VI, Colditz et al. 2011) and leaf area index (LAI, Gao et al. 2008; Yuan et al. 2011).

However, the applied quality specifications for the DL time series excluding only clouds and shadow are lenient in comparison to many other studies using MODIS vegetation index data. Colditz et al. (2008a) recommended that at least clouds, snow/ice and shadow should be excluded for time series over central Europe. Other studies are based on the usefulness index (UI, Lunetta et al. 2006; Colditz et al. 2006, 2011), a score that is derived from more detailed quality and angular information (Solano et al. 2010). Clouds (3) and shadow (2) combine a score of 5, equal to UI Intermediate or below (in case there are further quality issues), that is considered lenient (Colditz et al. 2008a) and only meaningful for areas with substantial quality issues such as tropical Africa (Colditz et al. 2006). Lunetta et al. (2006), for instance suggest using only observations of UI acceptable (maximum score 3) for the eastern United States. Although the study site is located in a dry region with mostly cloud-free observations throughout the summer months and comparatively little cloudiness during winter, there are substantial quality issues that are related to the spectral thresholds to define low data quality. Even though substantially improved, e.g. by a new backup algorithm for the EVI over high reflectance surfaces in the most recent data collection (Didan and Huete 2006; Colditz et al. 2008b; Solano et al. 2010), the algorithms still flag very flat specular surfaces, in particular if there is a salt crust that is often misinterpreted as snow and ice. Specular surfaces reflect radiation like a mirror if incoming and outgoing angles are similar. Water surfaces, on the other hand may be confused with shadow, if located close to a detected cloud.

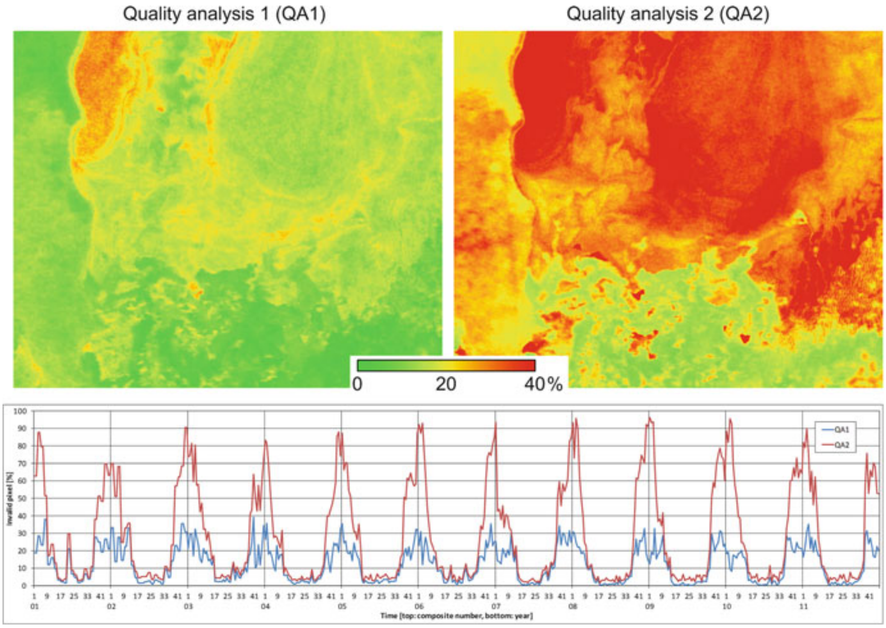

Fig. 10.1 Number of invalid pixels in space and time for two quality specifications (Note: QA1 excludes pixels that were identified as cloud and shadow. In addition QA2 excludes pixels flagged as snow/ice and with a usefulness index below fair (score 4))

Figure 10.1 depicts the proportion of invalid pixels spatially and temporally and compares two quality specifications: quality analysis QA1 excludes clouds and shadow and was used to generate the DL time series and QA2 excludes in addition a UI below fair (score 4) and pixels detected as snow and ice and thus is a typical setting for mid-latitudinal regions (Colditz et al. 2008a; Lunetta et al. 2006). Spatially, the comparison shows a much wider distribution of invalid pixels for QA2, in particular over water surfaces but also for desiccated areas of the Eastern basin and the developing Aralkum desert. The Amu Darya Delta region in the southern portion to the former coastline of the year 1960 shows relatively few invalid pixels also for the QA2 setting. The temporal plot illustrates that less data are available during the winter months (composite 37 to 11, corresponds to the end of October until the end of March). That coincides with the period of increased cloud cover. Setting QA2 more strictly shows higher proportions of invalid pixels during wintertime, also flagging existing ice on the Aral Sea as well as thin snow cover on the land. Still, the area proportion and length, especially for potential snow on the land, is clearly exaggerated.

An issue in time series generation is the length of the data gap to be interpolated (Colditz et al. 2008a, 2011). Although the period of invalid data between QA1 and QA2 seems similarly long, the temporal gap for QA1 is shorter for many pixels because short peaks up to 35 % invalid data soon drop below the 20 % threshold in wintertime. This pattern is even better illustrated by the maximum gap statistic that measures the longest consecutive gap of data and therefore is a useful measure for the capability to interpolate data temporally. For time series filtered with QA1, 80 % of the data can be processed with a maximum gap of 6 composites (48 days). Similar measures for QA2 yield a maximum gap of 19 (152 days), that is the entire winter period as described above. The longest gaps are located in the inundating and desiccating areas of the Eastern and Western basin and the adjacent Aralkum desert and less in the permanent water bodies.

10.5.2 Regional Landscape Dynamics as a Consequence of Desiccation

Figure 10.2 illustrates the water body dynamics within the observed period 2001–2011. The colored lines represent the minimum extent of the water bodies during each year within the observation period. Clearly the general retreat of both water bodies can be observed as a consequence of the desiccation process. This trend is most obvious in the Eastern basin of the southern Aral Sea but is also observed along the eastern shoreline of the Western basin. Up to the year 2009 a general decline of the water surface can be documented. Seasonal water surface fluctuations can be significant and therefore the yearly documented desiccation refers to the maximum area between the minimum water extent of that year and the year before. The ranges of the desiccation fringe show a great variance, which is basically a function of micro-topography/bathymetry and available water inflow as potential evaporation does not change significantly over the years. Water availability is mainly determined by groundwater inflow (fairly constant), precipitation and surface runoff. The latter shows the largest intra-annual fluctuations, as principally affected by Amu Darya discharge, irrigation drainage water return flows from agricultural fields and water received by outflow from the North Aral Sea.

The dynamic of the desiccation process is generally high although less prominent in certain years such as the years 2002/2003 and 2003/2004. Nevertheless intra-annual changes in water body extent may be substantial as mentioned before and the yearly desiccation fringe may not be the result of a linear process but can also be affected by temporary flooding. The areas of the southern-most extension of the Eastern basin seem to show the highest landscape dynamics with respect to alternation of flooding and drying. The already dried seabed of the years prior to 2001 and 2002 were substantially flooded during the years 2003, 2004, 2005 and even 2010. The large flooding extensions of varying magnitude towards the south might also be the result of the changing topography and anthropogenic activities besides the yearly differences in hydrology. These flood events on the already dried seabed of different temporal length have consequences on the plant colonization process in these areas and on the growth dynamics of the sparse vegetation in general.

In the year 2009 for the first time a nearly complete temporary drying up of the Eastern basin water body was observed. On the other hand, in the following year of

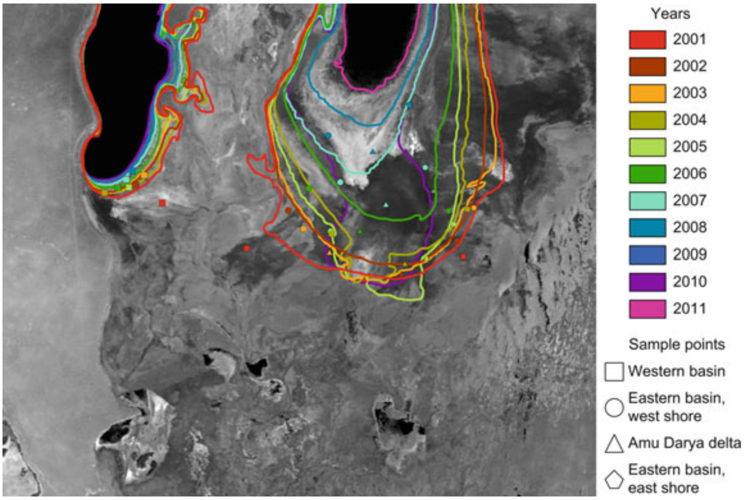

Fig. 10.2 Study area of southern Aral Sea with Western and Eastern basin (Note: The lines indicate the minimum water surface area derived from MODIS surface reflectance images between mid August and mid September for the respective years (*color*). The sample locations are indicated for each year (*color*) and site (*shape*). The image in the background shows the near infrared surface reflectance of September 15th 2011)

2010 the same water body of the Aral Sea showed a dramatic increase in surface size, resulting in a non-permanent flooding of large areas of seabed that dried up in earlier years. This year (2010) seems to show a rupture of the general desiccation trend. The Western basin in 2010, nevertheless, shows the smallest surface extent for the observation period, which was even less than the following year of 2011. It may be reasonable to conclude that this effect of the opposite desiccation dynamics of the two water bodies is caused by an exceptional discharge of the Amu Darya to the Eastern basin as a consequence of high precipitation during the winter month resulting in a strongly fluctuating hydrology (Breckle and Wucherer 2011).

To characterize these inter- and intra-annual changes concerning temporary flooding and potential vegetation dynamics, temporal profiles of the time series data of four annually selected observation points were analyzed. Figure 10.1 shows the distribution of these points within each desiccation fringe with the respective color of the shoreline of each individual year (minimum water extent).

10.5.3 *Vegetation Index and Time Series for Landscape Dynamics*

A vegetation index is a ratio between two or more spectral bands. In remote sensing the visual red and the near infrared bands are used to enhance vegetation patterns because of their high contrast with absorption due to plant pigments (chlorophyll a) in the visual red band but reflection in the near infrared (Jensen 2007). A vegetation index such as the widely used Normalized Difference Vegetation Index (NDVI) is calculated by dividing the difference between the near infrared and the red band by the sum of both bands (Tucker 1979). The enhanced vegetation index also includes the blue band and soil correction factors to compensate for atmospheric disturbances and soil background (Huete et al. 2002). Normalization ensures that the index ranges between -1 and 1. In practice NDVI and the more recently developed EVI range between -0.2 and values close to 1. A negative vegetation index value can be observed over deep water with low sediment content and no aquatic vegetation. Bare soil shows slightly positive vegetation index values (0–0.1). Vegetation index values increase with increasing density of green, photosynthetically-active, healthy vegetation. Very high vegetation index values (0.8–1) may be measured over tropical regions, and in particular the NDVI begins to saturate.

Thus vegetation indices have a non-linear relationship to biophysical variables such as the Leaf Area Index or LAI (Myneni et al. 1997) and biomass (van der Meer et al. 2000). This saturation for high-biomass and very dense vegetation is compensated in the EVI that may show highest values of 0.7–0.8 but still with a non-linear relationship to biophysical variables. Besides, the EVI has been significantly improved in the most recent MODIS data collection. For surfaces such as snow and ice but also salt crusts, there is a high reflectance in the blue band that causes atmospheric over-correction (Didan and Huete 2006). Instead of using the Soil Adjusted Vegetation Index (SAVI) as in previous collections, MODIS collection 5 data employ a 2-band EVI (excluding the blue band), also known as EVI2 (Jiang et al. 2008). This was the main reason for presenting plots of the EVI instead of the NDVI in this study. However, plots of the NDVI show very similar ranges and only a few differences in the temporal course over the years.

The EVI DL and LS time series data plots were analyzed to illustrate the usefulness of MODIS time series to describe dynamic processes in the desiccated areas. The main interest was to investigate if the rather small vegetation dynamics on the newly dried seabed can be detected by the spectral sensitivity of the sensor. The assumption was that early plant succession on the newly desiccated areas might increase EVI values slightly over the years, which should be reflected in the time series. The natural process of plant colonization through halophytes and xerophytes is slow and our interest was to examine if an 11 year observation period would be sufficient to pick up any plant colonization trends over the entire period and if any intra-annual changes could be observed. The high temporal resolution of the MODIS sensor was expected to compensate to some degree for the lower spatial resolution in comparison to other imaging sensors. On the other hand, it could be hypothesized that the sparse vegetation would only result in small inter-annual changes in the EVI values and therefore in limited LS and DL time series value ranges. Additionally it could be supposed that the time series might eventually be noisy, as the landscape dynamics is rather high, especially along the Eastern basin due to the high inter annual fluctuations of the water extent between summer and winter months. As described above, eventually this results in temporary flooding of the already dried seabed, which alters the EVI signal. It could be expected that the selected observation points along the shorelines within each yearly desiccation fringe could be affected by these inter annual changes, thus reflecting an associated yearly landscape dynamic.

10.5.4 General Description of Time Series and Trends

The graphs in Figs. 10.3 and 10.4 depict the EVI time series over 11 years of analysis (2001–2011). Each plot shows four samples (observation points) that dried in that year in comparison to the year before (for their spatial location see Fig. 10.1), except for the samples of 2001 that may have been dry for several years. For each year the samples were carefully selected at the southeastern shore of the Western basin (squares in Fig. 10.1, blue line in Figs. 10.3 and 10.4), the western shore of the Eastern basin (circles, red line), the Amu Darya Delta (triangles, green line), and the eastern shore of the Eastern basin (pentagons, orange line). The red bar at the bottom of each graph indicates the period of seabed drying for samples of that year, i.e. EVI, 2003 in Figs. 10.3 and 10.4 show the plots of samples that fell dry between 2002 and 2003 (minimum water extents in Fig. 10.2), thus the bar begins in 2003. Samples may inundate again in following years (not indicated by the red bars), as described before. Figure 10.3 presents the layerstack (LS) compared to Fig. 10.4 that shows the quality-filtered and smoothed double logistic time series (DL).

Before analyzing the plotted time series of Figs. 10.3 and 10.4, one should consider the very small dynamic range of the vegetation index (EVI) that, with a few exceptions, only varies between −0.2 and 0.1. Effectively, that describes the difference between water surfaces and barren land and thus highlights the landscape dynamics between advancing and retreating sea levels on an intra- and inter-annual temporal scale. Only one profile in 2001, sampled in the Amu Darya Delta, increased well above 0.2 (in DL up to 0.35 for the end of 2005 and with plateaus of 0.25 for the end of 2007 and 2008), that could be interpreted as a typical vegetation signal.

In comparison to the smooth curves of the DL time series the LS EVI plots show much noisier patterns with frequent positive and negative peaks with an EVI around 0. However, in relation to the potential range of the EVI (for MODIS the valid range is between −0.2 and 1) the variability is still small. On the contrary, some features that are visible in the LS disappear in the DL time series, e.g., some decreases of the EVI below 0 for the plot of EVI samples of 2006, 2007 and 2008 and in particular for the end of the year such as for samples of 2002 and the transition between 2003 and 2004. In the DL time series data were filtered for low quality, which mainly occurs during wintertime (see plot in Fig. 10.1). Applying low weights to those composites for a longer data gap paired with the strong smoothing characteristic of the double logistic function causes the DL plot to remain constant, although in reality the pixel should represent water as indicated by a slightly negative EVI. Potentially a more local smoothing function, e.g., a local box-car filter could have

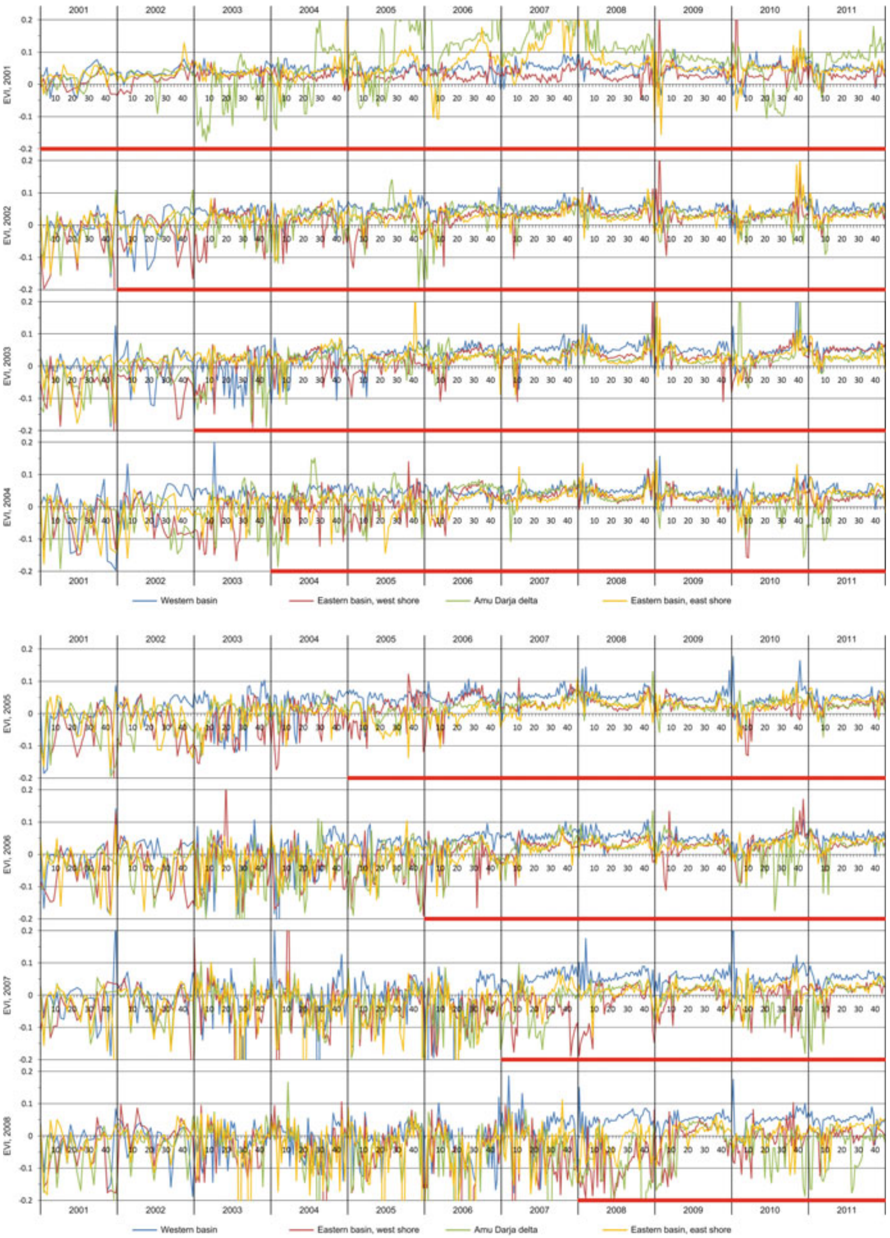

Fig. 10.3 Layerstack (*LS*) of EVI for samples collected in desiccation fringes of each year (see Fig. 10.2)

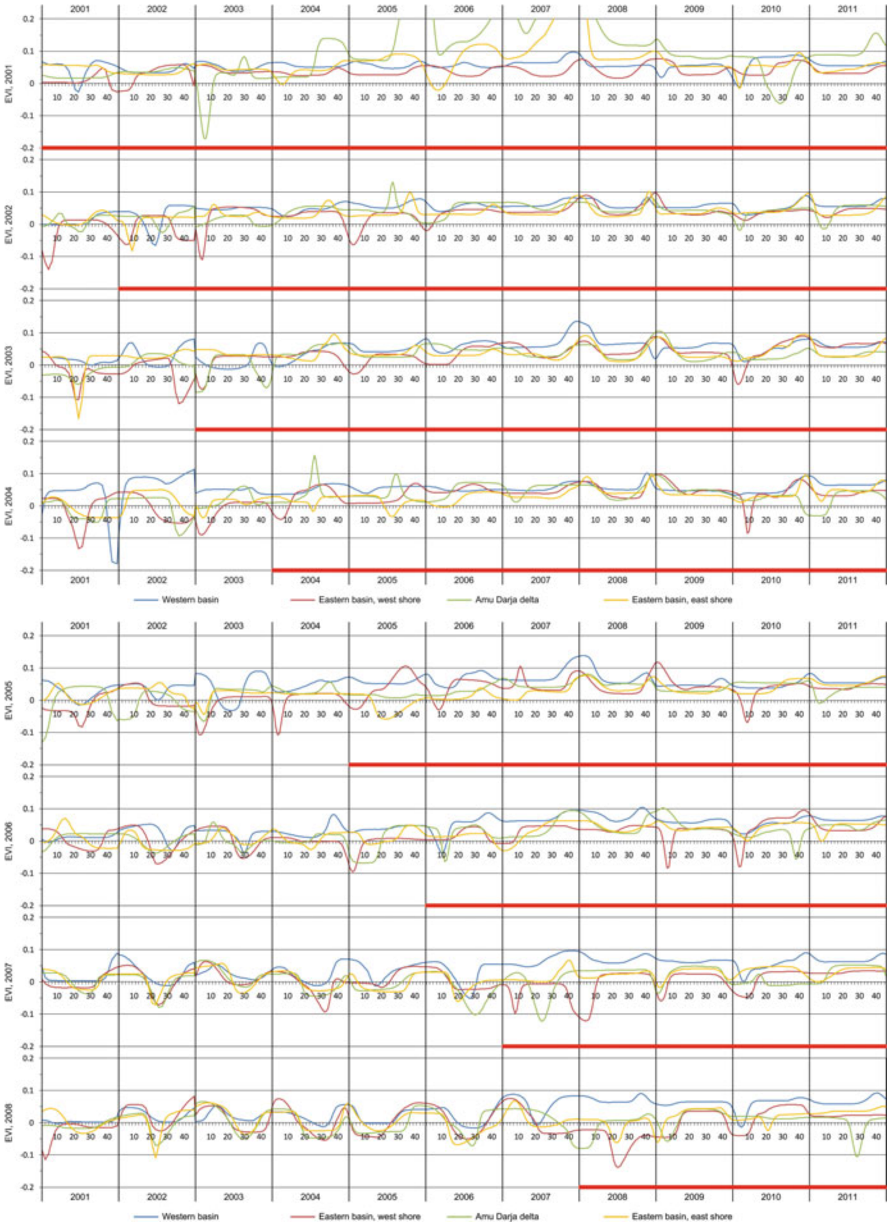

Fig. 10.4 Double logistic (*DL*) time series of EVI for samples collected in desiccation fringes of each year (see Fig. 10.2)

resolved this issue, but initial tests using a localized Savitzky-Golay filter of Timesat (Jönsson and Eklundh 2004) did not show satisfying results. In many other cases the DL function decreases for a short period, depending on available vertexes for modeling during that period. Therefore the result of DL time series depends on the local temporal data availability by quality-filtered data and the generalization that was applied by a smoothing algorithm. Thus, the LS and DL time series have to be used together for the interpretation of landscape dynamics and desiccation patterns in the Aral Sea region.

A second feature is the displacement of EVI profiles between the end of 2002 and the beginning of 2003 for the DL time series. It should be noted that 2001 and 2002, when only Terra data were available, was processed apart from the period 2003 to 2011 with combined Terra/Aqua data. Although the year at the beginning and end of the time series were doubled to improve the stability at the temporal extremes of the time series (Jönsson and Eklundh 2004), also known as shouldering (Colditz et al. 2008a), fewer available data and a lack of overlap with the next actual year caused differences in curve fitting of the more global double logistic fitting function. However, the discontinuity in the time series is small and in most cases much less than 0.05.

A generalized analysis of plots over all years indicates a slightly positive slope. In fact, not a single slope showed a negative sign, albeit the increase is small. For instance the DL time series of the Western basin for the sample of 2007 shows a slope of 0.000121. The comparison of slopes between LS and DL time series shows almost constantly higher slopes for LS. This pattern is not surprising because many spikes were removed in the DL time series that generally were negative for the years 2001–2005 and became more positive for the period 2006–2011. Still, this pattern of declines for the earlier years and peaks for the later years during the winter period is notable in all time series. For instance the EVI samples of 2004 depict drops in the DL and a generally noisy pattern in LS time series for the period 2001–2004. The years 2005–2007 show less clear patterns in the DL but the LS also depicts a decreasing annual variability with a general tendency for increasing EVI values. For 2007 onwards most curves show more positive values during winter than for the rest of the year in DL and also in the LS time series (the exception is the west shore of the Eastern basin in 2010). The explanation of this pattern could be the permanent or frequent inundations of the sample points during the high water extents in the winter period, which causes the drop of EVI values (period 2001–2004). Although the sample became dry in 2004 in the minimum sea level mask, it may have inundated due to seasonal variations in 2005 and 2006 for shorter periods that were hardly detected by the DL time series but can still be noted by decreasing noise in the LS. With a longer distance from varying water levels the EVI shows a more steady soil signal (EVI between 0 and 0.1).

10.5.5 Particular Features in the Time Series

Despite the generally low dynamic range of the DL and LS time series several interesting features in the individual time plots can be observed. As already mentioned above there was an unusual flooding of the Eastern basin of the Aral

Sea in 2010 resulting in a large extension of the water body southward toward the Amu Darya Delta. This flooding mostly affected the central part of the Eastern basin and to a lesser degree the eastern and western shores and even reached the southern extent of the desiccation fringe of 2001. This effect can be seen in the EVI 2001 LS and DL time series plot within the portion for 2010. Clearly a steep decline of the EVI between the composites 17 and 41 (equivalent to the period between early May and mid November) of the year 2010 can be observed. In 2011 the EVI reaches rapidly positive values again throughout the year, which indicates the retreat of the exceptional flooding of the year 2010. The observation points of the years 2002, 2003, 2004 and 2005 appear to be less affected, some actually never reach negative EVI values, which seems to be consistent with their location as almost all points were only disturbed slightly during the maximum size increase of the water body or are located in the margins of the flooding zones. The observation points of the years of 2006, 2007 and 2008 nevertheless have been heavily affected by the flooding, which is also clearly reflected in the LS time series plot by a significant decline of the EVI values of these years in the summer month of 2010. Similar plot behavior can be observed at the observation points on the west shore of the Eastern basin, where the EVI drops to negative values in the years 2004, 2005, 2007 and 2008, but with a notable shift towards the beginning of the year. This may be explained by a larger flood extension towards the western part of the basin during the winter months.

The observation points collected at the Western basin show a different pattern in most plots. With the exception of samples from 2003, the samples hardly ever drop to values below 0 and show a steady curve with comparatively little variation also in the LS. The reason is the steeper gradient in topography in comparison to the Eastern basin. Once the samples became dry they are unlikely to inundate once again because of the steadily decreasing water level. The higher gradient of the shoreline makes it also less likely that seasonal water level changes can periodically or episodically flood samples taken at a higher level.

Looking at the intra-annual yearly dynamic of the DL time series, no significant peaks can be determined which could be related to the phenological activity of the sparse halophytic and xerophytic vegetation. Most likely is that early plant colonization during the observation period is not sufficiently dense to alter the EVI in a substantial way towards positive values. In other words, the MODIS signal in the desiccation fringes seems to be consistently dominated by the dry and sandy soils and salt crusts, which does not seem to change in a meaningful way even over the entire 11-year observation period. Even though plant colonization may progress over this time period, the MODIS signal appears not to pick up any associated changes concerning vegetation density or phenology.

Small changes towards the end of each year during the winter months may be observed in the EVI DL time series plots, but is less obvious in the observation points in the Amu Darya Delta. These small "peaks" at the end of the year seem to be surprising and cannot logically be related to a higher vegetation activity during these months.

10.6 Conclusions

MODIS time series data were analyzed for the Aral Sea and adjacent Amu Darya Delta for the years 2001–2011. The main interest was to evaluate the usefulness of MODIS surface reflectance data as well as 16-day EVI composites (linearly interpolated to 8-day intervals using phased Terra/Aqua production) for documenting the desiccation process in the Eastern and Western basin of the southern Aral Sea and potential vegetation dynamics. For each dried fringe four observation points were selected to describe the general desiccation trend as well as associated landscape and vegetation dynamics.

MODIS time series data have proven to be an excellent information source for analyzing the yearly desiccation process and for the discrimination of yearly newly dried seabed. As the water bodies of the southern Aral Sea show large inter- and intra-annual fluctuations, multi-temporal satellite data and products with a high temporal resolution are needed to quantify these dynamic processes. Through the combination of Terra/Aqua MODIS data, sufficient time series information can be provided to describe the water and landscape dynamics, although data has to be filtered and selected concerning quality. Very lenient quality parameters were chosen that only excluded clouds and shadows due to particular conditions on and around the Aral Sea with ice on the water, episodic snow cover during wintertime and salt flats that are spectrally similar to ice and snow and thus erroneously flagged by automated MODIS quality assessment algorithms. Otherwise, commonly used moderate quality specifications that also exclude snow and ice would have yielded unsatisfying results with respect to the potential to temporally interpolate data gaps.

The resulting EVI time series were subsequently analyzed using DL and LS plots. The DL time series provide smoother trends in comparison to the LS time series, which facilitates interpretation of the data series but may not provide the same detail as the LS time series, which on the other hand are significantly noisier. The general desiccation trend can be interpreted in both time series types. Overall, this landscape dynamic is reflected more clearly at the observation points in the desiccation fringes of the Western basin in comparison to the Eastern basin. This is due to the fact that inter- and intra-annual water body fluctuations are less frequent in the Western basin. More interestingly, particular events such as the prominent flooding of the year 2010 could be identified quite well in the time series plots including the impact of this flood on various observation points of the different years.

MODIS time series data nevertheless showed very limited use to describe vegetation dynamics on the newly desiccated areas over the 11-year observation period. Although a consistent and slightly positive trend of the EVI values was found, this tendency is not obvious enough to relate it to plant colonization activities. In addition no typical intra-annual plant phenology activity could be identified from the time series plots. This may be due to the fact that plant colonization is too slow and scarce within the observation period. Furthermore, the high inter- and intra-annual dynamics of the water bodies, in particular of the Eastern basin of the Aral Sea, complicates plant colonization and growth, as pioneer species need to withstand repeated partial flooding by highly salinized water in addition to surviving the other harsh environmental conditions.

Finally, the MODIS sensor is not sufficiently sensitive to pick up small changes caused by the sparse vegetation as bare soil and sands dominate the signal. Longer observation periods may result in better outcomes as the vegetation density may increase with time. In order to compensate for this limitation, time series of satellite data with higher spatial resolution need to be applied to identify small regional changes and dynamics such as early plant colonization on the desiccation fringes.

Future studies with recently launched and upcoming satellite missions such as Rapideye, DMC, Sentinel-2 (ESA, launch 2014), Landsat-8 (launch 2013) will include the analysis of higher spatial resolution satellite data, to examine if partial plant colonization can be detected within the desiccation fringes of newly dried seabed. These systems will overcome limitations in spatial resolution of MODIS and will enhance the monitoring of landscape dynamics in general and plant succession dynamics in particular within the Amu Darya Delta and the Aral Sea region.

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Chapter 11
Aral Sea Hydrology from Satellite Remote Sensing

Jean-François Crétaux and Muriel Bergé-Nguyen

Abstract Space technologies have been widely used over the last 10 years for water surface monitoring worldwide and they have shown their capability to monitor components of the water cycle and water balance at regional scales and on time scales ranging from months to decades. We present here the applications of space data from radar altimetry and satellite imagery (Terra/MODIS) over the Aral Sea Basin (ASB). Radar altimetry, which has been designed to study the ocean, has opened a new era in monitoring lakes, rivers and reservoirs. The recent missions of satellite altimetry (Topex-Poseidon, Jason-1/2, Envisat, ERS-1 and ERS-2) have made it possible to measure with great precision inland sea level variations that can be used to determine water mass balances. Radar altimetry, coupled with complementary in situ data, has allowed quantifying precisely the water balance of the Aral Sea since 1992 as well as balances for large reservoir systems along the Syr Darya, in particular Chardarya and Toktogul, and for Lake Aydarkul. This approach has also made it possible to ascertain the water balances of lakes and wetlands in the deltas of the Syr Darya and Amu Darya.

Satellite imagery, from low to high resolution (1 km to a few meters) offers a useful tool to monitor surface water area for lakes and floodplains. MODIS data for example provide every 8 days, the surface water area from 2000 to 2012, with a spatial resolution of 500 m. It has been used to create a spatial time series for the Aral Sea and the lakes and wetlands in the deltas of the Amu Darya and Syr Darya where water area has been precisely measured. Along with in situ observations and hydrological modelling, space observations have the potential to improve significantly our understanding of hydrological processes at work in large river basins, (including lakes, reservoirs and floodplains) and their influence on climate variability and socio-economic life. Unprecedented information can be expected coupling models and surface observations with data from space, which offer global geographical coverage, good spatial-temporal sampling, continuous monitoring

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over time, and the capability of measuring water mass change occurring at or below the surface. Based on these different techniques we have determined the surface area of water features within the Aral Sea Basin, as well as volume variations, which are the key parameters to the understanding of the hydrological regime in ungauged basins. A focus on the Aral Sea and the water bodies in the deltas of the Syr Darya and the Amu Darya rivers over the last 20 years from satellite data is presented in this chapter, with some implications for the water balance. We will also describe the specific behaviour of the Western and Eastern basins of the Large (South) Aral Sea over the last 5–6 years

Keywords Radar altimetry • Satellite imagery • Water balance

11.1 Introduction

The satellite altimetry technique was developed in the early 1970s with the launch of Seasat (1978). The measuring of water levels using satellite altimetry has been designed and optimized for open oceans' studies (Fu and Cazenave 2001). Nevertheless, over the past 15 years, numerous studies have been published on continental hydrology utilizing satellite altimetry for global analysis (Birkett 1995; Crétaux and Birkett 2006; Calmant et al. 2008; Crétaux et al. 2011a, b) or in more specific lake or river basin case studies (Cazenave et al. 1997; Mercier et al. 2002; Frappart et al. 2005a; Birkett 2000; Coe and Birkett 2005; Aladin et al. 2005; Crétaux et al. 2005a, b; Swenson and Wahr 2009; Kouraev et al. 2009; Ginzburg et al. 2009; Kouraev et al. 2009, 2011; Lee et al. 2011; Zhang et al. 2011a; Abarca et al. 2012). When focusing on lakes, these studies have shown that radar altimetry is a very useful technique for different applications: hydrological water balance (Cazenave et al. 1997; Crétaux et al. 2005a; Swenson and Wahr 2009), prediction of lake level variations (Coe and Birkett 2005), studies of anthropogenic impact on lakes water storage (Aladin et al. 2005), correlation of inter annual fluctuations of lake levels on a regional scale with ocean–atmosphere interaction (Mercier et al. 2002; Becker et al. 2010). Thanks to these many studies, the altimetry technique has clearly shown its capability to monitor components of the water balance of lakes on time scales ranging from months to decades.

Radar altimetry has been used to monitor water level variations over the Central Asian lakes and reservoirs (Aral Sea, Sarykamysh, Chardarya, Aydarkul, Toktogul, Balkhash, and Issyk-Kul) (Peneva et al. 2004; Aladin et al. 2005; Crétaux et al. 2005a, b, 2009a, 2011a, b; Crétaux and Birkett 2006; Kouraev et al. 2009; Ginzburg et al. 2010). This is particularly valuable when in-situ data are not available (Aral Sea since the beginning of the twenty-first century, Lake Sarykamysh and some reservoirs along the Syr Darya and Amu Darya, and lakes and wetlands in the deltas). When in situ ground measurements are available this also allows assessing the quality of the altimetry measurements as done with Lake

Issyk-Kul, with observational accuracy observed of about 3–4 cm (Crétaux et al. 2009b, 2011a). It is therefore evident that altimetry provides a source of important independent information complementary to that produced by the ground-based networks and perhaps more critically, can provide hydrological information where gauges are lacking. In this respect it provides an additional tool for decision-makers in the field of water management of the ASB.

Satellite imagery is another remote sensing tool, which can be very useful for survey of continental water bodies. For example Liu et al. (2009) have studied Lake Namco (Tibetan Plateau) surface area variations from 1970 to 2005 from analysis of Landsat imagery to understand the long-term response of the lake system to climate change. Ye et al. (2007) have studied some lake basins in southern Tibet and have investigated the linkage between lake surface variations and glacier retreat in the Himalayas. Many other studies have been conducted in recent years over the Tibetan plateau using satellite images to quantify the linkage between lakes and climate (Huang et al. 2011; Zhang et al. 2011b).

Satellite images from the Moderate Resolution Imaging Spectral radiometer (MODIS) instrument is also well suited for monitoring the surface area of large lakes with high spatial variations at medium resolution of 250–500 m. It has been used, for example, in Abarca del Rio et al. (2012) to study the hydrological linkage between Lake Titicaca and Lake Poopo in the South American Altiplano. Peng et al. (2005) have used the MODIS data to develop a method of surface area extent and level monitoring, which, however, depends on knowledge of topographic maps of the area under study or on a relation between surface area and water level. They applied their method to Lake Dongting, which regulates flooding along the Yangtze River in China. The Meris instrument onboard the Envisat satellite has also been widely used to monitor lake surface changes as done in Yesou et al. (2011). Synthetic Aperture Radar (SAR) Interferometry (Alsdorf and Lettenmaier 2003; Alsdorf et al. 2007) and passive and active microwave observations (e.g., Prigent et al. 2001) also offer important information on land surface waters, such as the changing area of large wetlands.

In synergy with radar altimetry, satellite imagery is therefore a pertinent system to estimate water storage variability for different lakes (Crétaux et al. 2011a). In Crétaux et al. (2009a), MODIS images have also been used to estimate water surface variations of the Aral Sea. Section 11.2 describes the basics of the remote sensing techniques (radar altimetry and satellite imagery) while in Sect. 11.3 the main results obtained over the Aral Sea Basin from Remote Sensing data are presented. It focuses mainly on the Aral Sea (Large and Small) but also deals with artificial reservoirs in the deltas of the Syr Darya and Amu Darya (see Fig. 11.1), that could indeed, be monitored from the combination of radar altimetry and satellite imagery, allowing the calculation of their water volume variations. Section 11.4 is dedicated to the description of the water balance of the Aral Sea and the new information inferred from current satellite data.

Indeed, together with a precise digital bathymetry map (DBM) of the Aral Sea Basin, and some hydrometeorological information, the Remote Sensing data can be used to calculate the water balance of the Aral Sea (Crétaux et al. 2005a, 2009a).

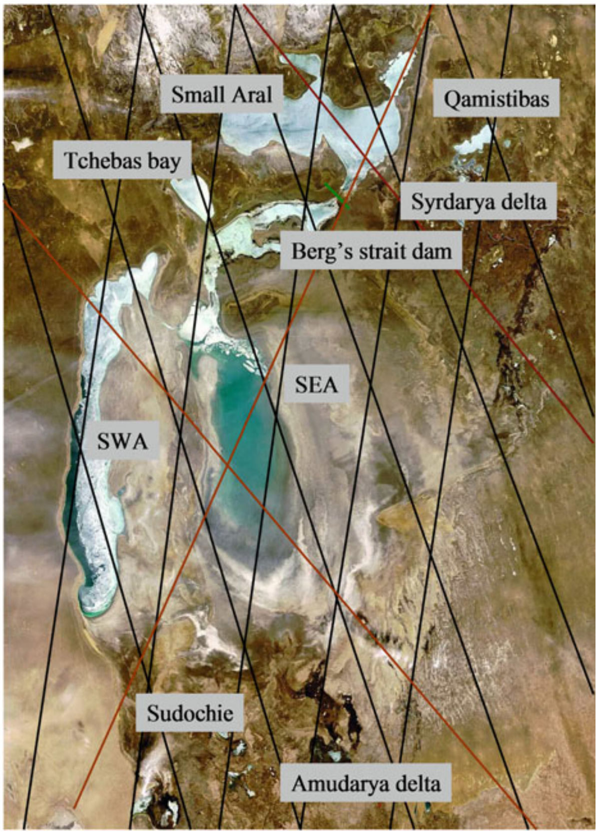

Fig. 11.1 Map of the Aral Sea with satellite altimetry mission tracks shown: T/P, Jason-1, Jason-2 (*red line*) and Envisat (*black lines*). The water bodies in the deltas of the Syr Darya and Amu Darya are shown

It could, for example, give answers to the questions of the existence and quantity of underground water inflow to the Aral Sea, which has been under debate among several researchers for the last 30 years (Sydykov and Dzhakelov 1985; Glazovsky 1990; Benduhn and Renard 2003; Jarsjö and Destouni 2004; Crétaux et al. 2005; Alexseeva et al. 2009; Oberhänsli et al. 2009). In this chapter an attempt to compute again the Aral Sea water balance from the data over the last 10 years [2002–2012] has been done.

For the next decade the space agencies around the world have programmed several new missions that would improve our knowledge of global hydrology, and at least will allow continuing the existing mission. We make a short review of those new missions and their potential implication for Central Asia, with a focus on the SWOT (NASA-CNES) mission based on a new concept of interferometry for hydrology.

Section 11.5 will describe some new missions that will allow continuing the survey of the Aral Sea in particular and continental water bodies worldwide in general.

11.2 Remote Sensing Techniques

11.2.1 Radar Altimetry

The classical radar altimetry measurements that mainly consist of waveform (e.g., raw radar altimetry echoes reflected from the land surface) are much more complex over land surfaces than over the oceans, and multi-peaked due to interfering reflections from water, the vegetation canopy, sand and or inhibited by rapidly varying topography (Frappart et al. 2006). These effects result in data having decreased validity, compared to those collected over oceans.

Radar altimetry is a profiling technique, which does not allow a global view of the Earth surface, hence limits worldwide surveying as well as spatial resolution in the cross-track satellite direction. Current altimetry satellites thus do not see large numbers of lakes. Stage accuracies are also dependant on targets size. However, radar altimetry is a good alternative for systematic monitoring of lakes where gauge data are absent. Typically altimetry measurements can range in accuracy from a few centimetres (e.g. Great Lakes, USA) to tens of centimetres depending on size and wind conditions (Crétaux et al. 2011a). It primarily measures the surface water level of water bodies in a terrestrial reference frame with a return time varying from 10 to 35 days depending on the orbit cycle of the satellite, with fairly good accuracy (a few centimeters over large bodies such as Lakes to tens of centimeters over rivers Calmant et al. (2008)).

The concept of satellite altimetry measurement is rather straightforward. The onboard radar altimeter transmits a short pulse of microwave radiation towards the nadir. Part of the incident radiation is bounced back to the altimeter, providing distance between the water surface and the satellite position, which is then transformed to the instantaneous water height above a reference fixed surface, a geoid model for instance. The accuracy of a single lake height measurement will vary depending on the knowledge of the range, the orbit and the various corrections (Cretaux et al. 2011c). The precision of the measurement will then strongly depend on the capability to retrieve the time that corresponds to the actual height at the nadir of the antenna. The major difficulty in retrieving ranges over continental waters results from the variability in shape of the return waveforms when onboard trackers are designed for a typical ocean waveform. Some algorithms have been developed to analyze waveform on a non- oceanic surface, (see Calmant et al. 2008 for details). Experts agree that among the existing algorithms, the so-called “Ice-1 retracker” is the most suitable to extract range over continental water bodies (Frappart et al. 2006). Kouraev et al. (2009) have also demonstrated that over water surfaces with winter ice cover, like the Aral Sea, this algorithm (Ice-1) better fits the water surface.

Several satellite altimetry missions have been launched since the early 1990s: ERS-1 (1991–1996), T/P (1992–2005), ERS-2 (1995–2002), GFO (2000–2008), JASON-1 (2001-), JASON-2 (2008-) and ENVISAT (2002–2012). ERS-1, ERS-2 and ENVISAT have a 35-day temporal resolution and 80 km inter-track spacing at the Equator. T/P, JASON-1 and JASON-2 have a 10-day temporal resolution and

350 km inter-track spacing at the equator. GFO has a 17-day temporal resolution and 170 km inter-track spacing at the Equator. The derivation of time series of surface height variations involves the use of the repeat track method. This methodology employs the use of a mean (reference) lake height profile. This is derived from averaging all height profiles across the lake within a given time interval, effectively smoothing out the varying effects of tide and wind set-up. The height differences between the reference pass and each repeat pass enable the time series of lake height variation to be created. The combined global altimetry historical data set now spans over two decades and is intended to be continuously updated in the coming decade (AltiKa, Jason-3, Sentinel-3, Jason-CS). Combining altimetry data from several in-orbit altimetry missions also increases the spatial-temporal resolution of the remotely sensed hydrological variables.

For the Aral Sea (Small and Large), Tchebas Bay, and the different water bodies in the deltas of the Amu and Syr Darya, we present in the following section, water elevation time series deduced from radar altimetry and multi-satellite data, from T/P, Jason-1, Jason-2 and Envisat. This has allowed us, for example, for the Small and Large Aral to derive water level variations from 1992 to 2012, which constitutes 20 years of continuous measurements with a time interval between measurements of 10 days.

11.2.2 Satellite Imagery: MODIS

In order to measure the surface area of water over the Aral Sea Basin, which is a key parameter for determining the water balance of the Aral Sea, we have used the data of the MODIS instrument. It was launched in December 1999 on the sun-synchronous polar orbiting Terra spacecraft (at an altitude of 705 km) and since Feb 2000 has been acquiring daily global data in 36 spectral bands with spatial resolution of 250 and 500 m. The MODIS instrument is a multi-spectral imaging system that observes the whole Earth every day. The basic measurements used to classify the earth's surface are surface reflectance measured over seven spectral bands from the visible to the middle Infrared. The surface reflectance product, which we have used, is defined as the reflectance that would be measured at the land surface if there were no atmosphere. It provides information on the type of surface, which reflects the incident solar energy. A classification method based on the fact that water does not reflect incident solar energy in the infrared part of the spectrum has been developed (Crétaux et al. 2011d) and has enabled monitoring the water surface area of the Aral Sea (see Sect. 11.4 for results).

The surface reflectance product we used (MOD09GHK) is corrected for atmospheric effects. These data are distributed by the Land Processes Distributed Active Archive Center (LP DAAC), located at the U.S. Geological Survey, Earth Resources Observation and Science (EROS) (http://lpdaac.usgs.gov). The MODIS images are very useful because they offer high temporal and spectral

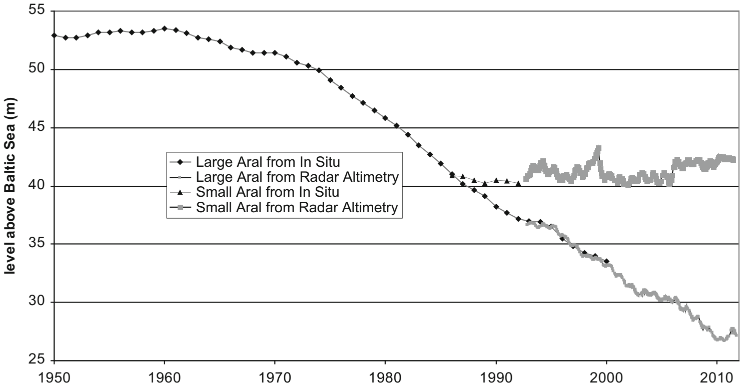

Fig. 11.2 Levels of the Small and Large Aral from 1950 to 2012 from in situ measurements and radar altimetry data

resolution while covering broad areas measured in the several tens of thousands square kilometres and are free of charge. Spatial resolution is 500 m for the images used in our study. Here, we used MODIS images to detect open water area changes over time, principally for the water bodies in the delta of the Amu Darya. MODIS images over the Aral Sea have also been processed.

11.2.3 Aral Sea Monitoring Products from Remote Sensing and Insight on the Water Balance

To understand the use of remote sensing techniques for the contemporary Aral Sea survey, let us first provide a summary of the historical water balance since 1960. At that time, after a few decades of stable water level for the entire Aral Sea, a decision made by political leaders led to a rapid drop of the sea's level and shrinkage of the sea's area (Bortnik 1999). It is not the object of this chapter to report on the historical Aral Sea water level variability, but we nevertheless can note that from the period starting at the beginning of the twentieth century until the latter part of the twentieth century, the Aral Sea level was measured by in situ instruments (staff gauges). From 1992 to 2000 we are therefore able to compare the results obtained from radar altimetry with those measured in situ (See Fig. 11.2). It first of all shows the quite good quality of radar altimetry measurements and allows considering this technique as a good tool for measuring water level variations of the Aral Sea, especially for the last 10 years when no in situ data are available.

11.3 Monitoring of the Aral Sea Basin from Remote Sensing Techniques: Radar Altimetry and MODIS Imagery

11.3.1 Small Aral

From Fig. 11.2, we see that in 1989, the Aral Sea separated into two progressively disconnected water bodies, the Small Aral in the North, and the Large Aral in the South. And as we will see further, 2009 was the first year when the Large Aral has been also separated into two water bodies (SEA for South East Aral, and SWA for South West Aral). On the northern part of the former Large Aral, a smaller saline lake, named Tchebas Bay also formed (see Fig. 11.1). All of these water bodies (Small Aral, SEA, SWA and Tchebas) are crossed by altimetry tracks, which allow measuring their respective levels.

After separation from the Large Aral, the water level in the Small Aral began to rise due to a positive water balance, and as a result, water began to flow southward into the Large Aral (Fig. 11.3). This outflow took place in the central part of the Berg Strait, which was dredged earlier (in 1980) in order to maintain navigation between the northern and the southern basins. This southward current was slow at first but increased as the level of the Large Aral continued to fall. When the Big Aral level fell to +37 m the difference of level between the two water bodies reached 3 m and flow reached 100 m^3/s (Aladin et al. 1995). This canal was dammed in the summer of 1992 and the flow stopped. Over the next few years the dam in the Berg Strait (also called Kok-Aral Dam) was partly destroyed by accumulated water pressure and was restored several times (for details see Cretaux et al. 2005).

In April 1999 the dam was completely destroyed and the water of the Small Aral again flowed southward. The water level in the Small Aral dropped about 3 m after this dam's destruction (Fig. 11.3). In 2005 a new dam was built with support of the World Bank and Kazakhstan's government. It has made possible, again, to regulate the water level of the Small Aral: After a sudden increase in level of about 2 m in a few weeks, the dam gates were opened to release the surplus spring-melt water carried by the Syr Darya River, thus maintaining the mean level of the North Aral Sea at 42 m through seasonal releases (in spring) via the Berg Strait dam. These releases of water have sent a few cubic kilometres of water per year to the south via the Berg Strait. Some of this water has reached the former Tchebas Bay maintaining it as a very saline, small lake (Fig. 11.1).

A small amount of water also reached the Large Aral Sea, without, however, being able to stop the level dropping (Fig. 11.4b). During 2010, the level of the North Aral Sea rose more than in previous years (during which there was a systematic surplus due to the spring floods of the Syr Darya River being drained by opening the dike gates), to an average of 42.5 m instead of its normal 42 m. The opening of the gates in 2010 also made it possible to supply a greater volume of water via the Berg Strait towards the south, which also no doubt helped raise the level of Tchebas Lake and the basins of the southeast and southwest Aral.

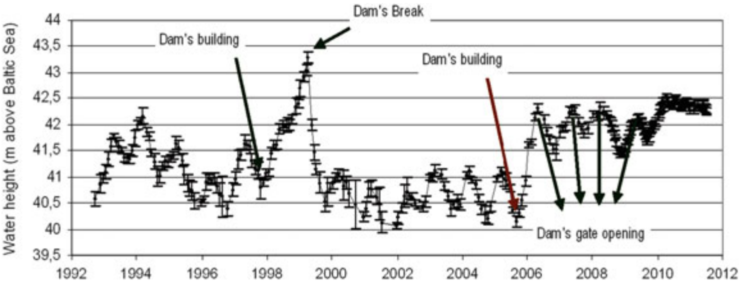

Fig. 11.3 Levels of the Small Aral from radar altimetry measurements (T/P, Jason-1, Jason-2, and Envisat satellites)

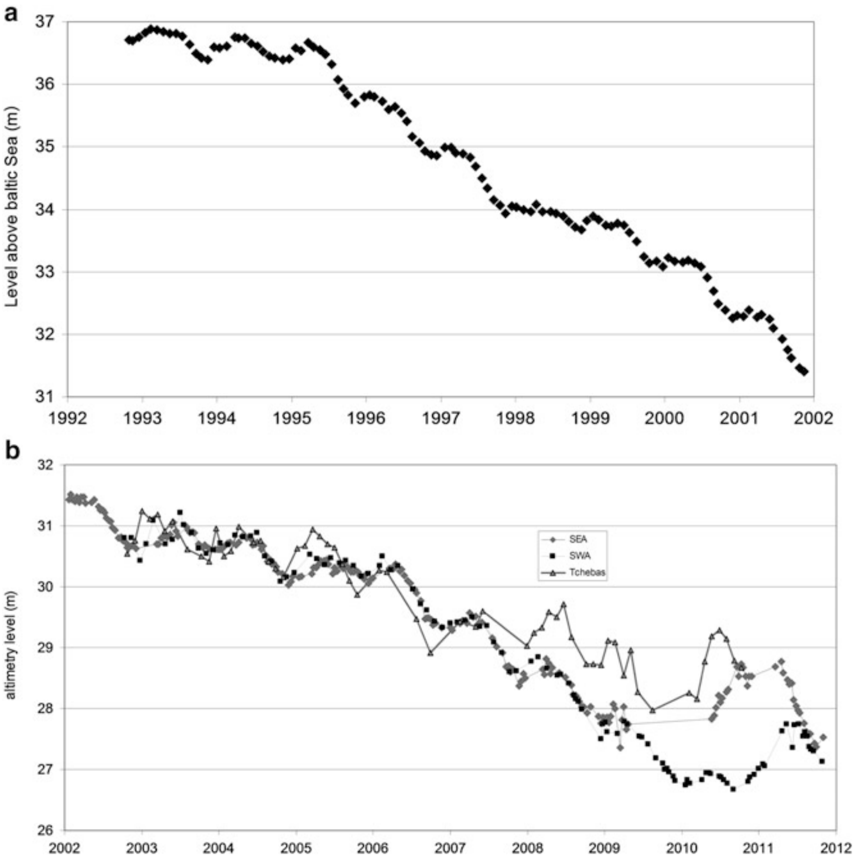

Fig. 11.4 (**a**) Level of the Large Aral 1992–2002 from radar altimetry measurements (T/P, Jason-1 and Envisat); (**b**) of Large Aral (West and East Basin) and Tchebas bay 2002–2011 from radar altimetry measurements (T/P, Jason-1 Envisat and Jason-2)

Furthermore, an article was published on 20 August 2011 in a Kazakhstan daily newspaper about the decision of the Kazakh government to finance the construction of a new dike for the North Aral basin. In an appendix we investigate the impact of this new dike and we provide an estimate of the time needed to fully fill the Small Aral.

11.3.2 Large Aral

Figure 11.4a shows the water level fluctuations of the Large Aral from 1992 to 2005 deduced from T/P, Jason-1 and Envisat. It clearly shows the significant and continuous shrinkage of the Large Aral. The rate of water level decrease was 20 cm/year for wet years (e.g., 1998) to about 1 m/year for very dry year (e.g., 2001). Figure 11.4b shows the water level variations of the Large Aral west (SWA) and east basins (SEA) and of the Tchebas bay, from 2002 to 2012 deduced from radar altimetry of Jason-1, Jason-2 and Envisat only. For the years 2002–2009, the level of both basins dropped at the same rate and their levels were essentially the same.

For 2009, since the level of the SEA had previously dropped so much and its area grown so small, the ground tracks of the *Jason*-1 and *Jason*-2 satellites no longer covered the flooded area; consequently the altimetry measurements were not as capable of showing the level. At the beginning of 2010, the measurements were again able to show the level, following the renewed inflow to the SWA from the Amu Darya, which greatly increased its area. For the SWA, this rise in level occurred later. It probably took some time for the flood arriving from the south east of the basin via the Amu Darya Delta, and which was recorded by altimeters fairly early in this flood episode, to propagate gradually to the North and thus supply the south-west Aral basin whose level also increased strongly during the summer of 2010.

At the beginning of 2011, the southeast Aral was entirely frozen (personal communication from Dr. Peter Zavialov, a Russian researcher at the Shirshov Oceanographic Institute in Moscow), which was not the case for the SWA and which might explain the "gap" in the altimetry measurements at the beginning of 2011 for the SEA. During the spring of 2011, the SEA began to again dry out but, for the first time since this basin had been observed by satellite altimetry, this was not the case for the SWA, or at least it has occurred much later (in June). It is possible that the drop in the level of the SEA was due to an adjustment between the two basins via the Kulandy strait separating SEA and SWA in the north (Fig. 11.1). Altimetry measurements showed that the levels of the two basins were fairly similar during early summer 2011 and then followed again the same behaviour. A time lapse was also observed for the conveying of water between the Amu Darya Delta and part of the southeast Aral basin, which are now about 100 km apart.

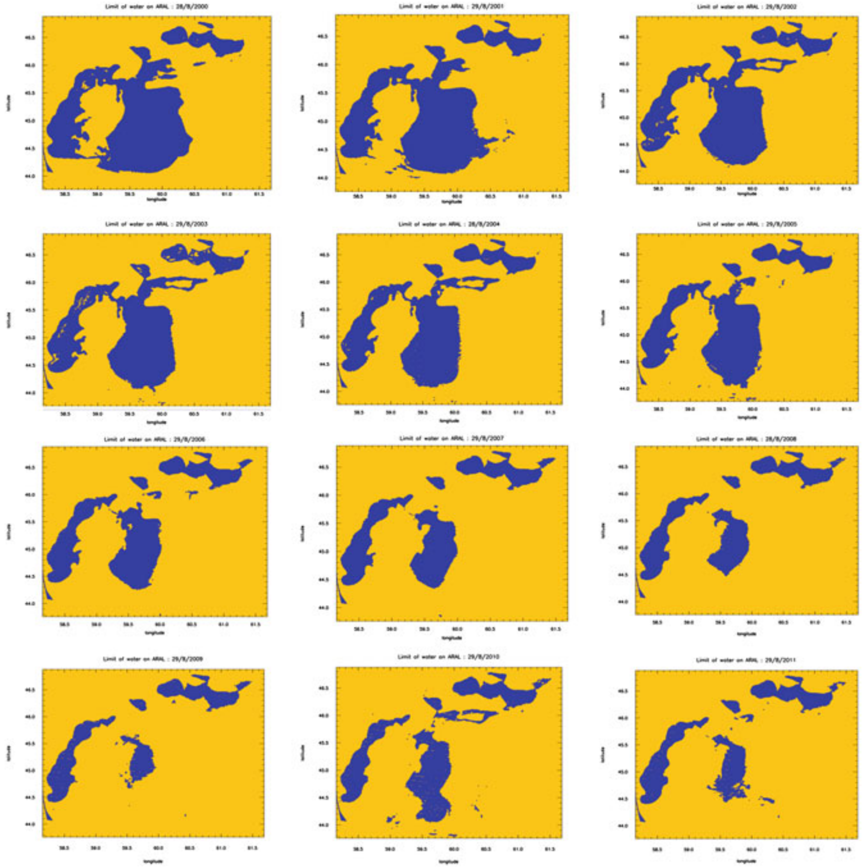

Fig. 11.5 Surface area of Aral Sea 2000–2011 derived from Modis images. Each image was acquired at the end of August of each year

The filling or draining of the SEA and SWA sub basins is no longer instantaneous: we are witnessing the gradual separation of the Large Aral into two basins, which, if the level continues to drop, will become independent of each other as was the case more than 20 years ago for the Small and Large Aral. The MODIS data analysis confirms quite well this scenario. Figure 11.5 shows the water surface decline of the Aral Sea from 2000 to 2011 (each image on this figure corresponds to the end of August of each year). The continuous shrinking of the Large Aral is highlighted by the significant dry year of 2009, and the following year of 2010 when there was a new increase of water surface area of the Large Aral. Between the end of August 2005 and 2006 the effect of the Kok-Aral Dam is also evident on the Small Aral. Figure 11.6 shows, using four MODIS images from March and July 2009 and March and December 2010, that the level drop that occurred in spring 2009 was so large that no altimetry tracks were still crossing the SEA, while in 2010

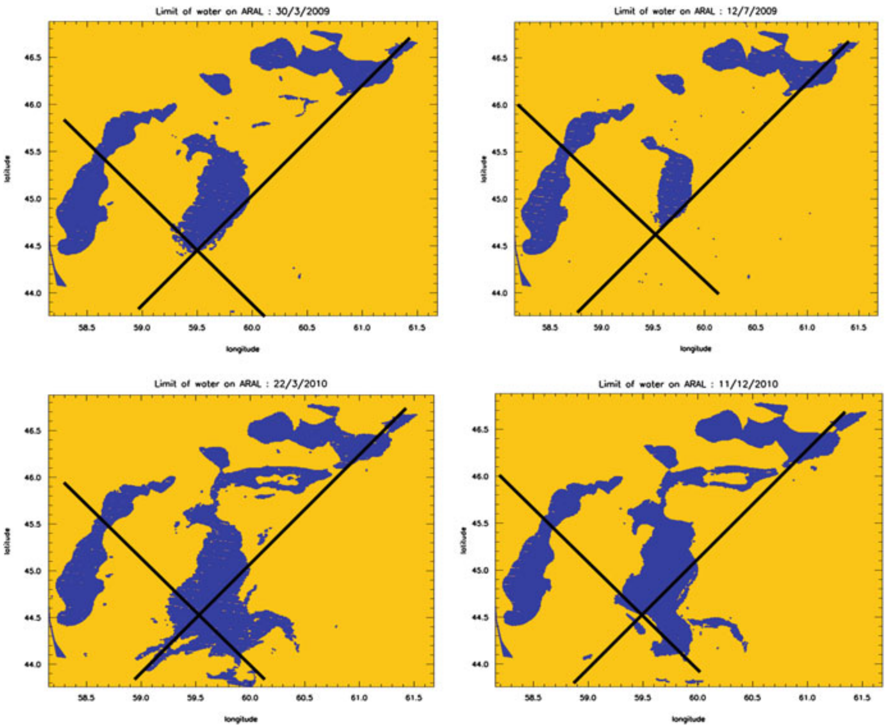

Fig. 11.6 Surface area of Aral Sea in March and July 2009, and March and December 2010 calculated from Modis images. *Black lines* represents the Jason-1, and Jason-2 satellites tracks

the total surface area of the Large Aral increased sufficiently that its surface was rather well covered by radar altimetry. It also shows that during the whole year 2010, overflow from the Berg Strait Dam reached the Eastern Basin of the Large Aral. The Kulandy strait separating SEA and SWA does not appear on this image because of the coarse resolution of the MODIS images (500 m) which resulted in retention of only pixels of 500 m fully covered by water in the classification results. As the Kulandy strait is currently rather narrow it does not appear as inundated although it was. Note that using a high resolution Satellite Image, P. Zavialov observed that a very narrow channel remains open in the Kulandy Strait in 2009 but, not wider than 200 m, smaller than the resolution of the MODIS images we used (P. Zavialov, personal communication). A Recent Landsat 7 band 5 panchromatic image with 15 m resolution acquired on July 14, 2012, shows the Kulandy channel is almost closed at its eastern end, with a width not more than 30 m. (scene ID LE16102820196PFS00, available at http://glovis.usgs.gov/).

11.3.3 Tshchebas Bay and the Water Bodies in the Deltas of Amu and Syr Darya

Tchebas bay (Fig. 11.1) located in the North West of the former Large Aral was at the same level as the Large Aral until 2007. In recent years its decline was less than the Large Aral with an average difference about 1 m higher (Fig. 11.4b). Water level variations of Tchebas Bay have been obtained from radar altimetry measurements from the Envisat satellite. From the DBM (digital bathymetric map) it could be explained by the fact that below a level of around 29.5 m (±50 cm) the Large Aral is not connected anymore to the Tchebas bay, therefore the evaporation volume from Tchebas Bay is smaller (the surface is on average 370 km^2) than from the Large Aral. When water is released from the Kok-Aral Dam, some part still reaches the Large Aral (as seen on the MODIS images in 2008 or 2010 for example, see Fig. 11.5), some part is filling Tchebas Bay (which explains the spring increase in its surface area as seen on Fig. 11.4b). But most of the year we see from MODIS (Fig. 11.5) that the Large Aral and Tchebas Bay are disconnected after 2007. The water level variation of the Tchebas Bay, coupled with DBM data, has allowed calculating the total amount of water entering annually in this bay and therefore not reaching the Large Aral. This has been used to better constrain the water balance of the Large Aral (see Sects. 11.3.2 and 11.4).

The deltas of the Amu Darya and Syr Darya are both regions of ecological importance. The desiccation of the Aral Sea has enhanced the need to maintain sustainable water bodies in the deltas by the construction of artificial reservoirs and wetlands in the deltas. Currently, lakes in the delta of the Amu Darya are either fed by drainage water like the biggest one (Sudochye: Fig. 11.1) or by direct diversion of the Amu Darya River (Mezdurechye). In recent years, with the cooperation of Germany, a plan of rehabilitation of the so-called Priaralye reservoirs in the delta of the Amu Darya has been underway (see CAWATER web site: http://cawater-info.net). In situ monitoring of the water quantity in the Amu Darya Delta, with collection of in situ measurements every 3 months has been performed since 2009.

Thanks to satellite altimetry, with the Evisat satellite, it is also possible to estimate the water level of some reservoirs in this delta. In Fig. 11.7a for example we can see the water level variations of the Sudochye reservoir. From 2003 to 2008, its level has been around 52.5 m, but in 2009 the water balance of this reservoir was mainly negative, hence a significant decrease of 2 m has been observed. This is confirmed by in situ data downloaded from the CAWATER web site. The same observations from satellite altimetry have been made on other reservoirs of the delta. These altimetry measurements, coupled with CAWATER observation data on lake surface areas (confirmed by MODIS data) have allowed computation of the volume of water, which was retained every year in the delta and, therefore, did not reach the Large Aral. This has been used for the water balance computation of the Large Aral (see Sects. 11.3.2 and 11.4).

In the delta of the Syr Darya, a large lake (Kamyshlybas) with an area of about 400 km^2 is also by chance crossed by altimetry tracks (Envisat: Fig. 11.1). Water

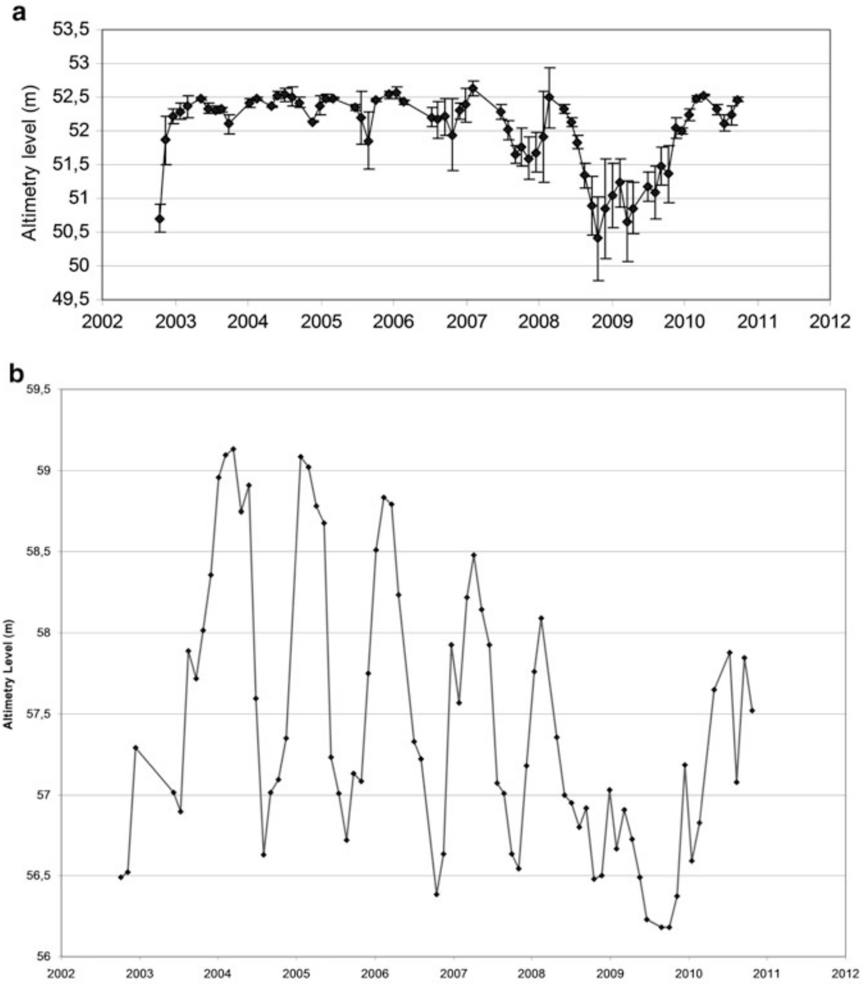

Fig. 11.7 Levels of Lake Sudochie in the delta of the Amu Darya (**a**) and Lake Kamyshlybas in the Syr Darya Delta (**b**) from 2002 to 2010 calculated from altimetry measurement of the Envisat satellite

level variations have hence been calculated from 2002 to 2010. It is shown in Fig. 11.7b. A significant annual oscillation of about 1.5–3 m has been observed from 2002 to 2008 with an inter-annual decrease trend, followed in the very dry year of 2009 by stagnation of the reservoir, and in 2010, due to higher inflow and atmospheric precipitation, it rose again. Using MODIS images to estimate the surface variations of this reservoir in time, and the altimetry data for water level variations, the water balance of the Kamyshlybas reservoir has allowed calculation of the amount of water entering the delta at the post of Kazalinsk and which was retained annually in the reservoir. From 2005 (after the construction of the Kok-Aral dam) to 2010 it has reached between 0.1 and 0.7 km^3/year, which represented 4–10 % of total runoff measured at the entrance of the delta at Kazalinsk. This has also allowed to better estimate total surface water inflow to the Small Aral.

11.4 Water Balance of Aral Sea: Generalities

The volume of stored water in an inland sea like the Aral will vary with time according to changes in the hydrological budget. Lakes and reservoirs will thus exhibit seasonal changes in surface area and level due to proportional changes in precipitation and evaporation (Mason et al. 1994). Under a constant climate scenario the volume will tend towards reaching an equilibrium level over a given time period, displaying a perfect balance between inflow and outflow (Mason et al. 1994). Lakes and reservoirs will thus exhibit seasonal changes in surface area and level due to proportional changes in precipitation and evaporation. In an arid region, marked by low precipitation and high evaporation, the sensitivity of an inland sea to water use and climate change is therefore enhanced and the assessment of the lake water balance could provide improved knowledge of regional and global climate change and a quantification of the human stress on water resources across all continents.

The water balance is simply given by the difference of the water inflow and the water outflow, and for a closed (terminal) lake it can be represented by the following equation.

$$\mathrm{dV/dt} = (\mathrm{R} + \mathrm{Gw}) - (\mathrm{E} - \mathrm{P}) * \mathrm{S(t)} + \varepsilon \tag{11.1}$$

Where dV/dt is the volume's variations with time, R is the river runoff, Gw is the underground net inflow, E the evaporation rate, P the precipitation rate, S(t) the surface at the time t, and ε the sum of the remaining uncertainties.

Several publications have reported on studies of the water balance of the Aral Sea. Small et al. (1999), resolved the water balance equation by using a regional lake model and have obtained values of evaporation minus precipitation (accounting for seasonal but not interannual variability) up to 1990. Small et al. (2001) have also evaluated the effect of evaporation and precipitation on the Aral Sea level decrease up to 1990 and have separated anthropogenic and climatic factors.

As far as the water balance is concerned in a very arid region like Aral Sea, the contribution of rainfall is slight (of the order of 10–15 cm per year) whereas evaporation is much higher (of the order of 1–1.2 m). Evaporation minus precipitation for the Large Aral Sea has represented an average loss of 25–30 km^3/year during the last decade, while river discharge from the Amu-Darya varied from 0 to 15 km^3/year in the 1990s (Fig. 11.8a). Thus, in the last decade of the twentieth century the water supply deficit reached 10–15 km^3/year depending on the year, and the Large Aral has continued to shrink as the equilibrium level was not reached. The only contributor

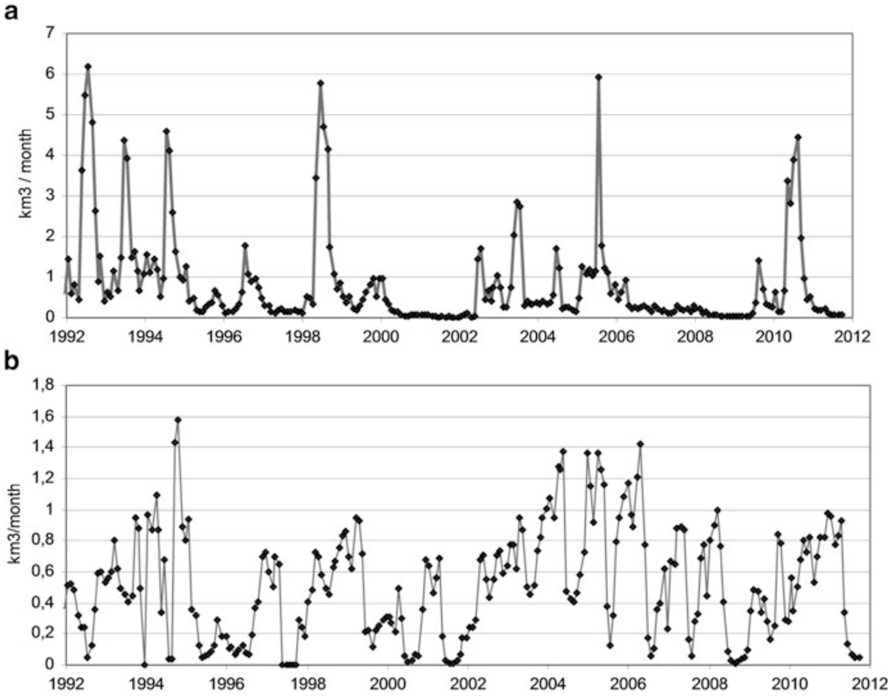

Fig. 11.8 Runoff of Amu Darya (**a**) and Syr Darya (**b**) from 1992 to 2011 from in situ measurements

which could stop the Large Aral basin from drying up would be surface run-off from the Amu Darya whose delta is located in the south-east part of this basin, but this is not possible since too much water is tapped for irrigation in Uzbekistan.

Only excess rainfall would enable a very temporary respite. This is what happened in 2010 with a level which had not been reached for at least 20 years, since, as can be seen in the time series of the level of the Southeast Aral (SEA), the level rose by about 1.4 m in 2010 (Fig. 11.4b). The flooded surface area doubled (from 2,400 to 4,900 km^2 as measured by MODIS data) and the volume was increased fourfold (from 1.75 to about 7 km^3). In situ measurements of the flow of the Amu Darya from the Kyzldjar station (Fig. 11.8a), have confirmed this phenomenon, which occurred in 2010 and explain it very well. The same phenomenon was revealed by altimeter measurements for several other major lakes in central Asia (Balkhash, Zaysan, Sassykol, Issykul, Kapchagayskoye (see Hydroweb: http://www.legos.obs-mip.fr/soa/hydrologie/hydroweb/).

Other years with as much rainfall (1998 for instance) did not reproduce this phenomenon since at that time, evaporation predominated. The surface area of the Large Aral Sea was then about three times larger (25,000 km^2 as compared with 8,500 km^2 in 2010) and consequently the evaporation was three times as great. In 2005, since the surface area of the Large Aral had again decreased, the particularly strong floods in that year were also able to prevent the Large Aral basins from drying out but without however reversing the trend.

Benduhn and Renard (2003) developed a model of evaporation for the Large Aral based on the Penman equation and used the water mass balance equation to estimate the interannual groundwater inflow to the Large Aral until 1990. They showed that this contribution to the water mass balance has a high variability (from 1 to 15 km^3/year) and has an average value of 8 km^3/year. Jarsjö and Destouni (2004) have also estimated the ground water discharge by using the water mass balance equation and different scenarios for the evaporation and precipitation rates. They concluded that ground water has become a major contributor to the hydrological budget of the Aral Sea, with annual values varying from 5 to 30 km^3 depending on the scenario. Alexseeva et al. (2009), have estimated that the underground water should range between 2 and 7 km^3/year, with increases of the rate of underground discharge of 0.013 km^3/year related to increases of hydraulic gradient correlated to the Aral Sea level drop. Those results also confirm the study made in Oberhänsli et al. (2009) who have detected underground water inflow from oxygen and hydrogen isotopic analysis based on vertical lacustrine profiles collected in the Eastern and the western basin of Aral Sea as well as in the Kulandy strait which connects both basins. Their study however did not provide quantification of this additional water to the Aral Sea, but they concluded their article saying "effluent flows of groundwater have reached a state where they are relevant for the groundwater reservoirs and water balance of the large Aral Sea" (quoted in Obershänli et al. 2009). Other studies drew opposite conclusions about underground inflow to the Aral Sea: indeed according to older studies Sydykov and Dzhakelov (1985) and Glazovsky (1990) the groundwater component of the Aral Sea water balance must be negligible and not exceeding 2–3 % of water volume variations. During Soviet times, experts estimated net groundwater inflow from -1.3 to $+ 3.4$ km^3/year (Bortnik and Chistyayev 1990, p. 38)

Another component of the water balance equation, which is hard to accurately measure, is the runoff of the rivers, Amu Darya to the Large Aral and Syr Darya to the Small Aral. Runoffs for these two rivers are measured only at the entrance of their respective deltas, at Kazalinsk for Small Aral and for the Large Aral at Kyzyljar. In such arid regions, and also due to diversion of river water to small reservoirs in both deltas, it is therefore very uncertain to determine the exact water entering into the Aral Sea at the mouths of the deltas (Crétaux et al. 2005; Small et al. 1999, 2001). In Aladin et al. (2005) an attempt to adjust for water lost in the delta of the Syr Darya (based on the water balance of the Small Aral and radar altimetry measurements) have shown that about 10–20 % of water that reached Kazalinsk was lost in the delta. For the Large Aral no real measurements exist for this component although a monthly measurement of river runoff is made at Kyzykjar, which is available on the web site of the CAWATER project (http://cawater-info.net). From 2000 to 2012 we have noted from data extracted from the CAWATER web site the very high interannual variability of river runoffs especially of the Amu Darya (see Fig. 11.8a).

11.5 Aral Sea Current Water Balance: What Do We Learn from Modern Satellite Techniques?

The problem with most of the water balance studies of the Aral Sea is that for several decades there were no continuous observations of water level, and the few data that do exist are fragmentary or unavailable. Because the historical Aral Sea volume cannot be determined accurately, there are large uncertainties in the water balance equations and the reliability of the results has suffered.

By using a combination of satellite altimetry measurements and a dedicated DBM with a 250 m spatial resolution, it is now possible to observe the volume variations of the Aral Sea (See Crétaux et al. 2005) for more details).

A verification of the validity of this DBM has been performed by comparison of surface water area of Large and Small Aral inferred from the combination of radar altimetry and DBM with surface area of the Aral Sea measured by MODIS over the last 10 years. Figure 11.9 shows that the agreement between both methods of calculation of surface area has a correlation coefficient of more than 0.99. It is therefore possible to estimate water volume variations of Small and Large Aral with high precision and use them to solve the water balance equation. Here we determine a water balance for the Large Aral utilizing satellite techniques in conjunction with terms for the equation for evaporation, precipitation and river runoffs taken from different sources. The purpose is to determine if right and left members of Eq. 11.1 can be equalized and if underground water inflow to Aral Sea can be estimated.

As far as evaporation is concerned, we used the model given in (Bendhun and Renard 2003) and (Gascoin and Renard 2005), who have taken into account the salinity of the Large Aral, which tends to diminish the evaporation rate. From their estimation this component of the water balance has an absolute value of 1,160 mm/year.

For precipitation input, monthly averaged in situ data are available on the CAWATER project website but end at the beginning of 2000. On average the precipitation over the region is 1.3 cm/year. From other sources like the GPCP products or the satellite data (TRMM) the precipitation is higher but there is general agreement among different studies (Crétaux et al. 2005) that converge to 1.3–1.4 cm/year. We simply used the TRMM data to modulate yearly the average amount of precipitation in order to better take into account the succession of wet and dry years over the period of observation (for example a 30 % water excess was observed in 2010). From the CAWATER web site the precipitation measured near the Aral Sea until the end of the 1990s was between 40 and 170 mm/year depending on the year. Due to uncertainties on these two components of the water balance we consider that the error is about 100 mm/year.

To solve the question of the "real" amount of water entering the Small and Large Aral from rivers we have calculated the water balance of each as well as for the water bodies in the delta and for Tchebas Bay from September 2005 (just after the construction of the Kokaral dam) to the end of 2010 (period of the last Envisat data). Figure 11.7a, b gives water level fluctuations of Tchebas Bay and reservoirs in both

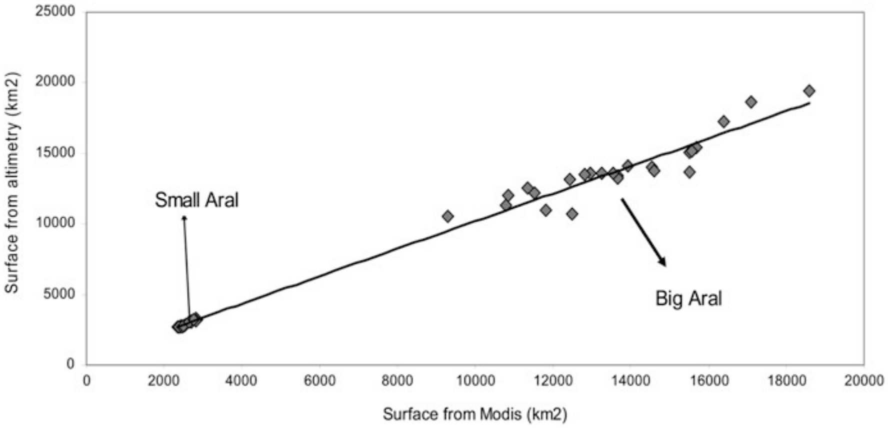

Fig. 11.9 Scatter plot of surface area of Small and Large Aral comparing measurements from Modis images, and Altimetry combined to DBM

deltas. To convert into volume, we have used MODIS water surface area variations for each of these water bodies.

We have calculated for each delta the water losses from the measurement station to the Aral Sea (respectively Small and Large Aral). Yearly losses from 2005 to 2010 varied from 3 % to 40 % in the Amu Darya Delta. The remaining discharge to the Large Aral ranged from 1 km^3 (2009) to 16 km^3 (2010) leading to a highly variable inter-annual water balance. From the Small Aral, we have calculated yearly discharge across the Berg Strait Dam of excess water in the Small Aral and then we have subtracted water that enters Tchebas Bay and estimated evaporation from the water bodies formed south of the Berg Strait Dam. The residual added to Large Aral water balance: it has ranged from 0 to 2.6 km^3/year.

We then have calculated the water balance of the large Aral by resolving the equation:

$$dV/dt = (P(t) - E(t)) * S(t) + R_{ad} + R_b \tag{11.2}$$

$R_{ad} + R_b$ are the monthly inflow from the Amu Darya and from the Berg Strait, and S(t) is the inundated area of the Large Aral (including West and East basins) deduced from satellite altimetry and bathymetry of the Aral Sea bed. From this study, we did not find any evidence of underground water inflow as shown on Fig. 11.10. As the uncertainty on evaporation and precipitation rate may be in the range of 10 % we have made several small changes in the E-P component of the water balance, but this did not change the conclusion. Water balance in the two deltas has also been modified (using different assumptions on evaporation, water withdrawal from the rivers and precipitation) but this had also a small impact on the water budget. In all cases, we simulated realistic changes of the different

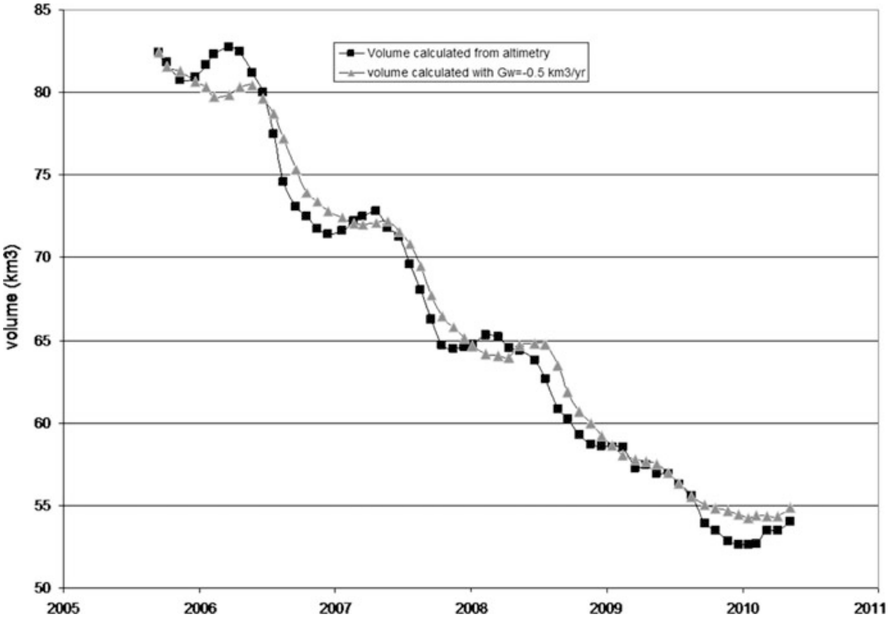

Fig. 11.10 Volume of Large Aral from combination of altimetry and DBM versus volume deduced from water balance with an adjusted ground water input of −0.5 km^3/year

parameters. The underground water component from our analysis comprises between −0.5 and +0.5 km^3/year, numbers that are within the global uncertainty of the calculation.

The Fig. 11.8a. b gives the monthly river runoff at Kyzyldjar and Kazalinsk. Figure 11.10 shows the volume variation of the Large Aral in two cases: from radar altimetry and from the water balance equation with underground water of −0.5 km^3/year which is the adjusted value for closing the water budget of the Large Aral. However this conjecture needs to be further assessed by hydrogeological modelling and more accurate data on the evaporation and precipitation rates that are, for all studies made until now, the main limiting parameters of the water balance.

11.6 Future of Remote Sensing for Hydrology and Conclusions

What does the next decade hold for Aral Sea Basin monitoring from Space? Multispectral imagery from MODIS is still (in 2012) operating and is well suited to monitor the water surface area of water bodies over large regions with continuous data at relatively high temporal resolution. It is particularly well adapted for the Arid Zone as the cloud cover is often rather low. In the framework of the establishment of the new Global Monitoring for Environment and Security (GMES) capacities by the European Union, several new missions have been planned for the next decade, with dedicated missions in land monitoring from multispectral sensors (Sentinel-2), and radar altimetry in dual Ku-C bands (Sentinel-3). Sentinel-2 will provide multispectral imagery at high resolution (4 spectral bands at 10 m, 6 at 20 m and 3 at 60 m), with full coverage of the Earth every 5 days. It will consist of a pair of satellites, with initial launch in 2013. This will be more suitable to monitor the areas of small water bodies in the deltas of the Amu Darya and Syr Darya. The Sentinel-3, mission is designed to measure sea surface topography but classical radar altimetry will also be used for water level estimation on lakes and reservoirs. Sentinel-3 will also consist of a pair of satellites with expected first launch in 2013. In 2013, the Centre National d'Etudes Spatiales (CNES) and Indian Space Research Organisation (ISRO) will launch the Saral/Altika mission, which will be the first altimeter operating in Ka band which will have the main advantage of a better spatial resolution due to the smaller footprint of the radar signal (150 m instead of several km), allowing a better discrimination of surface water area for small water bodies. This mission will be placed in the same orbit as Envisat and will hence allow continuing the monitoring of water bodies irs in the delta. It should be noted that Envisat ceased at the end of 2010 to provide data on repeat orbit, and was totally switched off at the beginning of 2012. In 2013, the CNES, EUMETSAT, and NASA will continue the Jason program, with the launch of Jason-3 radar altimeter in Ku and C bands and in 2017 with the launch of the Jason-CS mission for operational oceanic purposes.

However, none of those missions is dedicated exclusively to continental hydrology. The future SWOT (Surface Water and Ocean Topography) mission is the first satellite mission dedicated to the measurement of continental surface water. SWOT will provide a global inventory of all terrestrial water bodies whose surface area exceeds 250 m by 250 m and rivers whose width exceeds 100 m, at sub-monthly, seasonal and annual time scales (Biancamaria et al. 2010). The principal instrument of SWOT will be a Ka-band Radar Interferometer (KaRIN), which will provide heights and co-registered all weather imagery of water over two swaths, each 60 km wide, with an expected precision of 1 cm/km for water gradients and absolute height level precision of 10 cm/km^2. SWOT will also provide an estimate of river discharge, and map floodplain topography and channel reaches.

For the Aral Sea Basin, the monitoring improvement will be enormous. River runoff will be estimated every 10 km along the Syr Darya and Amu Darya rivers. The whole delta's wetlands (with a resolution of 250 m by 250 m) will also be monitored. Volume fluctuations of small water bodies will also be estimated from SWOT missions, which is a key parameter for water balance computation. The potential of SWOT measurements will be enhanced if coupled with other remote sensing data (radar altimetry, imagery, gravimetry and meteorological satellite data sets). It will considerably improve our understanding of the Aral Sea Basin, not only just the terminal Aral Sea water body, but in fact, all water bodies in Central Asia (including small reservoirs and lakes, rivers and floodplains).

The combined radar and multispectral approach described in this chapter demonstrates the current capabilities for operational space monitoring of the areas and levels of the Aral Sea and water bodies in the deltas. It also shows the serious limitations of current technologies, which could be overcome by future missions. By complementing in situ observations and hydrological modelling, space observations have the potential to improve significantly our understanding of hydrological processes at work in the entire Aral Sea Basin (ASB) and their influence on climate variability, and socio-economic life. It offers a comprehensive view of the ASB, continuous and accurate spatial-temporal sampling, and the capability to determine with reasonable accuracy the water balance of the Aral Sea. It also helps to understand in "real time" how the Aral Sea is evolving.

Appendix: Scenarios of Evolution of Small Aral

On August 20, 2011 an article was published in a Kazakhstan daily newspaper about the Kazakh Government's plan to refill the Small Aral to the level of 50 m above the Baltic Sea as measured at the Kronstadt gauge on the Gulf of Finland near St. Petersburg. The purpose is to fully renew the Small Aral as it was before and that the city of Aralsk becomes again a major fishing center on the North coast of the Aral Sea. To accomplish this, two scenarios are under consideration.

The first one is to raise the existing dike in the Berg Strait, which today does not allow reaching this objective. The second one consists in the construction of a new dike at the mouth of the bay southwest of Aralsk's harbor, hence leading to the separation of the Small Aral into two separate water bodies (upper and lower, see Fig. 11.11). The height of this new dike would allow the level in the upper reservoir to reach 50 m. The reservoir formed would have a maximum depth of about 10 m, and a volume of 5 km^3. A canal coming from the Syr Darya would supply it. This project costing millions of dollars would be partly financed by the Kazakh government and partly by the World Bank, as was the case in 2005 for the Kok-Aral Dam.

From DBM (digital bathymetry map) of Aral Sea and the water balance equation we are able to compare both scenarios in terms of the time necessary for achieving the final objective. With the current average water inflow into the Small Aral from river runoff (R) of the Syr Darya river (~5/6 km^3/year) and with annual water release through the berg's strait of about 2–3 km^3 the total annual average area of the Small Aral (A_0) is about 3,200 km^2 and the current annual average volume of the Small Aral (V_0) is 26.8 km^3.

Scenario 1

If the Kokaral dam is raised to 50 m at least and if water release is stopped during the filling of the Small Aral, the new equilibrium surface of this basin is given by

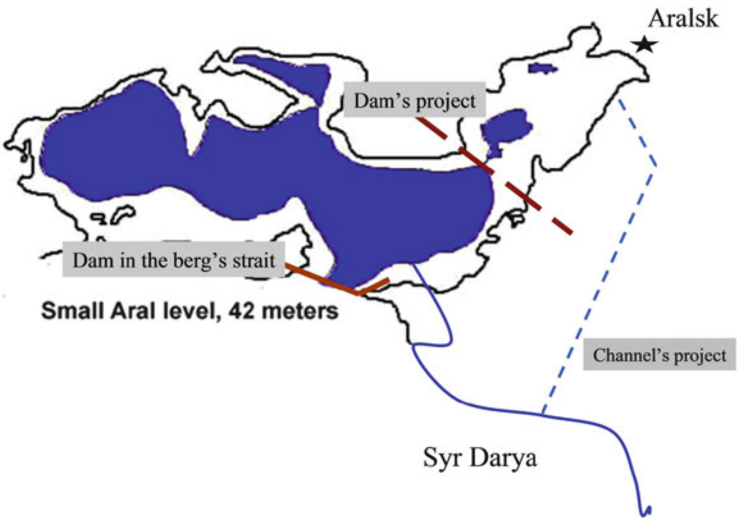

Fig. 11.11 Map of Small Aral with the project for construction of a new dike at the entrance to the Gulf of Saryshaganak southwest of the city of Aralsk

$$A_{LE} = \frac{R}{(E - P)} \tag{11.3}$$

From the DBM, at water height of 50 m, the surface of the Small Aral is 5,066 km^2. It corresponds well to equilibrium water surface of this basin with R = 5 km^3/year and average net evaporation of 1 m/year. From Mason et al. (1994) we may calculate the "equilibrium response time", τ_ε, to reach a fraction (1 − 1/e), which represents 63 % of the total area change. That current equilibrium is broken by the additional water supply from the Syr Darya River (3 km^3/year of net supply after subtracting the water discharged from the Berg Strait Dam).

τ_ε is given by the following equation:

$$\tau_e = \frac{1}{dA/dV(E_l - P_l)} \tag{11.4}$$

Where dA/dV corresponds to the average slope of the bottom topography and is given by $(A_{LE} - A_0)/(V_{LE} - V_0)$

From Mason et al. 1994, we also may calculate the Area of the Small Aral at each time span (yearly in our case) given by the following equation:

$$A_l\,(t) = A_0 + [A_{LE} - A_0]\left(1 - e^{\frac{-t}{\tau_e}}\right) \tag{11.5}$$

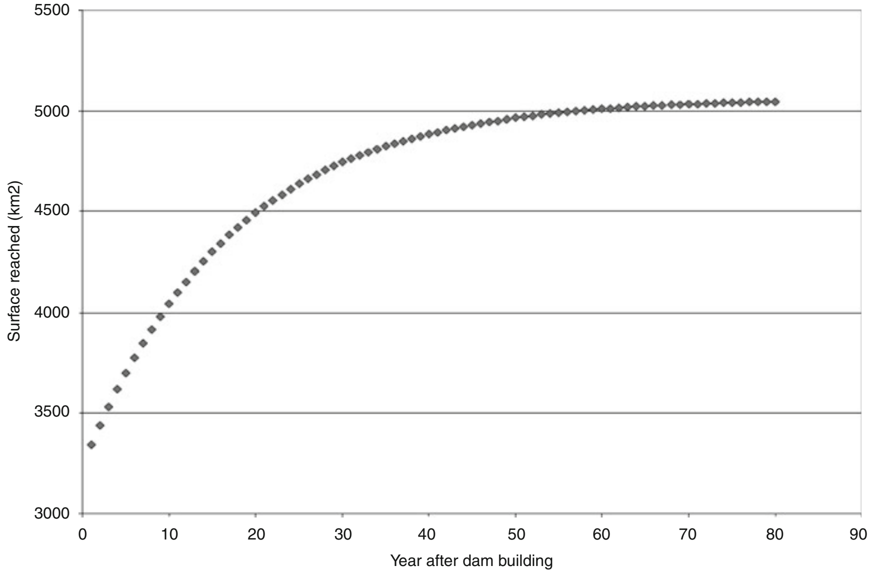

Fig. 11.12 Evolution of surface area of the Small Aral for the next 80 years if the existing dam is raised to 50 m

We have obtained for τ_ε, a value of 17.3 years, and from Eq. 11.5 (Fig. 11.12) the total time to reach the water level of 50 m, therefore an equilibrium surface of 5,066 km^2, is about 70–80 years.

Scenario 2

Let us see now about the time to fill both reservoirs if a second dam is built as explained above. From DBM we have calculated that the surface of the upper reservoir would be 800 km^2. From Eq. 11.3 we calculate that the runoff necessary to insure equilibrium at this surface area is 0.8 km^3/year. From Eq. 11.4, considering that a canal would divert this amount of fresh water into this reservoir yearly, the equilibrium response time τ_ε, would be 6.25 years, and from Eq. 11.5 the time for fully filling the reservoir would be about 25–30 years. For the lower reservoir, which would receive the residual runoff from the Syr Darya of about 4–5 km^3/year, and have a surface of about 3,000 km^2, this would limit annual releases from the Berg Strait Dam southward toward the Large Aral to about 1–2 km^3.

Let us now assume that for a short period of time, the flow of water into the upper reservoir would be more than the runoff of 0.8 km^3/year necessary to maintain a surface area of 800 km^2. This would obviously accelerate the filling of this water body. Assuming that 3 km^3/year is necessary to maintain the lower reservoir at equilibrium, about 2–3 km^3/year would remain that could be used to fill the upper reservoir. Employing the same computation that has been done above indicates that only 2–3 years would be required to fill this reservoir.

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Chapter 12
Nature and Economy in the Aral Sea Basin

Kristopher D. White

Abstract The desiccation of the Aral Sea since 1960 has been a notorious and well-documented example of anthropogenic ecological devastation. Equally ominous has been the devastating impact on the livelihoods and health conditions of the human populations inhabiting the Aral Sea region. As a socio-ecological crisis, the Aral Sea's recession has demonstrated interrelationships between humans and the biophysical environment. An important societal dimension through which to access these relationships is the Aral basin's regional economy. The Aral crisis itself has largely been a result of the large-scale Soviet-era water diversion projects whose impetus was primarily the production and export of cotton. The Aral Sea Basin today remains a globally important cotton production and export region. The most important economic activities devastated by the crisis have been fishing and fish processing. Once defunct enterprises, these activities have only recently been revived with the recent rehabilitation of the northern Aral Sea in Kazakhstan. This chapter examines the post-1960 developments of the cotton sector within the Aral basin and the fishing sector in the Aral Sea itself. Nature-economy linkages inherent in these sectors inform broader generalizations regarding human-environment interrelationships in the Aral Sea Basin today.

Keywords Aral Sea • Socio-ecological crisis • Cotton • Fishing • Human-environment interrelationships

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12.1 Introduction

The Aral Sea, situated along the border between southwestern Kazakhstan and northwestern Uzbekistan, is a notorious example of human-induced ecological disaster. Once the world's fourth-largest inland water body according to surface area, the famously shrinking Aral today is but a small fragment of its former grandeur. The Aral Sea's recession, symbolized for many by the rusting hulks of former fishing vessels now stranded in the desert, is a dramatic, blunt, and unavoidable reminder of humankind's ability to sow environmental destruction. Following a recent visit to the Aral Sea's former shoreline in Moynaq (Muynak), Uzbekistan, UN Secretary-General Ban Ki Moon lamented that the Aral's demise "is clearly one of the worst environmental disasters in the world. I was so shocked. It really left with me a profound impression, one of sadness that such a mighty sea has disappeared" (United Nations 2010, p. 1). The ecological consequences of this environmental disaster referenced above are many, and include environmental ills associated with desertification, salinization of both terrestrial and aquatic resources, regional climate change, destruction of aquatic, estuarial, and terrestrial habitats, and corresponding losses in biodiversity across a wide range of flora and fauna species.

Just as a fishing vessel decaying in the desert symbolizes the Aral Sea's retreat and associated ecological disaster, it is also emblematic of an equally ominous crisis – that facing the region's human inhabitants. The Aral's recession brought with it a loss of fish species and the disappearance of the Aral Sea's once flourishing fishing industry, a vital source of employment, income, and dietary nutrition within the immediate region. The societal impacts of the Aral crisis are also many, and range from those associated with unemployment and poverty, to a staggering barrage of human health problems (see e.g. Ataniyazova et al. 2001; Kaneko et al. 2002; Muntean et al. 2003; Wiggs et al. 2003; Small et al. 2001b; Cox et al. 2004; Crighton et al. 2003, 2011), ecological crisis-driven nationalism (Hanks 2000; Saidazimova 2008), and the loss of important ecosystem services.

Clearly the Aral Sea environmental crisis and human crisis are related. In this sense, then, that ubiquitous image of the fishing vessel in the desert is also symbolic of the close linkages between humans (society) and the natural environment (nature). The vanishing Aral Sea has abandoned these ships to a similar fate (through decay or scrap metal harvesting). The plights of the Aral (symbolizing nature) and the ships (symbolizing society) have a common root cause and exhibit a strong spatial and temporal correlation. The fates of the Aral and the populations inhabiting its immediate region are intertwined to the extent that, as Sandra Postel (2000, p. 943) stated so elegantly, "The Aral Sea tragedy provides the most striking example of the interconnections between the health of an ecosystem and that of the economy, community, and people dependent on that ecosystem".

The Aral Sea crisis has generated widespread superlatives describing the destructive nature of its desiccation. The drying Aral and its host of regional impacts has alternately been referred to as "one of the world's major environmental problem areas" (Spoor 1998, p. 409), "an ecological catastrophe zone" (Lipovsky

1995, p. 119), "one of the major human-induced environmental degradations of the twentieth century" (Glantz 1998, p. 26), "one of the most serious, if not disastrous anthropogenic environmental crises of the 20th century" (Zonn, et al. 2009, p. 1), and "one of the saddest tales of human-induced ecological disaster in history" (Middleton 2007). Mindful that the above direct quotes emanate from academic literature, written by individuals ideally not prone to hyperbolic excess, the negative consequences may even, if possible, be understated. While without question an anthropogenic crisis, the Aral basin's physical environment has contributed. The region's arid environment and hot summers (influencing evaporative losses), low precipitation totals, and naturally occurring drought conditions have also influenced the Aral Sea's water balance.

This chapter aims to investigate the interrelationships between the natural, physical environment and human society in the Aral Sea Basin. The primary focus will be on the basin's regional economy and two of its important sectors, fishing in the Aral Sea and cotton production elsewhere in the basin. Examining these two vital economic sectors, as well as some general linkages between them and the natural environment can inform a broader examination of nature-society interrelationships operating in the Aral Sea Basin and inherent in the Aral Sea crisis. The chapter proceeds, following this introduction, with a description of the Aral Sea Basin, first in its environmental (biophysical or 'natural') setting and second in reference to its human (societal) dimensions. The author will provide a historical overview of Aral basin developments since 1960 highlighting elements of human-environment interaction. Next, the Aral Sea Basin regional economy will be introduced, including more detailed examinations of basin cotton production and fishing in the Aral Sea. Following this, an attempt will be made to tease out some of the nature-economy linkages that can offer insight and guide a broader view of human-environment interrelationships within the basin and the Aral Sea crisis. The chapter concludes with contrasting outlooks, one of optimism for the northern Aral Sea and another of resigned acceptance that the southern Aral's dire condition is unlikely to improve in the near to medium term.

12.2 The Region

The region of analysis here will be the Aral Sea Basin, including what remains of the Aral itself, as well as the drainage basins of its two feeder river systems, the Syr Darya (Jaxartes of antiquity) and Amu Darya (famed Oxus of old) (Fig. 12.1). The Aral basin-level of analysis presented here is the most appropriate for this examination of the interrelationships between the region's human populations and its natural, physical environment for several reasons. First, while the most dramatic environmental damage has occurred in the Aral itself and the deltas of the Syr Darya and Amu Darya, the anthropogenic drivers of such damage, both historical and contemporary, have taken place well upstream of the Aral Sea. Second, the major population concentration in the Aral basin, the Fergana Valley (also well

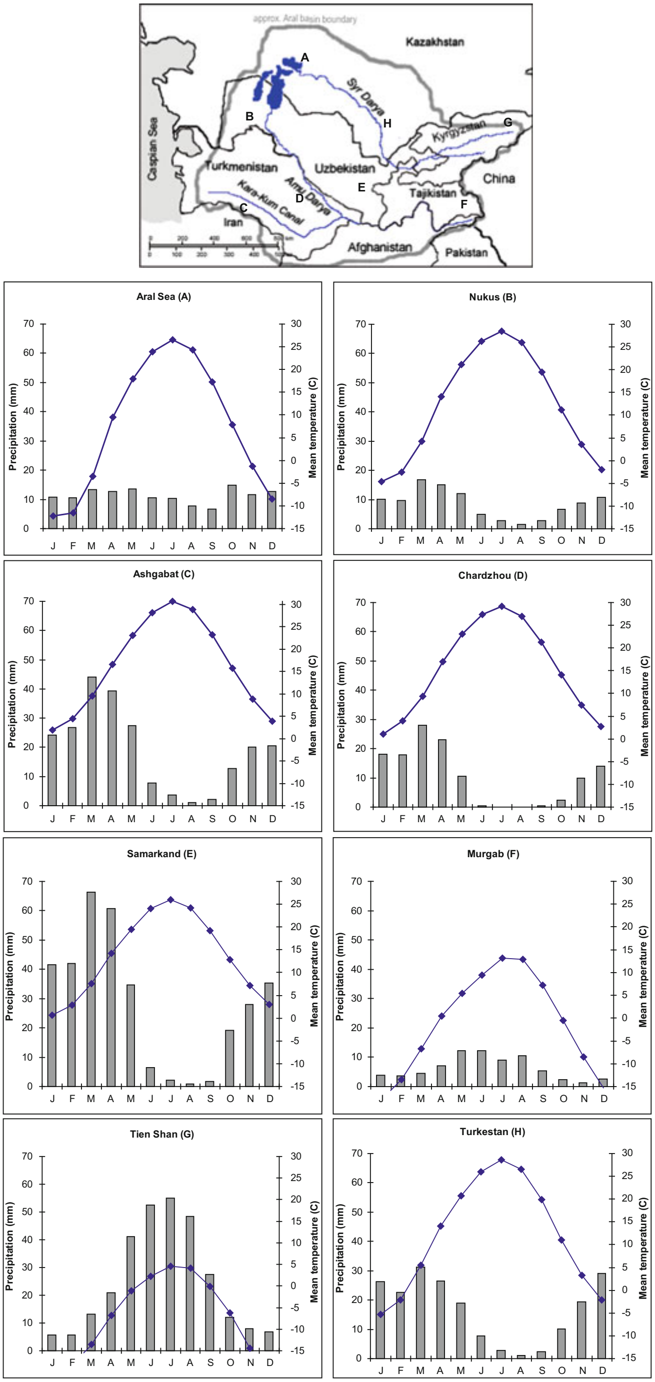

Fig. 12.1 The Aral Sea basin, and selected climographs

upstream of the Aral), is the current site of increasing pressure on freshwater resources, as well as tenuous (and curiously delimited) international borders between Uzbekistan, Tajikistan, and Kyrgyzstan. While increasing population pressure and the complexity of the international boundaries here greatly enhance the potential for water conflict in the Fergana Valley, conflict over water resources exist throughout the basin. Third, the main (though not entire) brunt of the detrimental effects on human health conditions as a result of the Aral Sea crisis seem to be concentrated in three administrative divisions within the Aral basin, the autonomous Republic of Karakalpakistan in Uzbekistan, the Kyzylorda *oblast* in Kazakhstan, and the Dashaguz *velayat* in Turkmenistan.

Clearly, then, limiting regional focus to what remains of the Aral Sea is not sufficient in examining the largely anthropogenic causes of the Aral crisis, nor is it adequate in addressing the natural environmental or societal impacts. Glantz (1999, p. 24), for one, emphasizes the regional (basin) dimension of the Aral crisis and the necessity of this regional view for any successful amelioration efforts, arguing for the imperative that “the Aral Sea Basin be viewed holistically as a ‘meta-ecosystem’: a system that cannot be separated into its many linked parts”. As this meta-ecosystem approach highlights spatial flows between different ecosystems (Loreau et al. 2003), it is particularly relevant to the Aral Sea crisis case given the multitude of biotic and abiotic flows (the most obvious being water, but also energy, nutrients, fish, agricultural chemicals, dust, etc.) across the entire expanse of the Aral basin.

12.2.1 The Physical Setting

Covering an area greater than two million km^2 (Micklin 2010), the Aral Sea Basin lies within the predominantly arid environs of Central Asia. What remains of the Aral itself lies in the border region between Kazakhstan and Uzbekistan. The lake’s recession caused it to split in the late 1980s into a smaller northern portion (today the northern Aral Sea or NAS) in Kazakhstan and a larger southern section, much of which is situated in Uzbekistan. Continued desiccation during the ensuing two decades has resulted in a further fragmentation into four distinct water bodies, the northern Aral Sea (NAS), western and eastern basins of the larger, southern Aral, and the Tshche-bas Gulf positioned equidistant between the NAS and the western basin of the large southern Aral. Both of the basin’s river systems originate to the east, among the glaciers nestled atop the Tien Shan (for the Syr Darya) and Pamir/Hindu Kush (for the Amu Darya) mountain ranges. As the rivers flow generally westward and northwestward toward the Aral Sea, they traverse alpine, foothill, steppe, and desert environments. The Naryn and Karadarya rivers flow westward through Kyrgyzstan and join to form the main Syr Darya in the densely populated Fergana Valley. The Syr Darya continues its flow westward across northern Tajikistan, reenters Uzbekistan, continuing its northwestern flow through Kazakhstan to the NAS. Flowing generally westward, the Amu Darya forms much of the political boundary between Afghanistan and Tajikistan, the entire boundary between Afghanistan and Uzbekistan, part of the Turkmen-Afghan border, and turns northwest through eastern Turkmenistan into the autonomous republic of Karakalpakistan. Here it expires (except in heavy flow years such as 2010 when it still reaches the Eastern Basin of the Large Aral) in the lower Amu Delta near where it once emptied into the Aral Sea from the south. While not a 'natural' river, Turkmenistan's Kara-Kum canal is the largest irrigation canal in the world (O'Hara and Hannan 1999), and has been described as "the single most important factor contributing to the diminution of inflow to the Aral" (Micklin 1988, p. 1171). Following its construction in 1954 and subsequent lengthening nearly to the Caspian Sea, the Kara-Kum canal has greatly expanded the areal extent of the Aral Sea Basin.

Climatic conditions within the basin vary widely. Immediately surrounding the Aral Sea are midlatitude deserts (Köppen climate classification BWk), including the Kyzylkum desert primarily in western and central Uzbekistan and western Kazakhstan and the Kara-Kum desert throughout much of Turkmenistan. Much of the northern Aral basin lies in midlatitude steppe (Köppen's BSk) while southernmost portions are considered subtropical steppe (BSh). The other highly generalized climate category in the Aral basin represents the great mountains (H) that dominate the eastern and southeastern boundary of the region, of particular note the Tien Shan, Pamir, and Hindu Kush ranges.

Intra-basin climatic variation can also be discerned from an examination of selected climographs from across the region (Fig. 12.2). Monthly precipitation (total, mm) and temperature (mean, °C) data were acquired from a dataset (Williams and Konovalov 2008) covering over a century of readings from 270 weather stations and data collection points across Central Asia. Eight locations in the Aral basin were chosen to show spatial variation in temperature and precipitation patterns across a variety of broad climate classifications and elevations. For each location (Aral Sea, Nukus, Ashgabat, Chardzhou, Samarkand, Murgab, Tien Shan, and Turkestan) monthly data values for both temperature and precipitation were averaged for the entire period (generally about a century, though duration of coverage and gaps in data collection varied among weather stations) of available data. The resulting climographs, therefore, represent the longest-term averages possible of collected precipitation and temperature data within the Aral basin.

In general, the region's aridity conforms to expectations of desert and steppe climates, though average monthly and yearly precipitation amounts vary by location. The most arid location among those presented here is the Murgab (location E in Fig.12.1) meteorological station in the Pamir Mountains (station elevation 3,576 m) with a long-term average yearly precipitation total of just 74 mm. Other locations with less than 200 mm average yearly precipitation totals include Nukus, Uzbekistan (B in Fig. 12.1, elevation 75 m, average yearly precipitation total 103 mm), Chardzhou, Turkmenistan (D, 193 m, 125 mm), the Aral Sea station near Aralsk, Kazakhstan (A, 62 m, 136 mm), and Turkestan, Kazakhstan (H, 207 m, 198 mm). Ashgabat, Turkmenistan (C in Fig. 12.1, elevation 227 m, average yearly precipitation 229 mm) and Samarkand, Uzbekistan (E, 726 m, 337 mm) have somewhat greater yearly precipitation totals, although monthly averages peak in

Fig. 12.2 Cotton featured in official Soviet seals of the Kyrgyz (*top left*), Tajik (*top right*), Turkmen (*bottom left*), and Uzbek (*bottom right*) republics (Source: USSR Constitution (USSR Eighth Congress 1972))

the spring and, like most of the lower elevations throughout the Aral basin, summers are very dry. At some places within the Aral basin, summer 'dry rains' occur, where the extreme desert heat results in the evaporation of precipitation before it hits the ground (Sinnot 1992). At mountain locations, precipitation peaks in the summer, as exemplified by the Tien Shan station in Kyrgyzstan (G, 3,614 m, 297 mm), and even the Murgab (F) location at which sparse precipitation 'peaks' in May and June. Throughout the lower elevation portions of the Aral basin, summer temperatures are high (at Ashgabat, for instance the long term average temperature in July exceeds 30 °C), and the very large range between high (summer) and low (winter) monthly mean temperatures (most dramatically at the Aral Sea station near Aralsk, where the difference between January and July monthly temperature averages is nearly 40 °C) demonstrate the influences of continentality in this aspect of climate in the Aral basin.

Beyond the spatial characteristics of its river systems, landforms, and climate, the natural, physical environment of the Aral basin also features a unique milieu of plant and animal species. A region's biodiversity is represented by such species variation, as well as genetic variations within and across species and of the various taxonomic groupings of species (Wilson 1992). Biodiversity is a vital component of ecosystem integrity, and minimizing biodiversity loss is important for the continued provision of ecosystem services (Hooper et al. 2005). This is especially the case in arid regions, where the loss of a single species has a greater proportional impact on biodiversity than in, say, a rainforest environment with a greater density and richness of biotic species (McNeely 2003). As a result, maintaining biodiversity in the arid Aral basin is of paramount importance given the general ecological damage and biodiversity losses stemming from the Aral Sea crisis, and the continued anthropogenic pressures currently threatening the sustainability of much of the region's habitat.

In recognition of regional aggregate species uniqueness and the anthropogenic threats to ecosystems and biodiversity vitality, a prioritization of global conservation efforts has led to the delimitation of 'biodiversity hotspots' in places displaying "exceptional concentrations of endemic species and experiencing exceptional loss in habitat" (Myers et al. 2000). Conservation International (2012) has identified the "Mountains of Central Asia" as one of 34 such biodiversity hotspots based on the endemic species in the region and based on habitat losses, both those that have occurred to date and those forecast in the future. Much of the Aral Sea Basin is incorporated into this biodiversity hotspot. Included here are all the territories of Tajikistan and Kyrgyzstan, northeastern Afghanistan, southeastern Uzbekistan, southern and southeastern Kazakhstan, and part of eastern Turkmenistan. This biodiversity hotspot includes 1,500 endemic species of plants and 16 such species of animals (Conservation International 2012), although some are found in hotspot habitats outside the Aral basin in extra-basin regions of Kazakhstan and western China.

In addition to the many endemic species in the Aral Sea Basin, a significant number of plant and animal species are threatened and/or endangered (including those inhabiting the basin and not endemic). Such floral species include several species of tulip, almond and walnut trees, and several types of fruit trees (Conservation International 2012). A selection of threatened and/or endangered fauna species on which scholars have written include the Snow Leopard (*Uncia uncia*) (see Jackson et al. 2006), waterfowl species including the Great White Pelican (*Pelecanus onocrotalus*), Pygmy Cormorant (*Phalacrocorax pygmaeus*), Marbled Teal (*Marmaronetta angustirostris*), and Glossy Ibis (*Plegadis falcinellus*) (Kreuzberg-Mukhina 2006), the Marco Polo sheep (*Ovis ammon polii*) (Michel and Muratov 2010), Argali wild sheep (*Ovis amman*) (Shackleton 1997) the Striped hyena (*Hyaena hyaena*) (Harihar et al. 2010), and the Saiga antelope (*Saiga tatarica*) (Bekenov et al. 1998). In the Aral Sea itself, threatened and/or endangered species include many aquatic invertebrates from the family *Podonidae* (Aladin

1995), and a number of fish species including the possibly globally extinct shovelnose sturgeon (*Pseudoscaphyrhynchus fedtschenkoi*) (United States Agency for International Development 2001). High profile global extinctions of species once inhabiting the Aral Sea Basin include the Aral salmon (*Salmo trutta Aralensis*) (see e.g. Micklin 2006), and the Turan tiger (*Panthera tigris vergata*) (Prynn 2003).

12.2.2 The Human Presence

Humans have inhabited the Aral Sea Basin region for many millennia. In the wider region of Central Asia, human existence dates to the early Paleolithic (Stone Age) more than a million years ago (Zerjal et al. 2002). Stone Age archeological sites are scattered throughout the Aral basin, and Neanderthal remains have been unearthed at Teshik-Tash (southeastern Uzbekistan), representing the southeastern extent of known Neanderthal settlement (Krause et al. 2007). More recently, the region has been both a recipient of human migrations and incursions from elsewhere, and has also been the center of a number of empires that have diffused outward from the Aral basin. Extra-regional immigrants to the region (more often than not as conquering forces) have included the Scythians (see Rolle 1989), Arabs (Gibb 1923), Persians (Fuller 1990), Turks (Findley 2005), Mongols (Grousset 1970), Russians (Peirce 1960), and most recently (until 1991) citizens of the Soviet Union Gleason (1997, p 32) has described the inflow and outflow of these various peoples and empires as an “ebb and flow of invasion and retreat.” Adding to this dynamism has been a number of empires whose geographical foci have been in Central Asia’s Aral Sea Basin and whose outward influences have also waxed and waned. Among these were the Bactrian (centered on the upper Amu Darya river valley) (Rawlinson 2002), Seljuk (from Merv, in today’s Turkmenistan) (Dinc et al. 2012), Khwarezm (based in the Amu Darya Delta south of the Aral Sea) (Tolstov 1946), and perhaps most dramatically Timurid (founded by Tamerlane and centered on Samarkand in today’s Uzbekistan) (Manz 1989) empires.

In addition to the inward and outward diffusion of peoples and empires into and out of the Aral basin, another major cultural influence on the region was the great Silk Road network of trade routes traversing the region from the second century B.C. to roughly the fourteenth century A.D. These routes linked China and India with Europe and represented a continental flow of traded goods, as well as the migration of people and such cultural attributes as language, religion, and ideas. In many ways the Aral Sea Basin was the main nexus of the Silk Road network, with Merv (today’s Turkmenistan), Bukhara (Uzbekistan), Samarkand (Uzbekistan), Khojand (Tajikistan), and Osh (Kyrgyzstan) important centers facilitating East–west movements, and Samarkand, Bukhara, Termez (Uzbekistan), and Balkh (Afghanistan) anchoring an important North–south route to and from India (see e.g. Abazov 2008). Beyond trade, exchange, and cultural influences, it appears that the Silk Road has also influenced the very genetic makeup of Central Asian populations. Regional populations exhibit a striking genetic ‘admixture’ of

European and eastern Asian genes (Comas et al. 1998), seen as very likely the result of contact between eastern Asians and Europeans via the Silk Road (Comas et al. 2004). In recognition of the region's unique historical influences and articulating wonderfully the impact of this on the region's population, Starr (2009) states "somewhere in the DNA of these peoples is the capacity to manage great empires and even greater trading zones, to interact as equals with the other centers of world cultures, and to use their unique geographical position to become a link and bridge between civilizations" (p. 43).

Today, approximately 60 million people inhabit the Aral Sea Basin (a rough estimate based on adding to the populations of Uzbekistan, Kyrgyzstan, and Tajikistan populations from northern Afghanistan, southern Kazakhstan, and subtracting westernmost Turkmenistan; the number corresponds to a figure given in IFAS (2009)). Human population distribution within the region is largely conditioned by the availability of fresh water, resulting in clusters of population in oasis urban centers and riparian river locations. A rough population density estimate for the Aral basin (using the aforementioned estimates for land area and population) is approximately 30 persons per square kilometer. Aside from the basin's major urban concentrations (e.g. Tashkent, Dushanbe, or Ashgabad) the most densely populated region is the Fergana Valley (northern Tajikistan, northeastern Uzbekistan, and southwestern Kyrgyzstan) where Uzbekistan's Andijan region (formerly *oblast*, now *velayat*) has a population density close to 490 persons per square kilometer (Hanks 2005). At the other extreme are vast expanses of uninhabited territory through much of the Kara-Kum desert in Turkmenistan, the Kyzylkum desert in Karakalpakistan, and similar desert and steppe regions in Kazakhstan's Kyzylorda *oblast*.

The people of the Aral Sea Basin speak, collectively, a number of different languages. As spoken today, much of the language differentiation across the region owes its current form to historical developments, most importantly perhaps the Soviet experience. The Russian language remains the lingua franca across the basin, as invariably any regional gathering of government officials or individuals working in regional water management is conducted in this language. Russian retains its status as an official language in both Kazakhstan and Kyrgyzstan. Turkic languages are also widespread, including Uzbek, Kazakh, Kyrgyz, Turkmen, and Karakalpak. Tajik, a Persian language, is widely spoken throughout Tajikistan as well as in other areas with minority Tajik populations in the Fergana Valley and ancient Silk Road centers in Uzbekistan, particularly in Bukhara.

In terms of religion, the entire Aral Sea Basin falls within the larger Islamic realm, though religiosity and the brand of Islam adhered to do vary across the region. Muslim religiosity through the wider region has been contextualized by the observation that nearly "all indigenous Central Asians consider themselves Muslim, although a large number of Central Asians have only a vague idea about what that implies" (Gleason 1997, p. 42). Islamic influences in the Aral basin primarily stem from Sunni Islam (the Hanafi school), Sufism, Shi'ism, and a popularized Islam that features frequent pilgrimages to local shrines and tombs, often to those of venerated Sufi scholars and teachers (Gunn 2003).

Politically, the Aral Sea Basin today is fragmented into territories of six independent states (five former Soviet republics plus Afghanistan) and two autonomous regions (Karakalpakistan in Uzbekistan and Gorno-Badakhshan in Tajikistan). The political borders of the former Soviet republics owe their demarcation to the early Soviet period, and are often rather arbitrary in the sense that they neither follow nor correspond to natural geographical or national/ethnic divisions. In many ways, in fact, these borders were delimited intentionally to minimize cultural homogeneity (a beneficial factor for an independent state) and separatist pressures (see International Crisis Group 2002). Each of the former Soviet Central Asian republics has pursued its own political and economic transition path since gaining independence with the USSR's dissolution in 1991. Over the course of the ensuing two decades, Uzbekistan and Turkmenistan have become home to strong authoritarian presidencies exercising near complete control over respective populations, and feature the most repressive regimes in the region (Anceschi 2010). Kyrgyzstan, the region's lone member of the World Trade Organization (WTO), was once, shortly after independence, hailed as the region's most liberal reformer. The state has experienced two revolutions since 2005 and most recently (2010) a bloody ethnic conflagration in and around the southern city of Osh. Tajikistan, upon independence, plunged into civil war that raged through much of the 1990s. War and instability have hindered Tajikistan's transition efforts, and it remains today an exceptionally weak state (Heatherwhaw and Herzig 2011).

Large and natural resource-rich Kazakhstan features a strong presidency, and despite a marked diversity among its ethnicities and nationalities, has been noted for its two decades of political stability (Ó Beacháin and Kevlihan 2011). Unstable and war-ravaged Afghanistan descended into civil war shortly after the Soviet withdrawal in 1989 and continues to be besieged by armed conflict today following US and NATO military action since 2001. The current transboundary nature of the Syr Darya and Amu Darya now poses international challenges to basin water management, and adds an international political element to potential solutions to the Aral Sea crisis.

12.3 The Aral Sea and Its Basin Since 1960

The year 1960 is perhaps the most prominent date referenced in Aral Sea scholarship produced over the past three decades. This date's near ubiquity stems from its reference as a starting point from which subsequent area, water level, or volume (to name just three characteristics, salinity is another) of the Aral Sea are compared (a subset includes Micklin 1988, 2007, 2010; Aladin et al. 2009; Micklin and Aladin 2008; Glantz 2007; Jarsjö and Destouni 2004; Spoor and Krutov 2003; UNDP 2003; Postel 2000; Spoor 1998; McKinney 1997).

Whereas 1960 represents the start of the Aral's "most recent and rapid anthropogenic desiccation" (Aladin et al. 2006, p. 1), a near century of key developments within the Aral basin presaged this cataclysmic development. First, largely spurred by cotton supply disruptions stemming from the US Civil War (1861–1865), Tsarist Russia focused on the newly-acquired Central Asian territories for large scale cotton production. Such a focus in the basin's arid environment necessitated a sharp increase in irrigation systems. By the start of World War I (1914) Russia had become a leading world cotton producer (Whitman 1956) and a number of now-familiar problems, including the raising of groundwater tables and increased soil salinization, within the Aral basin became apparent. Water logging had created flooded swampland areas to such an extent that outbreaks of malaria had become widespread in certain areas (Matley 1970).

Second, as part of what has been termed the 'Stalin plan' to remodel or transform nature (see Grigoryev 1952; Hollis 1978; Kovda 1953), the Aral basin became the locus of plans for gigantic dams and hydroelectric projects as well as expansive irrigation canal networks showcasing Marxist (Stalinist) – informed human conquest of nature. The most grandiose of the Stalin plans were abandoned after his death in 1953 (see Chap. 16). But other smaller scale, although gigantic, projects were implemented. These included the Kara-Kum canal (initial construction started in 1954 and continues today), the world's largest such structure that certainly fit the mold of Soviet "grandiose projects aimed at radically altering the natural environment to meet the needs of an industrial society" (Micklin 1969, p. 199). Irrigation would continue to expand in the Aral basin after 1960, although the scale of the projects undertaken during the 1950s (and of course the water these canals diverted from the rivers to anchor a burgeoning raw cotton production system) proved a tipping point for the Aral Sea that would soon prove unsustainable.

The key to the post-1960 recession of the Aral Sea was a change in its water balance: the interplay between water gain and water loss in the hydrologic cycle. As a terminal lake with no outflow, the Aral's water balance is primarily determined by discharge from the Amu Darya and Syr Darya (gain) versus water losses through net evaporation (evaporation from the surface minus precipitation on it). By the 1960s, the Aral Sea had entered deficit conditions (net evaporative losses exceeding river inflow) that would continue to generally worsen to the present (Micklin 2010).

By the beginning of the 1970s, the Aral Sea had already begun to show the effects of nearly a decade of water deficit conditions. Between 1960 and 1971, for instance, the Aral's average level had dropped by 2.3 m, its area had declined by 6,700 km^2 and its volume shrunk by 165 km^3 (Glantz 1999; Spoor 1998). During the mid-1970s an additional challenge became apparent. Silt and sediment deposits within the basin's irrigation network demanded immediate attention. From the estimated 250,000 km of irrigation canals operating in the Aral basin at this time, 500 million tons of silt and sediment were extracted on an annual basis (Hollis 1978). This decade also witnessed the gaining traction of yet another grandiose project, the diversion of Siberian river water (from the Ob and Irtysh, which flowed to the Arctic Ocean) to the Aral Sea Basin (see Chap. 16 for more details on this project). This grand scheme would have brought water 2,500 km south to the Amu Darya through an immense canal (Sibaral) with supporting dams and pumping infrastructure (Micklin 1988). The sheer magnitude of this proposed plan might not have been overstated by Josephson (1995, p. 552) who remarked that it "would have exceeded the pyramids as a monument of engineering prowess."

The 1980s brought continued ecological damage to the Aral Sea, though the nature and severity of the crisis would not be publicly acknowledged by Soviet leadership until Mikhail Gorbachev's *glasnost* policy in the decade's second half. Throughout the decade the basin witnessed near exhaustion of all surface water, with no (or very little) water reaching the Aral in most years (Micklin 1992). In all, compared to its status in 1960, by 1987 the Aral Sea's level had dropped by almost 13 m and its area had decreased by 40 % (Micklin 1988). By 1987–1988, this continued recession caused the Aral to split into two main bodies, the smaller, northern portion (NAS = North Aral Sea) wholly within Kazakhstan and the much larger southern body (Large Aral) straddling the Kazakhstan-Uzbekistan border (though with most of its area within the latter). The Gorbachev era brought with its openness policy a frightening realization that natural environmental conditions within the USSR were much worse than anyone in the Soviet leadership had ever admitted (Pryde 1991). The Aral Sea crisis was in all likelihood the most glaring example of this, for some have labeled it "the worst single instance of agricultural ecocide in the Soviet Union: the murder of the Aral Sea and the contamination of the cotton fields that have swallowed the rivers that once fed it" (Feshbach and Friendly 1992, p. 73).

The 1990s soon brought the demise of the Soviet Union, and newfound political independence for Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan. Former largely nominal republican boundaries were quickly transformed into internationally recognized (for the most part) political borders, with the Amu Darya and Syr Darya basins (and the Aral itself) now politically fragmented. As the Aral had split into its northern and southern portions four years prior, the first major effort to ameliorate water losses in the NAS in Kazakhstan began shortly after independence. In 1992, an earthen dike was constructed across the Berg Strait, just to the southwest of the Syr Darya Delta. By April of 1993, the dike had been breached, largely by wave action and the lack of an adequate means to discharge excess water. Periodic breaches and stop gap repairs continued until a storm in the spring of 1999 destroyed the dike and swept 29 repair workers away, killing two of them (Aladin et al. 2008a). This tragedy stopped all further work on this version of the dike, though even this inferior structure yielded positive results for the NAS. With a more than 3-m rise in water level, the overall ecological integrity of the NAS greatly improved, with related partial restoration of biodiversity (Aladin et al. 2008b). The ecological improvements in the NAS resulting from this first dike showed that at least partial restoration of this relatively small part of the Aral was feasible, and paved the way for a second, more technically sound dike completed in 2005.

Just months following the Soviet collapse, representatives of each of the five Central Asian republics met in Almaty, Kazakhstan in an attempt to codify the pressing need for cooperation in managing the Aral basin's water resources. This meeting yielded a number of articles of agreement, including the formation of the Interstate Commission for Water Coordination (ICWC). In all, the 1990s featured a number of high level, official regional agreements, resolutions, and one declaration (Nukus in 1995) among the newly independent states of Central Asia focused on water, environmental conditions, and economic development in the Aral Sea Basin (see Mitchell 2002).

By the early 2000s, in spite of a decade of international attention focused on the plight of the Aral Sea, high-level rhetoric and meetings pledging cooperation and assistance, the Aral continued its recession. At this time, a number of studies lent credence to a popular belief that the Aral's recent recession and desiccation had itself changed the regional climate (see Chap. 17 for a more detailed treatment of climate change). Khan et al. (2004) show significant climate changes, particularly in the southwestern portions of the Aral basin, are possibly a direct result of the sea's desiccation. Small et al. (2001a) analyze the impact of Aral Sea recession (1960–1997) on regional surface air temperatures. They find more striking changes in the local climate, with minimum, maximum, and mean temperatures proximate to the Aral changing by as much as 6 °C with substantial warming in the spring and summer and cooling in the fall and winter. In addition, the groundwater contributions to the Aral Sea's water balance were found during this period to be increasing in importance. As of 2002, the discharge of groundwater to the Southern Aral's northwest area and to the NAS is likely to have increased, particularly in proportional terms (Jarsjö and Destouni 2004).

The year 2005 was a landmark for the Aral Sea, particularly for the NAS and its regional population and natural environment. This year marked the completion of what is formally called the Syr Darya Control and Northern Aral Sea Phase I Project (World Bank 2010), a nearly $86 million, World Bank and Republic of Kazakhstan sponsored effort to rehabilitate the NAS. Specific elements constructed included a 13 km (8-mile) dike (its location largely mirroring that of the ill-fated dike from the previous decade), 200 m Kok-Aral dam with release capacity of water to the south, and the concrete and steel Ak-lak spillway with additional rechanneling of the lower reaches of the Syr Darya.

The Berg Strait part of the project was completed in August of 2005. The rise of the North Aral Sea level began immediately and had near immediate positive results. Owing in part to greater Syr Darya winter discharge than expected into the NAS, the project's design height sea level target of 42 m above sea level (asl) was reached in March of 2006 (Micklin 2010). Subsequent popular press accounts heralded the 'return' of the Aral Sea (see e.g. Conant 2006; Finn 2007; Fletcher 2007). Others more accurately ascribed success to the much smaller NAS (e.g. Pala 2011; Lillis 2009). Regardless, ecological conditions have greatly improved within this smaller part of the Aral Sea, with positive changes in biodiversity, habitats, and increasing numbers of migratory birds, waterfowl, and fish. The partial return of the fishing industry here (discussed later) has also engendered a true sense of hope among the region's human population.

The apparent success in stabilizing the NAS aside, the current state of the entire Aral Sea is more uncertain and somewhat more dismal. Comparing satellite imagery over just the past decade shows a water body continuing its desiccating retreat, most dramatically in its southern areas (in particular the eastern basin of the larger

Southern Aral). As of 2009, the Aral Sea as a whole (compared to its 1960 state) had experienced a drop in water level by 26 m, a reduction in surface area by 88 %, and a decrease in water volume by 92 % (Micklin 2010). Clearly any discussion of the return of the Aral Sea misses the mark, and currently borders on the unfeasible given current economic and political priorities. A number of experts have proposed plans (see Micklin 2007, 2010; Micklin and Aladin 2008) to at least stabilize what remains of the Large Aral Sea. These scenarios would require a much greater financial commitment, more dams and artificial rechanneling infrastructure, and perhaps most challenging, a greater degree of water use efficiency along the course of the Amu Darya. Given the recent success in the NAS, however, there may still be hope for stabilizing the Aral Sea at its current state.

12.4 Aral Sea Basin Regional Economy

The Aral Sea Basin regional economy, while politically fragmented as discussed earlier, remains unified in its primary sector dominance, particularly in agricultural production and natural resource commodity extraction. Both Turkmenistan and Uzbekistan are among world leaders in the production and export of both cotton (discussed later) and natural gas, with production of other agricultural products also important. In Kyrgyzstan, the mining of gold is an important economic sector, as is the extraction of other minerals. Production at the Kumtor gold mine (located at the northeastern end of the Aral basin), for instance, alone accounts for over half of Kyrgyzstan’s industrial output and more than twelve percent of gross domestic product (GDP) (Eurasianet 2012). Tajikistan remains among the world’s poorest countries, with nearly half its GDP coming from remittances, mainly from Russia (Danzer and Ivaschenko 2010). Aluminum, along with cotton is a major export for Tajikistan. The Tajik Aluminum Company (Talco) plant, situated between the capital city Dushanbe and the Fergana Valley, alone accounts for 60 % of Tajikistan’s exports (Radio Free Europe/Radio Liberty 2010). Kazakhstan has a region-leading economy greatly buoyed by its substantial petroleum production and exports. This state’s Aral Sea Basin region, while not involved directly in the extraction of oil or natural gas, is the site of a major oil refinery as well as two large uranium deposits that contribute nearly 75 % to its world-leading uranium production (KazAtomprom 2011). Irrigated agriculture (mainly rice and cotton) is also important here, as is the current revival of the fishing industry (discussed later) to the immediate NAS region. Afghanistan has been categorized as a “war economy” where 3/4ths of the world’s opium is produced (Rubin 2000, p. 1790), though the vast majority of poppy cultivation and opium production takes place in southern regions well distant from the Amu Darya Basin (BBC News 2011). Aral Sea Basin areas in northern Afghanistan are the state’s most productive agricultural lands with both irrigated and rain-fed farming (Ahmad and Wasiq 2004).

As noted previously, the Aral Sea Basin economy remains closely linked to regional natural-environmental resources, particularly as primary sector economic activity dominates. Especially important are the direct extraction of minerals, crude oil, natural gas, and uranium in addition to agricultural production, the rearing of livestock, and fishing. These latter primary sector activities are particularly sensitive to the Aral basin's ecological integrity. In an effort to examine the genesis, continued duration, impacts, and most recent human intervention to mitigate the Aral Sea crisis, two sectors of the regional economy will be discussed, cotton and fishing. The former is sown and harvested near the Aral Sea in Karakalpakstan, a semiautonomous Republic within Uzbekistan, but mainly well upstream of the Aral Sea, while the latter historically occurred in the entire Aral Sea but today is limited to the partially restored NAS.

12.4.1 Cotton

Cotton, likely the most important textile fiber in the world today is also, among the world's agricultural crops, one of the most demanding in terms of water consumption (Karlsson and Björklund 2009). Much of this voluminous water requirement is a result of cotton's relatively high sensitivity to water stress, where such stress results in individual plant growth retardation and ultimately in lower fiber yields (Wrona et al. 1999). Within the arid Aral Sea Basin, only a select few localized areas (along the bases of mountains where soil fertility and precipitation permit dryland farming) allow for non-irrigated agriculture (Craumer 1992). As a result, for large-scale cotton production to occur in the region, the continuous availability of irrigation water is vital. When the Russian empire set its sights on Central Asia's Aral basin as a focal point for cotton production in the mid nineteenth century, potential water supply from the mighty Amu Darya and Syr Darya rivers was indeed plentiful and must have seemed inexhaustible. By 1915, Russia had become the world's third largest cotton producer (behind only the United States and India) aided in large part by the expansion within the Aral Sea Basin of irrigation infrastructure and sown cotton area, and the introduction of an imported, higher-yield cotton variety (American upland, having longer fiber strands than the traditional Central Asian cotton) (Whitman 1956).

The Soviet period, as discussed previously, imposed upon the Aral Sea and its basin herculean irrigation projects, which were scaled-down from the Stalin era plans to remodel, transform, and conquer nature, but still were massive projects. Cotton production was the main driving force behind these. These human modifications did in fact transform the Aral basin landscape, to say nothing of the Aral Sea itself. The post-1960 recession of the Aral Sea corresponds with drastic increases in Soviet irrigation and production of raw cotton within the basin. Between 1960 and 1988, area under cotton cultivation rose from 1.9 to 3.1 million hectares, and cotton production increased from slightly less than 4.3 to 8.7 million tons (Pomfret 2002). Further evidence of the Aral basin's importance to Soviet cotton production can be seen in the official republican seals of the Kyrgyz, Tajik, Turkmen, and Uzbek republics during this time period (Fig. 12.2).

Unsustainable water withdrawals to irrigate cotton fields represent just one facet of negative environmental and societal repercussions resulting from the Soviet cotton monoculture in the Aral basin. Unlined irrigation canals were inefficient, losing water to both evaporation and seepage into the ground. Rising water tables brought salts and other minerals into the soil and surface water, with correlated land and soil degradation. Soviet cotton production also used the liberal application of agricultural chemicals in the form of fertilizers, herbicides, pesticides, and defoliants. Feshbach and Friendly (1992, p. 79) recount an incident from Tajikistan in 1983, one described as “shocking but not uncommon”. In this case journalists had observed a crop-dusting aircraft spraying defoliant from the air on cotton fields (multiple passes no less) while school children were picking cotton.

The shock of newfound independence with the demise of the Soviet Union in 1991 severely impacted economic, political, and social spheres within the Aral basin states. Against this transformative backdrop, in the early years of independence the region’s cotton sector was also impacted. Between 1990 and 1994, area sown in cotton decreased in each of the basin states (Spoor 1998), as did cotton production (United States Department of Agriculture 2012). During these early years of independence, declining cultivated cotton areas corresponded with increases in area under grain and rice (Spoor 1998). The lone exception was Kazakhstan, which showed declines in cultivated area for both grain and rice, though most of this state’s grain is grown and harvested outside the Aral basin. The other basin states (Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan) for which grain and rice cultivated area has increased show an understandable post-independence shift toward greater food self-sufficiency.

Over the past 15 years of independence, Aral basin cotton area harvested, cotton production, and cotton exports have generally trended upward with slight declines in the most recent (2011/12) marketing year (MY) (Table 12.1). In most cases cotton area, production, and export peaked for this period during MY 2006/2007, with the lone exceptions of cotton area harvested in Uzbekistan, highest in 1996/1997, and Turkmenistan where production and export are highest most recently (2011/2012). Considering the Aral basin’s three top cotton producers (earliest cotton area data for Kazakhstan and Kyrgyzstan were not available) yields have, since 1996/1997, increased rather dramatically in Turkmenistan and Tajikistan and remained essentially the same in Uzbekistan. Cotton yield in Turkmenistan more than doubled during the time period, rising from 1.1 480-lb. bales per hectare to 2.4. Tajikistan also improved its cotton yields (again bales/hectare) from 1.7 to 2.9. The region’s largest cotton producer, Uzbekistan saw a very slight drop in its yield since 1996/1997 from 3.2 to 3.1 bales per hectare.

Also of interest over the past 15 years has been a shift in the proportion of raw cotton production that is exported. In 1996/1997 the basin’s three leading cotton states exported nearly all of their production (98 % in Tajikistan, 100 % in Turkmenistan, and 92 % in Uzbekistan). By 2011/2012 each of these states’ export to production ratio had declined (to 81 % in Tajikistan and 64 % in both Turkmenistan and Uzbekistan). While not a perfectly accurate measure (holdover stockpiles of cotton, for instance, could result in a state exporting more cotton than

Table 12.1 Cotton area harvested, production, and export in the Aral basin: 1996–2012[a]

	MY 1996/97[b]			MY 2001/02			MY 2006/07			MY 2011/2012		
	Area[c]	Prod[d]	Exp[e]	Area	Prod	Exp	Area	Prod	Exp	Area	Prod	Exp
Kazakhstan	n/a	260	200	184	400	300	195	665	625	140	380	325
Kyrgyzstan	n/a	100	55	37	130	115	46	200	200	30	130	115
Tajikistan	235	410	400	245	500	400	255	625	500	200	585	475
Turkmenistan	550	600	600	500	900	600	600	1,100	650	575	1,400	900
Uzbekistan	1,490	4,750	4,350	1,430	4,600	3,600	1,424	5,400	4,650	1,340	4,200	2,700

[a] Data source: USDA Foreign Agricultural Service Office of Global Analysis, Cotton: World Markets and Trade Archives

[b] Marketing year (MY) extends from August 1 to July 31

[c] Cotton area harvested (1,000 ha)

[d] Cotton production (1,000 480 lb. bales)

[e] Cotton exports (1,000 480 lb. bales)

it produced in a given MY), the declining export to production ratios would appear to be a positive development in Tajikistan and particularly so in Uzbekistan and Turkmenistan. Rather than simply exporting nearly all raw cotton as was the case 15 years ago, it is possible (to a greater extent in Turkmenistan and Uzbekistan) that domestic raw cotton processing activities have increased, with corresponding retention of value added and additional domestic employment and income opportunities in processing and textile industries.

In the Aral Sea Basin today, cotton remains "by far the most important cash crop" (Aldaya et al. 2010, p. 15), with three Aral basin states among the world leaders in fiber production and export. March 2012 data (United States Department of Agriculture 2012) place Uzbekistan (ranked 7th globally in cotton production and 5th globally in cotton exports), Turkmenistan (9th in production, 7th in exports), and Tajikistan (17th in production, 11th in exports) among the world's cotton production leaders. Within Kazakhstan (22nd in production, 18th in exports) and Kyrgyzstan (34th in production, 27th in exports), while global rankings might be lower, cotton is still an important economic sector. Kyrgyzstan has strong potential for cotton to become a major GDP contributor, while for the Aral basin area of Kazakhstan cotton is a vital source of local employment and income (Sadler 2006).

In some ways similar to Soviet-era production, the cotton sector today in the Aral basin poses a number of problems for the region's ecology and society. Of primary importance to the Aral Sea's water balance is the continued necessity of the Soviet-scale irrigation infrastructure given the region's low precipitation and high rates of evaporation. In a study analyzing water consumption patterns in the world's top 15 cotton-producing countries (Uzbekistan and Turkmenistan were the only Aral basin states considered here) Chapagain et al. (2006) identify Uzbekistan and Turkmenistan as two of five states least attractive for growing cotton. Not surprisingly, then, water requirements for cotton production are found to be second highest in the world in Turkmenistan and fourth highest in Uzbekistan. The liberal use of agricultural chemicals for regional cotton production also seems to persist. Within both Uzbekistan and Turkmenistan, nitrogen-based fertilizer application rates (210 kg per hectare) are by far the highest, more than double the cotton-state average (91 kg per hectare) (Chapagain et al. 2006). While slightly less than Soviet-era intensity (largely a result of increased expense and/or availability constraints), rates of pesticide applications today on cotton fields in Uzbekistan exceed those recommended by 2–3 times (Williams 2007).

The economic functioning of the cotton sector within the Aral basin's three leading cotton producers resembles in many ways the Soviet centralized control of inputs, production quotas, procurement prices, and export. This is particularly the case in Turkmenistan where "extremely high" (Higgiston 2006) state orders of cotton conform to the annual Soviet-style production plan (Peyrouse 2009). The government of Uzbekistan still has a dominant role in the cotton sector (see Sadler 2006; Peyrouse 2009) with the state still setting production quotas and farmers having no choice in crop selection (Bloch 2002). Recently, however, gradual reforms in property rights and cotton procurement seem to have taken place in Uzbekistan (Spoor 2007). In Tajikistan, the central government still wields a heavy hand within the state's cotton sector. Much of this control is exercised through monopsonistic (single buyer) procurement of raw cotton (Sadler 2006), with government controlled commodity exchange, prices, and exports ensuring profit accrual to the state (Yuldashbaev 2005). In the regional state reform leaders, Kazakhstan and Kyrgyzstan, more liberalized policies have taken hold in general, and in the cotton sector the removal of government control allows farmers a greater freedom of choice between privatized cotton gins (Sadler 2006).

Within the above context, the Aral basin today exhibits wide variation in state control/involvement in the cotton sector, with significant spatial variation among states in the purchase price of raw cotton. In Kazakhstan and Kyrgyzstan, commodity prices paid mirror the global market price, whereas in the other three states such prices are set at artificially low levels. In Uzbekistan, for example, the state-set cotton procurement price was as low as 50 % of the world market price a decade ago (Abdullaev et al. 2007). This spatial price inequality and close proximity to multiple neighboring states (especially with the idiosyncratic international borders in the Fergana Valley) presents a salient regional economy, migration, and border security challenge. The smuggling of raw cotton into Kazakhstan and Kyrgyzstan (to fetch the higher market prices prevailing in these states) from Uzbekistan occurs to such an extent that production and yield statistics in the former two states are likely to be inflated (Sadler 2006). As one might expect, smuggling cotton out of Uzbekistan is a risky endeavor. In 2003, for example, individuals attempting such activity were shot and killed by Uzbekistani border guards (International Crisis Group 2005).

One issue that has gained international notoriety is a holdover from the Soviet period, the continued use of child labor in cotton harvesting. Uzbekistan has been the primary target of scrutiny, where as much as 50 % of annual cotton totals are hand picked by children (Saidazimova 2007). In the cotton-producing region of the Fergana Valley, an estimated 200,000 children are forced to work cotton fields each year (Environmental Justice Foundation 2005). Reports of children as young as 7 years of age helping with the cotton harvest exist, though most school children harvesting cotton in Uzbekistan are 10 years of age or older (International Crisis Group 2005). This situation has led to international calls to boycott cotton from Uzbekistan, though tracing the source of raw cotton in finished apparel is not an easy matter. Levi Strauss & Co., the well-known jeans and apparel manufacturer, recently issued a public statement affirming its ban on Uzbekistan cotton. This statement seems tempered somewhat by the admission that "as cotton makes its way through the supply chain to become finished apparel, there is little transparency into its country origins" (Levi Strauss & Co 2009, p. 1).

12.4.2 Fishing

In the twentieth century, the Aral Sea commercial fishery experienced both its zenith and nadir within the course of less than thirty years. At one time this single water body accounted for seven percent of all fish harvested in the Soviet Union, though by the 1980s the fishing industry had completely vanished from the Aral (Lipovsky 1995). The Aral Sea's long fishing history, of course, predates the USSR. Archeological exploration in the immediate Aral region has revealed a highly clustered pattern of early (Neolithic) human settlements, consistently showing small spear and harpoon points used for fishing (Boroffka et al. 2005). Additionally, fish skeletal remains have been found in excavated human settlement sites around the Aral dating to as early as the third century A.D. (Zonn et al. 2009). Clearly fishes have formed an important part of human diets and local consumption in the Aral region for a long time. With the Russian expansion into Central Asia and the establishment of fishing outposts, this likely marked the first time Aral Sea fish were exported from the region. During his famous expedition to survey and map the Aral Sea, Russian Admiral Alexey Butakoff spent the winter of 1848–1849 in a fort protecting an Orenburg company's fishing operations at the mouth of the Syr Darya (Butakoff 1853).

By the twentieth century fishing had become an important sector providing income and employment in the Aral Sea region. The extent of the Aral's fishery and export capacity during the early years of the Soviet Union may best be illustrated by a single event that rightfully became (and remains today) a source of pride for the city of Aralsk and fishermen based on the NAS. Faced with drought and impending widespread starvation in Russia's Volga and Ural regions, between the Bolshevik and White Armies during the Civil War, the leader of the new Soviet state, V. I. Lenin, penned a letter on October 7, 1921 requesting fish from the Aral Sea's northern shore to help alleviate the famine. In response, Aralsk-area fishermen (primarily from the nearby fishing village of Bogun) and workers loaded 14 rail cars of raw fish that were transported to the affected regions. The text of Lenin's letter remains today memorialized in stone in Aralsk's main square, and a colorful mural depicting the fishermen's response dominates the waiting hall of the city's train station. This particular event wouldn't be the final time that Aralsk and the Aral Sea's fishery would assist the Soviet state during a time of dire need. During WWII (Great Patriotic War) fish were processed, canned, and transported to Soviet troops fighting Nazi Germany under the guiding slogan 'More fish to the front and to the country' (Danish Society for a Living Sea 2004).

By the mid-twentieth century, the Soviet Union's Aral Sea fishery was focused on its two processing centers in Aralsk (Kazakhstan) on the northern shore, and Moynaq (Russian Muynak) in Uzbekistan to the south. In Aralsk, the *Aralrybprom* factory, initially established in 1925, was by the late 1950s processing 20,000 t of fish per year in an enterprise employing 3,000 people. Such fish species as carp, bream, roach, pike-perch, and sturgeon were canned fresh, smoked, salted, and frozen here at this time (Danish Society for a Living Sea 2004). In Moynaq, the fish

Table 12.2 Aral Sea fish catches, 1961–1984

Year	Harvest (tons)	%Δ(y−1)	%peak
1961	34,160	–	83.0
1962	41,170	20.5	100
1963	39,670	−3.6	96.4
1964	41,120	3.7	99.9
1965	31,040	−24.5	75.4
1966	25,060	−19.3	60.9
1967	21,820	−12.9	53.0
1968	16,470	−24.5	40.0
1969	18,900	14.8	45.9
1970	17,460	−7.6	42.4
1971	14,960	−14.3	36.3
1972	16,730	11.8	40.6
1973	16,970	1.4	41.2
1974	15,500	−8.7	37.6
1975	13,462	−13.1	32.7
1976	9,027	−32.9	21.9
1977	6,007	−33.5	14.6
1978	4,045	−32.7	9.8
1979	2,009	−50.3	4.9
1980	2,935	46.1	7.1
1981	656	−77.6	1.6
1982	76	−88.4	0.2
1983	53	−30.3	0.1
1984	0	−100	0

Data source: Yearly fish catch data: Unpublished, Kazakhstan Research Institute of Fisheries, Aralsk, Kazakhstan. Others author's calculations

canning factory, constructed between 1933 and 1941, reached its peak production in 1958 with nearly 22 million cans of fish produced for both Soviet (domestic) consumption and for export (Zonn et al. 2009). At this time, Moynaq's fish processing complex was supplied with fish from 12 collective fish farms, 113 fishing vessels, and 1,200 fishermen (Karimov et al. 2005). Across the entire Aral Sea, fish harvests reached their likely annual maximum in 1957, with 48,000 metric tons caught (Micklin 1988).

As 1960 marked the end of the Aral Sea's recent era of stability, with subsequent desiccation, shrinking surface area, dropping water volume, and increasing salinity this time period also marks a high point in the Aral Sea fishery – after which the economic resource suffered a rapid decline and eventual collapse. Annual commercial fish harvests from the Aral Sea have plummeted from a post-1960 peak in 1962 (41,170 t) to zero tons in 1984 (Table 12.2). Commercial fish harvests from the Aral remained at zero during subsequent years until the recent rehabilitation efforts began on the NAS a few years after the sea's split in 1989.

The Southern Aral today remains bereft of fish (RFE/RL 2009). Yearly fish harvest totals between 1961 and 1984 declined at a rapid rate (Table 12.2). Column three in this table shows each year's fish harvest in terms of percentage change from the previous year, while column four shows each year's harvest as a percentage of the 1962 peak. By 1968 Aral Sea fish harvests were just 40 % of what they were six years earlier. Annual rates of decline were fairly rapid during the 1965–1968 period, with both of these years recording nearly 25 % drops from the previous year. Between 1968 and 1973 Aral fish harvests stabilized at around 40 % of the 1962 total, though the following decade (1974–1984) witnessed the rapid decline and total collapse of the Sea's fishery. Interestingly, though perhaps not surprisingly, this time period corresponded to large water deficits that also resulted in rapid declines in Aral Sea water levels (Micklin 2007). From 1976 to 1978, each year's harvest declined by about 1/3 from the previous year. By 1981 that year's harvest had dropped 78 % from 1980s, and 1982s harvest dropped 88 % from 1981. In 1983, the final year of commercial fish harvests from the Aral Sea until recently, the total catch had dropped 30 % from the previous year and amounted to just one-tenth of 1 % of the Aral's harvest in 1962. At the time of the fishery's collapse, most fish species that disappeared from the Aral Sea were able to survive in the Syr Darya and Amu Darya, as well as in these rivers' deltaic lakes (Micklin 2007).

Prior to the twentieth century, the Aral Sea provided habitat for 20 indigenous fish species belonging to seven families. These native fish included 12 species of carp (*Cyprinidae*), three species of perch (*Percidae*), and single species of sturgeon (*Acipenseridae*), salmon (*Salmonidae*), catfish (*Siluridae*), pike (*Esocidae*), and stickleback (*Gasterosteidae*) (Ermakhanov et al. 2012). The aquatic ecosystem regime of the Aral during this long period featured a variety of ecosystem types, with the vast majority of area considered a brackish water ecosystem. Small areas of freshwater ecosystems existed at the mouths of the Syr Darya and Amu Darya, with transitional freshwater-brackish environments buffering the brackish water around these freshwater areas. Highest salinities in the Aral Sea at this time were found in a narrow zone of transitional brackish-marine ecosystem along the eastern and southeastern shore (Aladin et al. 2009).

After 1960, as other ecological changes in the Aral Sea took place, changes in its commercial fish stock composition (as well as numbers of individuals) occurred as well. Part of this change resulted from a number of introduced fish species. In the early 1960s four species of carp (*cyprinidae*) were introduced into the Aral from China, followed shortly by the introduction of the snakehead (*channidae*) from Turkmenistan's Kara-Kum Canal, and during the 1980s Black Sea Flounder (*Platichthys flesus*) were introduced from the Sea of Azov (Ermakhanov et al. 2012). By the 1980s, the Aral's aquatic ecosystem regime had changed greatly, to the extent that nearly the entire water body was then a marine ecosystem. At the mouth of the Syr Darya, an extremely spatially compact (and very small) variegation of habitats existed, including very thin ribbons of freshwater, transitional freshwater-brackish, brackish, and transitional brackish-marine ecosystems (Aladin et al. 2009).

During the 1990s the Aral Sea's fishery collapse led to severe contraction in the fishing and fish processing sectors. In addition to employment losses for fishermen, the fish processing centers of Aralsk and Moynaq were also decimated. To keep the

Table 12.3 Northern Aral Sea (NAS) fish harvests, 2005–2011

		By species (tons)						
Year	Total harvest (tons)	Flounder	Carp	Bream	Pike-perch	Roach	Asp	Saberfish
2005	695	303	181	57	30	–	–	–
2006	1,360	700	190	120	70	250	30	–
2007	1,910	640	260	410	260	370	80	40
2008	1,490	410	170	360	170	340	90	–
2009	1,885	615	125	470	185	410	80	–
2010	2,810	715	115	835	245	765	70	65
2011	3,520	710	70	1,210	365	1,040	65	60

Data source: Unpublished, Kazakhstan Research Institute of Fisheries, Aralsk, Kazakhstan

factories in operation, fish were imported over great distances for processing. In Aralsk's *Aralrybprom* factory, for instance before its closing in 1999, fish were imported from as far away as Russia's eastern port city Vladivostok. Following the USSR's collapse, the factory largely depended on domestic (Kazakhstan) fish supply from the Syr Darya and Lake Balkhash (Danish Society for a Living Sea 2004). The fish canning factory in Moynaq (Muyank) has had a similar experience, relying first on frozen fish imports from Russia, though its continued sporadic operation has been enabled through domestic (Uzbekistan) supply through fish farms and Amu Darya deltaic lakes (Karimov et al. 2005).

Today, the Aral Sea commercial fishery exists only in the NAS. What today remains of the Aral, the previously mentioned NAS, Tshe-bas Gulf, and East and West basins of the Large Aral, has experienced yet another shift in its aquatic ecosystem regime. Three of the four main bodies, Tshe-bas Gulf, and the East and West basins of the Large Aral represent hyperhaline (very high salinity) ecosystems. Most of the NAS currently constitutes a transitional brackish-marine ecosystem, though near the mouth of the Syr Darya there exists a small zone of brackish and very small areas of freshwater and freshwater-brackish habitats (Aladin et al. 2009). (Chief editor's note: based on salinity measurements taken during an expedition in August/September 2011, the NAS at that time was in a moderately brackish state with salinities ranging from 6 to 11 g/l. See Chap. 13, Table 13.1). The decreasing salinities in the NAS have come in large part from the completion of 2005s World Bank and Kazakhstan government-sponsored dam and dike complex, and the resulting greater freshwater inflows from the Syr Darya. Improving ecological conditions in and around the NAS have provided renewed habitat for migratory birds, other waterfowl, and in terms of the regional economy at present, the species with the greatest economic impact-fish.

NAS fish harvests increased rather dramatically between 2005 and 2011 (Table 12.3). The 2011 total harvest of 3,520 t was more than five times the 2005 total, although it remains today just a fraction of what was harvested in this part of the Aral Sea during the late 1950s and early 1960s. In 2005, flounder (*Platichthys flesus luscus*) accounted for the largest share (about 43 %) of that year's total fish harvest, followed by carp (*Cyprinus carpio aralensis*) (26 %), bream (*Abramis brama* *orientalis*) (8 %), and pike-perch (*Stizostedion lucioperca*) (4 %). Flounder continued to be the species leader in NAS yearly fish harvests until 2010, when it was surpassed by bream and roach (*Rutilus rutilus aralensis*). The most recent data available, for 2011, show the largest proportion of current NAS fish harvests being bream (34 %), followed by roach (29 %), flounder (20 %), pike-perch (10 %), carp (2 %), asp (*Aspius aspius iblioides*) (2 %), and saberfish (*Pelecus cultratus*) (2 %).

The recent increase in fish harvests from the NAS has been accompanied by an increase in employment (fishermen) as well as a seeming return of the fish processing industry. On the grounds of the abandoned *Aralrybprom* factory in Aralsk, a modernized processing and freezing facility ('Aral service') began operation in 2009. That same year, another fish processing factory, *Atameken rybprom* was established with the help of South Korean financing and Japanese equipment and technology (Abdualiev 2012). While each of the fish species harvested in the NAS are important for local and regional markets, perhaps the one with greatest export potential is the pike-perch. This fish has been noted for its high commercial value (Ozvaroi and Karabacek 2011; Tyutyunov et al. 2002; Kucharczyk et al. 2007) and has been priced at nearly 30 EUR per kilogram in Norway (Helsingin Sanomat 2008).

12.5 Nature-Economy Linkages in the Aral Sea Basin

Traveling across the desolate, desertified landscape of the former Aral seabed, one encounters a lonely watchtower marking the entrance to the barsekelmas Nature Reserve, the area of which includes the former island of the same name. Affixed to the top of this tower is a hand-painted sign, its rust and sand-swept faded message a testament to the harsh climatic reality of the region. The sign's statement, in the Kazakh language, translates as: *Humanity and Nature are twins. We need to protect nature to protect ourselves.* The poignancy of this statement at this location is striking. In layman's terms, it metaphorically codifies the interrelationships between humans and the physical environment and emphasizes the societal necessity for ecosystem integrity, biodiversity, and ecosystem services. This statement also alludes to a positive correlation between ecological sustainability and societal sustainability to the extent that the latter is dependent upon the former. As Postel (2000) noted, described earlier in this chapter, the Aral Sea crisis has been a powerful, tragic embodiment of the interrelationships between the basin's natural environment and human society.

The bi-directional nature of cause and effect relationships between humans and the biophysical environment has, generally speaking, been long understood. The concern with and study of natural environmental impacts on human beings dates back to at least Hippocrates (c. 460–377 B.C.) and his treatise *On Airs, Waters, and Places* that examined the effects of weather and climate on human health (Pattison 1964). Much more recently, George Perkins Marsh (1801–1882) was a pioneer in comprehensively and systematically detailing the human (largely negative) impact on the physical environment. Marsh's *Man and Nature: or, Physical Geography as Modified by Human Action*, first published in 1864, "showed how every human act affects nature and how technology expands collective impacts, augmenting erosive and other processes" (Lowenthal 2000, p. 16).

While the general nature of human-environment interaction has been long realized, the complex, multi-scalar, and often nonlinear nature of the interrelationship has only recently become evident. In describing complexity, the indirect nature of cause and effect, and the reflexive character of nature-society relations, Fraser et al. (2003, p. 137) observe "human management decisions may lead to changes in the environment, which in turn can impact upon the human population in new and often unforeseen ways. The result of these impacts may be new management decisions that feed a further cycle of environmental reactions and human responses." Observers of the Aral Sea crisis and its development since 1960 certainly recognize in the above statement an unmistakable salience.

The general scientific consensus today admits a lack of complete understanding of the multitude of cause and effect outcomes in nature-society interactions and recognizes the urgent need for a multidisciplinary approach in addressing resultant environmental change (Stafford 2010). As a result, at least in part, a burgeoning body of research aimed at investigating human-environment interrelationships has emerged in recent years under the rubric of sustainability science (Clark 2007; Komiyama and Takeuchi 2006), coupled human-environment systems (Turner II et al. 2003), social-ecological systems (Walker et al. 2006 or Folke 2006), or coupled human and natural systems (Liu et al. 2007). In each of these cases, the prevailing assumption is one of integration, where social systems and natural environmental systems operate jointly. From this, it follows logically that multidisciplinary research (incorporating concepts, methods, and tools from both social sciences and environmental sciences) is necessary for promoting sustainability of the integrated systems.

While the nature-society interrelationships within the Aral Sea Basin span a range of disciplinary foci, this chapter's focus is on the basin's economy (and more narrowly on two primary sector activities – cotton and fishing) and the interrelated nature of the links between it and the basin's biophysical environment. The relatively recently developed (though it seems to have predated the above coupled systems approaches by at least a decade) field of ecological economics offers an appropriate vantage point from which to begin such an undertaking. With its focus on the interrelationships between the economy and the natural environment, the former is viewed within ecological economics as situated within the latter (Costanza 1996). Put another way, the economy is seen as a subsystem of a larger ecosystem (Daly and Farley 2011), the finite bounds of which make continued economic growth impossible for the survival of the entire system. At a most general level, this view recognizes that human economic activity both extracts from (e.g. resources) and inserts into (e.g. pollution) the biophysical environment, which impacts the functioning of this environment. Changes in this environment's functioning in turn impact the supporting elements to human economic activity (Common and Stagl 2005).

Within the Aral Sea Basin, especially since 1960, the above generalization unquestionably holds true. Narrowing the focus to a single economic sector, cotton, illustrates well this sort of interrelationship. As for extractions from the biophysical environment, the obvious example would be water. The continued use of Soviet-era expansive (and inefficient) irrigation infrastructure has taken water well beyond the natural floodplains of the rivers and in many cases (i.e., Kara-Kum Canal in Turkmenistan) has artificially expanded river drainage basins. The numerous cotton sector insertions into the biophysical environment have also been well known, and include the fertilizers, herbicides, pesticides, and defoliants applied to the cotton fields. This set of extractions and insertions has clearly impacted the ecological functioning of the ecosystem within which the cotton sector operates. Furrow irrigation systems transporting water away from rivers have resulted in both increased evaporation and groundwater seepage, accompanied by rising water tables, as well as waterlogged and more saline soils. This in turn necessitates either the expansion of irrigated land (moving to less degraded, more productive soil), or using the common practice of soil leaching where even more water is used to flush away salts and other minerals from the degraded soil.

The Aral basin's cotton sector is spatially linked, in a meta-ecosystem sense, to the Aral Sea's fishing industry by the rivers providing the water that enables each sector to exist. The excessive extraction (diversion) of water from both the Syr Darya and Amu Darya has infamously led to the Aral's desiccation and salinization, diminishing its biodiversity stocks, including fish. The numerous agricultural chemicals inserted from the cotton sector, flowing downstream into the Aral Sea, also played an important role in degrading water quality and fish habitat. The resulting disappearance of fish from the Aral Sea had obvious, disastrous implications for the fishing industry (both fishing and fish processing activity), sharply reducing (if not eliminating) regional income and employment in this sector.

The Aral Sea Basin's interrelationships between the region's nature and economy are but components (albeit important ones) of the larger set of interrelationships between the basin's physical environment and its human society. Generally speaking, the Aral Sea crisis has been driven by human action, the clearly unsustainable water withdrawals from the Amu Darya and Syr Darya anchoring the successful (in a relatively short-term, economic sense) cotton sector. The resultant environmental destruction, the Aral Sea's notorious recession, was both predictable and inevitable under these circumstances. This ecological devastation, also aided by the agricultural chemical insertions from the cotton sector, in turn, negatively impacted human society through declining economic conditions, abysmal human health conditions, outmigration, and the loss of ecosystem services.

During the past decade, human intervention (ironically similar in form if not in scale to the Stalin-era remodeling and transformation of nature) resulted in the construction of a dam, dike, and river-rechanneling complex aimed at rehabilitating the NAS. The quicker than expected success of this project has enhanced ecological integrity, biodiversity, and ecosystem functioning. From both an ecological and economic standpoint, important biota making a dramatic comeback are the seven species of fish currently harvested from the NAS. The seeming return of the fishing industry has generated employment and income opportunities, has improved socio-economic conditions across the NAS region, and has engendered a tangible sense of hope and optimism among residents of the region.

12.6 Conclusion

The Aral Sea, its basin, and the post-1960 socio-ecological crisis provide a dramatic case study through which to examine interrelationships between humans and the natural/biophysical environment. The Aral basin regional economy, with this chapter's narrow focus on the cotton and fishing sectors, provides insight into such interrelationships, particularly through the temporal evolution of the Aral Sea crisis and its associated anthropogenic drivers and resultant ecological and social impacts.

The cotton sector within the Aral basin is routinely blamed for the drying of the Sea and a host of other social and ecological problems. The gigantic irrigation infrastructure projects emanating from the 'Stalin plan' certainly had an economic impetus, largely the Soviet desire for self-sufficiency and export of cotton. One might also surmise, however, that these projects also served an ideological purpose as a showcase of Soviet/Communist triumph over, or conquest of, nature. Today, cotton remains a vital economic sector within the Aral Sea Basin, providing employment, income, and export revenue (across the Aral basin, and particularly in Uzbekistan, Turkmenistan, and Tajikistan). This importance is unlikely to change anytime soon, in particular as further processing activities (and value added, employment, and income) increasingly gravitate toward Uzbekistan and Turkmenistan. Cotton will continue to be a water intensive crop, of course, and for the interest of the Aral Sea's water balance, more efficient use of this resource is of paramount importance. Savings could be achieved through the replacement of Soviet-era furrow irrigation systems with other more modern techniques (e.g. drip irrigation) though the expense of such an undertaking would likely be prohibitive. Further economic reforms (in procurement systems, property rights, etc.) are also needed within the cotton sector, most so within the Aral basin's three largest cotton exporting states. As Spoor (2007) has argued, furtherance of such reforms in Uzbekistan could make cotton a strong future growth sector there. This potential seems to exist elsewhere in the Aral Sea Basin as well.

The Aral Sea fishing industry, for obvious reasons, is closely tied to the fate of the Aral itself, through its water level, salinity, integrity of spawning habitats, and availability of food sources. As unsustainable upstream water withdrawals have led to the Aral's desiccation, so to have they led to the disappearance of fish and the important regional fishing industry. Greater upstream water use efficiency (savings) and management, so vital for the Aral's water balance, are also of paramount importance to the fishing industry. Aral Sea fishing today only takes place on the NAS, its resurrection made possible by human intervention; first from the construction by local authorities of a dike to block Berg Strait that repeatedly failed owing to structural inadequacies and finally in 2005 from the completion of a structurally sound dam, dike, and rechanneling/spillway complex in the same location. Fish and fishing have disappeared from southern portions of the Aral Sea, and here (as with the NAS) the industry's fate mirrors that of the water body. Under present conditions, the eastern basin of the southern Aral may vanish altogether, though the deeper and groundwater-fed western basin will endure, though with salinity levels unfit for fish.

The Aral Sea ceased to exist as a single contiguous entity in the late 1980s following its split into the smaller NAS in Kazakhstan, and the larger southern Aral that lies mostly in Uzbekistan. Since that time, the integrity of the ecological and social systems in and around these separated areas has shown a similarly marked divergence. Today, the NAS in Kazakhstan is recovering, both in terms of its overall ecology and, with the seeming return of the fishing industry, its socio-economic conditions. Political leadership in the Republic of Kazakhstan has demonstrated a combination of financial resources and political will to improve the socio-ecological crisis in and around the NAS. In Uzbekistan, the southern Aral continues its desiccation, and the socio-ecological crisis is as dire as ever. Leadership there appears to lack the same combination of financial resources and political will needed to simply stabilize what remains of this part of the Aral Sea. Cotton production is a top economic priority in Uzbekistan, and if current oil and gas exploration efforts on the Aral's former seabed in Karakalpakistan are successful, stabilization and/or partial restoration of the Sea here is an unlikely prospect.

In examining nature and economy in the Aral Sea Basin, this chapter's overarching guidance has come from a broader interest in the interrelationships between the region's human populations and the biophysical environment. Large scale human modifications of this environment, the purpose of which were to 'transform' or 'remodel' nature, proved unsustainable in a fairly short time. The magnitude of these projects (dams, canals, and related hydrologic infrastructure), and that of the water they diverted, largely led to the destruction of the Aral Sea. Somewhat ironically, this same sort of human intervention (dam, dike, hydrologic infrastructure, though on a much smaller scale) has been heralded for 'saving' the NAS and could, under ideal conditions, stabilize the southern Aral Sea. As recent history has shown, the fates of the human populations and the biophysical environment in the Aral Sea Basin have been closely linked.

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Chapter 13

An Expedition to the Northern Part of the Small Aral Sea (August 29 to September 16, 2011)

Philip Micklin, Nikolay V. Aladin, and Igor S. Plotnikov

Abstract This chapter is a report about an international expedition to the northern part of the Aral Sea that took place from August 29 to September 16, 2011. The expedition was organized by the Zoological Institute of the Russian Academy of Sciences in St. Petersburg Russia and received logistical support from the Barsakelmes Nature Preserve (Zapovednik) headquartered in the Kazakhstan City of Aralsk and the Aralsk Branch of the Kazakhstan Fisheries Institute. The major focus of the expedition was to investigate the biological and hydrological improvements to the Small Aral Sea that had occurred as a result of raising its level by 2 m in 2005–2006 as well as what might be done to further improve the ecology and economic value of this water body in the future. The expedition also visited the channel that connects the Western and Eastern basins of the Large Aral Sea as well as the former Barsakelmes Island, now a desolate plateau on the dried bottom of the Aral Sea.

Keywords Small Aral Sea • Barsakelmes Island • Aralsk • Ak-basty • Karateren • Connecting channel • Ak-Lak • Kyzyl-Orda • Tastubek • Kok-Aral

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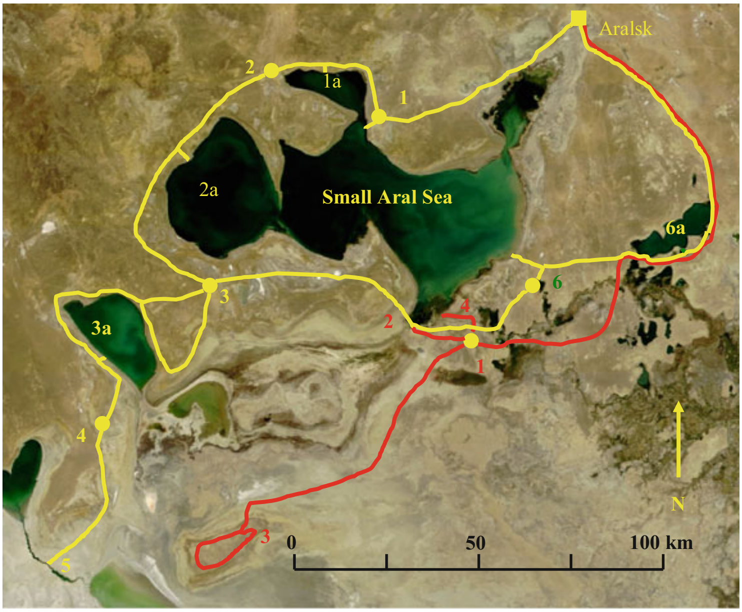

Fig. 13.1 Image map of 2011 expedition around the Northern Part of the Aral Sea (Base image from MODIS, Terra, 250 m resolution natural color acquired on Sept. 23, 2011). First half of expedition from 9-1-2011 to 9-3-2011 (*red line*); numbers indicate sequence of visit: (*1*) Village of Karateren, (*2*) Kok-Aral dam and dike, (*3*) Barsekelmes Nature Preserve, (*4*) New delta of Syr Darya. Second half of expedition from 9-5-2011 to 9-10-2011 (*yellow line*); numbers indicate sequence of visit: (*1*) Village of Tastubek, (*1a*) Butakov Bay, (*2*) Village of Akespe, (*2a*) Shevchenko Gulf, (*3*) Village of Ak-basty, (*3a*) Tshche-bas Bay, (*4*) Village of Kulandy, (*5*) Channel from Western Large Aral basin to Eastern Large Aral Basin (UzenAral), (*6*) Village of Bugun, (*6a*) Lake Kamyshlybas

13.1 Introduction

An international expedition to the northern part of the Aral Sea, which lies within the Central Asian nation of Kazakhstan, took place from August 29 to September 16, 2011. Dr. Nikolay Aladin and Dr. Philip Micklin led the expedition with considerable support from Dr. Igor Plotnikov, who is also affiliated with the Zoological Institute in St. Petersburg, Russia. Dr. Aladin is an aquatic zoologist and well-known international expert on the Aral Sea. Dr. Micklin is a geographer and water resource management specialist who has conducted research on the Aral Sea and surrounding region since the early 1980s. Dr. Plotnikov is a specialist on the plankton and benthic communities of the Aral Sea. The image map above (Fig. 13.1) shows the routes of the expedition and the places visited. Drs. Micklin, Aladin and Plotnikov have participated in three previous expeditions to the Aral Sea in 1990, 2005, and 2007. The field part of the expedition consisted of two parts as discussed below.

We were accompanied for the whole expedition by a diverse group including two journalists (one American, the other Swiss), a limnologist from Ljubljana University in Slovenia, two geographers, one American and the other Swedish, a French concert pianist who is interested in the Aral Sea, and a videographer (Ivan Aladin, Engineer, BAN,). For parts of the expedition we were also accompanied by representatives from the International Fund for the Aral Sea (IFAS) which is the official Central Asian regional entity charged with overseeing efforts to improve the condition of the Aral Sea and surrounding zone of so-called "Ecologic Catastrophe" along with personnel from the two local organizations that handled logistics for our field work.

The main purpose of the expedition was to evaluate the success of a project to raise, stabilize, and improve the ecology of the Small Aral Sea. The Small Sea, also known as the Northern Aral, separated from the Large (southern) Aral in 1989. The Syr Darya, one of two major rivers that enter the Aral Sea, flows into it. Beginning in 1992, local attempts were made to raise its level, lower its salinity, and improve ecological conditions via construction of an earthen dike to block outflow of Syr Darya water to the Large Aral. The makeshift dikes repeatedly failed and were rebuilt until a catastrophic breach in April 1999 that cost two lives. Beginning in 2003, the World Bank and Government of Kazakhstan funded an $85 million project to build a reliable, properly engineered dike and dam, to construct a regulating hydrocomplex at Ak-Lak on the lower Syr Darya about 15 km up river from that river's entrance into the Small Aral and to make other improvements to the bed of the Syr Darya to improve its flow carrying capacity (see Chap. 15). The discharge gates of the new dam were closed in August 2005 and the Small Aral reached the design level of 42 m above sea level (ASL), which was 2 m above the August 2005 mark, by March 2006, far faster than anticipated. Since 2005, the ecology and fishery of the Small Aral Sea have undergone dramatic improvement.

Dr. Micklin flew to Almaty, Kazakhstan, leaving the U.S. on Sept. 27 and arriving early morning on Sept. 29. There he met Kristopher White, an American geographer and participant in our expedition, who has been teaching at an English Language University in Almaty for some years. The next morning Micklin and White flew to Kyzyl-Orda, the administrative capital of the province of the same name that includes all of the Kazakhstani territory around the Small Aral Sea. Kyzyl-Orda has a population of about 150,000. Dr. Torekhan Karlikhanov, a Professor from Korkyt-Ata Kyzylorda State University (who had formerly worked for the International Fund for Saving the Aral Sea – IFAS) met Micklin and White at the airport. All three, along with other expedition participants who had arrived earlier, took the train to Aralsk, the administrative capital of district and the formerly most important port town at the northern end of the Aral Sea. After a 7-hour trip, the group arrived in Aralsk late on the 30th of August and was met by other expedition participants who had come by train from St. Petersburg and Almaty. Aralsk, as was the case for our previous expeditions, served as the base location for the expedition. The entire group stayed in the only hotel in town, not surprisingly named "Aral".

Aralsk (Aral in the Kazakh language) was formerly a fishing port and harbor located at the northern end of the Gulf of Saryshaganak which forms a northeastward extension of the Small Aral Sea (Fig. 13.1). The town was an important supplier of fish to the neighboring regions as well as being a transshipment point for the railroad connecting Russia and Ukraine to Central Asian cities, primarily Tashkent in Kazakhstan and Tashkent in Uzbekistan (Kazakhstan 2012). Aralsk had a population of about 30,000 in 2009 (Kazakhstan 2012). The climate of the area is sharply continental semi-desert with little precipitation (about 120 mm a year).

The following day, August 30th we met with local officials, including the deputy *Akim* (mayor) of the city and district to explain the intent and purpose of the expedition. Dr. Aladin as the most knowledgeable and locally known member of our party took the lead on this. The local administration was friendly and supportive of our efforts. Micklin requested a visit to the newly rebuilt fish processing plant, which they granted. This was one of the highlights of the trip. The old fish canning plant, left over from Soviet days that had been in decline owing to the lack of catch as the fishing industry on the Aral collapsed (and may even have closed down), had been demolished and replaced by a very modern facility. The rapid recovery of the Small Aral fishery (both in terms of total catch and species diversity of catch) that has taken place since the Kok-Aral dike completion in 2005 made possible the plant restoration.

Now sufficient fish, and especially valuable types, are being caught in the Small Aral to supply the plant with all the fish it can handle. Fish are brought in refrigerated trucks along rutted two track roads from the village of Tastubek, which lies on the shore of the Small Aral some 71 km southwest of Aralsk (see Fig. 13.1). The less valuable fish (e.g., catfish) are processed for sale locally or in nearby communities. The more valuable types are cleaned and frozen for sale in more distant locales. The most valuable fish (pike-perch – *sudak* in Russian) are filleted and flash frozen in a state-of-the-art facility. We saw a large room filled with plastic sacks of frozen sudak fillets for sale in Russia, Ukraine and other parts of the former Soviet Union. The plant manager said that they are seeking certification to sell the frozen *sudak* in European Union countries where they would draw a very high price.

13.2 The First Field Excursion

The first, and shorter, part of the fieldwork began early on September 1 and ended late on September 3. The Barsakelmes Nature Preserve, headquartered in Aralsk, provided logistical support and the director (Zauresh Alimbetova) accompanied us on the visit. Other participants in the first phase were Philip Micklin (retired geography professor, Western Michigan University, USA); Dr. Nikolay Aladin and Dr. Igor Plotnikov (aquatic zoologists from the Zoological Institute, Russian Academy of Sciences); Ivan Aladin videographer (Engineer BAN); Dr. Kristopher

White an American geographer who teaches at the Kazakhstan Institute of Management, Economics and Strategic Research (KIMEP) in Almaty; Dr. Gunilla Bjorkland (Swedish geographer from GeWa Consulting); Chris Pala, an American journalist; Peter Durtschi, a Swiss Jounalist; Wilfred Humbert, a French pianist with an interest in the Aral Sea; Dr. Torekhan Karlikhanov and Erzhan Alimbaev from Korkyt-Ata Kyzylorda State University; Dr. Michael Toman (limnologist from Ljubljana University in Slovenia) and a group from the IFAS office in Almaty, including Albert Diebold, Technical Director, and Murat Bekniyazov, Representative for the Republic of Kazakhstan in the Executive Committee of IFAS. Myrzagaziev Zhasulan, Nurlan, Satikeyev Timerbek, Absultan and Bekbulat drove the vehicles used in the trip.

We visited the Kok-Aral dike and dam, the delta of the Syr Darya (darya means river in the Turkic language) near the dam, the nearby village of Karateren and the recently completed Ak-Lak hydrocomplex north of it on the Syr Darya intended to regulate the flow of the lower Syr and divert some water to nearby lakes to maintain their levels and ecologic conditions, and the former Island of Barsakelmes far out on the dried bottom of the Aral Sea, which is a nature preserve. We traveled in four-wheel drive jeeps known as "Uazik", an acronym for the factory in Russia that produces the vehicles. Although providing a very rough ride over the rutted two-tracks that pass as roads, they are extremely durable and well suited to local conditions.

Micklin used the YSI-85 salinity, conductivity, temperature and dissolved oxygen meter acquired for the 2005 expedition (from funds provided by the National Geographic Society) to measure key ecological parameters at the Kok-Aral dam and in the lower Syr Darya (Table 13.1). Salinity in the lake above the dam was higher than expected (slightly more than 6 g/l) but we were informed that so far this year inflow to the Small Aral has been below the average for recent decades owing to a low-flow year on the Syr, which would mean less fresh water input near the dam and, thus, higher salinity. During the 2005 expedition, salinity here was 3.5 g/l. Nevertheless, ecological conditions near the dam seemed very good with high water transparency and very high levels of dissolved oxygen (DO). Dr. Toman, the Slovenian limnologist, raised a concern that the presence of bottom rooted macrophytes and extensive areas of reeds could signal a future problem of eutrophication from high levels of nutrients in the bottom sediments. Certainly this is something that needs careful monitoring as the lake evolves. DO levels in the Syr Darya Delta were around 60 % saturation and salinity 0.9 g/l; the latter figure is below the often-cited values for river salinity in the lower Syr Darya of 1–2 g/l.

We saw many small family-scale fishing boats near the dam. The American journalist with us (Chris Pala who has written on the Aral for Science, the Wall Street journal and other media) talked with local fishers who confirmed the fishing was excellent. Ivan Aladin took extensive video and interviews (including with local folk) of this portion of the expedition. Igor Plotnikov collected plankton for his studies of these organisms. We stayed one night in Karateren, a former fishing village on the shore of the Large Aral Sea, with local families in comfortable, newly renovated and expanded homes with new electric appliances, and satellite TV on

Table 13.1 Environmental Data from 2011 Expedition from YSI-85 Meter, Optical Brine Refractometer (for higher salinity conditions) and GPS

	Date	GPS COOR. (deg-min-sec)		Salinity	Temp	Dissolved O_2	
Location (at or near)	(month/ day/year)	Latitude	Longitude	(mg/l)	(celsius)	mg/l	% sat.
1. Kamyshlybas Lake bridge	9/1/2011	N 46-08-21.4	E 61-25-10.9	3.5	20.4	6.9	82
2. Kok-Aral Dam (channel below)	9/1/2011	N 46-06-45.8	E 60-46-18.9				
a. Reading 1 (shallow water)				5.6	20.2	5.4	63
b. Reading 2 (shallow water)				6.5	21.8	5.36	64.3
3. Kok-Aral Dam (above dam)	9/1/2011	N 46-06-45.8	E 60-46-18.9				
a. Reading 1				6.2	20.5	8.97	106.8
b. Reading 2				6.4	22.3	9.48	107.8
4. Syr Darya delta (south side)	9/1/2011	N 46-06-7.3	E 60-51-51.7	0.9	20.1	5.26	60
5. Syr Darya delta (north side side)	9/3/2011	N 46-05-23,2	E 60-58-40.7				
6. Tastubek	9/5/2011	N 46-36-33.6	E 60-46-53				
a. Reading 1 (shallow water)				8.3	24.7	7.65	100
b. Reading 2 (about 1/2 m)					24.6	9.06	121
c. Reading 3 (from boat ~ 2 m depth)				7.7	24.6	10.91	137
7. Butakov Bay by barge	9/6/2011	N 46-46-32.4	E 60-37-08.7				
a. Reading 1 (shallow water)				11	23.1	8.61	101.5
b. Reading 2 (shallow water)				11.1	23.3	8.56	107
7.Artesian well E. of B. Bay nr Aksepe	9/6/2011			20	45–50 C		
8. Shevchenko Bay along west side	9/6/2011	N 46-36-42.5	E 60-05-14.6				

(continued)

Table 13.1 (continued)

	Date	GPS COOR. (deg-min-sec)		Salinity	Temp	Dissolved O_2	
Location (at or near)	(month/ day/year)	Latitude	Longitude	(mg/l)	(celsius)	mg/l	% sat.
a. Reading 1 (shallow water)				7.9	26.2	9.98	129.1
b. Reading 2 (shallow water)				7.9	25.3	9.12	126
9. Ak Basty		N 46-22-24.6	E 60-11-33.6				
a. Reading 1 (shallow water)	9/7/2011			7.9	19	8.8	
b. Reading 2 (shallow water)	9/8/2011			8	22.1	6.53	78.3
c. Reading 3 (shallow water)	9/8/2011			8	22.1	6.41	76.9
10. Tshche-bas Bay	9/8/2011	N 46-17-47.8	E 59-31-14.8	84/85			
11. Channel from W. to E. Large Aral basins	9/9/2011	N 45-41-46.4	E 59-14-59.5	110	21.1	5.79	98.8
12. Beach north of Bugun	9/10/2011	N 46-12-18	E 61-06-11.5				
a. Reading 1 (shallow water)				7.7	17.5	7.32	80.1
a. Reading 1 (shallow water)				6.8	17.4	7.8	74.7

digital flat screens. Karateren appeared much better off economically than was the case during visits there in 2005 and 2007. We were told this owed primarily to the rejuvenated fishing industry in the nearby Small Aral Sea. The catch has greatly enhanced local incomes.

The trip to the former Barsakelmes Island across the dried seabed was long and hot (Fig. 13.1). The island is now a plateau standing above this barren wasteland, with scattered salt-cedar and saksaul bushes breaking the monotony. The former island is considerably more vegetated than the surrounding dried sea bottom, but its flora and fauna have suffered serious degradation and simplification as the surrounding sea disappeared. Kulan (wild Asiatic Ass) formerly roamed the island, but owing to rapidly degrading habitat conditions, mainly lack of drinkable water, were moved to other locations in Kazakhstan in the mid-1980s. We stayed at the former research complex. Some of the buildings here have been refurbished and others have been torn down. Some of our party made the “Grand Tour” of

Barsakelmes, including visiting the ruins of the meteorological station, the Butakov (Butakoff) Monument (in honor of Russian Lieutenant Butakov who investigated the sea in the 1840s) and other sites. Dr. Aladin visited the former shoreline below the cliffs on the southern part of the island. There he collected detritus (including invertebrate shells), which were left by the influx of Amu Darya water in the summer of 2010.

Some of our party slept outside that night. For them, the breathtaking view of the night sky was most memorable as the extremely clear air, lack of clouds, and absence of lights made the stars, constellations and Milky Way visible in a rarely seen way. The next day, representatives of IFAS drove to Kzyl-Orda and the remaining members of the expedition visited the lower reaches of the Syr Darya Delta and then returned to Aralsk.

13.3 The Second Field Excursion

After a 1-day rest in Aralsk, on September 5 we set out on the second phase of the fieldwork. The branch of the Kazakhstan Fisheries Institute located in Aralsk handled logistics for us. A smaller group participated in this phase of the expedition as the IFAS people had returned to Kyzyl-Orda and Almaty. The director of the Fisheries institute (Zaulkhan Ermakhanov) accompanied us on the trip. Those participating in the second phase besides him were Philip Micklin (retired geography professor, Western Michigan University, USA); Dr. Nikolay Aladin and Dr. Igor Plotnikov (aquatic zoologists from the Zoological Institute, Russian Academy of Sciences); Ivan Aladin (Engineer BAN), Dr. Kristopher White an American geographer who teaches at the Kazakhstan Institute of Management, Economics and Strategic Research (KIMEP) in Almaty; Dr. Gunilla Bjorkland (Swedish geographer from GeWa Consulting); Chris Pala, an American journalist; Peter Durtschi, a Swiss Jounalist; Wilfred Humbert, a French pianist with an interest in the Aral Sea; and Dr. Michael Toman (limnologist from Ljubljana University in Slovenia). The drivers for this portion of the trip were Myrzagaziev Zhasulan, Satikeyev Timerbek, and Bakhit.

Our route is shown on Fig. 13.1. We first visited the village of Tastukbek located on the north shore of the Small Aral. This settlement has become the most important fishing center on the Small Sea. As noted earlier, fish from here are sent to the new processing plant in Aralsk. Fishing is small-scale with boats ranging from about 14 ft (4.3 m) to over 20 ft (6 m). Most have an inboard or outboard motor. Gill netting is the catch mode. The fishers set their nets in the late afternoon and gather them early the next morning (Fig. 13.2).

We had the opportunity the next morning to watch the boats come back with their catch. The nets were loaded with fish including sazan, *Cyprinus carpio* L. (a carp-like species that is highly prized by local people), som, *Silurus glanis* L. (catfish), shchuka, *Esox lucius* L. (pike), zherekh, *Aspius aspius* L. (aspe), lyosch, *Abramis brama* L. (bream), vobla, *Rutilus rutlis aralensis* L. (roach) and

Fig. 13.2 Fisherman of Tastubek setting out in the late afternoon of Sept. 5, 2011 to place their nets in the Small Aral Sea (Photo by P. Micklin)

Fig. 13.3 Some of the fish catch by Tastubek fisherman on Sept. 5–6, 2011 (Photo by P. Micklin)

the very valuable sudak, *Lucioperca lucioperca* L. (pike-perch) (Fig. 13.2). Philip Micklin used the YSI-85 m to measure dissolved oxygen (DO), temperature and salinity near shore and in deeper water (Table 13.1). DO was high and salinity low (7–8 g/l), indicating excellent aquatic habitat conditions for native brackish water fishes (Fig. 13.3).

The Fisheries Institute monitors the industry carefully to protect against over fishing and to gather biological data on the fish species inhabiting the sea. Currently the institute estimates the fish biomass of the Small Aral at 18,000 metric tons/ annually. The legal catch is 4,500 t and the illegal (poached) catch is estimated to be 1,500 t. Hence the overall take is 6,000 t, one-third of the estimated biomass. Chris Pala, the American journalist who has written on world fisheries issues said that this is the most restrictive (and protective) catch limit of which he is aware (Pala 2011). The Christian Science Monitor for October 3, 2011 (Volume 103/issue 45, pp. 24–25) has a brief piece on the Small Aral that states the catch is slated to reach 10,000 t by 2012.

The next morning (Sept. 6) we went to Butakov Bay (Fig. 13.1), where Micklin again measured aquatic environmental parameters with the YSI-85 and Igor Plotnikov collected plankton samples (Table 13.1). DO levels here were excellent, but salinities were significantly higher (11 g/l) than at Tastubek owing to limited water exchange between the hydrologically isolated Butakov Bay and the main part of the Small Aral Sea. The group then proceeded to the village of Akespe where we conversed with local people and ate lunch in a local home. Akespe, a former fishing village, seemed improved from the last visit in 2007, including having converted a sulfurous, hot artesian well gushing from a pipe into a fancy new "hot-spring" fountain and associated swimming hole. One of our drivers swam in the pond even though the water temperature was over 45 °C! In Akespe we met with a revered fisherman and Dr. Aladin and Ivan Aladin conducted a video interview with him.

We then proceeded southward to the main part of the Western Small Aral known as Shevchenko Bay, stopping along the way so Dr. Micklin could take more readings with the YSI-85. DO levels were high and salinity at 8 g/l, surprisingly, essentially the same as at Tastubek far to the east. We spent the night in Akbasty, a major former fishing village on the southern coast of the bay. The next morning (Sept. 7) we went to the shoreline about 5 km away where P. Micklin gathered more YSI-85 data and Igor Plotnikov collected more plankton samples. Nikolay Aladin collected benthos samples and washed them with the help of a special sieve. For the other expedition members, most of the day was spent relaxing at a pleasant sand beach where Dr. Micklin gathered additional data with the YSI-85. DO levels along the southern shore of Shevchenko Bay near Akbasty were considerably lower (76–79 % saturation) than we measured in other parts of the Small Aral. This may be due to the sandy bottom with a lack of bottom-rooted, oxygen producing vegetation. Salinity was the same as along the western shore (8 g/l).

Part of our group stayed overnight at the beach, a most enjoyable experience of exceptionally clear skies and refreshing breezes from the lake. There were extensive wetlands lying behind the primary dune adjacent to the lake. These were filled with waterfowl of various types and sizes, including sandpipers, swans, flamingoes and pelicans.

September 8 we traveled from Akbasty to Kulandy, a village to the southwest (Fig. 13.1). Along the way, we stopped along the shoreline of Tshche-bas Bay formerly part of the southern (Large) Aral Sea. We visited the old military port that was used as the Aral Sea shallowed and ships were not able to reach Aralsk to transport supplies to the super-secret bioweapons-testing complex on Vozrozhdeniya (Resurrection) Island that, as the sea shrank, grew enormously into a peninsula separating the Eastern and Western basins of the Large Aral Sea. Practically nothing was left of the port except some concrete ruins and a few pieces of ship not taken by scrappers for recycling.

We also visited a few mainly intact vessels stranded and abandoned along the west coast of the bay. Zaulkhan Ermakhanov, the director of the fisheries institute, showed us a place where one could walk to the sea (very difficult most places because of extensive flats of gooey, deep mud that are almost impossible to cross). Walking through a short expanse of mud, Philip Micklin was able to reach the bay and collect a bottle of water. He measured the water's salinity with a brine refractometer. This was necessary as the salinity is too high for use of the YSI-85. Two readings indicated salinity at 84/85 g/l, considerably lower than we expected. The explanation is likely considerable inflow to the gulf of relatively fresh water from the plateau like highlands surrounding the water body (as evidenced by artesian springs of relatively low salinity water on the slopes) and inflow of relatively fresh water when spring discharges from the Small Aral to Large Aral via the Kok-Aral dam create a chain of shallow lakes south of the dam. Nick Aladin and Igor Plotnikov took the bottle of water back to their lab in St. Petersburg for further analysis and to see if there are interesting phyto or zoo plankton in it for culturing. We also looked over the abandoned hydrometeorological vessel "Otto Schmidt." Dr. Aladin repeatedly sailed on board this ship in the 1980s to collect samples. An abandoned high-speed military vessel (number 99) that during Soviet times patrolled around Vozrozdeniya Island to keep the curious away is situated nearby this vessel.

The night of Sept. 8 we spent in Kulandy. The population of this small village is primarily engaged in raising of camels, goats, sheep, cattle and horses. Although some distance from the Small Aral this village appeared better off than when we visited in 2005 and 2007. Kulandy has been connected to the electric grid and that may have played a major role in its improved fortunes. Next morning (Sept. 9) we made our way southward to the long channel connecting the Western and Eastern basins of the Large Aral. This river-like artery continues to persist as the two basins grow farther and farther apart owing to the continuing desiccation of the Large Aral. Salinity as measured by the brine refractometer was 110 g/l, about what we expected. The day of our visit, there was no perceptible current, interpreted by us to mean the levels of the East and West basins were the same. There were many brine shrimp in the water and accumulations of their eggs along the shore. As the Large Aral has salinized and become more favorable for harvesting brine shrimp eggs, there have been pilot projects to see if a viable commercial industry is possible. So far the answer has been no. We also saw a number of flamingo and other smaller shore birds feeding on the shrimp.

We traveled all the way back to the Kok-Aral dam that day via Akbasty and the former Kok-Aral peninsula. Then we journeyed northward to the village of Bugun (Fig. 13.1) where we spent the night in a rather nice private home. Some of us even slept in a Yurt that the owners use mainly for cooking purposes. The next morning (Sept. 10), we visited the shore of the Small Aral north of Bugun where Philip Micklin took more YSI-85 readings. DO levels were 75–80 % saturation here and salinity around 7 g/l. (Table 13.1). Igor Plotnikov collected plankton, and Nikolay Aladin gathered benthos samples. On the way back to Aralsk, we visited a fish-hatchery and nursery on the shores of Lake Kamyshlybas (Fig. 13.1). The fish as they grow larger are progressively raised in a series of ponds and then released into the Lake, which has an important fishery. The hatchery is jointly funded by Israel and the United States (for the latter through the United States Agency for International Development or USAID).

We arrived back in Aralsk the evening of 10 September and remained there until the 12th when the Western contingent took the train to Kyzylorda. All three Russian participants in the expedition went by train to St. Petersburg and were not able to participate in the conference described below.

13.4 Post Excursion Conference in Kyzyl-Orda

The Executive Committee of the International Aral Sea Rescue Fund (IFAS) and its branch office in Kyzylorda, St. Petersburg Scientific Center of the Russian Academy of Sciences, Kyzyl-Orda Oblast Governor's Office and Korkyt-Ata Kyzylorda State University organized a mini-conference titled, "The Northern Aral Sea – 20 Years on the Way to Revival" held at the University on 15 September. They invited members of our expedition to participate and provide results of our expedition as they related to the present condition and future of the Small Aral Sea. Three reports were delivered.

Philip Micklin gave a report titled, "Aral Sea: Past, Present, and Future," which he delivered in his considerably less than perfect Russian. Dr. Demesin Nurmagambetov, Deputy Chair of the Executive Committee of the International Fund for Saving the Aral Sea (IFAS), delivered a talk titled, "On the Aral Sea Basin Program (ASBP-3)". The ASBP is the main long-term action program in the Aral Sea Basin, funded by the basin governments and the international donor community, for promoting sustainable development, managing water resources and coping with climate change (Executive Committee 2011a, b). ASBP-1 ran from 1994 to 2002 and ASBP-2 went from 2003 to 2010. ASBP-3 is supposed to last from 2011 through 2015. Dr. Torekhan Karlikhanov, Director of the Applied Research Center at Korkyt-Ata Kyzylorda State University spoke on, "The integrated assessment of the second phase of the project 'Control of the Syr Darya river bed and the Northern Aral Sea (RRSSAM-2).'"

Michael Toman (Slovenian limnologist), Kristopher White (American geographer), Peter Durtschi (Swiss journalist), Zauresh Alimbetova (Director of the Barsakelmes Nature Preserve), Ospanov Medet (Director of the Kazakhstan branch of IFAS) and Zaulkhan Ermakhanov (Director the Aralsk Branch of the Kazakhstan Fisheries Institute) also made statements. Three talented people from the Foreign Department of the University translated the presentation of Russian speakers to English and vice-versa. Although of short duration, the conference was very well organized and informative on the key issues for the Small Aral Sea. A translation of the resolution from the conference is below.

13.5 Resolution of the International Scientific-Practical Conference "Northern Aral – 20 Years on the Way to Rebirth"

(translated from Russian by P. Micklin)

Kyzylorda: September 15, 201.

The Conference on the basis of the speeches, presentations, reports, and discussions:

1. Affirms the reality of the problems connected with the strengthening of the anthropogenic influence on the natural environment of the near Aral region, basin of the Aral Sea, and the planet as a whole.
2. Attests to the preservation of interest of the world academic community from a scientific point of view in the unique processes, which are occurring in the Aral Sea and near Aral region.
3. Establishes that the results of the expedition and the conference will become the basis of further cooperation of the International Fund for Saving the Aral, the Russian Academy of Sciences, Kyzylorda State University named after Korkyt Ata, and the Barsakelmes Nature Preserve with the World Academic Community.
4. Draws the attention of state management organs to the necessity to develop a practice of regular expeditions and conferences for accepting scientifically founded decisions for the further rebirth of the Aral Sea and sustainable social-economic development of the region.
5. Considers the real need for creation of an international scientific center to conduct eco-monitoring of the dried bottom of the Aral Sea within the framework of the branch program of the Ministry of Environmental Protection "Zhasyl damu" which is designated for the period 2010–2014.

We also met with the Rector of the University (Dr. Kylyshbay Bisenov) and the Pro-rector for scientific work and international relations (Dr. Urpash Shabalova). They stated their hope and willingness to develop cooperation and exchange programs with Western Universities. The University was impressive: new buildings, well equipped with computers and seemingly well funded. Kazakhstan is oil-rich and some of the new fields are located in Kyzlorda Oblast, which may have helped the University's financial fortunes.

We had considerable free time in Kyzylorda as we arrived on the 12th and didn't depart until the 16th. We visited a number of interesting historic sites around the city as well as the main hydrocomplex on the Syr Darya that regulates flow and diverts water into the extensive irrigation systems in the district. The hydrocomplex also had a very interesting associated museum with information about and photos of the hydrocomplex, irrigation, and other water management issues, including the Siberian water diversion project (for more information on the Siberian project, see Chap. 17).

We also visited a large rice farm (this is the most important crop grown in Kyzylorda Oblast). It was a state enterprise the director told us, which surprised us as we thought most agriculture in Kazakhstan had been privatized. The director also honestly stated the farm was in poor condition (e.g. fields not leveled properly, drainage ditches filled with weeds and sediment) that caused excessive water use and poor yields (see Chap. 8 for more information on irrigation problems in the Aral Sea Basin).

We want to thank Slamzhan Eskhozevich, head of the Kyzylorda branch of IFAS and Dr. Torekan Karlikhanov from Korkyt-Ata University for their hospitality to us when we were in Kyzylorda.

13.6 Concluding Comments

The Small (northern) Aral Sea appears to be in excellent ecological condition. Salinity, based on measurements taken during the expedition, averages 8–9 g/l and is ideal for the variety of brackish water acclimatized fish found in the lake. Dissolved oxygen levels are high, at least during the day when measurements were taken. There is the potential for future eutrophication owing to nutrients accumulated in the sediments, but this is far from a certainty. The lake has also developed into a major refuge for waterfowl, including important migratory species. We saw large flocks of swans, flamingoes, and pelicans a number of places around the Small Aral. Careful, regular monitoring of ecological conditions of the lake is essential to document the evolution of this restored water body, which could serve as a more general model of what is possible in terms of restoring such damaged aquatic ecological systems elsewhere in the world (e.g., Salton Sea in California and Lake Chad in Africa).

Measurements indicate salinity is relatively even around the sea, except for the isolated Butakov Bay where levels are higher. This indicates good water circulation, no doubt owing to the Kok-Aral dike and dam that has forced the fresh water input from the Syr Darya to circulate throughout the lake rather than just flowing south and out of the Small Aral as it did prior to the emplacement of the these structures. Furthermore, even though 2011 from January to early September had been a dry year with diminished inflow to the Small Aral from the Syr Darya, the level had not dropped that much (about 1/2 m as indicated by high water evidence along the shoreline) and salinity had remained surprisingly low. This suggests the sea can probably withstand the periodic cycles of low flow years without major level drops, major salinity increases, and significant ecological deterioration.

The fishery recovery is an amazing success story. Most of the major indigenous species have made a dramatic comeback providing bountiful catches that have led to new employment, higher incomes, enhanced local and regional food supplies, and foreign currency earnings through the export of the most valuable species. The new fish processing/freezing plant in Aralsk is the most dramatic sign of this. The Fishery Institute in Aralsk is doing impressive work to study and monitor the fishery in order to keep the catch at a level that does not threaten the long-term sustainability of the bioproductivity of the lake. As demand for fish increases and catch capabilities grow, it will be important for this organization to resist inevitable pressures to raise the catch limit above what is scientifically justified.

The government of Kazakhstan wants to institute a second phase of the North Aral Restoration Project (see Chaps. 11 and 15 for more information). Two options have been put forward. One is to raise the level of water only in the Gulf of Saryshaganak (Fig. 13.1) to 50 m from its current nominal level of 42 m. This would be accomplished by placing a new dam at the Gulf's mouth where it is connected to the main part of the Small Sea and diverting part of the flow of the Syr Darya northward into Saryshaganak to maintain the new reservoir. The project would bring the sea back to the former port town of Aralsk. The other project would rebuild the Kok-Aral dike and dam, raising the level of the entire lake to 48 m. The second project would likely provide more overall benefits, but the concern is that there is not sufficient water available from the Syr Darya on an annual average basis to maintain this level. However, calculations by Philip Micklin based on the estimated inflows to the Small Aral from the Syr Darya for 1992–2010 indicate there probably is sufficient water. There are strong supporters of each of the variants. Recent reports are that President Nazerbayev of Kazakhstan has selected the Saryshaganak variant. Cost of the project could run to $200 million USD. The World Bank is supportive of the project and would be asked for a loan to cover part of the cost.

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Part III
Aral Future

Chapter 14
The Biological Future of the Aral Sea

Igor S. Plotnikov and Nikolay V. Aladin

Abstract The Aral Sea in 2012 consisted of four residual water bodies with different hydrological regimes. The Kok-Aral dam raised and stabilized the level of the Small Aral Sea. Growth of salinity has stopped and a process of gradual salinity reduction is in progress. By the autumn 2011 water salinity in the open part of the Small Sea dropped to 8 g/l. The future of its biota depends on future salinity. If the current regime will remain, then the decrease in salinity will continue and the Small Aral will turn from a brackish to a nearly freshwater body. This freshening will cause substantial changes in the fauna as a result of the disappearance of marine and brackish species and reintroduction of freshwater forms. Currently two variants of further rehabilitation of the Small Aral are under consideration. The first one involves an additional dam at the entrance to Saryshaganak Gulf to create a reservoir out of it and the filling of this water body via a canal from the Syr Darya. The Small Sea under this plan would then have both freshwater and brackish water parts. The second variant is to increase the level and area of the Small Aral Sea by raising the height of the Kok-Aral dam. In this case, all the Small Sea remains brackish except the existing freshened zone in front of the Syr Darya Delta. Both these variants would avoid further strong freshening of the Small Aral Sea and associated with this adverse changes in the fauna. The expected future of the biota of the residual hyperhaline water bodies of the Large Aral is quite different. In this case, there is no possibility of reducing their salinity leading to recovery of fauna represented by marine and widely euryhaline species. On the contrary, even stronger salinization is likely. The East Large Aral Sea could dry out completely, and the West Big Aral could turn into a lifeless water body akin to the Dead Sea.

Keywords Aral Sea • Fauna • Residual water bodies

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14.1 Introduction

Currently (2012) the Aral Sea, formerly a single water body, consists of a system of four residual water bodies with different hydrological regimes to those that formerly characterized the sea as a result of its level decline. Its parts are the Small Aral Sea, Tsche-bas Bay and the western and eastern parts of the Large Aral Sea, which are connected by a channel.

The Kok-Aral dam, built across the dried Berg Strait, stopped the uncontrolled flow of water from the Small Aral Sea to the Large Aral. This prevented the threat of further decline in the level of the Small Aral Sea, and allowed to stabilize and raise its level by keeping in it the runoff from the Syr Darya River. Not only the growth of salinity stopped, but also began its gradual decrease helped by the lake's positive water balance with the seasonal discharge of excess runoff through the new dam. By the autumn of 2011 water salinity in the open part of the Small Sea (measurements by P. Micklin – see Table 13.1 in Chap. 13) dropped to 8 from 28 g/l in the early 1990s before construction of the first dam. In the area near the mouth of the Syr Darya, it is even lower while in the distant from it Butakov Bay, connected to the main part of the sea by a shallow, narrow strait, salinity is considerably higher. Thus the Small Aral Sea is once again not only a brackish water body but the average salinity of this separated part of the Aral Sea is even lower than before the beginning of its modern regression and accompanying salinization.

Future of the biota of the Small Aral Sea biota depends on the future character of hydrologic and salinity regimes. Under continuance of the existing hydrologic regime, decreasing salinity for the Small Aral Sea will continue. It gradually will be transformed from brackish to a nearly fresh water body. This freshening, in turn, will affect the fauna resulting in substantial changes in it.

On the one hand, new conditions in the Small Aral will be favorable for the life of freshwater species. There is the possibility for natural reintroduction of aquatic organisms, which inhabited strongly freshened sea areas and went extinct owing to salinization.

There is the possibility of the reappearance in the Small Aral Sea zooplankton of a number of freshwater and brackish-water species of rotifers, cladocerans and copepods, that in the past inhabited the Aral Sea. These consist of permanent residents of the sea as well as many species of riverine plankton, which are carried by river runoff into freshened areas near the mouth. Reintroduction of the first group of species can occur in two ways. They can be brought as dormant eggs by waterfowl or by wind from fresh or brackish water bodies in the Aral Sea region. Also there is the possibility of their transfer by water from lakes in the lower reaches of the Syr Darya. The mysids *Paramysis lacustris* living in the branch channels of the Syr Darya Delta will return to the Small Aral (Filippov et al. 1993).

Freshening of the Small Aral Sea water will create conditions for the return of the formerly common inhabitant of fresh-water areas of the sea the bivalve mollusk

Dreissena polymorpha aralensis. The presence of this mollusk in the Syr Darya and its associated lakes suggests the possibility of its return to the Small Aral from the Syr Darya via planktonic larvae (Starobogatov 1974). As for the halophilic brackish-water *D. p. obtusicarinata* and *D. caspia*, there is no reason to expect the real possibility of these mollusks preservation in refugia and their subsequent return to the Small Sea. Thus, these mollusks should be recognized as extinct. The bivalve *Cerastoderma rhomboides rhomboides* and all subspecies of bivalves from the genus *Hypanis* can also be counted among the species that have completely disappeared from the Aral Sea.

On the other hand, the decrease in salinity negatively affects the species for which salinization of the Aral Sea was beneficial. For example, the numbers of the marine bivalve Cerastoderma isthmicum will be reduced and may be forced into areas with higher salinity (Butakov Bay).

Very low salinity is unfavorable for the introduced into the Aral Sea marine species such as polychaete *Hediste diversicolor*, bivalve *Syndosmya segmentum*, planktonic copepod *Calanipeda aquaedulcis* as well as for native cladocerans of family Podonidae – representatives of the Caspian brackish-water fauna and halophilic gastropods of genus *Caspiohydrobia* – that have flourished owing to the sea's salinization.

Since freshening will be unfavorable for the polychaete *Hediste diversicolor*, the introduction of which to the Aral Sea was one of the reasons for the decreasing numbers and eventual disappearance of Chironomidae larvae, then there will be the prerequisites for the natural reintroduction of this species.

Currently there is an opportunity for further increasing the Small Aral Sea level by using the part of the Syr Darya flow discharged through the Kok-Aral dam in the direction of the Large. Most of this flow is lost in the salt marshes on the former seabed south of the Kok Aral dam.

There are two variants for accomplishing this. The first variant involves the construction at the entrance of Saryshaganak Gulf of a dam with a spillway to discharge water to the main part of the Small Aral Sea and a canal for diversion of water from the Syr Darya into this bay. After completion of this project the Small Sea will be turned into a cascade of two reservoirs with different hydrological regimes and different salinity conditions. In place of the former gulf will be created a fresh water body with a circulating regime whose level will be higher than the level of the main part of the Small Sea, which will remain brackish.

The second variant proposed to increase the level and area of the Small Aral Sea requires reconstruction of the Kok-Aral dam to increase its height. It is possible to build an additional regulatory spillway on the west of the Small Aral in the dried strait of Auzy-Kok-Aral. In this case the whole of the Small Sea will be brackish water with a freshened area in front of the Syr Darya Delta.

Implementation of either of these alternatives will result in the increase of the total area of the Small Aral Sea, and as a result, increase the volume of water lost by evaporation from its surface to equalize the gain and loss parts of the water balance, stabilizing salinity. This will stop further freshening of the sea and associated adverse changes in its fauna.

The expected future of biota in the residual hyperhaline water bodies into which the Large Aral Sea has turned is another matter. Despite the significant reduction of their surface area, their water balance remains negative. The discharge of the Amu Darya only reached the Eastern Large Aral in some years and for a time partially refilled it, as happened in 2010, not allowing it to disappear completely. The Western Large Aral and Tsche-bas Bay, in turn, receive a small amount of water from precipitation. Perhaps presently underground runoff from the Ust-Urt Plateau plays a marked significance in their water balance. In addition, part of the water discharged from the Small Sea reaches the separated Tsche-bas Bay. The Western Large Aral and East Large Aral can mutually provide water to each other via the channel connecting them. If the amount of water flowing from the Amu Darya River to the Eastern Large Aral does not increase, which under the current system of water use is likely, there is no reason to expect a near-term stabilization of the level or salinity of the two residual water bodies of the Large Aral Sea, let alone the possibility of reversing the process.

Fauna of the Eastern Large Aral, in contrast to the Western Large Aral Sea and the Tsche-bas Bay are represented at the present time most likely only by the halophilic crustacean *Artemia parthenogenetica*. It will survive even after salinization rises above the upper limit of its salinity tolerance range (300–350 g/l) (Aladin 1996), if there will be regular occurrences of flow from the Amu Darya into this residual lake as occurred in 2010. The source of recovery will be dormant eggs, remaining on the dried bottom or transferred by wind from the other water bodies.

If stabilization of the hydrological regime of the Western Large Aral Sea and Tshche-bas Bay does not occur, then as their salinity grows ciliates, turbellarians, nematodes, rotifers, ostracods and harpacticoids still living in these water bodies will begin to disappear, and in these residual lakes only *Artemia parthenogenetica* will remain (Mirabdullayev et al. 2004, 2007; Aladin and Plotnikov 2008; Mokievsky 2009). The deep Western Large Aral, if salinity in it will exceed the upper limit of the range of tolerance of brine shrimp, will turn into a water body like the Dead Sea (Oren et al. 2010).

14.2 Conclusions

Thus, the Aral Sea as a group of residual lakes in the future could have four biological forms.

1. All of the Small Aral or only Saryshaganak Gulf, dependant on future project implementation and inflow from the Syr Darya, as a water body with biota represented by freshwater species.
2. The Small Aral as a lake with biota where brackish-water species predominate that assumes present salinity conditions persist.

3. Tshche-bas Bay as a lake where marine species are predominate which depends on receiving regular annual discharges from the Small Aral to maintain sufficiently low salinity for marine flora and fauna. But this is very unlikely.
4. The Western and Eastern basins of the Large Aral Sea as lakes with biota represented by hyperhaline species under conditions of little or no inflow from the Amu Darya and the Small Aral. As recent years demonstrate, however, irregular heavy inflows to the Eastern Basin from the Amu Darya can temporarily revive this water body and lower salinities to conditions where marine species could survive.

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Chapter 15
Efforts to Revive the Aral Sea

Philip Micklin

Abstract The Aral Sea between 1960 and 2012 lost 85 % of its area and 92 % of its volume, while separating into four residual lakes. The Large Aral on the south endured a level drop of 25 m and rise of salinity from 10 g/l to well over 100 g/l. Over this period, the sea suffered immense ecological and economic damage including the destruction of its valuable fishery and degradation of the deltas of its two influent rivers. Nevertheless, in spite of this calamity, and contrary to reports that the sea is a lost cause (popular reports that the sea will "disappear" are simply false), hope has remained that the sea and its deltas could be partially rehabilitated. Various restoration scenarios are discussed. Full revitalization of the sea in the foreseeable future is extremely improbable, but cannot be ruled out for distant times. The project implemented in the first decade of the present century to partially restore the Small (northern) Aral Sea so far has been eminently successful. Partial restoration of the Large (southern) Aral is more problematic as it would be more costly and complicated than the north Aral project. Nevertheless, it is certainly worthy of further investigation. Projects to improve the deltas of the Amu Darya and Syr Darya are also underway. The interested reader should also see Chap. 14 which analyses the potential for biological rehabilitation of the Aral and Chap. 16 focusing on the grandiose Siberian water transfer schemes developed during the Soviet era to radically improve the water balance of the Aral Sea Basin.

Keywords Small Aral • Large Aral • Amu Darya Delta • Syr Darya Delta • Western Basin • Eastern Basin • Siberian diversion • Tshche-bas • Saryshaganak

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Table 15.1 Hydrological and salinity characteristics of the Aral Sea, 1960–2011

Year and portion of sea	Level (meters asl)	Area (km^2)	% 1960 area	Volume (km^3)	% 1960 volume	Average depth (meters)	Avg. salinity (g/l)	% 1960 salinity
1960 (Whole)	53.4	67,499	100	1,089	100	16.1	10	100
Large	53.4	61,381	100	1,007	100	16.4	10	100
Small	53.4	6,118	100	82	100	13.4	10	100
1971 (Whole)	51.1	60,200	89	925	85	15.4	12	120
1976 (Whole)	48.3	55,700	83	763	70	13.7	14	140
1989 (Whole)		39,734	59	364	33	9.2		
Large	39.1	36,930	60	341	34	9.2	30	300
Small	40.2	2,804	46	23	28	8.2	30	300
Sept. 2009 (Whole)		8,522	12.6	83	7.7	9.7		
W. Basin Large	26.5	3,702	8	56	5.7	15.1	>100	>1,000
E. Basin Large	26.5	857		0.64		0.7	150–200	1,500–2,000
Tshche-bas Gulf	28	363		0.51		1.4	>100?	>1,000
Small	42	3,600	59	27	33	7.5	10–14	100–140
Sept. 2011 (Whole)		10,317	15.3	84	7.7	8.1		
W. Basin Large	27.8	3,938	10.9	53	5.6	13.5	>100[a]	>1,000
E. Basin Large	27.6	2,268		3.0		1.3	>50?	
Tshche-bas Gulf	28.5	511		0.72		1.4	84[a]	840
Small	42	3,600	59	27	33	7.5	8[a]	0.8

Sources: (1) Data for 1960–2009 with some corrections from Micklin, Philip (2010), "The past, present, and future Aral Sea," *Lakes & Reservoirs: Research and Management*, 15, Table 1, p. 195. (2) Data for 2011 from Report: monitoring of the Amudarya river delta and the exposed bed of the Aral Sea within the framework of the CAWA Project – Dynamics of surface water and groundwater changes in the Amudarya river delta and the exposed bed of the Aral Sea June 2009 – September 2011, Tables 3 and 4 (Available at website Cawaterinfo http://www.cawater-info.net/aral/data/pdf/amudelta_monitoring_sept11_en.pdf)

[a] Salinity measurements taken with a YSI-85 electronic meter and an optical refractometer during an expedition to the Aral Sea from 28 August to 15 September 2011

15.1 Introduction

By September 2011, the Aral Sea had shrunk to a small remnant of what it was in 1960 (Table 15.1 above; Fig. 15.1 below). The lake had separated into four parts: the Small Aral Sea on the north, the Eastern Basin of the Large Aral Sea on the East, the

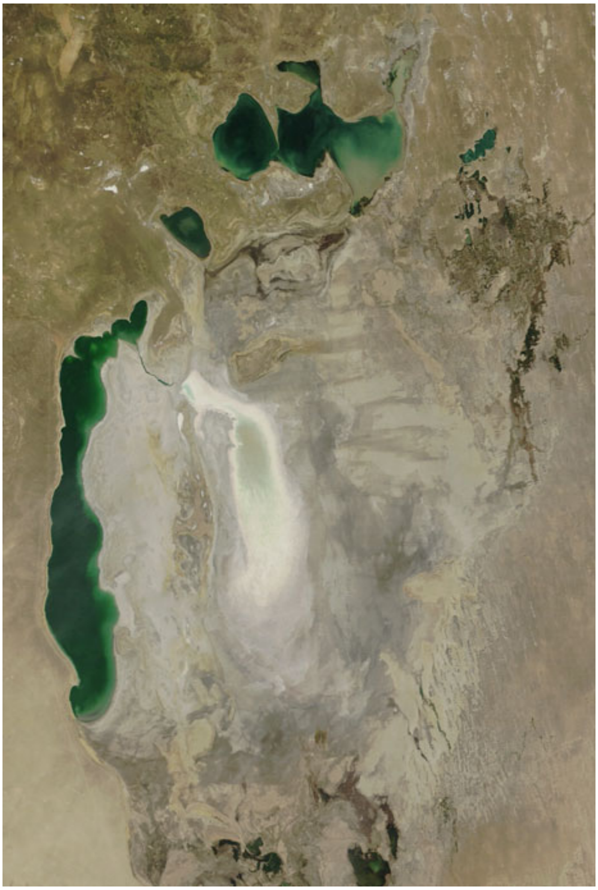

Fig. 15.1 MODIS image of Aral Sea September 22, 2009 (Natural color, 250 m resolution, Terra satellite) (Source: MODIS rapid response (Near real time images) lance.nasa.gov/imagery/rapid-response)

Western Basin of the Large Aral Sea on the west, and Tshche-bas Bay between the Small Aral on the north and the two remnants of the Large Aral on the south. A long, narrow channel, much like a slow moving river, connects the Eastern and Western basins of the Large Aral. Wind direction and speed, the relative levels of the two basins, and salinity-driven water density, determine the direction of flow in the channel: sometimes east to west and other times west to east. The aggregate area and volume of the Aral compared with 1960 had shrunk by 85 % and 92 % respectively.

The level of the Small (northern) Aral has been stabilized by a dike and dam finished in August 2005 at 42 m above sea level. (However, one should note that the measurement is made above the gage located at Kronstadt on the Gulf of Finland, which averages about 20 cm higher than ocean level). The Small Aral at 42 m is 11.4 m below its 1960s level. Owing to this project, its salinity decreased substantially reaching an average of about 8 g/l by September 2011, leading to greatly improved ecological conditions and a revitalized fishery (see Chap. 13).

The Large Sea on the south has not been so fortunate. The deeper (average depth 13.5 m) Western Basin at 27.8 m asl had fallen 25.6 m since 1960 and had salinities in excess of 100 g/l, creating conditions where no fishes could survive. The Eastern Basin had nearly dried up by September 2009 with salinities in the shallow pond (average depth 0.7 m) that was left probably exceeding 200 g/l (Fig. 15.1). The author (incorrectly) forecast the basin to completely dry during the summer of 2010 (Micklin 2010).

But 2010 turned out to be the highest flow year on the Amu Darya (measured at the Takhiatash Dam and representing water delivery to the Amu delta and the Aral Sea) since 1998, and the third largest since 1992 ending a 4-year cycle of low flows. Considerable water reached the Eastern Basin from the Amu for the first time since 2006 (Cawaterinfo 2012a, b, c; MODIS 2006–2011). Although providing the primary water supply to the Eastern Basin, this inflow was supplemented by substantial outflow from the Small Aral via the Kok-Aral Dam that creates a series of shallow lakes some of which connect to the Eastern Basin of the Large Aral. The outflow resulted from flow conditions on the Syr Darya in 2010 (fourth largest of the 20 years from 1992 to 2011), which delivered heavier than normal amounts of water to the Small Sea (Cawaterinfo 2012d, e). Between November 2009 and November 2010, the Eastern Basin's area rose from 857 to 5,211 km^2 and its volume from 0.64 to 8.4 km^3 (Cawaterinfo 2012a; Table 3 and 4) (Fig. 15.2). Salinity also dropped dramatically, perhaps, to as low as 20 g/l.

But this major expansion of the Eastern Basin was short-lived as Amu Darya flow decreased dramatically in 2011, the third lowest flow year for the 20-year period 1992–2011. Consequently, the area and volume of the Eastern Basin dropped rapidly reaching, respectively, 2,268 km^2 and 3.0 km^3 by September 2011 (Cawaterinfo 2012a; Table 15.1). Average salinity also rose considerably, certainly taking that parameter back above 50 g/l. By June 2012, the Eastern Basin had almost completely dried and was smaller than in September 2009 (MODIS 2012). Its complete desiccation by late summer seemed inevitable. But in late July Amu water again reached the basin and by mid-August the area of this extremely shallow water body approximated that of the Western Basin. This sequence of near (or complete) drying and then refilling, dependent primarily on inflow from the Amu Darya and secondarily from outflow from the Small Aral, will likely continue for the foreseeable future absent intervention by humans (see below).

By September 2009, Tshche-bas Bay, now cut-off from the Eastern Aral, had fallen 25.4 m from its 1960 level (Table 15.1). Its area had dwindled to 363 km^2, its volume to one-half cubic kilometer, average depth fell to 1.4 m, and salinity rose to probably over 100 g/l. However, in 2010, spring/summer outflow from the Small Aral via the Kok-Aral dam was of such size that a considerable amount of water reached the Bay, for the first time in several years, substantially increasing its area and volume (Cawaterinfo 2012a, Table 3). But as on the Amu, flow of the Syr in 2011 markedly dropped and the bay's area and volume rapidly decreased reaching 511 km^2 and 0.72 km^3 by September 2011.

The key question is what could the future hold for the Aral Sea and its river deltas? Will the Aral completely disappear? Is it possible to return the sea to its

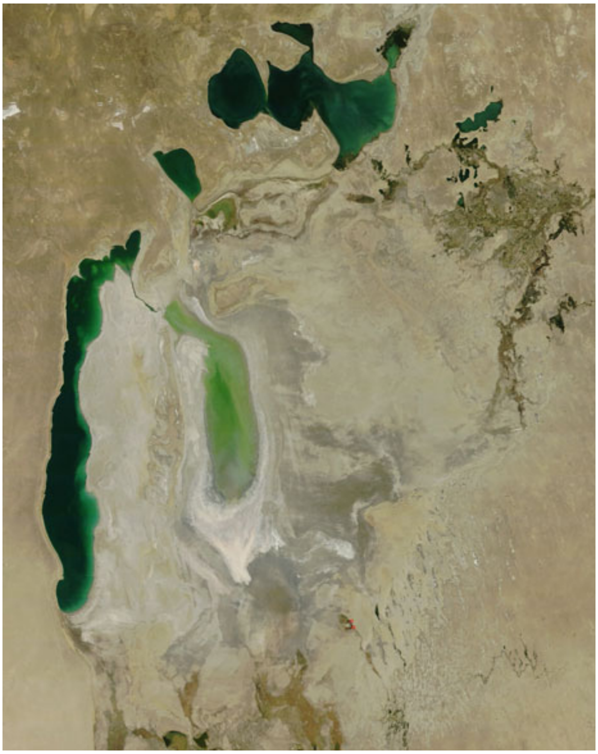

Fig. 15.2 MODIS image of Aral Sea September 16, 2011 (Natural color, 250 m resolution, Terra satellite) (Source: MODIS rapid response (Near real time images) lance.nasa.gov/imagery/rapid-response)

1960 size and ecological condition? What is feasible regarding preservation and restoration of the shrunken and degraded deltas of the Amu Darya and Syr Darya? Below are the author's best estimates of what the future may hold for the Aral and the river deltas.

15.2 Complete Drying Versus Full Restoration

First I must dispose of two diametrically opposite scenarios of the future Aral that are in one case impossible and in the other highly unlikely except, perhaps, in the distant future. The claim sometimes heard, usually in the popular media, that the lake will dry up completely in the twenty-first century is simply wrong and disregards basic physical and hydrologic principles. Even in the highly unlikely event that inflow from the Amu and Syr rivers were reduced to zero, there would still be residual input of irrigation drainage water, groundwater, and snow melt and rain that would probably maintain at least three lakes. Two would be remnants of the Small Aral Sea: Shevchenko Bay at the western end of this water body, which had a maximum depth in 2011 of 16 m and a basin just to the east of it with a maximum depth in 2011 of 18 m (Aral Sea 1981). These would primarily be fed by groundwater draining from surrounding highlands, which create a steep hydraulic gradient as evidenced by numerous artesian wells found around the western part of the Small Aral (Expedition 2005, 2007, 2011).

However, the largest remnant lake would be located in the Western Basin of the Large Sea in the south. In spite of the huge decline in level since 1960 (Table 15.1), the maximum depth here in 2011 was still 44 m and sizable parts of the basin had depths in excess of 15 m (Aral Sea 1981). As with the remnant lakes of the Small Sea, the lake (or lakes) here would mainly be fed by ground water emanating from the Ust-Urt Plateau rising to heights of slightly more than 200 hundred meters immediately to the west of the basin. On the other hand, the Eastern Basin of the Aral would completely disappear, as nearly happened in 2009. It is possible a small residual lake would be preserved in Tshche-bas Bay (2011 max depth of 4.5 m) owing to drainage from surrounding highlands (again evidenced by the presence of artesian wells). All the remnant lakes of the Aral Sea would be hypersaline and of little ecological or economic value, except, perhaps for the production of brine shrimp (Artemia) eggs.

What about bringing the Aral Sea back to its pre-desiccation conditions, characteristic of the first 60 years of the twentieth century with a level near 53 m, area of the water surface about 66,100 km^2, volume around 1,064 km^3 and average salinity from 9.3 to 10.3 g/l (Bortnik and Chistyaevaya 1990, p. 7)? This would be ideal, but is it realistic? Such rejuvenation would require average annual aggregate inflow from the Amu + Syr rivers of 56 km^3, assuming surface net evaporation of 869 mm (evaporation of 993 mm minus precipitation of 124 mm derived from data published in Bortnik and Chistyayeva 1990, p. 39, Table 4.2) and estimated net groundwater inflow of 2.5 km^3. According to an Excel based annually iterated fill model devised by the author that assumes a trapezoidal cross section for the portion of the sea to be restored, refilling would require about 103 years given its area and volume in September 2011 (Table 15.1) (Micklin 2012a). The restoration would follow a logistics curve: rapid at first as inflow greatly exceeded net evaporation, then slowing and approaching zero as net evaporation grew and approached total inflow from the rivers Amu Darya and Syr Darya plus net groundwater influx. However, the sea would reach 50 m (94 % of stability level) and have an area of 60,000 km^2 (91 % of stability area) and volume over 800 km^3 (75 % of stability volume) in just 43 years.

Complicating the situation, however, is the likely increase of surface evaporation from the Aral caused by global warming induced rising temperatures in its basin (Cretaux et al. 2009). Thus, it might take substantially more than an average inflow of 56 km^3 to raise and stabilize the sea near 53 m. For example, if surface evaporation for a future Aral rose to 1,100 mm/year or by 11 %, likely a conservative assumption, with other water balance parameters remaining the same, it would take 63 km^3/year and 97 years to refill the sea its pre-1960s conditions. The level of 50 m, area of 60,000 km^2 and volume of 800 km^3 would be reached in 40 years. But the recent flows to the Aral have been far below 56 km^3, let alone 62–63 km^3. The author estimates the average annual inflow to the sea from 2000 through 2011 at 8.8 km^3 (6.6 km^3 from the Syr and 2.2 km^3 from the Amu, including direct irrigation drainage channel inflow to the sea from the latter). This is only 16 % of what would be needed to refill the sea under the first scenario above.

The only realistic approach to substantially increasing inflow to the Aral is reducing the consumptive use of water (that portion of withdrawals not directly returned to river flow) for irrigation in the sea's drainage basin, by far the main contributor to decreased inflow. The irrigated area in the Aral Sea Basin by 2010 had reached 8.2 million ha for which 92 km^3 were withdrawn, accounting for 84 % of all water withdrawals in the basin during that year. (See Chap. 8 for a detailed discussion and analysis of irrigation in the Aral Sea Basin.)

Without question irrigation in the Aral Sea Basin is highly inefficient. Substantial improvements to it, technical, economic, and institutional, could save considerable water. Attempts are underway to implement improvement measures, but the comprehensive program needed would be extremely costly. According to estimates by water management experts in 1996, complete renovation of antiquated irrigation and drainage systems on 5.4 million ha could cost 16–22 billion USD (see Chap. 8). Certainly the cost today would be substantially more. The resulting net water savings based on 1995 withdrawals of 12,594 m^3/ha are estimated at 9.2 km^3/year. To reach substantially larger savings, let us say 20 km^3, which would require economically and institutionally reforming irrigation and implementing an array of modern technical improvements on the entire irrigated area to lower average withdrawals for irrigation from an estimated 11,258 m^3/ha in 2010 to 8,000 m^3/ha, would cost far more. It is likely today's cost to realize water savings of 9.2 km^3 and certainly 20 km^3 is beyond the willingness, and perhaps ability, of the basin states to pay, even with major aid from international donors. Indeed, 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 (see Chap. 8) The two largest cotton-growing nations in the Aral Sea Basin (Uzbekistan and Turkmenistan) have reduced their cotton hectarage. Between 1990 and 2011 the former decreased the planted area by 27 % and the latter by 8 % (see Chap. 8). However, further reductions in the area devoted to cotton in the two countries are unlikely as both are intent on keeping cotton as a major crop since it is the key foreign currency earner. The irrigated area in the Aral Sea Basin has remained essentially the same since 1995, increasing from 8.07 to 8.20 million ha. Future reductions are considered unlikely as all of the former Soviet Republics, except Kazakhstan, consider it necessary to raise more irrigated food crops to meet the needs of a growing population.

It is doubtful the Aral could be restored to its former grandeur in the foreseeable future. The amount of water that would need to be saved is far above even the most optimistic and costly scenario of water use efficiency improvements. For example, assuming net water savings in irrigation of 20 km^3/year could be reached, there still would be a deficit of 27 km^3, assuming average future inflow of 8.8 km^3 that was experienced from 2000 through 2011. Taking the 8,000 m^3/ha withdrawal estimate and reducing it by return flows to rivers that would be lost by taking land out of irrigation (estimated at 1,280 m^3/ha) gives net savings of 6,270 m^3/ha. Thus, to cover the deficit, would require reducing the 2010 irrigated area of 8.2 million ha by about 3.42 million ha or 42 %. Such a reduction would wreak economic and social havoc on the countries of the basin. It is more likely much larger reductions would be needed because it is doubtful the major irrigating nations of the basin could in the near or even medium term future meet the 8,000 m^3/ha efficiency goal.

Nevertheless, we should not give up hope for a completely restored Aral. As discussed in Chaps. 2 and 4, the Aral in the past has several times come back from very severe desiccations. Perhaps in the more distant future, when the economy of the Aral Sea Basin countries has become far less dependent on irrigated agriculture and great improvements have been made in irrigation efficiency, this could again happen.

15.3 The Siberian Water Transfer Project

Of course it is engineeringly feasible to bring water to the Aral Sea from outside Central Asia. Proposals for large-scale water transfers from Siberian rivers date to late nineteenth century Tsarist times. But serious interest in such projects only began during the Soviet period in the late 1940s after World War II. (See Chap. 16 for a detailed treatment of the Siberian river diversion question.) Beginning in the late 1960s, detailed plans started to be developed by the water management hierarchy in Moscow and in Central Asia to send massive quantities of water, up to 60 km^3, from the Siberian rivers Irtysh and Ob to the Aral Sea Basin as a panacea for perceived water shortage problems. The initial stage of this project would have taken 27 km^3 from the Irtysh-Ob river confluence on the Western Siberian Plain 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 cited as the chief reason for canceling the project, its enormous cost appears to have been the primary motivation behind this decision.

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. However, implementation of this project in any but the far term, if ever, seems a pipe dream. Costs today would likely run 50–60 billion USD, and even if Russia were willing to help finance the project, it is doubtful sufficient funds could be accumulated for construction from other sources. International donors, such as the World Bank, given their newfound sensitivity to environmental concerns, have stated opposition to such a project. 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 km^3 diverted, probably less than 15, 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. Thus, while it could certainly help significantly improve the Aral's water balance, it alone would not provide sufficient water to bring the sea back to its 1960 level. Even along with the 20 km^3 that might be saved by complete renovation of irrigation facilities in the Aral Sea Basin, the total, a maximum of 35 km^3 would still be 21 km^3 short of the amount of water needed to bring the Aral back to its 1960 level. Certainly, it would be more rational to spend precious capital and effort on improving regional water management rather than importing water from Siberia.

Recently, two "megaengineeering" proponents have proposed a variant of the Siberian project, which would take water only from Lake Zaysan in Kazakhstan, which is the source of the Irtysh, and deliver it into the Syr Darya from where it would flow into the Small Aral Sea (Badescu and Schuiling 2009; also see Chap. 16 of this book). This would make the political negotiations for implementing the project much simpler as it would be implemented in only one country. The authors also see a much lower cost for this project as the route would be considerably shorter and water would flow gravitationally to the Syr River rather than requiring huge electrical inputs for pumping over the low topographic divide (127 m) between Western Siberia and the Aral Sea Basin. But it would require drilling a 100 km tunnel through a mountain range for which the costs are speculative.

Although an interesting concept, it has serious deficiencies beyond the tunnel issue. The most serious problem is that the idea of taking water from Lake Zaysan to refill the Aral just won't work. Even if you were to take the entire available outflow from the Lake, which is controlled by a dam, it would amount to no more than 18 km^3/year on an average annual basis. There would also be inevitable losses along the canal part of the route and in the new Syr Darya Delta to evaporation, filtration and transpiration from hydrophytes. Farmers along the route would also surely take some of the additional water for irrigation. Hence, it is questionable that more than 12 or 13 km^3 would reach the Small Aral, not the 30–40 km^3 claimed by project proponents.

Furthermore, taking the entire water balance surplus of the Lake would mean no outflow and hydropower from the Bukhtarma Dam, which is a major power producer. Also, the bed of the Irtysh would be dry for many kilometers downstream, which would be very ecologically harmful and cause water supply problems for people, industry and agriculture along the river as well as losses of power production at other dams farther down that river. Realistically, it is doubtful the Kazakhstan government would ever allow diverting more than about 1/2 of the surplus, which would be 9 km^3. If this were all that could be sent toward the Aral, the project would just not be worth the cost.

15.4 Other Improvement Scenarios for the Aral Sea and Its Deltas

Although restoration of the Aral to, or even near, its 1960 level is not realistic in the foreseeable future, partial rehabilitation of parts of the sea and its river deltas hold considerable promise and are discussed below.

15.4.1 Partial Restoration of the Small (Northern) Aral Sea

The Aral separated into two water bodies in 1987 – a “Small” Aral Sea in the north and a “Large” Aral Sea in the south. The Syr Darya flows into the former, and the Amu Darya into the latter. After separation, a channel formed connecting the two lakes, with flow from the higher level Small Sea to the lower level Large Sea. This flow was primarily during the spring/early summer period when discharge from the Syr Darya to the Small Aral was greatest. Local authorities constructed an earthen dike in 1992 to block outflow in order to raise the level of the Small Sea, lower salinity, and improve ecological and fishery conditions (Aladin et al. 2008). This makeshift construction had only crude means (a culvert) to release water southward toward the Large Aral. The dike breached and was repaired several times in the 1990s, but did considerably lower salinity and improve biodiversity and the fishery (primarily of the introduced kambala or Black Sea flounder). On April 20, 1999, the dike suffered a catastrophic failure after the lake level rose to 43.5 m ASL and overtopped the structure during a windstorm that drove water against the dike. It was completely destroyed with the loss of the lives of two workers who were attempting emergency repairs (Micklin 2010).

The World Bank and the Government of Kazakhstan had been considering funding construction of a more engineeringly sound facility as part of the Phase 1 Aral Sea Basin Program (ASBP) since the program inception in 1993 (Aral Sea Program 1994). Detailed Design of the project was completed by the early years of the new century (Expedition 2005). The main element of the project would be a 13-km low dike (named Kok-Aral for the former Island/peninsula on its western side) across the former Berg Strait that formerly connected the Small Aral to the Large Aral. The dike would have a concrete regulating dam with 9 gates to control outflow from the Small Aral. A new dam was also to be built at Ak-Lak on the lower Syr to regulate flow and allow the diversion of some water eastward to supplement the water balance of deltaic lakes. The dam was to be equipped with a fish ladder to allow access of migratory fish to the Syr Darya upstream of the dam. Improvements were also to be made to the bed of the Syr Darya down stream of the Chardarya Dam to enhance water flow to the sea. Cost of the entire project was set at 86 million USD with the World Bank providing 65 million and the Kazakhstan government 21 million.

Construction work began in 2003 and the dike and dam were completed by August 2005 (Expedition 2005). Because of heavier than expected winter inflow to the Small Aral, the level rose much more rapidly than expected and reached the design mark of 42 m above the Kronstadt sea level gauge on the Baltic Sea by March 2006, allowing renewed outflow to the Large Aral. For a number of reasons, the Ak-Lak facility was not completed and put into operation until 2011 (Expedition 2011).

The Small Aral at 42 m asl has an area around 3,600 km^2, volume of 27 km^3 and average salinity (as measured in early September 2011) at 8–9 g/l (Expedition 2011). Assuming net evaporation from the water body of 840 mm/year (evaporation of 960 mm and precipitation of 120 mm taken from Shivareva et al. 1998) and net average annual groundwater inflow estimated by the author at no less than 0.1 km^3, 2.3 km^3 is all that is required to maintain stability at the 42 m level.

The author estimates that for the period 1992–2011 Syr inflow was near 6 km^3 (based on adjustments for flow losses downstream of the lowest gauging station of Ak-Lak), well above what is needed to maintain the 42-m level. Since the completion of the Kok-Aral dike in 2005, excess water has been released southward creating large, shallow lakes with very high evaporation losses but that during some years have reached the Eastern Basin of the Large Aral and Tshche-bas Bay, supplementing their water balances and even creating flow through the connecting channel into the Western Basin of the Large Aral. A case may be made that these releases could be considerably reduced and used for further raising the level of the Small Aral. The key reason for this belief is that they serve no beneficial purposes to the south of the dam as it is doubtful that the outflow from the Small Aral is sufficient to contribute in any meaningful way to restoration to an ecologically productive state of the Eastern Basin and Tshche-bas Gulf in the foreseeable future. However, at times some releases may be necessary to adjust salinity in the Small Aral.

The Kazakhstan Government is planning a second phase to the Small Aral restoration project. Two alternatives have been under consideration. One is to raise the level of water only in the Gulf of Saryshaganak, which extends northeast off the eastern part of the Small Sea, to 50 m from its current level of 42 m. This would be accomplished by placing a new dike and dam at the Gulf's mouth where it is connected to the main part of the Small Sea and diverting part of the flow of the Syr Darya northward via a canal into Saryshaganak to maintain its level. The project would bring the gulf back to the town of Aralsk the former main port and transshipment point at the northern end of the Aral Sea, but the canal dug earlier to connect the port to the receding sea would need to be restored to maintain adequate depths for vessels to reach Aralsk.

The reservoir created would have near fresh water salinities of 2–3 g/l. Locks would be installed at the dam allowing passage of fishing and cargo boats from the main part of the Small Aral to the gulf and vice versa. This would allow fishing vessels direct access to unload their catch at the newly rebuilt and quite modern fish processing plant in Aralsk. Currently fish are hauled some distance to the plant via refrigerated truck (Expedition 2011). Cost of this project is estimated at 200 million USD. In September 2011, the word was that President Nazerbayev of Kazakhstan had selected the Saryshaganak variant (Expedition 2011). The World Bank is supportive of the project and the Kazakhstan Government has requested a loan to cover part of the cost from that organization.

The other project would rebuild the Kok-Aral dike and dam, raising the level of the entire lake to 48 m and increasing its area and volume to 4,830 km^2 and 53.5 km^3 respectively. The second project would likely provide more economic and ecological benefits than the Saryshaganak Reservoir plan, including more improvements to the fishery, better sea-borne transport prospects, and more ecologically suitable salinity conditions that are closer to what prevailed prior to the modern desiccation. The main objection to this plan is concern over insufficient water available from the Syr Darya on an annual average basis to maintain this level. However, calculations by the author suggest there may be sufficient inflow from the Syr Darya.

The estimated average annual inflow to the Small Aral from the Syr Darya for 1992 through 2011 is 5.98 km^3. Assuming the same average annual water balance parameters as used earlier for the Small Aral ($E = 960$ mm, $P = 120$ mm and net groundwater inflow $= 0.1$ km^3), the 48-m level could be maintained with an average annual discharge from the Syr of 4.55 km^3. But you would also need an outflow from the sea sufficient to maintain a reasonably stable salinity, which means in the simplest terms removing with the outflow the amount of salt brought in by the river (the salt contribution of net groundwater inflow is excluded from the calculation as groundwater is likely so small compared to river input).

Using values measured during our groups September 2011 expedition (Expedition 2011; see also Chap. 13) of salinity (1 g/l) for inflow from the Syr Darya and outflow salinity of 6 g/l at the Kok-Aral Dam, this could be realized with a discharge of 1.14 km^3 on an average annual basis (calculated using an iterative approximation process that takes account of the additional salt added by the increased inflow). Therefore, the average minimum annual inflow would need to be 5.69 km^3, which based on estimated inflows for the period 1992–2011 is obtainable. Average annual outflow from the Kok-Aral Dam would be 1.43 km^3 ($5.98 - 5.69 + 1.14$) based on the estimated Syr Darya flows to the Small Aral from 1992 through 2011.

If the outflow point were shifted to the very western end of the Small Aral where the salinity is higher, the salinity balance could be maintained with less discharge. For example using the same salinity of 1 g/l for Syr Darya inflow and what the author measured at several points around the western end of the water body (8 g/l), only 0.76 km^3 would be required, lowering the necessary inflow from the Syr Darya to 5.31 km^3. Moving the outflow location would also improve the water circulation in the Small Sea. Obviously, average annual outflow from the discharge works at the western end of the Small Aral would be the same as for the other variant 1.43 km^3 ($5.98 - 5.31 + 0.76$) based on the Syr Darya flows to the Small Aral from 1992 through 2011, but this variant is better adapted to lower inflow conditions.

What this design for the second phase of the Small Aral restoration project would look like is shown on Fig. 15.3. The cost of facilities to raise the level of the entire Small Aral from 42 to 48 m is unknown. It would require a much more massive Kok-Aral dike and completely replacing the concrete regulating dam. If the discharge point were moved to the western end of the sea, only a higher dike

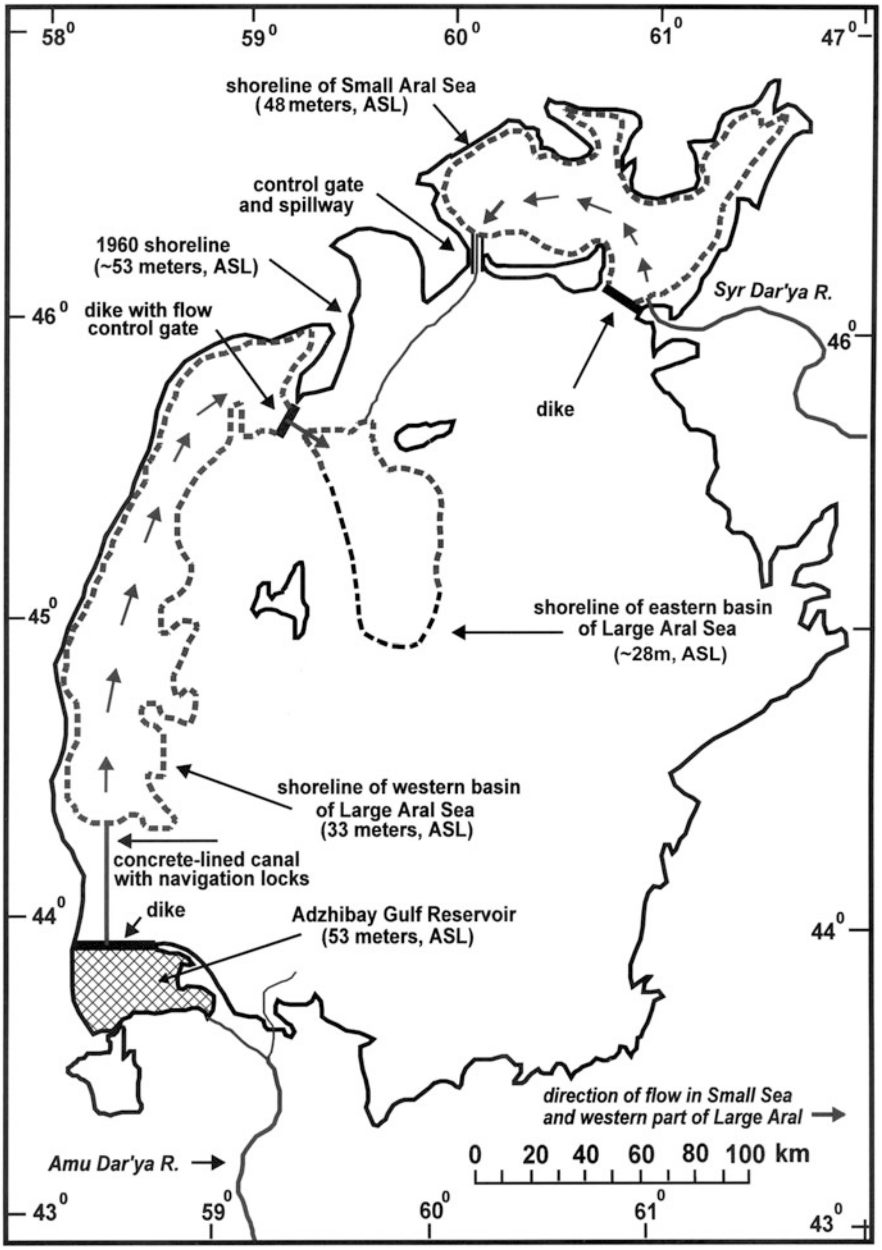

Fig. 15.3 Optimistic scenario of the future Aral Sea (after 2030) (Legend. *Small Aral Sea*: level = 48 m, surface area = 4,830 km^2, volume 53.5 km^3, avg. annual river inflow = 5.31 km^3, avg. annual outflow = 1.43 km^3, avg. annual salinity = 8 g/l. *Western Basin of Large Aral sea*: level = 33 m, surface area = 6,200 km^2, volume = 85 km^3, average annual river inflow = 6.6 km^3, avg. annual outflow to Eastern Basin = 2.09 km3. Salinity steadily decreasing reaching 42 g/l by 2055 and 15 g/l by 2110. *Eastern Basin of Large Aral Sea*: level ~ 28 m, surface area ~ 2,378 km^2, volume ~ 3.0 km^3, avg. annual salinity > 200 g/l. *Adzhibay Gulf Reservoir*: level = 53 m, surface area = 1,147 km^2, volume = 6.43 km^3, inflow = 8 km^3, outflow to Western Basin of Aral Sea = 6.6 km^3, avg. annual salinity = 2 g/l)

would be necessary to replace the present Kok-Aral facility. But a second dike and flow regulating structure would need to be built at the new discharge point. Also a ship access canal would be needed to the former port of Aralsk.

15.4.2 Restoration Prospects for the Large (Southern) Aral Sea

The future for the Large (southern) Sea is more uncertain. The Eastern Basin nearly disappeared in 2009. Owing to a heavy flow year in 2010, substantial flow reached it from the Amu Darya (and lesser amounts via outflow from the Small Aral Sea) and it was rejuvenated as a large, but very shallow lake (Table 15.1). Owing to another low flow year on the Amu in 2011, little or no water reached the Eastern Basin and it shrank rapidly. Assuming no human intervention, this pattern of shrinking (and perhaps even disappearing) during low flow cycles on the Amu Darya alternating with partial refilling during higher flow years will likely go on for the foreseeable future.

The Western Basin's fate in the absence of human intervention depends largely on net groundwater inflow, as it does not receive any direct flow from the Amu Darya. This input is not known with any degree of accuracy, but may be substantial owing to the hydraulic gradient from the Ust-Urt plateau, which it abuts on the west (Micklin and Aladin 2008; Expedition 2011). Nevertheless, if present trends continue, the level and area of the Western Basin will decrease considerably from the 2011 figures (Table 15.1), perhaps stabilizing around 21 m above the Kronstadt gauge at 2,100 km^2. It 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.

On the other hand, there are more optimistic scenarios for the Western Basin of the Large Aral. Figure 15.3 shows a concept developed by the author (Micklin 2010). It is adapted and updated to take account of current conditions from designs first put forward in 1978 by two Soviet water management experts (Lvovich and Tsigelnaya 1978). It would require an average annual inflow in the lowest reaches of the Amu Darya of around 8 km^3. However, adding this to the water needed to support deltaic lakes (4.35 km^3) the total inflow needed would be near 12.5 km^3. The author estimates average annual flow here for 1990–2011 at about 5.4 km^3, so it would require more than doubling this. Although substantial this could be accomplished with reasonably obtainable improvements in irrigation efficiency in the basin of the Amu River where withdrawals in 2010 were 58.6 km^3 (Cawaterinfo 2012f). So for example, assuming present overall irrigation system efficiency at 65 % (ratio of water withdrawn to that used productively), raising it to 75 % (a 20 % improvement) would reduce withdrawals by 7.8 km^3.

All of the residual flow of the Amu (after meeting needs of deltaic lakes and wetlands, described below) would need to be directed northwestward into the former Adzhibay Gulf refilling it to 53 m with an area of 1,147 km^2, volume of 6.43 km^3 average depth of 5.6 m, and salinity around 2 g/l. This would mean no water would be allowed to flow to the Eastern Basin, except possibly in very heavy flow years on the Amu Darya. The existing channel (Glavnoye myaso) that currently takes a portion of river water to maintain a wetland/lake (Muynak Bay) 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 non migratory birds and aquatic mammals, and could become a major fishery.

Adzhibay Gulf reservoir, on average, is estimated to have evaporation of 1,400 mm/year, precipitation on its surface of 105 mm/year and groundwater inflow of 0.1 km^3/year (evaporation data from Gorelkin and Nikitin 1985, Fig. 8, p. 22; precipitation data from Bortnik and Chistyaeva 1990, Fig. 2.2, p. 20, and groundwater estimate by Micklin). Thus to maintain it would require 1.4 km^3 of water. The remainder, averaging 6.6 km^3/year, would be released via control gates to a channel connected to the Western Basin of the Large Aral Sea. The channel would need to be lined with concrete or clay to reduce filtration losses. Assuming water balance parameters for the Western Basin of $E = 1{,}000$ mm, P (on the sea surface) $= 111$ mm (E and P values taken from Bortnik and Chistyaeva 1990, Fig. 2.5, p. 20 Table 4.1, p. 36) and using an estimated net groundwater inflow of 1 km^3 (which may be on the low side), a level of 33 m, area of 6,200 km^2, and volume of 85 km^3 could be maintained with an average annual inflow of 4.51 km^3.

The excess inflow (2.09 km^3) would be discharged to the Eastern Basin via a regulating structure (dike and dam) at the northern end of the Western Basin where the connecting channel now joins the East and West basins of the Large Aral. The Western Basin would freshen as more salt is carried out than is brought in. At first this process would go rapidly with inflowing river water at 2 g/l and groundwater (also assumed at 2 g/l) while outflow would be at more than 100 g/l, but slow as the average salinity of the Western Basin decreased. Assuming project construction starting in early 2015 and finishing in early 2018, when filling would commence, the design level of 33 m, based on the spreadsheet fill model mentioned earlier, would require another 10 years and be completed by early 2028, when water releases to the Eastern Aral would begin (Micklin 2012a). At this time owing to the inflow of lower salinity (2 g/l) water from the Adzhibay Reservoir and groundwater, average salinity would be around 79 g/l compared to 110 g/l before filling started.

Employing an Excel based salt balance model indicates that by 2058, the average salinity would drop to less than 42 g/l allowing the introduction of kambala (Black Sea flounder) and possibly other salt tolerant fishes (Micklin 2012b). When salinities fell below 15 g/l, stocking with indigenous Aral Sea species such as sazan (a type of carp) and sudak (pike-perch) would be possible. However, this could take until 2119. But it is possible that density stratification would create a layer of saline water on the bottom and less saline on top that would accelerate the freshening process (Kostianov et al. 2004). Of course if inflow from Adzhibay Gulf could be increased the process could go more rapidly. For example, if this were 10 instead of

6.6 km^3, increasing outflow to 5.49 km^3, less than 42 g/l would be reached by 2039 and salinity would fall below 15 g/l by 2057. This would require raising the average annual delivery of water to the lower Amu Darya Delta to 15.9 km^3, about three times what the average was for 1990–2011.

The saline lake formed on the former Eastern Aral Basin would have a level near 28 m, surface area of 2,378 km^2, assuming precipitation on its surface of 111 mm/year, evaporation from the surface of 1,200 mm/year (evaporation would be higher than from the Western Basin owing to higher water temperatures in this very shallow water body) and estimated net groundwater inflow of 0.5 km^3. Its volume would be about 3 km^3. It would be beneficial in its own right by reducing the area of barren, salt-covered desert that contributes so heavily to dust/salt storms. Also, it might be used for harvesting of brine shrimp eggs, as with salinities over 200 g/l the water body would provide ideal habitat for brine shrimp.

This concept has so far been little studied as to its engineering feasibility, ecological consequences, and economic benefits and costs. Without doubt it would require more funding than the 85 million USD spent to implement the first stage restoration project for the Small Aral. This project would also eliminate the possibility of commercially harvesting brine shrimp eggs in the Western Basin, as salinity would be far too low for this species' survival. Implementation would require agreement, funding and cooperation from both Kazakhstan and Uzbekistan, as about 30 % of the Western Basin is within the former country and the remaining 70 % in the latter. Kazakhstan where the outflow structure would be build might not have that much interest in the project as restoration of the Small Sea is far more important to that nation's government. Even more critical, the expanding search for gas and oil being pursued by a consortium of Chinese, Uzbekistan, Russian, Malaysian, and Korean companies and extraction of these fossil fuel resources on the bottom of the former Adzhibay Gulf and southern Aral Sea would be made considerably more difficult (CNPC 2012). If major deposits are found, as is expected, this in itself may doom the restoration plan to never going beyond the drawing board, as Uzbekistan would have little interest in it (CNPC 2012).

15.4.3 Restoration of the Lakes and Wetlands of the Deltas of the Amu Darya and Syr Darya

The Soviet government initiated rehabilitation of the lakes and wetlands of the lower Amu Darya Delta in the late 1980s. After independence at the end of 1991, the new states of Central Asia in collaboration with international donors continued this work. The prime objective of the largest effort (the Aral Sea Wetland Restoration Project or ASWRP), which was implemented by the International Fund for the Aral Sea (IFAS) and funded by the Global Environmental Facility (GEF), has been rehabilitation of former lakes and wetlands (of greatest importance Sudochye) and the creation of several artificial lakes and wetlands in the lower delta (Mezhdurechensk and

Dumalak) and on the dry bed of the Aral Sea (Muynak, Rybachye, Dzhiltyrbas) (Micklin 2007; Scheme 2002; GTZ and ICWC 2007, pp. 136–137). The objective was to restore the biological diversity and productivity of these water bodies that have not only great ecological importance (for migratory birds, fishes, and aquatic mammals) but considerable economic value as well as sources of edible fish, for trapping fur bearing mammals, and as places where reeds can be harvested for domestic animal feed and for construction purposes.

The rehabilitation plan cost six million USD. Experts have estimated that 4.35 km^3 of water (3.1 of relatively clean river flow supplemented by 1.25 of irrigation drainage) are needed to support minimally acceptable “hydro-ecological conditions” in the lower delta of the Amu Darya, including 1,800 km^2 of natural and artificially created lakes and wetlands there (MKVK 2002, p. 39, 2010, p. 75). Water requirements would specifically depend on the flow year on the Amu: 8 km^3 in a high flow year, 4.6 in an average flow year, and a minimum of 3.1 in a low flow year. As mentioned earlier, remaining flow could be used to support the rehabilitation project for the Large Aral Sea described above. For the plan to work successfully salinity of the river flow needs to be maintained between 0.8 and 1.2 g/l and even in low-flow years, priority water bodies must receive adequate inflow.

A problem for the restoration program has been that in low flow cycles on the Amu Darya, the lakes and wetlands dry and shrink with severe adverse effects on the habitat for migratory birds and on fisheries (Micklin 2010, pp. 74–78). For example in the 2000-mid 2002 drought and low-flow period, the lake/wetland area suffered a severe decline, with the aggregate area falling from 1,276 in April 2000 to 796 km^2 by August 2002 (GTZ and ICWC 2007, pp. 136–137). The area of Lake Sudochye, the largest and most important water body, shrank from 419 to only 65 km^2. Normal and above normal flows returned in ensuing years, and by June 2005, the aggregate area had grown to 3,293 km^2 and the area of Lake Sudochye to 621 km^2.

Drought and low-flow conditions recurred in the 2007–2009 period with the aggregate area falling from 2,674 in the former year to 1,049 km^2 by November of the latter (Cawaterinfo 2012a, Table 5, 5a). Figures for Lake Sudochye for the same time period were 534 and 314 km^2. As noted earlier, 2010 was a heavy flow year and much water reached the lakes and wetlands of the lower Amu Delta with the aggregate area growing to 3,561 and Sudochye to 597 km^2.by October. Dry conditions returned in 2011 and very little water reached the lower delta. As a result, aggregate area shrank to 2,928 and Lake Sudochye to 389 km^2 by September 2011. Complaints have been made that even in average flow years, deliveries of water to the lower delta are only half of what they should be (MKVK 2010, pp. 74–78). In early 2011, 21 new gages were installed at key locations in the lower delta to provide more accurate measurements of water levels and discharges in canals, collector drains, and lakes in the Amu Darya Delta (Cawaterinfo 2012f).

V. Dukhovnyy head of the Scientific Information Center (SIC) of the Interstate Coordinating Water Management Commission (ICWC) has promoted a more ambitious version of the restoration plan for the Amu Darya Delta. In addition to the lakes and wetlands of the delta, it would create so-called large, shallow “anti-polder” reservoirs on the dried bottom of the southern Aral Sea to stop sand dune encroachment on the delta and reduce the wind transport of sand and dust here. These have been controversial for a number of reasons, including fears of excessive evaporation from them and insufficient water availability to sustain them. So far none have been constructed.

A related effort has been the development of a technology and its implementation for afforestation of parts of the dried bottom of the southern portion of the Aral Sea. Known as "Stabilization of the desiccated Aral Sea bottom in Central Asia," this program has been funded and conducted by the German government foreign aid agency GTZ in cooperation with the Forestry Research Institute of Uzbekistan (GTZ and ICWC 2007, pp. 10, 123–127). Its purpose is to plant drought resistant trees and shrubs (mainly saksaul- *Haloxylon aphyllum*) on the dry bottom to help stabilize the soils and lower their deflation potential. Reportedly by 2010 this program had led to self-sustaining forests growing on 2,000 km^2 of the dried bottom (MKVK 2010, pp. 74–78)

Less ambitious, but still significant' efforts are underway to improve wetlands and lakes (mainly Kamyshlybas, Karashalan, and Tushchibas) in the lower Syr Darya Delta by providing them with more water from the Syr (as noted earlier this is one of the purposes of the Ak-Lak hydrocomplex) and undertaking other measures to enhance their ecological condition and improve their fishery potential (Expedition 2011; MKVK 2010, pp. 74–78). For the Syr Darya Delta preservation of the lakes and wetlands of six lake systems encompassing an area of 1,520 km^2 requires an ensured water delivery of 1.78 km^3, including 0.133 km^3 of collector-drainage water. After reconstruction of the lake systems, this could be reduced to 1.4 km^3. In recent years a fish hatchery and nursery has been built on the shore of Kamyshlybas, the largest of the lakes, which has by far the most important fishery (Expedition 2011; also see Chap. 13. The fish as they grow larger are progressively raised in a series of ponds and then released into the lake fishery. The hatchery is jointly funded by Israel and the United States.

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Chapter 16
The Siberian Water Transfer Schemes

Philip Micklin

Abstract The twentieth century was the era of mega-engineering thinking. This was a worldwide phenomenon, but perhaps had its clearest expression in the Soviet Union, a nation with a well-developed ideology promoting man subduing nature for purported human betterment. Soviet plans to transfer huge amounts of water long distances from Siberian rivers to Central Asia were initially conceived, during the Stalinist era, as a way to fundamentally transform the physical environment of this region. During the period 1960 to the mid 1980s, these projects were primarily seen as the best means to provide more water for irrigation expansion and, secondarily, as a way to provide more water to the Aral Sea. After several decades of intense scientific study and engineering development, a final design for Siberian water transfers was on the verge of implementation when an abrupt change of national policy in 1985–1986 put it in on hold for the foreseeable future. The plan foundered owing to Russian nationalist opposition, enormous costs, a changing political environment, and the threat of significant environmental damage. The collapse of the USSR has probably doomed the project although it continues to be promoted by Central Asian governments and even some prominent Russians as a means to bring back the Aral Sea.

Keywords Davydov Plan • Siberian water diversion • Siberian water transfer • Ob • Irtysh • NAWAPA

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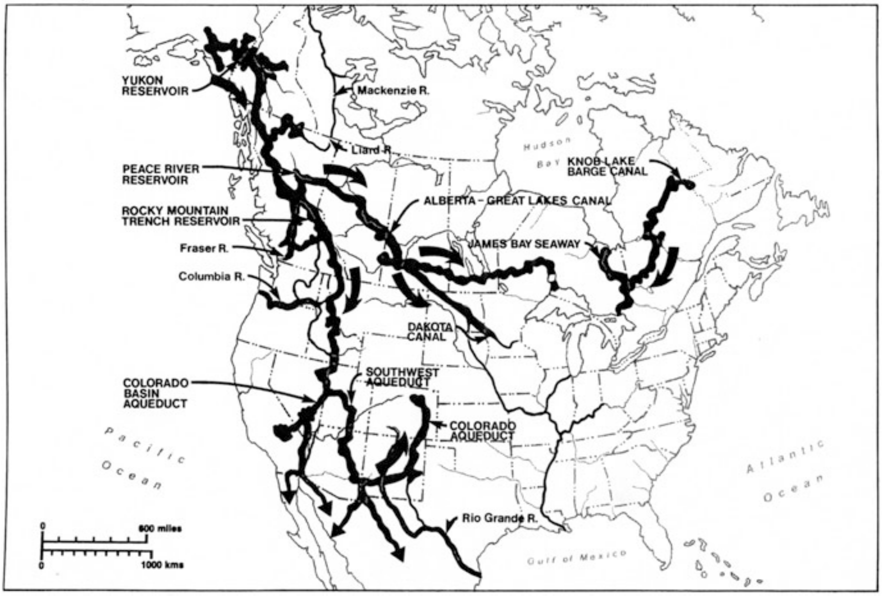

Fig. 16.1 The North American Water and Power Alliance Scheme (NAWAPA) (Source: Sewell, W.R. (1974). “Water Across the American Continent.” *Geographical Magazine*, Vol. XLVI, No. 9 (June), Figure 1, p. 472. Used by permission of Wiley, the Publisher.)

16.1 Introduction

The twentieth century was the era of mega-engineering water development projects. We were confident that humans not only had the technology but the need and right to remake and control nature. Beginning in the 1930s, chains of gigantic dams were built on a number of the World’s major rivers for hydroelectricity, flood control, irrigation and navigation purposes turning them from free flowing to a series of lakes. In the second half of the century, engineers moved on to designing and even building projects to move large volumes of water from one drainage basin to another for hydroelectricity production (e.g., The James Bay Project in Canada) or from perceived regions of surplus to perceived regions of deficit (e.g., the California State Water Project). The most grandiose scheme of this genre was NAWAPA (North American Water and Power Alliance) (Fig. 16.1). Conceived in the 1950s and 1960s, it would have involved connecting via a vast system of dams, canals, and pumping stations all the major drainage basins of western North America and the Great Lakes (Micklin 1985) in order to transfer up to 300 km^3 of water annually from humid northern to arid southern regions at an estimated cost in 1975 USD of 120 billion. Seen by proponents as a continent-wide scheme to solve all critical North American water supply problems for the next several centuries, it never went beyond the conceptual design stage owing to its huge expense, likely significant negative environmental consequences, and opposition from Canada and the northwestern U.S. states (Washington, Oregon, Idaho and Montana), which would have been the major "donors" of water. By the 1980s NAWAPA had retreated to the status of an ambitious engineering dream.

However, in the Soviet Union, a smaller, but still of unprecedented scale, inter-basin water transfer project was on the verge of implementation. It contemplated taking flow from the huge northward flowing Siberian rivers Ob and Yenisey and sending it thousands of kilometers southward to the mainly arid Aral Sea Basin. The Siberian Water Diversion Project (better known simply as "Sibaral" the abbreviation for "Siberia to Aral Sea Canal"), promoted and discussed since the latter part of the nineteenth century, underwent sophisticated refining, designing, and environmental evaluation from the late 1960s until the early 1980s. By 1985, the route was chosen, survey work completed, specialized construction equipment built and, it appeared, construction imminent. But in August 1986, the Soviet government announced the "Project of The Century" had been indefinitely postponed.

16.2 Rationale and History

Why was the Government of the USSR so interested in large-scale north to south water transfers? The primary motivation was the sharp geographical non-correspondence between regions with abundant fresh surface water resources, which consists mainly of river flow, and regions, which had high demand for water (Micklin 1987). Rivers carrying 84 % of average annual discharge flowed north and east across sparsely inhabited, economically underdeveloped territory to the Arctic and Pacific oceans (Fig. 16.2). The remaining 16 % of flow crossed the southern and western zones of the country where some 75 % of the population lived, which generated 80 % of economic activity, and which contained over 80 % of cropland, including the most fertile. Furthermore, although southern regions of the former USSR have the best soils and thermal conditions for agriculture, they have a decidedly deficit moisture balance (i.e. potential evapotranspiration significantly exceeds precipitation).

Hence during the Soviet years, irrigation had been increasingly developed to both increase and stabilize agricultural production (Micklin 1983a). In 1980, of 337 km withdrawn for all uses in the USSR, 177 km^3 or 53 % went for irrigation, nearly all of which was confined to southern semi-arid and arid regions. With a 1985 irrigated area of 19.6 million ha, the USSR tied for third place in the world with the USA and behind China and India. Soviet officials viewed irrigation expansion in the south, particularly in Kazakhstan and the four Central Asian Republics (Uzbekistan, Turkmenistan, Tajikistan, and Kyrgyzstan) as absolutely essential for the economic improvement of those regions and of the entire country. And the logical place to get the needed water was from the giant rivers of the northern zone of "surplus" flow.

The condition of several southern water bodies: the Azov, Caspian and Aral seas (strictly speaking, these are lakes) was a second powerful factor motivating interest in north to south water diversions (Micklin 1986). Since the 1930s, periods of low natural flow, the construction of reservoirs, and irrigation measurably reduced inflow to the Caspian and Azov seas, leading to a 3-m drop in the level of the

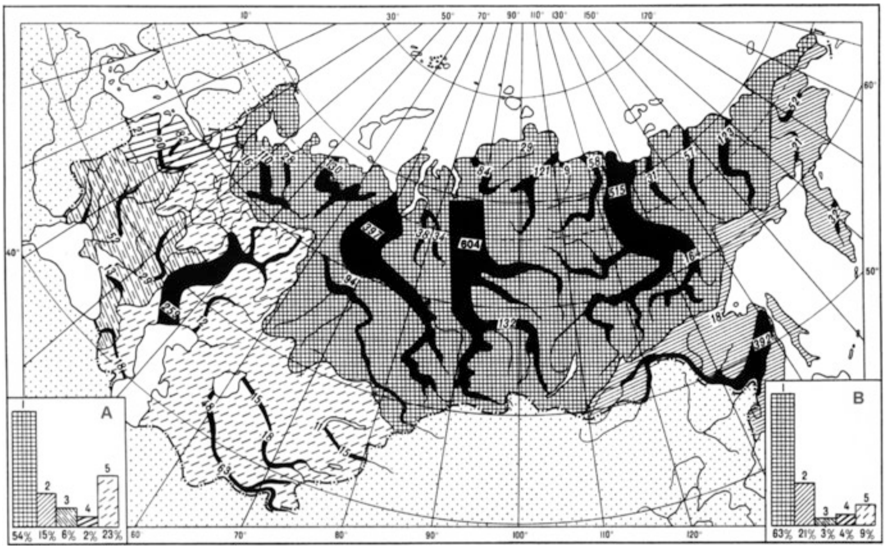

Fig. 16.2 Mean flow of USSR Rivers (km^3/year) (*Bar chart A* (*left*) indicates percentage of the USSR's territory with river discharge into specified sea and ocean basins. *Bar chart B* (*right*) indicates percentage of USSR's average annual river discharge accounted for by rivers flowing into specified sea and ocean basins. Numbers above the bars indicate drainage basins: 1-Arctic Ocean; 2-Pacific Ocean; 3-Black and Azov seas; 4-Baltic Sea; 5-Caspian and Aral seas) (Source: Adapted from Nikolskiy I.V, V.I. Tonyayev and V.G. Krasheninnikov (1975). *Geography of water transport of the USSR* (Moscow: Transport) (In Russian))

former by 1977. Soviet water management planners wanted to send part of the flow of northern European rivers southward to improve the water balances and salinity of these two water bodies. Contrary to expectations and forecasts, inflow since the late 1970s to both the Azov and Caspian seas rose substantially and the level of the latter has risen over 2 m (Aladin et. al. 2008). The Aral Sea fell 10 m from 1961 to 1985 and its salinity doubled, owing to the great reduction of discharge to the lake from its two influents (the Amu and Syr rivers) owing to very heavy irrigation withdrawals.

Although not the primary goal, which was expansion of irrigation in the Aral Sea Basin, water transfers from Siberian rivers would have aided in ameliorating this problem by increasing return irrigation drainage flows to the two rivers which feed the lake. Opposite to what happened with the Caspian, inflow to the Aral from the Amu and Syr has remained very low and the lake has continued to rapidly shrink and salinize with severe environmental and economic consequences.

A third factor making the transfers appealing was the relatively straightforward, given the projects scale, nature of the requisite construction required for their implementation. The headwaters of north and south flowing rivers in the former European USSR, now Russia, are proximate and separated by low divides. In the Asiatic part of the former Soviet Union, on the other hand, although long, a natural route of transfer across the low Turgay Gate dividing Western Siberia from

Kazakhstan and Central Asia is available. These features simplified the engineering and lowered the estimated costs of the diversions.

Politics and ideology also played a substantial role in the push for huge water transfer projects. They were to be built within one nation having an authoritarian and powerful central government. This negated the need for time consuming and complicated negotiations with other states (as would have been necessary, for example, to implement NAWAPA, requiring the acquiescence not only of the United States but of Canada and Mexico). It also meant that the Central Government could override opposition (that, as we shall see, was quite strong against the Siberian project). Soviet dogma was also favorable to such mega engineering ideas. An ideological commitment to economic determinism and the concept of humans mastering and remaking nature for human betterment through science and technology was a fundamental tenet of Marxism-Leninism (Micklin 1971). Hence, Soviet leaders tended to reject the idea of environmental constraints and looked favorably on gigantic "nature transformation" efforts.

The potential for moving water from Siberian rivers into Central Asia was recognized even in Tsarist times. In 1871, the engineer Demchenko proposed diverting water from the Ob River into the Aral Sea and from there into the Caspian (Micklin 1971). The plan was an engineering dream and well beyond construction technology of the day. During the 1920s and 1930s, both European and Siberian diversion concepts were seriously studied as part of the plans for the general development of the nation's water resources (Berezner 1985, pp. 13–18, 106).

M.M. Davydov, a Leningrad engineer, proposed the most grandiose Siberian water transfer scheme in the late 1940s as part of the "Stalin Plan for the Transformation of Nature" (Rus: Stalinskiy plan dlya preobrazovaniya prirody) (Micklin 1971, pp. 251–253, 1977). The goal was radical improvement of the climate of the entire Aral-Caspian lowland and the conversion of steppe and desert regions into productive pastures and croplands. This grand concept, to be implemented in stages, proposed ultimately taking 315 km^3 annually from the Ob and Yenisey rivers of Western Siberia, which flow into the Kara Sea, which is a marginal sea of the Arctic Ocean and sending it gravitationally via a 930 km canal to be dug through the Turgay Gate water divide (maximum elevation 125 m) to Kazakhstan and Central Asia (Fig. 16.3).

The water would have been used to expand irrigation in this region from less than 5 to 25 million ha and to supplement inflow to both the Caspian and Aral seas to make up for river water flowing to the two water bodies that would be withdrawn for irrigation. The length of water transfer from Western Siberia to the Caspian Sea would be 4,000 km.

The plan would have reduced the average annual discharge of the Ob and Yenisey by 32 %, created a gigantic 250,000 km^2 reservoir on the West Siberian Plain, inundating swamps, forests, farmland, and the largest, but unknown at the time, oil deposits in the USSR. Costs would have been enormous, running in today's U.S. dollars up to 200 billion. The plan, similar in scale to the NAWAPA scheme, would have taken 30–50 years to implement. Little was heard of it after Stalin's death in 1953 when the grand plans for "Nature Transformation" were quietly shelved.

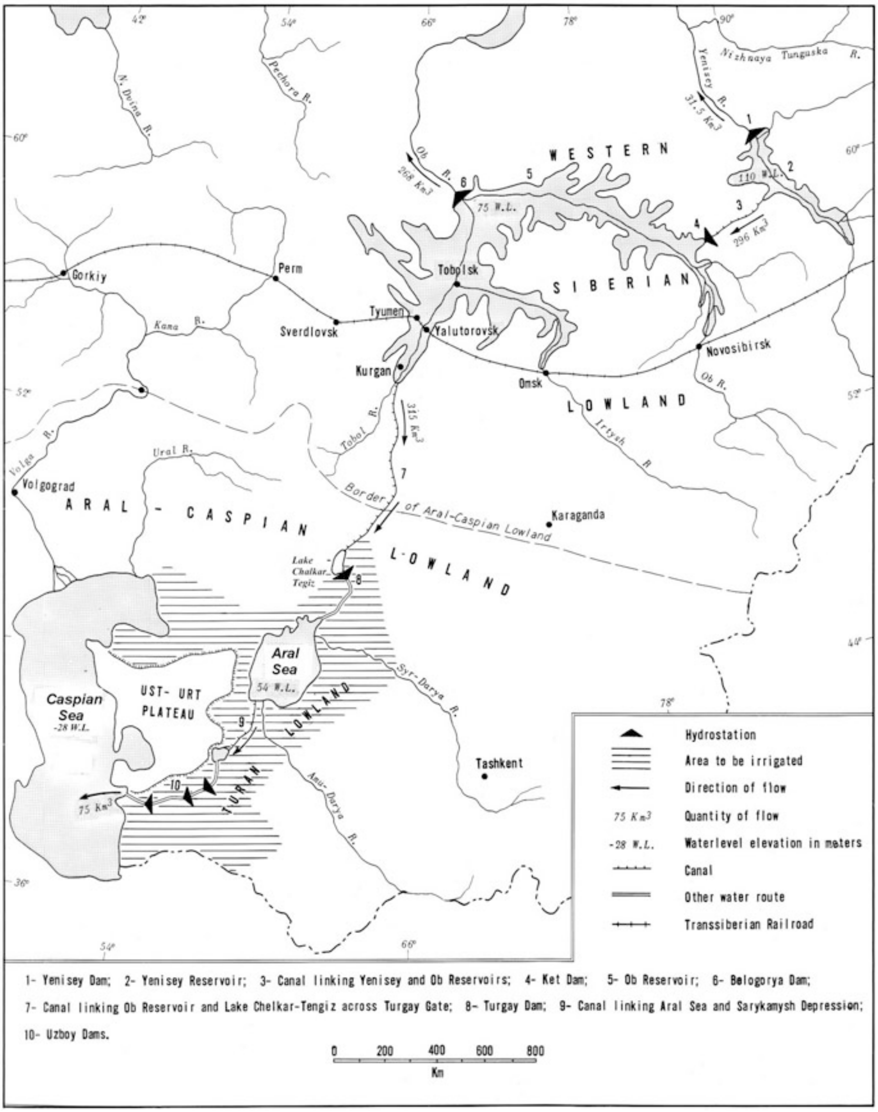

Fig. 16.3 The Davydov Plan (Source: Adapted from Davydov, M. M. (1949), "The Ob-Aral-Caspian Water Connection," *Gidrotekhnicheskoye stroitel'stvo*, No. 3, p. 10 and Davydov, M. M. (1949), "Transformation of the drainage network in the Soviet Union," *Geografiya v shkole*, No. 3, p. 15 (both in Russian))

During the 1950s and 1960s, primary attention was focused on water transfer plans in the European part of the USSR where the water management situation was perceived as more critical than in Central Asia (Micklin 1983b). However, in the early 1970s as water use in Central Asia grew rapidly and the Aral Sea continued to recede, interest renewed in schemes for sending Siberian water southward. Design efforts initially were the responsibility of Soyuzvodproyekt (National Water Management Design Corporation), but in the late 1970s, primary responsibility was assigned to Soyuzgiprovodkhoz (National Water Management Design and Scientific Research Institute). Both of these agencies were subordinate to the Ministry of Reclamation and Water Management (Minvodkhoz).

The 10th Five Year Plan (1976–1980) was a period of intense research and design work on both European and Siberian diversion schemes (Micklin 1986, 1987). Planners recognized that identification and study of the potential environmental impacts of water transfers as well as development of mitigation measures for these lagged design efforts. A major effort to correct this deficiency was launched under the general supervision of the State Committee for Science and Technology and the specific guidance of the Institute of Water Problems of the Academy of Sciences in which more than 120 scientific and planning agencies participated. Research results were presented and discussed at a series of conferences as well as being published in numerous articles and in several summary volumes. Technical-economic feasibility studies (TEOs) were also completed on the initial phases of both European and Siberian diversion projects. These documents were subsequently submitted to Gosplan (the state planning agency) for their evaluation and approval.

Research and design work on diversion projects continued in the 11th Five Year Plan (1980–1985) but the emphasis was on the latter. The 26th Communist Party Congress in 1981 called for initiating construction work on European diversions before 1990 and for continuing scientific evaluation of and design work on Siberian transfers. An expert commission of Gosplan during 1980–1983 evaluated the TEO for the first phase Siberian project. In August of 1983, it approved the scheme with one minor change that increased the proposed annual diversion from 25 to 27.2 km^3 (Micklin 1984). In January 1984, the USSR Council of Ministers accepted the positive recommendation of the expert commission and directed the Minvodkhoz to prepare the detailed engineering designs necessary for construction of the main diversion canal known as “Sibaral”.

The director of the Institute of Water Problems, Grigoriy V. Voropayev, who headed the research program on the environmental effects of water transfer projects, indicated to the author of this paper in February 1984 that, dependent on a favorable decision by the Government on the final design, first phase Siberian diversions could be under construction by 1988. Figure 16.4 shows European and Siberian diversion schemes according to the designs worked out by 1984 (Micklin 1986). Figure 16.5 shows the Siberian diversion plan in more detail

Implementation of European transfers would occur in several phases and stages. The first stage of the first phase (5.8 km^3/year) was to be started in the 12th Five Year Plan (1986–1990) and completed in the 1990s. First phase transfers (19.1 km^3/year) were to be completed in the early twenty-first century. European diversions could possibly be increased to more than 60 km^3/year during this century, but would require much more research and design work prior to construction.

Two phases were planned for Siberian diversions (Micklin 1986). The first would draw 27.2 km^3 annually from the Ob River and its right-bank tributary the

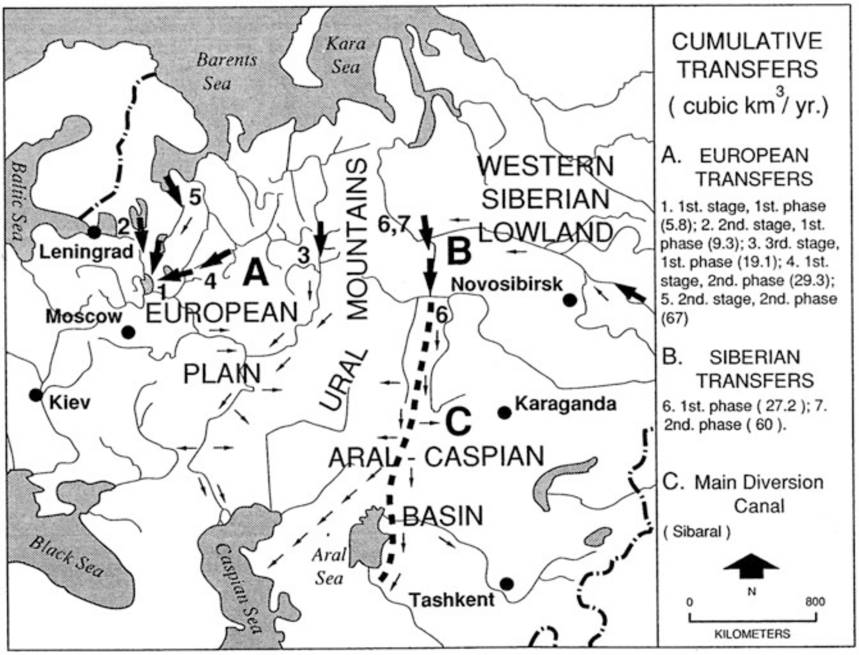

Fig. 16.4 Final diversion plans for European and Siberian Parts of USSR (1984) (Source: Micklin (1991). "The Soviet Experience with Large-Scale, Long Distance Water Transfer Planning," p. 94, Fig. 14. In Marie Sanderson (ed.), *Water Pipelines and Diversions in the Great Lakes Basin,* Department of Geography Publication Series, Occasional Paper No. 13. Waterloo, Canada: University of Waterloo)

Irtysh and send it southward. The route from the Ob to the Amu Darya River in Central Asia would stretch 2,544 km. The first 344 km would follow the Irtysh River from its confluence with the Ob to the city of Tobolsk; the river over this part of its course would have its flow reversed (i.e. become an "anti-river") to deliver water from the Ob from September to April. Water would then be pumped on a year-round schedule from Tobolsk up and across the Turgay divide and from here move mainly by gravity to the Amu Darya via a huge earth lined canal. Another possible variant was a left bank canal that would parallel the Irtysh and avoid the need to reverse its flow. By 1985, however, the anti-Irtysh variant, apparently, had won out. The cost of the project was estimated to be 13 billion rubles. An additional 18 billion rubles was estimated to be necessary for the construction of water distribution and irrigation facilities along the route, for a total project price of 32 billion rubles (a dollar figure is problematic, but the first phase certainly would have run into the equivalent of several tens-of-billions of 1984 U.S. dollars).

Construction of first phase transfers was set to begin by the late 1980s and to be completed around the turn of the century. Table 16.1 shows basic economic and environmental information related to first phase Siberian diversions. A second phase would raise Siberian diversions to 60 km^3/year. It would likely require

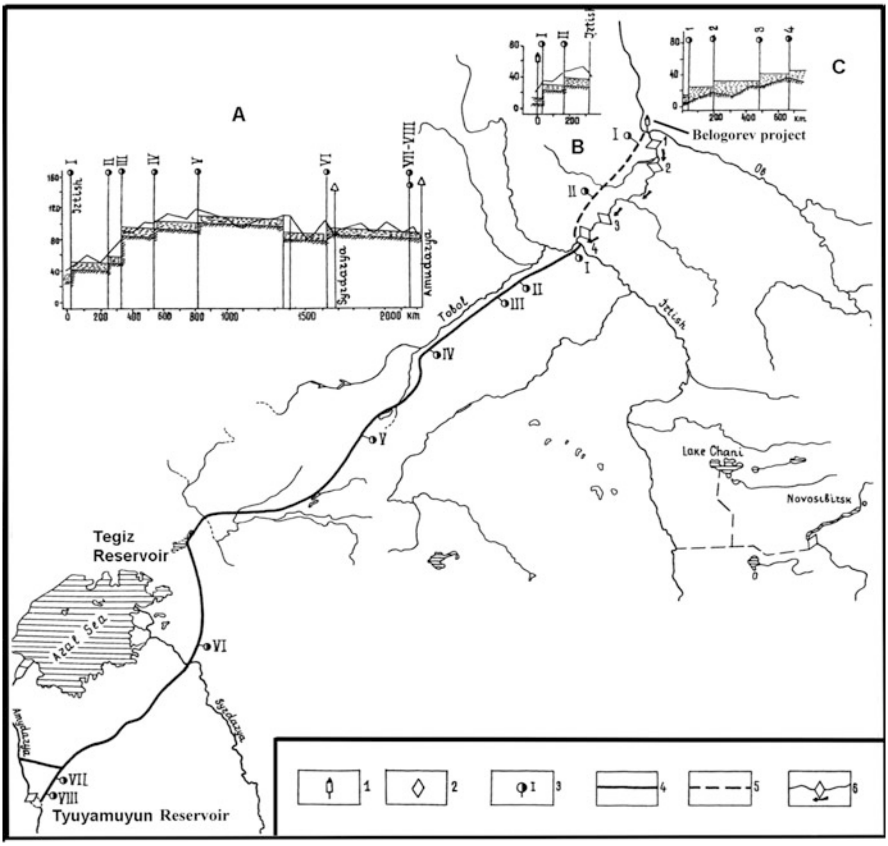

Fig. 16.5 The First Phase Design for the Siberian Water Diversion Project as of the Early 1980s (*Diagram A* (*upper left* on map) shows the N to S cross section of the main diversion canal with elevations in meters on the Y axis and distance in km on the X axis. Roman numerals I–VIII on this diagram indicate pumping stations. *Diagram B* (*top center*) shows the cross section of the variant with a *left* bank Irtysh canal (*dashed line*) and two pumping stations. *Diagram C* shows the so-called "anti-Irtysh" variant in which the flow of the Irtysh River would be reversed for more than 600 km by four hydrocomplexes (low dams and pumping stations). The anti-Irtysh design was selected in the final project plan. *Symbols* on the *bottom* of the map indicate (1) water withdrawal facilities without dams, (2) hydrocomplexes, (3) pumping stations, (4) main diversion canal, (5) left bank Irtysh canal and (6) anti Irtysh) (Source: Adapted from Voropayev, G. V. (1982), "Problems of water ensuring of the country and the territorial redistribution of water resources.", *Vodnyye resursy*, No. 6, Fig. 3, p. 7 and Voropayev, G.V. and A.L. Velikhanov (1985), "Partial Southward Diversion of Northern and Siberian Rivers," Fig. 4, p. 76. In Genady N. Golubev and Asit K. Biswas (eds.), *Large Scale water Transfers: Emerging Environmental and Social Experience*, UNEP Water Resources Series 7. Oxford: Tycooly)

supplementing the Ob with water from the Yenisey River, which lies to the east. Implementation of the second phase would require further research and design work and was not viewed as necessary until well into the twenty-first century.

Table 16.1 Selected economic and environmental characteristics of the First Stage Siberian water diversion project

Annual average diversion (cubic kilometers)	27.2
Capital cost of main diversion canal (millions of rubles)	
Total	13,000
Per cubic kilometer	478
Capital cost of water distribution and irrigation facilities	
(Millions of rubles)	18,000
Amortization (payoff) period (years)	10
Irrigated area (millions of hectares)	
1984 irrigated area in affected zone(1)	87
Area to be irrigated from diversions	45
Percentage increase over 1984 irrigated area	50
Feasible irrigation area in affected zone by 2010	16–17
Benefits of first phase Siberian diversion (claimed)	
Increased food production: grain (17.1 mill. tons), including 13.1 of corn; vegetables, potatoes and melons (6.7 mill. tons); fodder crops (45.1 mill. tons); meat (2.9 mill. tons); milk (10.9 mill. tons); eggs (9.2 bill.); vegetable oil (130,000 t)	
Creation of a navigable waterway from the Amu to the Ob	
Improved industrial and municipal water supplies	
Creation of employment opportunities for the rapidly growing population of Central Asia	
Improved water quality along the Amu and Syr rivers	
Some reduction of flooding and water logging below points of diversion along the Ob and Irtysh rivers in Western Siberia	
Potential harmful consequences of diversion project to northern regions of water export (Western Siberia) (examples)	
Flooding of land including agricultural (amounts unknown)	
Inundation of commercial timber (amount unknown)	
Resettlement of people (numbers unknown)	
Deterioration of fisheries of the Ob and Irtysh as well as Ob Gulf	
Worsened ice (i.e. lengthened cover) and climatic (i.e. cooler spring and summer) conditions in Ob Gulf	
Degradation of water quality downstream from points of diversion deterioration of flood plain meadows with agricultural value downstream from points of withdrawal owing to reduced spring flooding	
Worsened low-flow navigation conditions below points of diversion	
Slower summer melt of Kara Sea ice cover	

Source: Micklin (1987), p. 72

(1) Kazakhstan and the republics of Central Asia; some water would be used for irrigation in the RSFSR (southern Western Siberia)

The October 1984 plenary meeting of the Soviet Communist Party confirmed the start of construction on the initial phase of European diversions (5.8 km^3) by 1990 and indicated design work would continue on Siberian diversions but did not provide any timetable for implementation of the latter (*Pravda*, 27 October 1984, pp. 1–2). On the other hand, the Uzbek paper *Pravda Vostoka* reported in January 1985 that construction crews had arrived in Western Siberia from that republic to start work on infrastructure facilities for the main diversion canal to Central Asia (*Pravda Vostoka,* 9 January 1985, p. 1). On June 5, 1985, Vasilyev, Minister of Land Reclamation and Water Management, announced at a press conference that both the European and Siberian water diversion projects would proceed as planned (*Reuters*, 5 June 1985). In August 1985, a series of articles promoting the rapid implementation of the first phase of Siberian water transfers appeared in *Pravda Vostoka* (7 August, p. 1, 21 August, p. 31, 24 August, p. 1). It was reiterated that a large detachment of personnel from Uzbek water management construction agencies were building housing facilities and a construction base in anticipation of the initiation of work on the main Siberian diversion canal. Design work for this canal was now supposed to be completed in 1987.

16.3 The Fall of Sibaral

However, when the government released the draft guidelines for the 12th Five Year Plan in November 1985, there was no mention of Siberian diversion projects, only the vague statement that the "Scientific justification of the regional redistribution of water resources needed to be raised" (Basic directions… 1985, p. 47). Construction of the initial phase of north–south European diversions, however, was included in the plan. From September 1985 to the 27th Party Congress in late February 1986, scathing criticisms and denunciations of diversion plans by well-known Russian writers and prominent scientists appeared in a number of popular national circulation papers as well as Communist party papers and journals (Micklin 1987). The water transfers were barely mentioned at the 27th Congress. The final guidelines for the 12th Five Year Plan stated only that it was necessary, "To deepen the study of problems connected with the regional redistribution of water resources."

Nevertheless, *Minvodkhoz* continued to proceed with route and facility design work for the Siberian first stage transfer and preliminary construction work on the first stage European diversions. These actions were denounced as a violation of Party intent at the Eighth Congress of the USSR Union of Writers in July 1985. In August 1986, the Central Committee of the Soviet Communist Party and the Council of Ministers, the top governmental body, stopped all construction work on first phase European diversions and design efforts on Siberian transfers (Micklin 1987). However, the decree did allow further research on the scientific problems associated with water diversions, stressing ecological and economic concerns, and the utilization of mathematical models as well as domestic and foreign experience.

The stopping of design work on the Siberian project, postponing of the decision about its implementation into the indefinite future, and the call for further basic research into its economics and ecological consequences represented a surprising and fundamental change in Soviet national water management policy. The official Party and government line since the early 1970s was that this project required implementation by the turn of the century to meet the increasing water needs in Central Asia (Micklin 1986, 1987, 1988; Micklin and Bond 1988). National Party and governmental leaders as well those from the Republics of Central Asia (including Kazakhstan) who would receive the Siberian water, and national and republican reclamation and water management design and construction organizations strongly supported implementation of diversion projects as would be expected. However, the need and inevitability of Siberian (as well as European) water transfers was also widely accepted by many experts in the Soviet scientific establishment. These scientists' basic concern was that water transfer concepts be carefully investigated and their likely consequences (economic, social, environmental) understood in order to select routes and facility designs that would minimize harm while providing the necessary amount of water to southern regions.

Soviet scientists involved with the research effort on diversions were, in the 1970s, critical of many aspects of the then current proposals (Micklin 1983a, b, 1986, 1987). They believed research on environmental and ecological effects lagged behind design efforts. The massive environmental impact assessment program conducted in the 11th Five Year Plan (1976–1980) was intended to resolve this problem. There is no doubt the findings influenced the selection of the final routes, volumes and designs of transfer facilities as well as being used to develop mitigation measures. By the early 1980s Soviet water management experts and scientists working on the diversion projects (while admitting that not all questions about water transfers had been adequately answered) publicly professed that the main environmental concerns had been addressed, that appropriate modifications had been incorporated into the schemes to minimize environmental harm, that though there would be local environmental and economic damage from the projects, the probability of catastrophic and widespread effects was minimal, and that, on balance, the benefits of diversions to the south would outweigh costs to northern regions of water export. The impression was conveyed that, with some further research and minor design refinements, the initial stage of European and Siberian transfers could safely proceed.

Although the 1970s and early 1980s were years of general optimism about north–south water transfers, there was a consistent thread of concern about and criticism of them. The milder critiques tended to dwell on the need for further research. Thus, the directors of the Institute of Water Problems and Institute of Geography, (both supporters of water transfers) were still in 1982 calling for deeper research into a number of issues related to Siberian diversions including social-economic consequences and better estimates of future water requirements in regions of proposed import (Voropayev 1982; Gerasimov et al. 1982).

But the most rigorous and persistent critics of the Siberian project were natural and social scientists from Western Siberia, the region where negative effects of the transfer would be concentrated. The scientists at professional meetings and in publications expressed grave concern about the negative impacts of the proposed water transfers (Micklin 1986; Voronitsyn 1986). Yu. P. Mikhaylov, a Siberian resource geographer, for example, stated the designers had exaggerated the benefits, minimized the harm, and greatly underestimated the cost of the scheme. He called for much more research on the project and alternative means of meeting water needs in Central Asia and cautioned against any rapid move toward project implementation. However, since the conference proceedings and other publications were released in small numbers, the serious substantive issues raised about Siberian diversions did not reach even a broad scientific audience, let alone the general public.

However, early in 1982 the Siberian project was subjected to a major public challenge. The widely read and influential newspaper *Literaturnaya gazeta* (10 March 1982, p. 11) carried a full-page debate on the proposed diversion under the title "Project of the century from different points of view." Defending the scheme was chief project engineer Igor Gerardi; attacking it was economist Victor Perevedentsev who was affiliated with the Institute of International Workers Movement in Moscow who had worked at the Institute of Economics of the Siberian Branch of the Academy of Sciences in the 1960s. Gerardi asserted the first phase Siberian transfer had been thoroughly vetted by the experts and that it would have major economic benefits (chiefly for irrigated agriculture in Central Asia). He contended the project would quickly pay for itself with an amortization period of 10 years, that its environmental hazards were not severe, and that it must be implemented in the near future owing to the deteriorating water situation in Central Asia.

Perevedentsev categorically rejected these arguments, questioning the adequacy of the environmental research and the need for, and economic justification of, the project. He provided calculations indicating the payoff period would be at least 20 years and noted that it would be many years after construction started before water would be delivered and expenditures began to be recouped. Perevedentsev argued that more effective alternatives exist to increase food production and deal with water problems in Central Asia, including the irrigation of grains in Western Siberia and northern Kazakhstan and the reconstruction of old, inefficient irrigation systems. Perevedentsev and his views were bitterly denounced in April of 1982 in the Uzbek paper *Pravda Vostoka* (3 April, p. 3) by a member of the Uzbek Academy of Sciences and two individuals identified as "honored irrigators" of the Uzbek Republic. They stated that Perevedentsev was uninformed and his arguments absurd. They challenged his figures on the water savings from reconstruction of irrigation systems and said this program was already underway, as well as reiterating that the payoff period for the project would be 10 years (but no supportive calculations for this were provided).

This exchange occurred during the expert commission of Gosplan's evaluation of the technical document (TEO) on the Siberian project. The opposition may have been making a last attempt to derail the scheme and have it subjected to a thorough reappraisal, knowing how hard it was being pushed by Central Asian and reclamation interests. Perevedentsev worked at the Economics Institute in Novosibirsk during the 1960s. Academician Abel Aganbegyan, reportedly a long-time critic of Siberian diversions, was there at the same time. He and Perevedentsev no doubt knew each other well. It is likely Perevedentsev was presenting, as well as his own, the views of prominent scientists such as Aganbegyan, who opposed the project but felt they could not speak out publicly against it.

A number of Russian writers with a nationalist/populist/environmentalist orientation also played an important role opposing the river diversion projects, both European and

Siberian (Darst 1988). Sergey Zalygin, a former reclamationist and supporter of large-scale water management projects, who had a change of heart and became an adamant opponent of the proposed diversions, was the most well known member of this group. These writers saw the water transfer projects as a threat not only to the character and integrity of the environment of northern European Russia and Western Siberia, but to traditional culture and village life in these regions. They saw no reason to send precious Siberian water to Central Asia where, in their view, it would only be wasted. Their writings often had racist overtones toward the non-Russian Central Asian population.

The "official" approval of the Siberian scheme by the expert commission of Gosplan in August 1983 and the subsequent confirmation of this by the Council of Ministers in January 1984 had a chilling effect on the opposition. The clear message was that the decision had been made that the project will go forward and debates about it were over. The media were no longer open for any fundamental criticism of either European or Siberian diversions. Those who felt these projects were a mistake were relegated to sending private letters to high officials expressing their concerns and circulating underground manuscripts (samizdat – literally "self-published" documents).

A manuscript bitterly attacking European diversion plans, particularly for the damage they would do to historical, cultural, and archaeological treasures in the northern zone of water export, was smuggled to the west and published in 1984 ("One more time..." 1984). It contained copies of letters to the Politburo and Soviet Leader Andropov from prominent humanists, scientists (including many academicians, among them A. L. Yanshin, vice-president of the Academy of Sciences) and the group of nationalist/populist/environmental writers mentioned above. The manuscript pointed out the disastrous consequences of the European projects and called for a delay in implementation until much more thorough research has been conducted. One of the letters stated that the press was closed to critics of the project. Although the document did not deal with the Siberian project per se, one can reasonably assume its opponents were receiving the same treatment.

Hence, the evidence is unambiguous that by 1984 the proponents of moving rapidly toward final designs for and near-term implementation of the Siberian projects, in spite of opposition, had won the day. But their victory was short-lived; by the fall of 1985 they were on the defensive and 1986 saw the entire thrust of the early 1980s toward realization of the plan reversed with the cancellation of design work and a return to a phase of basic research and re-evaluation.

The ascension of Gorbachev to General Secretary of the Communist Party and leadership of the Soviet Union in March 1985 was the key factor in this sudden reversal. His background as the top party official for agriculture (1978–1983) and his emphasis on economic efficiency and the need for careful scientific founding and clear justification for large construction projects very likely had made him an opponent of the diversion projects long before he became the top Soviet leader. He had a close friendship with Academician Aganbegyan, with whom he attended Moscow State University in the mid-1950s and the latter had also served him as an unofficial economic advisor for some time.

After assuming leadership and placing his supporters on the Politburo and in the Government, Gorbachev moved to reverse the decisions that had been made about both European and Siberian diversions. That this would happen was no doubt clear to supporters of these projects. Thus, the flurry of optimistic articles in the Central Asian and some national papers from January until September 1985 on the Siberian project and the press conference of the Reclamation Minister Vasilyev in June 1985 promoting both European and Siberian transfers (which interestingly was reported in the Western media but not within the Soviet Union), with hindsight, appear to have been desperate attempts to keep the projects moving toward construction rather than a continuation of the steady progression of these projects to fruition which was assumed by Western observers (including this writer) at the time. Their efforts were to no avail. The fall of 1985 saw a resumption of the public debate over diversions (without doubt not only tolerated but encouraged by Gorbachev and his supporters) that had been silenced since 1982. This time around, however, the opponents of the water transfers commanded by far the most media attention

Project opponents' initial goal was the elimination of the go-ahead for construction on the first stage of European diversion (which had been included in the draft guidelines of the 12th Five Year Plan) as construction work had already commenced on it (Berezner 1985, pp. 13–18, 106). Consequently, most of the specific criticism was aimed at this project rather than the Siberian plan. It was charged that the scheme was unnecessary to meet water needs in the south and would be damaging to the environment of the north. A major issue was made of potential harm to cultural, historic, and archaeological sites, as it had been earlier in the 1982 *samizdat* manuscript. As noted above, permission for construction of the first stage European project was deleted from the final guidelines for the 12th Five Year Plan.

Discussion of the Siberian diversion disappeared from not only the national papers but also the Central Asian press in August 1985 (Brown 1985, 1986). Central Asian Party and governmental leaders also stopped talking about it and it was not mentioned at the 27th Party Congress held in February 1986. Favorable public discussion of the project, it appears, was declared off-limits. Nevertheless, *Minvodkhoz* (the National Ministry of Water Management) continued to push ahead with design work on the Siberian project and construction efforts on the European plan until the August 1986 decree finally halted these efforts and limited further work to basic research.

The reasons cited for suspending both the European and Siberian projects were economic, institutional–political, and environmental (Micklin 1987). A main economic argument was that not only would the projects be very costly and require a lengthy period of implementation, but that there are cheaper means of improving water supplies and agricultural production in the arid south. Reducing the great waste of water in irrigated agriculture in Central Asia was viewed as essential (see Chap. 8 for a more detailed discussion of this). Lining of earthen canals, accurate measurement of water use, more appropriate applications of water to crops, substitution of less for more water intensive crops such as cotton, among others, were put forward as means to "free up" ample water and obviate the need for Siberian water.

Critics charged that the water management agencies behind the design and environmental evaluation of the water transfers (*Soyuzgiprovodkhoz* and the Institute of Water Problems) had exaggerated the benefits while minimizing the economic and environmental costs of these undertakings to make them look more favorable (i.e., to give them a strong positive benefit/cost ratio) (Micklin 1991, pp. 60–68). One critic of the Siberian project estimated the first phase would cost at least 45 and possibly as much as 100 billion rubles rather than the "official" figure of 32 billion rubles. The agricultural benefits of this project, its main justification, also were challenged. For example, deducting for losses in transport (2.6 km) and industrial and municipal uses (around 5 km^3), leaves 19.6 km^3 for irrigation. To irrigate 4.5 million ha from this, as claimed possible, implies an average consumptive withdrawal rate of 4,355 m^3/ha, which was far below actual irrigation usage in the Aral Sea Basin.

It was also alleged that most of the studies on project consequences were carried out by organizations whose leadership was committed to their implementation and/or whose studies *Minvodkhoz* financed, most notably the Institute of Water Problems. Concerns were also raised about the objectivity of this research (*Pravda Vostoka*, 9 January, 1985, p. 1). The project designers were also charged with excessive secrecy and trying to keep the projects from public debate (*Literaturnaya gazeta,* 3 September 1986, p. 10). Although this was standard operating procedure in the Soviet Union, Gorbachev's campaign for openness (glasnost) stressed denouncing such narrow, bureaucratic approaches and calling for wide public involvement in the planning of projects with far-reaching consequences.

Concern that the environmental consequences of the projects had not been adequately studied also was cited as a primary reason for not proceeding with them. The August 1986 decree stopping work on them alluded to the necessity of further study of their ecological and economic aspects. On the other hand, one must note that an enormous amount of effort was expended between 1976 and 1980 to forecast potential environmental changes (Micklin 1986). Studies revealed that there would be significant and complicated negative environmental impacts, mainly in areas of water export, but that these would be of a local or in some cases regional nature (Fig. 16.6). The "official" position of the Soviet government until 1985 was that environmental consequences were not sufficient to forego implementation of the projects. Indeed, Soviet experts rejected as absurd specters invoked by some Western writers of initial phase Siberian diversions (27 km^3 /year) causing global climate changes as a consequence of their impact on the Arctic ice cover (Gerasimov et al. 1982). Independent research by Western scientists supported the Soviet view on this issue (Micklin 1981, 1986). After the water transfers were halted in 1986, the Soviet popular media promoted global climate change as a serious threat from the planned Siberian diversion (*Sovetskaya Rossiya*, 1 Jan. 1986, p. 3).

Certainly the potential adverse consequences from the proposed first phase Siberian diversion would have been consequential and deserved careful attention. A case can be made that the seriousness of environmental concerns was downplayed and some key economic and socio-cultural problems were largely ignored. However, it appears that following the policy reversal in 1986, these were exaggerated, probably to lend further credence to the fundamentally

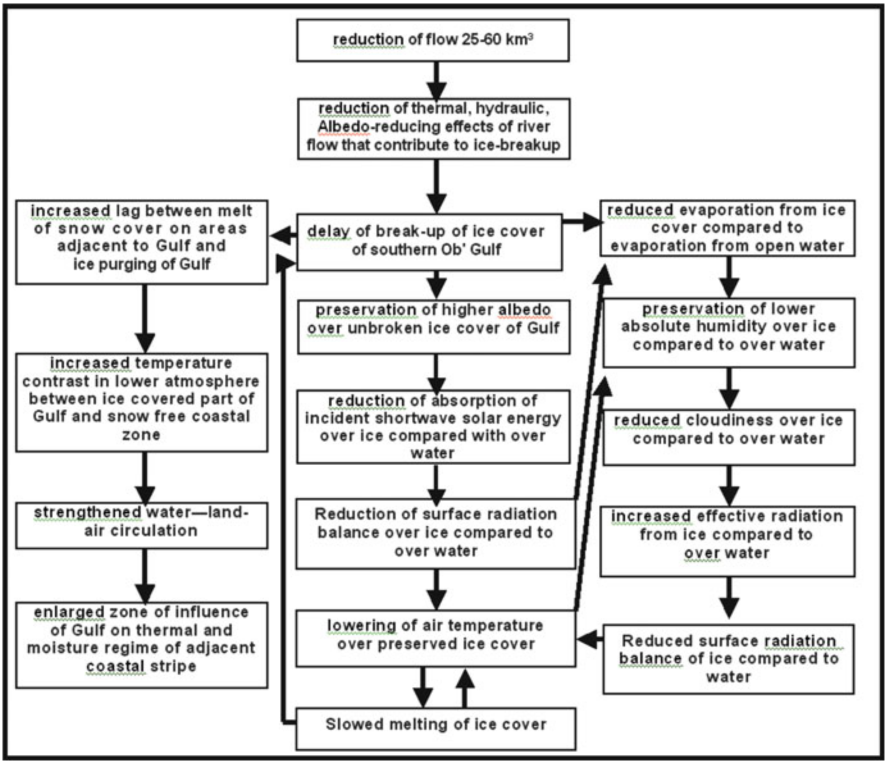

Fig. 16.6 Likely effects of diversion of 25–60 km^3 from the Ob River on the climate of the Southern part of Ob Gulf and adjacent regions in June and July (Source: Micklin (1986), p. 317)

investment-based decision to halt the projects. Indeed, a case may be made that environmental concerns probably did not play the dominant role in the Soviet government's decision to cancel the project. The decision to stop further work on diversions was economics based. The leadership became convinced their costs would be too great, their benefits too small, and that better means existed to obtain their nominal goals. Environmental arguments against them were primarily made to reinforce a decision made fundamentally on economic grounds.

The campaign against river diversion schemes did not cease with their official suspension in August 1986 (Micklin 1991, pp. 60–68; Darst 1988; Micklin and Bond 1988). Savage criticism of the Ministry of Water Management and Reclamation (*Minvodkhoz*), its subagency which designed the diversions, *Soyuzgiprovodkhoz*, and the Institute of Water Problems, which was the main organization evaluating the environmental consequences of these projects, continued unabated in both the popular and scientific media. As a result basic research on water transfers, even though not only permitted but required by the August 1986 decree, virtually stopped. The much (and often-unfairly) maligned Voropayev was forced to resign as director of the Institute of Water Problems in September 1988.

A.S. Berezner, Deputy Director of *Soyuzgiprovodkhoz*, who had headed design efforts on the diversions was sent to Mozambique to supervise Soviet-aided water management construction projects there. The full name of *Soyuzgiprovodkhoz* was changed from the "All-Union Design and Scientific Research Institute for the Diversion and Redistribution of the Waters of Northern and Siberian Rivers" to the "All-Union Design and Scientific Research Institute for the Design of Water Management and Reclamation Projects". Clearly, opponents of the schemes feared that they could be revived and were intent on ousting diversion supporters from positions of authority and stopping any further research.

For the remaining years of the USSR (1986–1991), there was little interest in north to south European water transfers. The level of the Caspian Sea was steadily rising, removing the key rational for them (to supplement that lake's water balance). The Siberian project, on the other hand, was another story (Micklin 1991, pp. 60–68). In January 1988 a joint decree of the Central Committee of the Communist Party and the Council of Ministers devoted to the improvement of water use, directed that scientific study of north–south water transfers continue. After a 2-year silence following the August 1986 decree, Central Asian water management officials, scientists and party and government officials began, again, to push publicly for water transfers as the only means to save the region from a water shortage catastrophe. Having counted on imported water from Siberia, the halting of the project was a great shock and disappointment for them (Micklin 1986, 1987; Micklin and Bond 1988).

In March 1988, a joint article in the Uzbek party and government paper, *Pravda Vostoka*, signed by the president of the Uzbek Academy of Sciences, R Khabibullayev, and Victor Dukhovnyy (at that time director of the Central Asian Irrigation Research Institute) stated that the ecological and social-economic difficulties of the Aral region could not be solved without diversion of water from Siberian rivers (*Pravda Vostoka*, 3 March 1988, p. 3). In October 1988, a water management expert from *Soyuzgiprovodkhoz* stated that water resources in the Aral Sea Basin would be exhausted no later than 2005, in spite of comprehensive and successful efforts to improve water usage (*Pravda Vostoka*, 10 October 1988, p. 3). He contended diversions would be needed by that date and, considering that 15 years are required for their implementation, stated that it was criminal that even research work on their ecological and economic aspects had come to a standstill.

By 1989, Central Asian political leaders, most importantly Islam A. Karimov, President of the Uzbek Republic and First Secretary of the Uzbek Communist Party, were stressing the dire nature of the water management situation in Central Asia, raising the question if the region could survive without water from outside, and calling on Moscow for help (*Pravda Vostoka*, 23 September 1989, pp. 1–2 and 1 December 1989, p. 2). With the weakening of central (Moscow) authority and the declarations of sovereignty by the Union Republics, Central Asian politicians became more adamant. On June 23, 1990, the presidents of the four Central Asian republics and Kazakhstan signed a joint declaration on mutual problems and approaches to their solution, contending the ecological catastrophe of the Aral Sea and adjacent areas was so acute that it could not be solved by regional efforts (*Pravda Vostoka*, 24 June 1990, p. 1). The leaders called on the national government to declare the Aral region one of national calamity and to provide real help. They also stated that it was necessary to return to the idea of water diversions from Siberia as one of the principal routes of saving the Aral and ensuring an adequate food supply for the region. In their view, diversions were to decide the region's future.

By the early 1990s, it appeared a Siberian diversion "compromise," involving a downsizing of the early 1980s design, might be possible. Ten to fifteen cubic kilometer annually (rather than 27 km^3) could be sent directly into the northern part of the Aral Sea or into the Syr Darya Delta by a concrete lined canal and huge pipelines, somewhat shortening the route and considerably reducing filtration and evaporation losses. This would reduce impacts downstream from points of diversion on the Ob and Irtysh rivers in Western Siberia. In conjunction with institution of widespread irrigation efficiency measures in the Aral Sea Basin to free water, a portion of which would go for the Aral, it might have been possible to raise the level of the sea and lower salinity to levels that would allow significant ecological improvement and partial restoration of the fishery, without any significant cutback in irrigation. It could have been argued that saving the Aral outweighed the harm to Western Siberia (although inhabitants of the latter region, no doubt, would have taken grave exception). The Soviet government and Russian Republic could also have insisted that no Siberian water be used for irrigation, encouraging Central Asian water interests to be more efficient, since expansion of irrigation and other water uses would be possible only from water freed by this means.

The Central Asian republics might also have been able to use their exports of food and cotton to the Russian Republic as bargaining chips (i.e., a "food and cotton for water trade"). On the other hand, the Government of the Russian Republic (and popular opinion) at the time remained strongly opposed to Siberian water transfers to Central Asia. Given the balance of power between Moscow and the Republics at the end of the Soviet era, diversions without the approval of Russia, even with the okay of the national government would have been difficult. Nevertheless, two prominent Central Asian water management experts and officials told this writer in 1991, not long before the collapse of the USSR, that Siberian water transfers would go ahead as a means to hold the Soviet Union together.

16.4 Sibaral in the Post-Soviet Era

The short-lived coup against Gorbachev and the imminent signing of the "Union Treaty" in August 1991 effectively ended the Soviet Union, which formally dissolved at the end of that year. The USSR became 15 Independent nations, pursuing their own national interests. All of the former republics except the three Baltic States joined a new organization known as the Commonwealth of Independent States (CIS). However, it had no real power or influence over its members and any decisions reached would require approval of all.

The leaders of the five Central Asian Republics strongly supported the continuance of the Soviet Union and the Union Treaty, but were forced by circumstances to adapt to independence. They believed the economic power and common markets of the USSR were their best hope to prosper (Wikipedia Contributors 2008). No doubt the belief that the Siberian water diversion project stood a far better chance to be implemented by the central government of one nation as opposed to the central governments of six countries also contributed to this support.

Objectively, the dissolution of the USSR was a severe blow to Sibaral. Rather than being a project within one country it now would involve taking water from the Ob and Irtysh rivers flowing to the Arctic through the Western Siberian part of Russia and routing it southward to Central Asia. This would entail formal, complicated international agreements among the six nations on such key issues as construction details and cost sharing, payments for water, allocation of water among the receiving countries, compensation for resulting environmental damage in the water donor regions, etc. Russia clearly had little interest in or incentive to send Siberian water southward.

Nevertheless, proponents in Central Asia did not abandon Sibaral. This grandiose scheme continued to be discussed and promoted in Central Asian water management and governmental circles during the 1990s and into the new millennium. While promoting the need for improved irrigation water use efficiency in Central Asia, they made the argument that even a very costly and intensive program to implement such measures, would not free enough water to expand irrigation to meet the food needs of a growing population and to increase flow to the Aral Sea to stabilize, let alone, raise its level and improve its ecology and restore its fishery.

In the early years of the new century, Sibaral 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 and Rustam 2003; Timashev 2003). Luzkhov even approached Russian President Putin in 2002 about supporting the Siberian Diversion Project, but Putin was, evidently, not impressed with his arguments (Savelyeva 2010). Not giving up, Luzkhov published a book titled *Water and Peace* in 2008 that promoted the project as beneficial to both Russia and the nations of Central Asia. Victor Dukhovnyy, now head of the Scientific Information Center (SIC) of the Intergovernmental Coordinating Water Management Commission (ICWC) and a long-time supporter of the Siberian Project enthusiastically commented on the book (Dukhovnyy 2009). In his positive review, he reiterated his long held view that the water transfers are absolutely necessary for the future of Central Asia.

An article in the British popular science magazine *New Scientist* (2004) talked of the revival of interest in the plan among Russian Scientists as a means to reduce the flow of Siberia's rivers that have increased (purportedly owing to Global Warming) and could upset the salt balance and circulation of the Arctic Ocean, leading to shutdown of the Gulf Stream that would trigger colder winters across Europe. Igor Zonn, at the time director of *Soyuzvodproject*, told *New Scientist*, "We are beginning to revise the old project plans for the diversion of Siberian rivers. The old material has to be gathered from more than 300 institutes."

The proposed diversion would be the same as under the Soviet plan – 27 km^3/year. It would require a 2,500 km canal 200 m wide and 16 m deep. Costs were estimated at 40 billion USD. Proponents of the project again made the arguments that Siberian water is needed to expand irrigation in Central Asia and improve the condition of the Aral Sea, but added several new reasons: increased usage from the Amu Darya (up to 10 km^3) by Afghanistan, a predicated (by climate models) major decrease in Central Asian rainfall as a result of Global Climate Change, and the need to protect Central Asian economies from collapse to prevent a flood of refugees to Russia. Proponents also portrayed the scheme as a way for Russia to rebuild its political and economic power in the region.

But, the scheme continues to be hugely controversial in Russia. According to the *New Scientist*, the chairman of the Siberian branch of the Russian Academy of Sciences, Nikolay Dobretsov, believes the diversion would threaten the Ob basin with eco-catastrophe and socio-economic disaster, including destroying fisheries and upsetting the local climate. Dr. Nikita Glazovskiy, a corresponding member of the Russian Academy of Sciences and former deputy director of the Institute of Geography, now deceased, who was very knowledgeable about the Siberian diversion project as well as being an expert on Central Asia, offered a scathing criticism of the "revived" project (Glazovskiy 2003). He viewed the project as an ecological disaster and financial boondoggle that would neither benefit Russia nor Central Asia. Along with others, he contended that there is enough water available in Central Asia to meet all legitimate needs, if used efficiently. Even some Central Asian experts agree that it would be wiser to spend precious capital and effort on improving regional water management rather than importing water from Siberia (Kamalov and Yusup 2003; Savitski 2003).

Even if the Russian Government were willing to permit the southward transfer of Siberian water, obtaining financing for the project would be extremely difficult. The five Central Asian State do not have the likely $50–$60 billion needed to build the project. Russia, flush with oil and gas revenue, might be willing to provide a loan for part of the cost but certainly nowhere near the amount needed (Temirov and Rustam 2003). Earlier, Central Asian governments had hopes that international donors, chiefly the World Bank, might be willing to help finance the plan, but that organization has given a firm no, probably owing to its newfound sensitivity to environmental issues surrounding huge water infrastructure projects, such as the Three Gorges Dam in China for which the Bank refused to provide a loan owing to social and environmental impact concerns (The Three Gorges… 2012).

In 2009 two "mega engineeering" proponents proposed a variant of the Siberian project mainly focused on restoring the Aral Sea (Badescu and Schuiling 2009). It would take water only from Lake Zaysan in Kazakhstan and deliver it into the Syr Darya from where it would flow into the Small Aral Sea raising its level and allowing considerable outflow to the Large Aral Sea on the south). Lake Zaysan is the source of the Irtysh, which is the main tributary of the Siberian River Ob. Diverting the water from Lake Zaysan would make the political negotiations for implementing the project much simpler as it would be implemented in only one country. The authors also see a much lower cost for this project, as the route would be considerably shorter than other Siberian water transfers schemes. Also, water would flow gravitationally to the Syr River rather than requiring huge electrical inputs for pumping over the topographic divide between Western Siberia and the Aral Sea Basin. However, it would require constructing a large diameter, 100 km tunnel through a mountain range for which the costs are very speculative.

Although an interesting concept, it has serious deficiencies beyond the tunnel issue (Micklin 2010). The most serious problem is that the idea of taking water from Lake Zaysan to refill the Aral won't work. At Ust-Kamenogorsk, immediately downstream from the Bukhtarma dam, which controls out flow from the lake (now a reservoir), the average annual discharge is around 18 km/year (Davydov 1955, p. 354). Thus, even if you took all the flow collected in Lake Zaysan and sent it toward the Aral through the proposed tunnel, the average maximum diversion would be 18 km/year. There would also be inevitable losses to evaporation (and unless the canal was lined to filtration) along the part of the route requiring a canal and in the Syr Darya Delta to both of these plus transpiration from hydrophytes. Farmers along the route would also surely take some of the extra water for irrigation.

It is doubtful more than about 12 km^3 or 13 km^3 would reach the Small Aral, not the 30 km^3 or 40 km^3 the authors talk about. So it is in no way a "solution" to the Aral problem. Furthermore, taking all the water balance surplus of the Lake would mean no outflow and hydropower from the Bukhtarma Dam (which with an installed generating capacity of 750 MW is a major power producer). Also, the bed of the Irtysh would be dry for many kilometers downstream, which would be very ecologically harmful and cause water supply problems for people, industry and agriculture along the river as well as losses of power production at other dams farther downstream. Realistically, it is doubtful the Kazakhstan government would ever allow diverting more than 1/2 of the surplus (9 km^3). If this were all that could be sent toward the Aral, the project would just not be worth the cost.

Will "Sibaral" the "Project of the Century" for the twentieth century be realized in the twenty-first? Given the hurdles it faces one must conclude it is unlikely. Yet, water shortage problems grow worse in Central Asia and regional leaders continue to call for its implementation (*Central Asian Environment, Science, Technology and Health News*, June 16–20, 2008, pp. 28–31). In 2007, Nursultan Nazyrbayev, President of Kazakhstan called for the building of Sibaral at the International Economic Forum in St. Petersburg and Moscow Mayor Luzkhov repeated the call at this event in June 2008. But the Siberian Project has lost its most powerful Russian supporter since Luzkov was stripped of his duties as Moscow Mayor in 2010, partly because of proposing what were considered a series of zany ideas (including the Siberian Diversion scheme) (Savelyeva 2010). And opposition to Sibaral from prominent Russian scientists as well as cultural and political figures continues unabated. Nevertheless, the project has risen from the dead before and may again.

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Chapter 17
Impact of Climate Change on the Aral Sea and Its Basin

Elena Lioubimtseva

Abstract Climatic and environmental changes in the Aral Sea Basin represent a complex combination of global, regional, and local processes of variable spatial and temporal scales. They are driven by multiple interconnected factors, such as changes in atmospheric circulation associated with global warming, regional hydrological changes caused by mountain-glacial melting and massive irrigation, land-use changes, as well as hydrological, biogeochemical, and meso- and microclimatic changes in the Aral Sea and its quickly expanding exposed dry bottom. Human vulnerability to climate change involves many dimensions, such as exposure, sensitivity, and adaptive capacity and affects various aspects of human-environmental interactions, such as water availability and stress, agricultural productivity and food security, water resources, human health and well-being and many others at various spatial and temporal scales.

Keywords Climate change • Climate variability • Land use • Human vulnerability • Arid environments • Adaptations • Aral Sea

17.1 Introduction

Society and environment of the Aral Sea Basin have been increasingly affected by climate change and variability that occur at multiple temporal and spatial scales. Climate, land-use, and hydrology are interconnected in complex ways. Any change in one of these systems induces a change in the other. For example, basin-wide hydrological and land cover changes have caused changes in temperature patterns and a decrease of precipitation, when local boundary conditions dominate over the large-scale circulation. On the other hand, global and regional climate change

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affects hydrological processes with respect to mean states and variability as well as land-use options. Water use is impacted by climate change, and also, more importantly, by changes in population, lifestyle, economy, and technology; in particular by food demand, which drives irrigated agriculture, globally the largest water-use sector. Significant changes in water use or the hydrological cycle (affecting water supply and floods) require adaptation in the management of water resources (IPCC and WGII 2007).

Climatic and environmental changes in the Aral Sea Basin represent a complex combination of global, regional, and local processes of variable spatial and temporal scales. They are driven by multiple interconnected factors, such as changes in atmospheric circulation associated with global warming, regional hydrological changes caused by mountain-glacial melting and massive irrigation, land-use changes, as well as hydrological, biogeochemical, and meso- and microclimatic changes in the Aral Sea and its quickly expanding exposed dry bottom. To understand the problem requires a nested multi-scale conceptual model addressing multiple natural and human-induced processes of various scales, their interrelations, and feedbacks. The purpose of this paper is to discuss climate change and human vulnerability in the Aral Sea Basin at several interconnected scales.

Human vulnerabilities to climate in drylands are strongly correlated with climate variability and changes, and especially variability of precipitation and runoff. These vulnerabilities are particularly high in the Aral Sea Basin, where stream flow is generated by the mountain glaciers and concentrated over a short period of time measured in months, and year-to-year variations are significant. A lack of deep groundwater wells or reservoirs leads to a high level of vulnerability to climate variability, and to the climate changes that are likely to further increase climate variability in the future. In addition this region, already stressed due to local, regional and global climatic changes, is likely to be vulnerable to non-climatic stresses (e.g. political, economic, institutional, etc.).

Climate change impacts and human vulnerability involve many variables, such as impacts of climate change on food security, water resources, health, security and other aspects of human life. Regional development factors contribute to the global climate change both through greenhouse emissions and the interactions between land cover and the boundary layer of the atmosphere. Exposure, sensitivity, and adaptive capacity of different regions and sectors also vary depending on spatial and temporal scales.

This chapter consists of four sections. Section one provides a brief discussion of the study area, overview of the essential terminology and provides the key references to the seminal bibliography. Section two describes the climate and climate change in the Aral Sea Basin at four scales: from the global to regional. This section is based on an extensive literature review, meteorological records, and climate change scenarios generated by the Atmosphere–ocean General Circulation Models (AOGCMs). Section three provides a discussion of the key aspects of human vulnerability, such as exposure, sensitivity and adaptive capacity, with regard to climate change impacts on water resources, agriculture, and human health. Finally, section four draws conclusions and offers some reflections on potential mitigation and adaptation policies for the Aral Sea Basin countries.

17.2 Climate Change in the Aral Sea Basin: A Multi-Scale and Multi-Dimensional Problem

The Aral Sea drainage basin area is approximately 1,874,000 km^2, of which the individual Amu Darya and Syr Darya catchments constitute a major part, and smaller catchment areas amount to about 321,000 km^2 (Shibuo et al. 2007). Afghanistan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan share the basin of the Amu Darya River. Kazakhstan, Kyrgyzstan, Tajikistan and Uzbekistan share the basin of the Syr Darya. The Aral Sea Basin comprises the Turan Lowland including the Kara-Kum, Kyzyl-Kum, and Muyun-Kum deserts and is bordered by the Kazakh Hills in the north and the ranges of Kopet-Dag, Tian Shan and Pamir mountains in the south.

Numerous biostratigraphic, geomorphological and archaeological data indicate that the climate of the Aral Sea Basin has been experiencing natural fluctuations for many thousands of years (Vinogradov and Mamedov 1991; Boomer et al. 2000; Sorrel et al. 2007). In addition, the global climate change of the past century associated with enhancement of the greenhouse effect, has contributed to much faster changes in meteorological and hydrological regimes, causing shifts in the major circulation systems, temperature and precipitation regimes and accelerating melting of the mountain glaciers in Central Asia (Thompson et al. 1993; Oerlemans 1994). The major controls on precipitation change in the Aral Sea Basin include latitudinal shifts of the westerly cyclonic circulation and position of the Siberian high. The level of the Aral Sea entirely depends on the run-off of the Syr Darya and Amu Darya, starting in the Pamir and Tian Shan mountains, and ultimately depends on the rhythm of mountain glaciation. Temporal variability of precipitation is very high and precipitation has a distinctive spring maximum in most of the region. Very high daily temperature variance is recorded with frequent sand storms and intense sunshine. As in many other arid and semi-arid regions, the climate of Central Asian deserts and semi-deserts is highly variable. The major controls on precipitation change in Central Asia include latitudinal shifts of the westerly cyclonic circulation and position of the Siberian high (Lioubimtseva 2003). The North Atlantic Oscillation (NAO) exerts an important control over the pattern of wintertime atmospheric circulation variability over arid and semi-arid zones of Central Asia. Over the past four decades, the pattern captured in the NAO index has altered gradually from the most extreme and persistent negative phase in the 1960s to the most extreme positive phase during the late 1980s and early 1990s.

At a regional scale, two interconnected anthropogenic factors have been increasingly contributing to climate change in Central Asia: basin-wide land-use and land-cover changes (Lioubimtseva and Henebry 2009; Kariyeva and van Leewuven 2011) and rapid degradation of the Aral Sea itself (Micklin 2010). Therefore, current and future climatic trends in this region can best be addressed as a combination of nested interconnected processes and feedbacks operating at several spatial and temporal scales. I will discuss four groups of such factors:

(a) Natural long-term global climate change and variability;
(b) Anthropogenic global climate change (global warming);
(c) Regional land-use and land cover changes in the Aral Sea Basin;
(d) Meso-climatic changes caused by the Aral Sea degradation.

17.3 Natural Long-Term Climate Changes

The landforms of this region carry relict features both of relatively short humid intervals with runoff higher than modern, and long arid periods (Boomer et al. 2000; Lioubimtseva 2003; Lioubimtseva et al. 2005; Boroffka et al. 2006). Pollen and archaeological data from the Aral Sea Basin suggest that climate change was followed by significant ecosystem changes. Marine fossils, relict shore terraces, archaeological sites, and historical records point to repeated major recessions and advances of the Aral Sea (Varuschenko et al. 1987; Kes et al. 1993). Although the structure of the Aral Basin can be traced back to the late Neogene, the Sea has only existed in its present form for the past 10,000 years and its Holocene history has been shaped by regional climatic variations, the development of the associated drainage system and anthropogenic forces (Boomer et al. 2000). Significant cyclical variations of regional climate and sea level during this period resulted from major changes in river discharge caused by climatic changes and several natural diversions of the Amu Darya River away from the Aral Sea (Micklin 1988; Kes et al. 1993; Vinogradov and Mamedov 1991; Boomer et al. 2000).

Paleoenvironmental reconstructions based on pollen and archaeological data suggest that the Aral Sea experienced a period of almost complete desiccation during the Late Glacial Maximum (around 20–18,000 years before present) and again in the Younger Dryas (12,800 and 11,500 years before present), when the climate of Central Asia was characterized by colder winter temperatures, cooler summers and greater aridity (Boomer et al. 2000; Lioubimtseva et al. 2005; Tarasov et al. 2007). The Djanak arid phase of the Younger Dryas was followed by an increase in temperatures and precipitation during the Early and Mid-Holocene (Sorrel et al. 2007; Tarasov et al. 2007). A trend towards greater humidity during the Holocene culminated around 6,000 years ago, a phase known in Uzbekistan and Turkmenistan as the Liavliakan pluvial (Vinogradov and Mamedov 1991; Lioubimtseva et al. 1998). According to Vinogradov and Mamedov (1991) mean annual precipitation in the deserts of Central Asia could have been three times higher than at present and desert landscapes were possibly entirely replaced by mesophytic steppes, with well-developed forest vegetation along the river valleys. Climate variations resulted in multiple shifts from hyper-arid to semi-arid steppe vegetation (Varuschenko et al. 1987; Tarasov et al. 2007). A general aridization trend that started approximately 5,000 years ago was interrupted by multiple minor climatic fluctuations in this region at a finer temporal scale (Esper et al. 2002; Sorrel et al. 2007).

17.4 Impacts of Global Climate Change: Current Trends and Projections

In addition to the natural climatic variability, more recent and shorter-term climatic changes have been observed in the Aral Sea Basin and are likely to be caused by global and regional anthropogenic factors. Recent climate trends and variability in Central Asia are generally characterized by increasing surface air temperature, which is more pronounced during winter than in summer. Meteorological data series available in the Aral Sea Basin since the end of the nineteenth century show a steady increase of annual and winter temperatures in this region. Studies of climate data (Neronov 1997; Chub 2000; Lioubimtseva et al. 2005; Lioubimtseva and Henebry 2009) indicate a steady warming trend of 1–2 °C per century throughout the region. Steady temperature increases during the past century might be an indication of a general spatial shift in the atmospheric circulation in Central Asia (Lioubimtseva et al. 2005). The recorded increases in both mean annual and seasonal temperature trends are likely to result from the decreasing intensity of the southwestern periphery of the Siberian high in winter and the intensification of summer thermal depressions over Central Asia.

Reliable and well-distributed climate observations are essential for monitoring and modeling climate change and developing informed adaptation policies. Unfortunately, the climate observing system in Central Asia is currently the worst in the former Soviet Union and continues to deteriorate. Meteorological stations that operated before collapse of the USSR have been closed or operate sporadically. For example, out of nine stations that existed during the Soviet time, now there are only three stations that still collect data near the former shore of the Aral Sea: Aralskoye Morye near Aralsk on the north, Muynak on the south, and Aktumsyk on the Ust-Urt Plateau on the west (Philip Micklin, 9 May 2012, personal communication).

Warming of the global climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level (IPCC, WGI 2007). The last two decades appear to be the warmest years in the instrumental record of global surface temperature since 1850. The temperature increase is widespread over the globe and is greater in the Northern hemisphere and at high and mid-latitudes. While meteorological data consistently indicate the warming trend throughout Central Asia since the beginning of the nineteenth century, the precipitation trends are much more variable (Neronov 1997; Chub 2000; Lioubimtseva et al. 2005). Precipitation records show a slight decrease during the past 50–60 years in the western part of the region, no change or slight increase throughout most of the region, and much more significant local increase in precipitation recorded by the stations surrounded by irrigated lands (Lioubimtseva and Henebry 2009).

Based on the multi-model (MMD) simulations discussed in the IPCC Fourth Assessment report, Central Asia is likely to warm by a median of 3.7 °C by the end of this century (IPCC, WGI 2007). The seasonal variation in the simulated warming is modest. This author conducted several comparative studies of climate change scenarios produced by the Atmosphere Ocean Global Climate Models (AOGCMs) used by the IPCC (Lioubimtseva et al. 2005; Lioubimtseva 2007; Lioubimtseva and Henebry 2009). Annual, seasonal and monthly AOGCM scenarios for Central Asia used in the Third and Fourth IPCC Reports (TAR IPCC 2001 and AR4 IPCC and WGI 2007) indicate a generally good agreement among the models suggesting that the current trend of temperature increase in arid Central Asia is likely to continue through the entire Aral Sea Basin. Lioubimtseva and Henebry (2009) analyzed the regional scenarios derived from 23 AOGCMs using MAGICC/SCENGEN 5.3 software developed by the National Center for Atmospheric Research (Wigley 2008). Annual and seasonal temperature and precipitation scenarios were examined under A1FI-AIM and A1B-MES IPCC SRES scenarios (Nakicenovic et al. 2000). Temperature changes in the Aral Sea Basin are projected to increase by 3–5 °C by 2080 and all AOGCMs agree that the warming is very likely to be accompanied by a further intensification of aridity. Climate change scenarios significantly differ across seasons, with much higher temperature changes generally predicted by all models during the winter months.

The range of precipitation projections produced by AOGCMs is much more uncertain. Precipitation over central Asia increases in most MMD-A1B projections for winter but decreases in the other seasons. The median change by the end of the twenty-first century is −3 % in the annual mean, with +4 % in winter and −13 % in summer (IPCC, WGI 2007). This seasonal variation in the changes is broadly consistent with the earlier multi-model study of Meleshko (2004), although they find an increase in summer precipitation in the northern part of the area. The majority of climate models project a slight decrease in precipitation rate over most of the region (~1 mm/day by 2050) with a stronger decrease in the western and southwestern parts of the region and a very slight increase in the northern and eastern part of Central Asia (~1 mm/day) (Lioubimtseva and Henebry 2009). Average MMD projections for the annual temperature and precipitation changes driven by the A1FI SRES scenario by the middle of this century are summarized in Table 17.1.

The majority of the AOGCM experiments used in the IPCC AR4 (2007) suggest a high probability of increasingly dry conditions with a slight increase in winter rainfall, but decreases particularly in spring and summer. This trend towards higher aridity is projected to be more significant west from 70 °E to 72 °E latitude. According to the IPCC, the western part of Central Asia (area between the Caspian and Aral Seas) is very likely to become drier during the coming decades, while the central and eastern part might experience a slight increase in precipitation (IPCC and WGII 2007). The MMD scenarios appear to be consistent with the observed temperature and precipitation trend over the past decades in most of the region. Given the low absolute amounts of precipitation and high inter-annual, seasonal, and spatial variability of precipitation across the region, the changes in precipitation rate projected by the AOGCMs cannot be deemed very reliable. Due to the complex topography and the associated mesoscale weather systems of the high-altitude and

Table 17.1 MMD -AF1 climate changes scenario for the Aral Sea basin by 2050, relative to 1961–1990

Seasonal changes	Winter	Spring	Summer	Fall
Mean temperature, °C	1.5–4.95	2.87–3.99	3.24–7.36	3.05–3.99
Maximum temperature, °C	1.9–4.5	2.33–3.99	2.88–9.33	2.88–3.99
Minimum temperature, °C	1.7–4.95	1.88–3.30	3.99–5.33	2.69–3.91
Precipitation, mm/day	0.01–0.1	0–0.09	−1.11–0.09	−0.5–0.09

Climate change scenarios were generated by the author with MAGICC/SCENGEN5.3.2 model (Wigley 2008)

arid areas, AOGCMs typically tend to overestimate the precipitation (IPCC and WGI 2007).

It is the change in the temporal and spatial variability of precipitation and its seasonal distribution – rather than absolute precipitation values – that are more important for the assessment of human vulnerability in this arid region, but they are also more difficult to project. It is uncertain the extent to which the observed and projected trends result primarily from the global restructuring of atmospheric circulation and changes in the teleconnections controlling macroclimatic conditions over Central Asia versus mesoclimatic changes induced by regional land use change. There are several sources of uncertainty associated with the AOGCM scenarios. The resolution of these models is quite coarse (a horizontal resolution of between 250 and 600 km and 10–20 vertical layers in the atmosphere). Many physical processes, such as those related to clouds, occur at more detailed scales and cannot be adequately modeled; instead, their known properties are averaged over a larger scale in a technique known as parameterization (IPCC and WGI 2007). Other uncertainties relate to the simulation of various feedback mechanisms in models concerning, for example, water vapor and warming, clouds and radiation, ocean circulation and ice and snow albedo (Arnell 2004; IPCC and WGI 2007).

17.5 Regional Land-Use and Land-Cover Changes in the Aral Sea Basin

At the regional scale, effects of the global climatic changes might appear insignificant compared to the superimposed land changes and processes, such as irrigation, overgrazing, wind erosion, ground water depletion etc. Arid areas all over the world have shown themselves to be highly susceptible to the effects of human intervention (de Sherbinin 2002; Glantz 2005). Conversion of desert and semi-desert rangelands into irrigated cropland made many parts of this region particularly vulnerable to recent environmental, economic, and political changes. The most dramatic land use changes were driven by two factors. First, is the rapid and massive expansion of irrigation, water diversion, and conversion of desert rangelands into irrigated croplands that occurred primarily under the Soviet regime from the mid-1950s to the mid 1980s (Micklin 1988, 2007; Glantz 2005). Second, is the decline of agriculture and livestock in the 1990s due to the collapse of the USSR at the end of 1991 (Lioubimtseva and Henebry 2009).

Irrigated arable land, principally for cotton monoculture, increased by 60 % in the region from 1962 to 2002 (Lioubimtseva et al. 2005). The total irrigated area in the study area increased by over half a million hectares (5.2 %) just from 1992 to 2002 (Lioubimtseva and Cole 2006). Turkmenistan alone accounted for 59 % of the change, increasing its irrigated area by 300,000 ha (20 %). Total water withdrawals (all uses) were 125 % of the average annual water resources in 1988 (Glazovsky 1995). Such dramatic human-induced changes in the hydrological cycle led not only to a significant decrease of river runoff, changes in the number and area of lakes and rise of groundwater levels, but also to significant changes in evapotranspiration and precipitation.

The dissolution of the Soviet Union had a dramatic impact on the agricultural sector of the newly independent Central Asian states. With little or no access to fertilizers, pesticides, subsidies, and markets, a substantial amount of land was idled with longer fallow periods. Furthermore there were significant shifts in crop composition that differed among the Central Asian states as a result of internal policies regarding land reform and farm restructuring (Sievers 2003). Across the Central Asian States, the impact of the political and economic transition on agricultural production was very severe (Chuluun and Ojima 2002; Lioubimtseva and Cole 2006). In Kazakhstan, sheep numbered 33.9 million in 1992. By 1999 that figure had dropped 74 % to 8.6 million, but by 2005 had risen 11.4 million. In 1992 Kazakhstan had 57 % of the sheep in Central Asia; in 2005 that share was only 29 %. The total number of sheep in Central Asia in 2005 was 40 million or 67 % of what it had been in 1992 (Lioubimtseva and Henebry 2009). The sheep stock time series indexed to 1992 show the divergence among the Central Asian States from collapse and slow recovery in Kazakhstan to steady growth in Turkmenistan (Fig. 17.1). From a 9 % share of the regional sheep stock in 1992, Turkmenistan reached a 36 % share in 2005 with 14.3 million sheep (Lioubimtseva and Henebry 2009).

The decline of agriculture was sufficiently great to be captured by the Normalized Difference Vegetation Index (NDVI) derived from the red and near-infrared channels of the NOAA AVHRR imagery, despite the high climatic inter-annual variability (de Beurs and Henebry 2004; Lioubimtseva 2007; Kariyeva and van Leewuven 2011).

The principle behind NDVI is that the red-light region of the electromagnetic spectrum is where chlorophyll causes considerable absorption of incoming sunlight, whereas the near-infrared region of the spectrum is where a plant's spongy mesophyll leaf structure creates considerable reflectance (Tucker et al. 1991). As a result, vigorously growing healthy vegetation has low red-light reflectance and high near-infrared reflectance, and hence, high NDVI values. This relatively simply algorithm produces output values in the range of -1.0 to 1.0. Increasing positive NDVI values, shown in increasing shades of green on the images, indicate increasing amounts of green vegetation. NDVI is calculated from these individual measurements as follows: $\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{RED})/(\mathrm{NIR} + \mathrm{RED})$, where RED

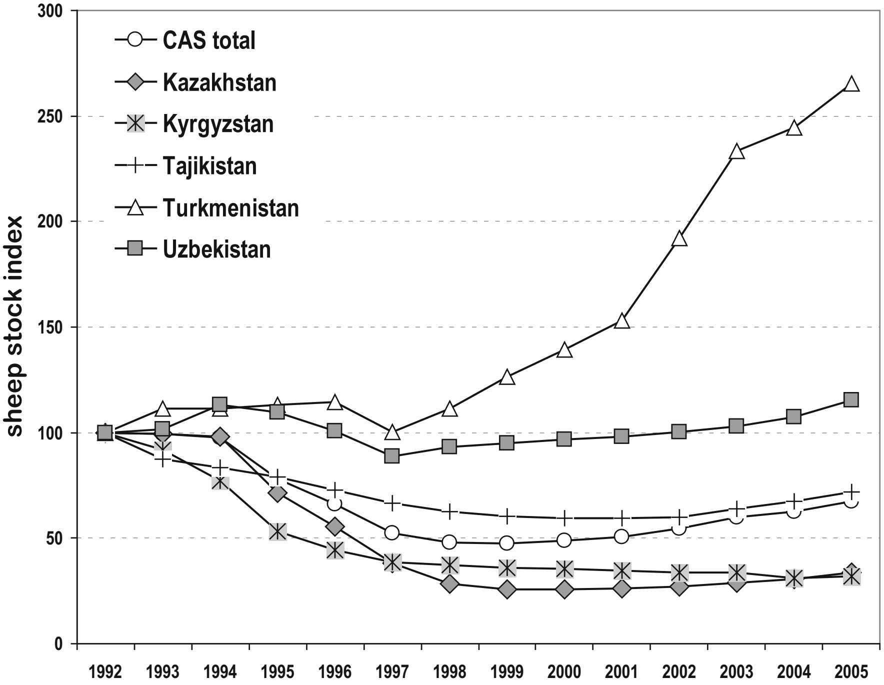

Fig. 17.1 Sheep stocks indexed to 1992 reveal divergent trajectories: collapse in Kazakhstan, Kyrgyzstan, and Tajikistan; little change in Uzbekistan; and significant growth in Turkmenistan (Lioubimtseva and Henebry 2009)

and NIR stand for the spectral reflectance measurements acquired in the red and near-infrared regions, respectively. NDVI values near zero and decreasing negative values indicate non-vegetated features such as barren surfaces (rock and soil) and water, snow, ice, and clouds.

First, a significantly higher NDVI was observed at the start of the growing season. Second, the peak NDVI values occurred at significantly fewer accumulated growing degree-days indicating a shift toward an earlier seasonal peak in vegetation. De Beurs and Henebry (2004) interpreted these changes as resulting from increases in fallow area and fewer herbicides available to control weeds during the 1990s. In the irrigated areas of Kazakhstan, there were no significant shifts toward earlier peaks, but there were higher NDVI values at the beginning of the observed growing season, that were likely to reflect the changes in land management practices, including crop types and composition.

The overall regional trend in this region indicates a slight decrease in rainfall throughout the western part of the region and a slight increase in the eastern part of the Aral Sea Basin. However, data series from meteorological stations located in quasi-pristine ecosystems significantly differ from those reported by the stations located on irrigated lands (Neronov 1997; Lioubimtseva et al. 2005). Stations located in the major oases indicate precipitation increase over the past decades (Lioubimtseva 2007). These trends are a result of the hydrological and albedo changes due to the expansion of irrigation. Modeling experiments (Wang and Eltahir 2000) and field studies (Pielke et al. 2007) show that changes in albedo and other biophysical parameters of vegetation cover caused by massive irrigation might establish totally new equilibria in the climate-vegetation relations and reverse previously existing feedback mechanisms. While a desert environment is featured by strong negative biosphere-atmosphere feedbacks, perturbation of a large area by irrigation induces a positive feedback that brings the system to more humid climatic conditions with new climate-vegetation equilibria (Lioubimtseva et al. 2005).

17.6 Mesoclimatic Changes in Vicinity of the Aral Sea

The Aral Sea degradation has resulted in significant changes in surface albedo, soil temperature and moisture, evapotranspiration, cloud cover, precipitation patterns, wind speed and direction, atmospheric transparency, and many other mesoclimatic parameters in the immediate vicinity of the Sea (Varuschenko et al. 1987; Small et al. 2001; Micklin 2007; Shibuo et al. 2007). The surface area of the Aral Sea declined from ~65,000 km^2 in 1960 to 10,317 km^2 in 2011 (Micklin, Table 15.1, Chap. 15 this volume). During the same period of time the lake volume decreased by 90 %, its level dropped by 23 m, area shrunk by 75 % and salinity increased from 10 g/l to more than 100 g/l (Micklin 2007; Micklin, Table 15.1, Chap. 15 this volume). Desiccation of the Aral Sea has resulted in an extensive, massive modification of land cover both of its barren bottom and the immediate vicinity. The thermal capacity of the remaining lake has substantially decreased due to reduction of its surface, volume and depth. Significant changes in the interactions between the land and boundary layer of the atmosphere have resulted in dramatic air temperature changes in this area. Several studies (Chub 2000; Small et al. 2001; Micklin 2007) identified significant mesoclimatic changes resulting from the desiccation of the Aral Sea, as opposed to the impacts of global changes.

The climate records from around the sea show dramatic temperature and precipitation changes since 1960. Mean, maximum, and minimum temperature near the Aral Sea have changed by up to 8 °C, increasing both seasonal and diurnal amplitudes (Small et al. 2001), as the lake effect has diminished. The magnitude of such changes decreases with distance from the coast, with effects extending about 200 km from the original 1960 shoreline. Precipitation records also show a shift in seasonality. The Aral Sea desiccation has caused significant climate change not only in the coastal area but affected the entire system of atmospheric circulation in its basin. Summer and winter air temperatures at the stations near the seashore increased by 1.5–2.5 °C and diurnal temperatures increased by 0.5–3.3 °C (Glazovsky 1995; Chub 2000). Near the coast the mean annual relative humidity decreased by 23 % and recurrence of drought days increased by 300 % (Glazovsky 1995). The annual cycle of temperature and precipitation has also changed. A sevenfold rise in the albedo of the area previously occupied by the Aral Sea caused a threefold increase in reflected solar radiation and increased overall continentality of the climate (Glazovsky 1995). Some regional modeling scenarios suggest that rise of the air temperature in Central Asia should cause a further 8–15 % increase in evaporation both from the sea and the land surface (Small et al. 1999; Chub 2000).

According to a study by Small et al. (2001), an increase in diurnal temperature range of 2–3 °C is observed in the Aral Sea area in all months. These authors examined the Aral Sea surface temperature (SST) trends between 1960 and 1996 using in situ buoy and boat SST measurements from the State Oceanographic Institute of Russia, combined with Multi-Channel SST derived from the Advanced Very High Resolution Radiometer satellite imagery. They found that the highest change in the Aral SST occurred in spring – a 4–5 °C increase in April and May. SST increase in summer was about 3 °C, and there were no changes between August and October. During the same period of time SSTs decreased by 4–5 °C in November and December.

Basin-scale water diversion and irrigation, along with the desiccation of the Aral Sea have considerably increased evapotranspiration and thereby decreased net water flux from the atmosphere to the surface. Increased evaporation cools the irrigated areas, and the decrease of net atmosphere water influx is likely to affect the entire basin. Modeling studies by Shibuo et al. (2007) indicate important effects of water diversion on the regional climate. The excessive irrigation in the southeastern part of the Aral Sea Basin appears to have significantly increased evapotranspiration and cooled this area in the process. By contrast, temperature increases are considerable in non-irrigated areas, where hydro-climatic changes reflect local effects of the Aral Sea shrinkage itself in addition to the regional manifestation of global climate change. The main reported precipitation increase in the Aral Sea Basin is also localized to the southeastern part of the basin. It is probably an effect of the local evapotranspiration increase due to irrigation. By contrast all stations in the immediate vicinity of the Aral Sea have experienced precipitation decreases during the same period of time (Lioubimtseva and Cole 2006). Such influence of the local land-cover changes has been reported in many studies in other arid and semiarid regions (Pielke et al. 2007).

In addition, exposure of the former lakebed areas, especially on the eastern side of the Aral Sea, represents an enormous source of highly saline wind-blown material (up to 1.5 % salt in the total mass of hard particles transported by the wind). According to Semenov (1990) the amount of aeolian redeposition from the former Aral seabed is exceeding 7.3 10^6 t per year, comprised of between 5 and 7×10^4 t of salt per year. Today the drying bed of the Aral Sea has become one of the biggest sources of dust aerosols in the world. Salty dust blown into the atmosphere is another important factor that needs to be considered in model simulations of both global and regional climates. Dust tends to cool the earth by reflecting sunlight back into space, and it decreases rainfall by suppressing atmospheric convection (Lioubimtseva et al. 2005).

Restoration and conservation efforts in Kazakhstan have recently resulted in improvement of microclimatic conditions in the vicinity of the Small Aral (former northern part of the Aral Sea). Separated by a dike from the Large Aral, the Small Aral Sea is now showing steady signs of water level increase and decline of water salinity (Micklin and Aladin 2008). In the early 1990s Kazakhstan constructed an earthen dike to block outflow to the south but in April 1999 the dike collapsed. The second 13-km earthen dike with a gated concrete dam for water discharge was completed in November 2005. Heavy runoff from the Syr Darya in the ensuing winter jump-started the Small Aral's recovery. The water rose from 40 to 42 m – the intended design height – in only 8 months. Area increased by 18 %, and salinity has dropped steadily, from roughly 20 to about 10 g/l today. Fishers are once again catching several species in substantial numbers – most important, the highly prized pike perch and carp (Aladin et al. 2005; Micklin and Aladin 2008). As the restoration of the Small Aral continues it is likely that its moderating impact on the local climate will continue to increase.

17.7 Human Vulnerability to Climate and Environmental Change

Although different authors have proposed many definitions of human vulnerability, it is usually understood as a function of the character, magnitude, and rate of climate change and the exposure, sensitivity and adaptive capacity of the human-environmental system (Schröter et al. 2005; Parry et al. 2007; Adger 2006; Polsky et al. 2007; Adger 2006; Lioubimtseva and Henebry 2009). One of the key dimensions of human vulnerability to climate change is exposure – the degree to which a system is exposed to a hazard, perturbation or stress caused by climatic change and variability. The second dimension is sensitivity; it can be defined as the degree to which a system is affected by, or is responsive to, climate change stimuli (Smit and Skinner 2002). The third dimension of vulnerability is adaptive capacity. Adaptive capacity or adaptability is understood as the potential or capability of a human-environmental system to adapt to climatic stimuli (Smit and Skinner 2002; Schröter et al. 2005; Polsky et al. 2007). The capacity of a sector or region to adapt to climatic changes depends on many non-climatic factors, such as level of economic development and investment, access to markets and insurance, social and economic policies, access to education and technology, cultural and political considerations, the rule of law regarding private and public properties, including natural resources, etc. Vulnerability can also be regarded as a function of potential impact of climate or other environmental change that can be in turn defined as all implications of the projected environmental change, without considering adaptations (Schröter et al. 2005). Therefore, impact depends primarily on exposure and sensitivity of a system. There is compelling evidence from around the world that there is a strong relationship between vulnerability to climate change and sustainable development. As the Fourth Report of the IPCC Working Group II states, "...sustainable development can reduce vulnerability to climate change, and climate change could impede nations' abilities to achieve sustainable development pathways" (Parry et al. 2007).

Due to their common environmental, political and economic legacy, countries of the Aral Sea Basin represent together a complex macro-regional system. Development of effective and realistic adaptation strategies would benefit from an integrated macro-regional approach reaching beyond the national borders, especially because adaptation measures are rarely undertaken in consideration of the impacts of climate change alone and are typically imbedded within other initiatives such as land-use planning, water resource management, drought warning, desertification control, health care programs, and diversification of agriculture.

Many non-climatic stresses might be increasing vulnerability of the Aral Sea Basin countries to climate change and reduce its adaptive capacity because of resource deployment to competing needs. For example, political isolation, low living standards and significant social inequality, limited access to sanitation, insufficient infrastructure and health care system in many parts of the region and many other non-environmental stresses generally decrease the adaptive capacity of Central Asian countries. When the region is increasingly exposed to climate-related stresses, such as increases in surface temperature and frequency of droughts in the Aral Sea Basin, decline of precipitation, and mesoclimatic changes caused by the Aral Sea, and other environmental stresses, such as soil salinization and degradation, water loss due to inefficient irrigation practices, chemical runoff from agriculture, its sensitivity to environmental impacts is very high while adaptability is low. In the context of the arid climate of Central Asia, short-term, unplanned reactive coping strategies that aim to address separately some of these stresses usually provide only an immediate solution for limited areas or groups of the population, but in the long-term they only exacerbates the problem.

Focusing on effects but not on the causes of the problem they risk aggravating the ongoing adverse environmental changes. For example, there is a continuous migration of the population from Karakalpakstan, an autonomous republic within Uzbekistan, adjacent to the Aral Sea, to eastern Uzbekistan and Kazakhstan. During the first years after collapse of the USSR the estimated number of environmental migrants from the Aral Sea area was more than 100,000 people and in the recent decade the net emigration from the areas adjacent to the Aral Sea has doubled from over 3,000 to over 6,000 persons per year (Akiner 2000). Between 5 % and 10 % of the working-age population of this region is leaving Karakalpakstan every year (Elpiner 2003; Elpiner, 2011, personal communication). Considering that these environmental refugees are usually individuals who had the best skills, opportunity, and psychological aptitude to migrate and adjust to different lifestyles in other regions or countries, there is concern that the population left behind would have even lower capacity, skills and potential to adapt to regional climate change.

17.8 Human Vulnerability and Water Resources

Significant temporal variability in the runoff of the Amu Darya, Syr Darya and smaller rivers of the Aral Sea Basin is largely controlled by hydrometeorological changes in the Pamir, Tian Shan, and Altai mountains. A regional modeling study driven by five AOGCMs under a business-as-usual scenario conducted by Uzhydromet (Hydrometeorological Service of Uzbekistan) suggests that by 2030–2050 the temperature in the mountains of southeastern Uzbekistan is likely to increase by 1.5–2.5 °C causing higher runoff of the Amu Darya, Zeravshan, and Syr Darya due to accelerated melting of the mountain glaciers and precipitation will increase by 100–250 % (Miagkov, 2006, personal communication). Glacial melt in the Pamir and Tian Shan ranges is projected to increase, initially increasing flows in the Amu Darya, Syr Darya, and Zeravshan systems for a few decades, followed by a severe reduction of the flow as the glaciers disappear (Glantz 2005). Field data indicate that significant changes in the seasonality of glacial flows have already occurred as a result of warming (Braithwaite 2002). Rapid melting of glaciers has increased runoff, which has led to an increase in the frequency of glacial lake outbursts that can cause devastating mudflows and avalanches in the mountainous regions of Tajikistan, Uzbekistan, Kazakhstan, and Kyrgyzstan.

Growing demand for water for irrigation, high levels of water pollution, and frequent droughts and widespread land degradation are among the key water-related issues that already threaten human development and security of the Aral Sea Basin countries. Overall water withdrawals in the Central Asia States have increased from 37 km^3/year in 1950 to 102 km^3/year in 2000 and are projected to reach 122 km^3/year by 2025 (Shiklomanov and Rodda 2001). The core regional problem, however, is not the lack of water resources but rather their management and distribution. A lack of coordination among irrigation systems, pervasive soil degradation, and inter-basin transfers are the persistent water problems in the region. The surface water resources of Central Asia are primarily generated in mountain glaciers.

Although differences in water stress at the country level are considerable, these are smaller than differences among the geographic regions within the basin. Kazakhstan and Uzbekistan are impacted by mesoclimatic changes directly caused by the reduction in water volume of the Aral Sea, sea-bottom exposure, and the associated toxic salt and dust storms. The salt content of the Southern Aral Sea now ranges between 100 and 150 g/l, which is more than triple the salinity of the open ocean (Micklin 2007). The quality of water for human consumption is poor in many parts of Central Asia. The same processes that contributed to the Aral Sea degradation – excessive irrigation and mismanagement of water – have also resulted in the rise of the groundwater table, contamination of groundwater with high levels of salts and other minerals. Groundwater quality ranges in the region from a minimum of 1.5 g/L TDS (total dissolved solids) to 6 g/L TDS and drinking water reaches levels of up to 3.5 g/L TDS. In Karakalpakstan (an autonomous republic of Uzbekistan adjacent to the Aral Sea) about 65 % of drinking water samples tested did not meet national standards of 1 g/L TDS (AQUASTAT 2011). There is a growing concern that water stress in Central Asia may lead to open conflicts over water, weakening the states to such an extent that they lose their capacity to address other threats to stability and development (Sievers 2003; Glantz 2005).

Water availability and water stress are expected to be highly sensitive to projected climate change scenarios (Shiklomanov and Rodda 2001; Alcamo and Henrich 2002; Arnell 2004). Assessment of water stress can be depicted as the current average annual withdrawals-to-availability ratio, where stress is indicated by a ratio of withdrawals to availability greater than 40 %. Water stress is a useful measure of human vulnerability to climate change as it measures the degree of demand on water resources by the users of these resources, including agriculture, industries, and municipalities. A larger increase in water stress represents a greater sensitivity of the water resources to global change. The future impacts of climate change on water resources are strongly dependent on the current conditions of existing water supplies and water control systems. A study by Alcamo and Henrich (2002) based on the WaterGAP model indicates severe water stress already occurring in all Central Asian countries. Given the very high level of water stress in many parts of the Aral Sea Basin, projected temperature increases and precipitation decreases in the western part of Kazakhstan, Uzbekistan, and Turkmenistan are very likely to exacerbate the problems of water shortage and distribution.

During the past 10–12 years, a series of droughts affected Turkmenistan, Uzbekistan, Tajikistan, Iran, Afghanistan, and Pakistan. These droughts have amply demonstrated the very high human vulnerability of this region to precipitation deficits. Agriculture, animal husbandry, water resources, and public health have been particularly stressed across the region as a result of the recent drought (Lioubimtseva and Henebry 2009). Climatic changes, projected by the models, are likely to impact regional hydrometeorology and hydrology and further exacerbate the human vulnerability of this region by reducing its overall water supply.

17.9 Human Vulnerability and Agriculture

Most croplands in Turkmenistan, Uzbekistan and southern Kazakhstan are irrigated and agriculture is potentially highly vulnerable to climate change because of the degradation of limited arable land and shortage of water available for irrigation. Almost two-thirds of domestic livestock are supported on grazing lands, although in Kazakhstan a significant share of animal fodder also comes from crop residues (Lioubimtseva and Henenbry 2009). Aridity is the primary constraint limiting the portion of land available for agriculture and livestock production in the Aral Sea Basin. The results of modeling studies suggest that at least some parts of the Central Asian region might benefit from an increase in winter temperatures and a longer growing season, the CO_2 fertilization effect and the projected increase in the water-use efficiency by agricultural crops, and probably also a winter rainfall increase in the eastern part of the region (Parry et al. 2007; Fischer et al. 2005). According to an agro-ecological zoning study by IIASA (International Institute for Applied Systems Analysis), almost 90 % of the land in Central Asia that was part of the former USSR has constraints for rain-fed crops: almost 76 % of the area is too arid, 4 % too steep, and about 7 % has insufficient soils. Out of the total 414 million ha approximately 45 million ha are currently used for cultivation of food and fiber crops and more than 14 million ha require irrigation (Fischer et al. 2005). The IIASA Basic Linked System models driven by the HadCM3-A1FI scenario suggest that, due to regional climate changes, by 2080 the total area with constraints will decrease to 84 %. On the other hand, the area in Central Asia deemed unsuitable for agriculture due to insufficient soils is projected to reach 17 % by 2080 (Parry et al. 2007; Fischer et al. 2005). The same studies suggest that the potential for rain-fed cultivation of major food and fiber crops in this region might increase by 2080 (primarily due to the CO_2 fertilization effect on C_3 plants).

The MMD experiments used in the IPCC WGII Assessment Report (2007) suggest that most of the Aral Sea Basin is likely to become more arid and probably less suitable for agriculture. AOGCM scenarios also revealed substantial geographic differences across the region. The major differences in the magnitude of projected temperature changes, however, result from the wide range of the SRES socio-economic pathways. The climate change scenarios discussed in the previous section of this chapter project temperature increases between 2.4 °C and 4.7 °C under B1 scenario and from 3.9° to 7.1° under A1 by 2080 with a particularly notable increase in winter temperatures. Precipitation scenarios vary, suggesting a slight increase in the eastern part of the region and a decrease in the west. However, even the wettest scenarios, do not seem to be sufficient to offset the aridity caused by elevated temperatures, especially in the southern and western sectors of the region (Turkmenistan, Uzbekistan and southwestern Kazakhstan). CGCM3 and HadCM3 scenarios suggest a risk of even higher levels of aridity in the southwestern part of Central Asia and a very insignificant increase in the northeast under all socio-economic scenarios. The CSIRO model projects the greatest increase of aridity throughout the entire region. The MMD assessments discussed by the IPCC (IPCC AR4 and WGII 2007) also indicate that the median precipitation change in Central Asia by the end of the twenty-first century is −3 % in the annual mean, with −13 % in summer (dry season) and +4 % in winter (IPCC and WGI 2007, Chap. 11). Combination of elevated temperatures and decreased precipitation in the deserts and semi-deserts of Central Asia could sharply increase potential evapotranspiration, leading to very severe water-stress conditions with dramatic impacts on agriculture and livestock production.

Climate models agree that the western part of the region (deserts of Turkmenistan and Uzbekistan and the Caspian coast) would be particularly vulnerable to the increase in potential evapotranspiration. Yet, perhaps of bigger concern in estimating impacts from temperature and precipitation changes on agriculture are the potential changes in variability and extreme events, such as frosts, heat waves, droughts, and heavy rains. Extreme events are responsible for a disproportionately large part of climate-related damages and sensitivity of extremes to climate change may be greater than one would assume from simply shifting the location of the climatological distribution. The global-scale study of Tebaldi et al. (2006), based on analysis of ten indicators of temperature and precipitation-related extremes computed by nine AOGCMs used in the IPCC-AR4, suggests that agricultural production in the Central Asian region could benefit from fewer frosts and an increasing length of the growing season. It could also be negatively affected by the increasing variability of precipitation and number of dry days, particularly at higher elevations and for rain-fed crops and orchards (Tebaldi et al. 2006).

Another factor that is likely to affect agricultural productivity in the Aral Sea Basin and adjacent areas is increasing surface runoff in the adjacent mountain systems of Tian Shan and Pamir-Alai. The projected increase in runoff could potentially accelerate soil erosion, especially in case of increasing frequency of catastrophic precipitation. Several multi-model assessments (Shiklomanov and Rodda 2001; Arnell 2004), suggest that the volume of runoff from glaciers in Central Asia may increase three-fold by 2050 leading to significant changes in the regional pattern of water and land use. In the long term, however, after decades of accelerated melting, the glacial runoff will dramatically decline as glacial mass significantly declines.

17.10 Human Vulnerability and Health

Changes in the regional climate and ecosystems might both increase or reduce the risk of some infectious diseases. Increase of temperature and climate variability can also increase the exposure of populations to heat stress, extreme weather events, such as droughts, dust-storms and floods, contribute to the already existing water stress, and also stress the existing institutional systems of public health (Confalonieri et al. 2007).

Epidemic malaria, including the tropical form of malaria, caused by *Plasmodium falciparum*, returned to Uzbekistan, Kyrgyzstan, Turkmenistan, and Tajikistan in the 1990s (World Health Statistics 2011). In 1994, the number of malaria cases reported in Tajikistan quadrupled compared to 1993 and peaked in 1997, when nearly 30,000 cases were registered (WHO 2011). In 2002, the explosive resumption of malaria transmission produced an epidemic situation with an incidence much greater than that reported in the past years in Kyrgyzstan, and a total of 2,267 autochthonous (i.e. endemic to the region) cases were reported in the south-western regions of the country (Fig. 17.2). The explosive resumption of malaria transmission in Kyrgyzstan started as a result of immigration of a number of infected people from Tajikistan into the Batken region where the Anopheles vector exists and conditions for malaria transmission are very favorable (Abdikarimov 2001). In 2004–2005, as a result of the application of epidemic control measures, there was a significant decrease in the reported number of autochthonous malaria cases.

However, in 2004 the first autochthonous case of *P. falciparum* malaria was reported in the southern part of Kyrgyzstan and in 2005 the number of

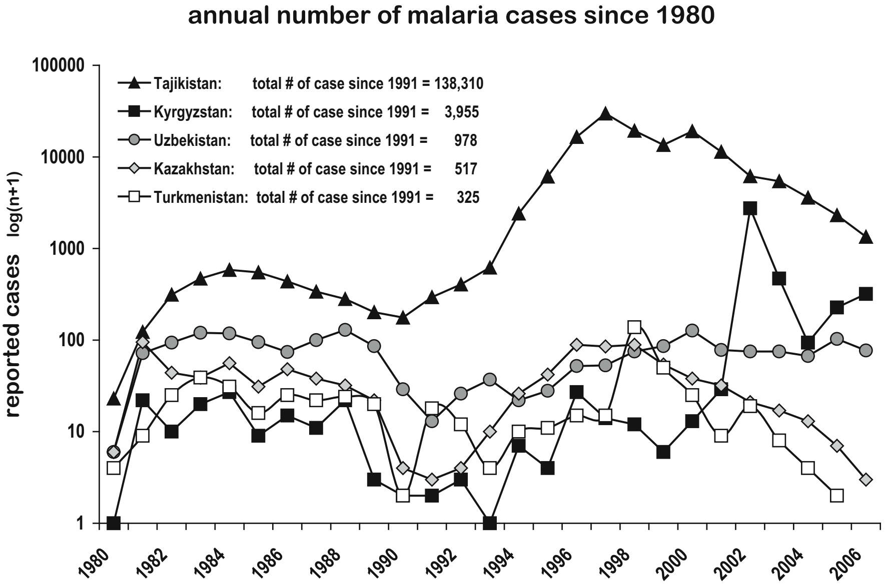

Fig. 17.2 Total number of malaria cases reported to WHO, 1980–2006 (Lioubimtseva and Henebry 2009)

autochthonous cases of *P. vivax* malaria increased in the capital city Bishkek. The resumption of *P. falciparum* cases in Tajikistan and Kyrgyzstan and the expansion of the territory in which this type of malaria is spread is a matter of particular concern. Endemic malaria has now returned to the southern part of Tajikistan (Sabatinelli 2000). Surveys conducted by WHO personnel in the southern part of Tajikistan bordering Afghanistan identified about 10,000 malaria-infected individuals in the Khatlon Region (WHO 2011).

The observed and predicted climate changes in Central Asia, such as the temperature increase, changes in climatic variability, and seasonal shifts might be responsible for creating more favorable mesoclimatic conditions for vectors and parasites. The last decade of the twentieth century was marked by a series of particularly warm years. Climate change has a direct impact on mosquito reproduction, development rate and longevity, and the rate of development of a parasite, as the parasites develop in the vector within a certain temperature range, where the minimum temperature for parasite development lies between 14.5 °C and 15 °C in the case of P. vivax and between 16 °C and 19 °C for *P. falciparum* (Martens et al. 1999). According to the study by Kayumov and Mahmadaliev (2002), the zone of potential malaria development in Tajikistan is likely to increase during the coming years up to an elevation of more than 2,000 m due to the continuous temperature increase. Climate change is also affecting malaria transmission indirectly through such factors as changes in vegetation, agricultural practices, desertification, migration of populations from areas in which vector-borne diseases are endemic into receptive areas (Kovats et al. 2001; Van Lieshout et al. 2004). Large irrigated areas and river valleys within these chiefly arid and semi-arid countries provide perfect habitats for mosquitoes. Increasing climate aridity and variability and increasing summer temperatures can increase the reliance of local agriculture on irrigation and cause an increase in the areas suitable for vector development.

Many non-environmental factors, such as migrations caused by war in neighboring Afghanistan, deterioration of national health systems, economic decline, reduction of the use of pesticides, and land use change have all contributed to the regional health crisis (Abdikarimov 2001; Razakov and Shakhgunova 2001). The number of malaria cases in Central Asia has gone down in recent years as a result of governmental programs involving widespread application of insecticides but the crisis that recently occurred here clearly indicates that climate change is likely to increase the risk of future outbreaks of malaria in parts of this region.

17.11 Conclusions

The Aral Sea Basin represents an area with diverse and overlapping environmental, social and economic stresses. It is projected to become warmer and probably drier during the coming decades. Aridity is expected to increase across the entire region, but especially in the western part of Turkmenistan, Uzbekistan, and Kazakhstan. The temperature increases are predicted to be particularly high in summer and fall, but lower in winter. An especially significant decrease in precipitation is predicted in summer and fall, while a modest increase or no change in precipitation is expected in winter months, particularly in the eastern part of Kazakhstan and in adjacent Kyrgyzstan and Tajikistan. These seasonal climatic shifts are likely to have profound implications for agriculture. Some parts of the region will be winners, while others will be losers (particularly western Turkmenistan and Uzbekistan, where frequent droughts will negatively affect cotton production, increase already extremely high water demands for irrigation, and exacerbate the already existing water crisis and human-induced desertification). The severe and ongoing droughts of the past decade have already resulted in multiple water disputes and increased tensions among the states of the Aral Sea Basin. Given that the aridity and water stress are likely to increase, new political and economic mechanisms are necessary to ease such tensions in the future.

The ability of the Aral Sea countries to adapt to hotter and drier climatic conditions is limited by the already existing water stress and the regional land degradation and poor irrigation practices. Central Asia inherited many environmental problems from Soviet times but many years after independence, the key land and water-use related problems remain the same. A decline in the intensity of agriculture after independence, documented by agricultural statistics, was significant enough to produce a signal in the temporal series of remote sensing data. Agricultural transformation had extremely high social costs but to date agricultural reforms and the transition to market conditions remain problematic in most of the region.

Increasing rural poverty and unemployment, particularly among females, growing economic inequality, and shortage of adequate living conditions, medical care and water management infrastructure have significantly increased human vulnerability of the majority of population in the region.

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Chapter 18
Summary and Conclusions

Philip Micklin

Abstract The first part of this final chapter summarizes the introductory chapter plus the chapters contained in Parts I, II, and III, exclusive of Chap. 18, to remind the reader of the key aspects of each. The second part lays out what in the author's view are the key lessons to be learned from Aral Sea and its modern desiccation. The final part lists and briefly discusses what needs to be done in terms of research and monitoring of the Aral Sea.

Keywords Lessons of the Aral Sea • Research and Monitoring • Remote sensing • MODIS • Landsat

18.1 Summary of Introduction and Part I (Background to the Aral Sea Problem)

The Introduction (Chap. 1) briefly lays out the basic parameters of the modern recession of the Aral Sea that began in 1960 and discusses the complex, severe environmental, economic and human consequences of this catastrophe. This is followed by a review of improvement efforts to alleviate these problems that began during the last years of the Soviet Union. These were carried on by the new Aral Sea Basin states and regional bodies formed by these governments, aided by international donors after the collapse of the Soviet Union in 1991. The last section explains the purpose of the book, its relationship to other recent edited works on the Aral Sea and the organization of the chapters.

Part I is intended to provide background information to better understand the modern (post 1960) desiccation of the Aral Sea (Chaps. 2, 3, and 4). Chapter 2 by

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Micklin provides key information on the Aral Sea and its region. The Aral Sea Basin's geographical setting is discussed, including location, climate, topography, soils, water resources, constituent nations, and basic demographic parameters. Next, the physical characteristics of the Aral Sea (size, depth, hydrochemistry, circulation patterns, temperature characteristics, water balance, etc.) prior to the modern desiccation are summarized. This is followed by analysis of level fluctuations of the Aral and their causes prior to the modern drying.

The author notes that the "Aral Sea is geologically young" with an estimated age around ten millennia, coincident with the Holocene geological epoch. Nevertheless, during this time owing to being a terminal or closed basin lake with inflow but no outflow and situated among the great deserts of Central Asia, the Aral has undergone significant recessions and transgressions as a result of both natural and human influences. The key natural factors have been climate change and the diversion of the Amu Darya westward so that it did not flow into the Aral. The primary human influence was the purposeful diversion of the Amu westward. However, from the mid-seventeenth century until 1960, lake level variations were likely less than 4.5 m. Instrumental observation began in 1911. For the next five decades the sea's water balance was remarkably stable with annual inflow and net evaporation (evaporation from the sea's surface minus precipitation on it) never far apart. The final section is devoted to tracing the most important events in the long history of research and exploration of the Aral up to 1960.

Chapter 2 by Plotnikov, Aladin, Ermakhanov and Zhakova discusses the faunal character of the Aral Sea from 1900 until the 1960s. The authors note that the original fauna of the Aral Sea was characterized by poor species composition. Originally in the Aral Sea there were at least 180 species (without Protozoa) of free-living invertebrates. The fauna had heterogeneous origins. Prior to the modern recession/salinization, species originating from freshwater, brackish-water and saline continental water bodies were dominate. The remaining were representatives of Ponto-Caspian and marine Mediterranean-Atlantic faunas. Parasitic fauna had poor species composition: 201 species were indigenous and 21 were introduced together with fishes. Ichthyofauna consisted of 20 aboriginal and 14 introduced species. The aboriginal fish fauna consisted of species whose reproduction typically occurs in fresh water. There was no fishery on the Aral Sea and local people caught a few fish only from the rivers until in the mid 1870s Russians came here. After construction of a railway in 1905 a commercial fishery developed. Bream, carp and roach provided approximately two-thirds of the commercial catch tonnage. A large number of vertebrate species inhabited the Aral Sea, its shore and islands, the Syr Darya and Amu Darya, and the deltas and lakes of these rivers in their lower reaches. The Aral Sea and its shores provided nesting sites for a large number of various floating and near shore birds. Tugay forests along the banks of the rivers constituted a type of oasis where many animal species lived. By the 1960s flora of the Aral Sea included 24 species of higher plants, 6 species of charophytes and about 40 other species of macroalgae.

Chapter 4 by Krivinogov provides a particularly detailed and interesting scientific discussion of the major level changes and evidence for them based on extensive fieldwork. The author reviews the available data on the Aral Sea level changes and presents the current thinking on the sea's recessions and transgressions prior to its modern desiccation. The geomorphologic, sedimentologic, paleoenvironmental, archaeologic and historiographic evidence is reconsidered and combined on the basis of calibrated 14C ages. According to the author, lithology and paleoenvironmental proxies of the sediment cores provide much consolidated information, as they record lake level changes in sediment constitution by deep and shallow water facies and layers of gypsum and mirabilite, which are of special importance for determination of low levels. High levels are recorded in several on-shore outcrops.

The new archaeological data from the now dry bottom of the Aral Sea and its surrounding zone in combination with the historiographic records provide a robust model for level changes during the last two millennia. Discovery of tree stumps in different parts of the bottom indicate low stands of the lake as well. During the last two millennia, there were two deep natural regressions of ca. 2.1–1.3 and 1.1–0.3 ka BP followed by the modern anthropogenic one. The lake level dropped to ca. 29 m asl. Their separating transgressions were up to 52–54 m asl. The middle to early Holocene record of level changes is probably incomplete. Currently the middle Holocene regressions are documented for the periods of ca. 5.5–6.3, 4.5–5.0 and 3.3–4.3 ka BP. The early Holocene history of the Aral shows a long period of a shallow lake.

18.2 Summary of Part II: The Modern Desiccation of the Aral Sea (1960–2012)

Part II presents key information on and critical analysis of the period 1960–2012, which encompasses the modern recession of the Aral Sea. At 67,500 km^2 in 1960, the Aral Sea was the world's fourth largest inland water body in surface area, behind the Caspian Sea in Asia, Lake Superior in North America and Lake Victoria in Africa. As a brackish lake with salinity averaging near 10 g/l, less than a third of 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 and Amu rivers 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.

Since the 1960s the Aral has undergone tremendous alteration. The level of the southern part of this water body (Large Aral) fell nearly 26 m between 1960 and September 2011 (see Chap. 15, Table 15.1). Its surface area decreased from 67,499 km^2 in 1960 to 10,317 km^2 by September 2011, an 87 % shrinkage. Volume shrank 92 %, from 1089 to 89 km^3, over the same period. Salinity for the southern sea rose from an average annual value of 10 g/l to over 100 g/l, a tenfold increase.

Chapter 5 by Micklin deals with two related water issues: the water resources of the Aral Sea Basin and the Aral Sea's water balance. The Aral Sea's size is dependent on the water resources in its basin and how much these are depleted by human usage. The chief water resources are the main basin rivers Amu Darya and Syr Darya and groundwater. The author discusses the size and character of these and their sufficiency for meeting human demand. Contrary to popular belief, the Aral Sea Basin is reasonably well endowed with water resources. But the high level of consumptive use, overwhelmingly for irrigated agriculture, has resulted in severe water shortage problems. Since the Aral Sea is a terminal (closed basin) lake with no outflow lying amidst deserts, its water balance is basically composed of river inflow on the gain side and evaporation from its surface on the loss side. Precipitation on the sea's surface contributes only about 10 % to the positive side of the balance. Net groundwater input is difficult to determine with any accuracy and likely had minimal influence until recent decades when, owing to major drops in river inflow, its impact on the water balance has grown.

The Aral's water balance was very stable from 1911 until 1960. However, since then it has been consistently negative (losses more than gains) owing to very substantial reductions in river inflow caused by large consumptive losses to irrigation. This was particularly pronounced for the decadal periods 1971–1980 and 1981–1990. More river flow reached the sea over the period 1991–2000, but its water balance remained negative. However, the water balance situation deteriorated during the subsequent decade (2001–2010) owing to recurring droughts. The decidedly negative water balance has led to a rapid and steady shrinkage of the sea.

Chapter 6 by Plotnikov, Aladin, Ermakhanov and Zhakova discusses the changes in the biology of the Aral as a result of the modern desiccation. Regression of the Aral Sea began in 1961. At first, changes in the fauna were primarily the result of fish and invertebrate introductions. In the 1970s regression accelerated. The main factor influencing fauna has been increasing water salinity. In the 1970s and 1980s invertebrate fauna went through two crises. First, freshwater species and brackish water species of freshwater origin became extinct. Then Ponto-Caspian species disappeared. Marine species and euryhaline species of marine origin survived, as well as faunal species of inland saline waters.

By the end of the 1990s the Large Aral became a complex of hyperhaline lakes. Its fauna was passing through the third crisis period. Incapable of active osmoregulation, hydrobionts of marine origin, and the majority of osmoregulators disappeared. A number of species of hyperhaline fauna were naturally introduced into the Large Aral. Salinization of the Aral Sea has resulted in depletion of parasitic fauna. All freshwater and brackish-water ectoparasites and a significant part of helminthes began to disappear. Together with the disappearance of hosts, the parasites associated with them in their life cycle also disappeared.

Regulation of the Syr Darya and Amu Darya and decreasing of their flow altered living conditions of the Aral Sea fishes, especially their reproduction. In 1971 there were the first signs of negative effects of salinity on adult fishes. By the middle of the 1970s natural reproduction of fishes was completely destroyed. Commercial fish catches decreased. By 1981 the fishery was lost. In 1979–1987 flounder-gloss was introduced and in 1991–2000 it was the only commercial fish. After the construction of the Berg Strait dike was completed in 2005 and the level of the Small Aral rose resulting in decreased salinity, aboriginal fishes began migrating back to the sea from lacustrine systems and the river. This allowed the achievement of commercial numbers of food fishes. Since the end of the 1990s, the Large Aral Sea is a lake without fishes. Regression and salinization of the Aral Sea caused destruction and disappearance of the majority of vegetational biocenoses.

Chapter 7 by Reimov and Fayzieva describes and analyzes the ecological and human situation in the South Aral Sea area (mainly the Republic of Karakalpakstan in Uzbekistan). They point out that the Aral Sea was once the world's fourth largest inland body of water in terms of surface area. Fed by two rivers, the Amu Darya and the Syr Darya, it supported a diverse ecosystem and an economically valuable fishery. Intensive agricultural activity related to cotton production with high water demands during the Soviet era caused excessive water diversion for irrigation purposes from the rivers. As a result, since the early 1970s the shores of the sea have been steadily receding. The disappearance of the Aral Sea has caused several severe environmental and economic impacts. The fishery is no longer viable. The seabed became exposed leading to the airborne dispersal of salts and pesticide residues. The river delta flora and fauna have deteriorated such that fewer species exist. The decreasing level of the Aral Sea was accompanied by a rise of salinity, which resulted in the degradation of the ecosystems in the Aral Sea area as well as those of the fertile delta lands. The exposed seabed has turned into a desert, which at the present time is a source of tons of salty dust, blown away by the wind and carried for thousands of kilometers. The quality of river water and other sources for drinking water have deteriorated. Environmental degradation in the Aral Sea area, especially in the south part in Karakalpakstan has resulted in significant worsening of the socio-economic and public health situation.

Chapter 8 by Micklin traces the history and development of irrigation in the Aral Sea Basin. In 2010, irrigation networks covered 8.1 million ha here and accounted for 84 % of all water withdrawals. Irrigation as a highly consumptive user of water is the primary cause of the desiccation of the Aral Sea as it has severely diminished the inflow to the Aral from the Amu Darya and Syr Darya. Irrigation has a long history in the Aral Sea Basin dating back at least 3,000 years. During the Soviet era, irrigation was greatly expanded and water withdrawals for it increased considerably, primarily to grow more cotton. In the post-Soviet period (after 1990), the area irrigated grew slowly while water withdrawals for it declined somewhat. The latter has been primarily due to shrinkage of the area planted to high water use crops such as rice and cotton and not to the introduction of more efficient irrigation techniques on a substantial scale. Irrigation systems in the Aral Sea Basin since collapse of the USSR have badly deteriorated owing to lack of proper maintenance of them and insufficient investment in them. And the problems of soil salinization and water logging continue to worsen. There is certainly much that could be done to improve irrigation and use less water for it. This in turn could allow much more water to be supplied to the Aral Sea. But significant improvement of irrigation will require much greater effort and investment along with institutional reforms.

Chapter 9 by Mukhammadiev deals with the challenges of transboundary water resources management in Central Asia, with a focus on the Aral Sea Basin. The major river basins of Central Asia link the countries of Afghanistan, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan. Water management in Central Asia continues to be the most important transboundary environmental issue and the biggest problem remains how to allocate water for upstream hydropower production and downstream irrigation. Disagreements between the upstream and downstream states have increased regional tensions and slowed development plans. National responses to existing cooperative opportunities are essentially driven by a policy of national self-sufficiency in energy and water.

While it is reasonable to be concerned about water and/or energy security, it is also critical to understand that a policy of self-sufficiency incurs substantial costs for all. As long as self-sufficiency dominates the policy agenda, the benefits of cooperation will not materialize. International water law could provide a rational avenue toward achieving international consensus on both use and allocation of water resources in the basin, with international legal agreements to reinforce the consensus. Incentives to cooperate through the application of the benefit-sharing concept as a development model in the basin would include decreased costs and increased gains in many dimensions of regional cooperation, including the benefits that stem from better agricultural practices and its competitiveness, joint developing of the region's energy resources, and better management of regional environmental risks.

Chapter 10 is the first of two chapters that focus on the use of remote sensing to study the Aral Sea and its regions. These techniques are essential to the timely, cost effective and comprehensive monitoring of such a large region and will become even more so in the future.

In Chap. 9 Ressl and Colditz use time series analysis of remote sensing data to study and monitor vegetation and landscape dynamics of the dried sea bottom adjacent to the lower Amu Darya Delta. The Aral Sea region is a rapidly transforming landscape due to the continuous desiccation process. This study describes the vegetation and landscape dynamics in the lower Amu-Darya delta and adjacent parts of the dried sea bottom using MODIS surface reflectance data and EVI time series for the years 2001–2011. The potential of MODIS time series for monitoring landscape and vegetation dynamics of the dried sea bottom adjacent to the lower Amu-Darya Delta was evaluated concerning data availability and spatial and temporal resolution. Two time series with different quality considerations were generated to subsequently characterize the yearly changes in the dried part of the sea bed, a simple layer stack (LS) of observations and quality-filtered and smoothed time series using a double logistic function (DL). The EVI values show a small dynamic inter- and intra-annual range. The majority of the EVI values fluctuate between −0.2 and +0.1, which indicates generally low vegetation dynamics in the desiccated areas.

Looking at the inter-annual behavior of the LS/DL time series plots, the noise of the data and data fluctuations seem to become less for areas which have been dry for a longer period. A regional differentiation of the landscape dynamics between the Eastern and the Western basin of the southern Aral Sea could be observed. The observation points for the Western basin show a more stable behavior of the EVI values in comparison to the samples on the Eastern basin as seasonal or inter-annual flooding is less frequent. A typical pattern as a result of clear vegetation dynamics could not be observed in the EVI LS and DL time series plots.

In Chap. 11 Cretaux and Berge-Nguyen employ remote sensing to analyze Aral Sea hydrology. According to them, space technologies have been widely used over the last 10 years for water surface monitoring worldwide and have shown their capability to monitor components of the water cycle and water balance at regional scales and on time scales ranging from months to decades. For their study they use data acquired from radar altimetry and satellite imagery (Terra/MODIS) over the Aral Sea Basin (ASB). Radar altimetry, which has been designed to study the ocean, has opened a new era in monitoring lakes, rivers and reservoirs. The recent missions of satellite altimetry (Topex-Poseidon, Jason-1/2, Envisat, ERS-1 and ERS-2) have made it possible to measure with great precision inland sea level variations that can be used to determine water mass balances. Radar altimetry, coupled with complementary in situ data, has allowed quantifying precisely the water balance of the Aral Sea since 1992 as well as balances for large reservoir systems along the Syr Darya, in particular Chardarya, Toktogul and Aydarkul. This approach has also made it possible to ascertain the water balances of lakes and wetlands in the deltas of the Syr Darya and Amu Darya.

Satellite imagery, from low to high resolution (1 km to a few meters) offers a useful tool to monitor surface water area for lakes and floodplains. MODIS data provide every 8 days the surface water area from 2000 to 2012, with a spatial resolution of 500 m. It has been used to create a spatial time series for the Aral Sea and the lakes and wetlands in the deltas of Amu Darya and Syr Darya where the water area has been precisely measured. Along with in situ observations and hydrological modeling, space observations have the potential to improve significantly our understanding of hydrological processes at work in large river basins, (including lakes, reservoirs and floodplains) and their influence on climate variability and socio-economic life.

Unprecedented information can be expected coupling models and surface observations with data from space, which offer global geographical coverage, good spatial-temporal sampling, continuous monitoring over time, and the capability of measuring water mass change occurring at or below the surface. Based on these different techniques the authors determined the surface area of water features within the Aral Sea Basin, as well as volume variations, which are the key parameter to the understanding of hydrological regimes in ungauged basins. A focus on the Aral Sea and the water bodies in the deltas of the Syr Darya and the Amu Darya rivers over the last 20 years from satellite data is presented in this chapter, with some implications for the water balance. The specific behavior of the

Western and Eastern basins of the Large (South) Aral Sea over the last 5–6 years is also described.

White in Chap. 12 discusses the complicated interrelationships between Nature and Society in the Aral Sea Basin. He notes that the desiccation of the Aral Sea since 1960 has been a notorious and well-documented example of anthropogenic ecological devastation. Equally ominous has been the devastating impact on the livelihoods and health conditions of the human populations inhabiting the Aral Sea region. As a socio-ecological crisis, the Aral Sea's recession has demonstrated interrelationships between humans and the biophysical environment. An important societal dimension through which to access these relationships is the Aral basin's regional economy.

The Aral crisis itself has largely been a result of the large-scale Soviet-era water diversion projects whose impetus was primarily the production and export of cotton. The Aral Sea Basin today remains a globally important cotton production and export region. The most important economic activities devastated by the crisis have been fishing and fish processing. Once defunct enterprises, these activities have only recently been revived with the recent rehabilitation of the northern Aral Sea in Kazakhstan. This chapter examines the post-1960 developments of the cotton sector within the Aral basin and the fishing sector in the Aral Sea itself. Nature-economy linkages inherent in these sectors inform broader generalizations regarding human-environment interrelationships in the Aral Sea Basin today.

Chapter 13 by Micklin, Aladin and Plotnikov describes an international scientific expedition to the northern part of the Aral Sea conducted from August 29 to September 16, 2011. The expedition was organized by the Zoological Institute of the Russian Academy of Sciences in St. Petersburg Russia and received logistical support from the Barsakelmes Nature Preserve (Zapovednik) headquartered in the Kazakhstan City of Aralsk and the Aralsk Branch of the Kazakhstan Fisheries Institute. The major focus of the expedition was to investigate the biological and hydrological improvements to the Small Aral Sea that had occurred as a result of raising its level by 2 m in 2005–2006 as well as what might be done to further improve the ecology and economic value of this water body in the future. The expedition also visited the channel that connects the Western and Eastern basins of the Large Aral Sea as well as the former Barsakelmes Island, now a desolate plateau on the dried bottom of the Aral Sea.

18.3 Summary of Part III: The Future of the Aral Sea

Part III discusses the future of the Aral Sea, or to speak more accurately, the possible futures of this Lake and its surrounding region. Chapter 14 by Plotnikov and Aladin discusses the biological future of the Aral Sea. The Aral Sea in 2012 consisted of four residual water bodies with different hydrological regimes. The Kok-Aral dam raised and stabilized the level of the Small Aral Sea. Growth of salinity here has stopped and a process of gradual salinity reduction is in progress.

By the autumn 2011 water salinity in the open part of the Small Sea dropped to 8 g/l. The future of its biota depends on future salinity. If the current regime will remain, then the decrease in salinity will continue and the Small Aral will turn from a brackish to a nearly freshwater body. This freshening will cause substantial changes in the fauna as a result of the disappearance of marine and brackish species and reintroduction of freshwater forms. Currently two variants of further rehabilitation of the Small Aral are under consideration. The first one involves an additional dam at the entrance to Saryshaganak Gulf to create a reservoir out of it and the filling of this water body via a canal from the Syr Darya. The Small Sea under this plan would then have both freshwater and brackish water parts. The second variant is to increase the level and area of the Small Aral Sea by raising the height of the Kok-Aral dam. In this case, all the Small Sea remains brackish except the existing freshened zone in front of the Syr Darya Delta. Both these variants would avoid further strong freshening of the Small Aral Sea and associated with this adverse changes in the fauna.

The expected future of the biota of the residual hyperhaline water bodies of the Large Aral is quite different. In this case, there is no possibility of reducing their salinity leading to a recovery of fauna represented by marine and widely euryhaline species. On the contrary, even stronger salinization is likely. The East Large Aral Sea could dry out completely, and the West Big Aral could turn into a lifeless water body akin to the Dead Sea.

Chapter 15 by Micklin describes and analyzes prospects for the recovery of the Aral Sea. He notes that this water body between 1960 and 2012 lost 85 % of its area and 92 % of its volume, while separating into four residual lakes. The Large Aral on the south endured a level drop of 25 m and rise of salinity from 10 g/l to well over 100 g/l. Over this period, the sea suffered immense ecological and economic damage including the destruction of its valuable fishery and degradation of the deltas of its two influent rivers. Nevertheless, in spite of this calamity, and contrary to reports that the sea is a lost cause (popular reports that the sea will "disappear" are simply false), hope has remained that the sea and its deltas could be partially rehabilitated. The author discusses various restoration scenarios. Full restoration of the sea in the foreseeable future is extremely improbable, but cannot be ruled out for distant times. Micklin devotes considerable attention to the project implemented in the first decade of the present century to partially restore the Small (northern) Aral Sea, an efforts that so far has been eminently successful. Partial restoration of the Large (southern) Aral is also discussed. This effort would be more costly and complicated than the north Aral project, but is certainly worthy of further investigation. Projects to improve the deltas of the Amu Darya and Syr Darya are also underway.

Chapter 16 by Micklin discusses the famous (or infamous depending on your point of view) plans to transfer water from Siberian rivers flowing to the Arctic to Central Asia. The author notes that the twentieth century was the era of mega-engineering thinking. This was a worldwide phenomenon, but perhaps had its clearest expression in the Soviet Union, a nation with a well-developed ideology promoting man subduing nature for purported human betterment. Soviet plans to transfer huge amounts of water long distances from Siberian rivers to Central Asia were initially conceived, during the Stalinist era, as a way to fundamentally transform the physical environment of this region. During the period 1960 to the mid 1980s, much scaled down, but still unprecedentedly huge versions of these projects were primarily seen as the best means to provide more water for irrigation expansion and, secondarily, as way to provide more water to the Aral Sea. After several decades of intense scientific study and engineering development, a final design for Siberian water transfers was on the verge of implementation when an abrupt change of national policy in 1985–1986 put it in on hold for the foreseeable future. The plan foundered owing to Russian nationalist opposition, enormous costs, a changing political environment, and the threat of significant environmental damage. The collapse of the USSR has probably doomed the project although it continues to be promoted by Central Asian governments and even some prominent Russians as a means to bring back the Aral Sea.

Chapter 17 by Lioubimtseva concerns the question of the impact of climate change on the Aral Sea and its basin. Climate change and its consequences is certainly one of the most crucial issues of our time. Climatic and environmental changes in the Aral Sea Basin represent a complex combination of global, regional, and local processes of variable spatial and temporal scales. They are driven by multiple interconnected factors, such as changes in atmospheric circulation associated with global warming, regional hydrological changes caused by mountain-glacial melting, massive land-use changes associated with irrigation, as well as hydrological, biogeochemical, and meso- and microclimatic changes in the Aral Sea and its quickly expanding exposed dry bottom. Human vulnerability to climate change involves many dimensions, such as exposure, sensitivity, and adaptive capacity and affects various aspects of human-environmental interactions, such as water availability and stress, agricultural productivity and food security, water resources, human health and well-being and many others at various spatial and temporal scales.

18.4 Lessons of the Aral Sea: Myths and Realities

Are their lessons that we can learn from the Aral and its modern desiccation? Below is an attempt to explicate what this writer views as the most important of these.

1. The modern desiccation of the Aral Sea illustrates once again that the natural environment can easily and quickly be wrecked but that repairing it, if possible, is a long and arduous process. Hence, humankind needs to be very cautious about large-scale interference in complex natural systems. And it is essential to carefully evaluate the potential consequences of such proposed actions before hand rather than, as so long has been the case, recklessly plunging ahead, hoping for the best as the Soviet Union did with the Aral Sea.

2. Even though a particular human activity has not resulted in serious problems in the past is no guarantee that it will not cause problems in the future. Wide-spread irrigation in the Aral Sea Basin did not seriously impact the sea prior to the 1960s because large water withdrawals were offset by compensatory factors such as significant irrigation return flows to the Syr and Amu rivers and reduced downstream flooding and associated losses to evaporation and transpiration by phreatophytes growing along the rivers and in the floodplain. However, these compensating factors were exhausted or overwhelmed as irrigation expanded from the deltaic zones into the surrounding deserts, increasing losses to exfiltration from lengthy, often unlined canals, and reducing return flows to the rivers as drainage water accumulated in lakes and evaporated or went to fill pore spaces in dry desert soils. The associated construction of extensive, shallow reservoirs in the desert and semi-desert plains also contributed to large water losses to the rivers owing to increased evaporation. Thus irrigation that had been practiced for thousands of years in this region with out placing major stresses on the natural environment passed a tipping point in the early 1960s beyond which the expansion of this activity could not be supported by the hydrologic and related natural systems without incurring significant damage to them.
3. Beware of appealing but facile solutions for complex environmental and human problems. The Aral situation has been unfolding for 50 years and will not be resolved over night. "Quick fixes" that have been proposed such as major cuts in cotton growing to save water and help the sea may well cause problems worse than they attempt to solve. Cotton growing is a key economic activity and source of employment in the Aral Sea Basin. Major cuts in it, if implemented hurriedly and carelessly would not only cause damage to national economies, but also substantially raise unemployment and contribute to social unrest. Long term, sustainable solutions require not only major investments and technical innovations, but also fundamental political, social and economic changes that take time.
4. But all is not gloom by any measure. The natural environment is amazingly resilient. Hence, don't abandon hope and efforts to save it, even when the task seems overwhelming. Many wrote off the Aral Sea earlier as a lost cause, but it now has been unequivocally demonstrated that significant parts of it can be preserved and ecologically restored. Furthermore, even though not realistic in the foreseeable future, over the long-term, it may even be possible to reduce the use of water sufficiently to provide adequate discharge to bring the sea back to what it was a half-century earlier. As the archeological and sedimentological record proves, the Aral has suffered desiccations as great as the present one and recovered.
5. Preservation of biological refugia is key for saving indigenous species. Even though a species may disappear from one habitat owing to changing environmental conditions that drive it to extinction, it may be preserved in another nearby location. If the alternative site is preserved, then if and when habitat conditions in the original site become favorable, indigenous species are able to return on their own or can be reintroduced by humans. This is exactly what

happened in the Small Aral Sea. A number of indigenous species (fishes and invertebrates) could not withstand the dramatic increase in salinity. But these species were preserved in the Syr Darya and in that river's deltaic lakes. When the Small Sea separated from the Large in the late 1980s and the first earthen dike was constructed in 1992, salinity began to drop and some of these species began to return. After the engineeringly sound Berg Strait (Kok-Aral) dike was completed in August 2005, the level was raised and stabilized and salinity dropped to near the levels characteristic of pre-desiccation conditions, many other indigenous species repopulated the sea.

6. Large-scale environmental restoration projects such as the Small Aral Sea project require careful monitoring and follow-up. This is necessary not only to make sure they are working as expected and to provide management feedback, but to learn new lessons that may improve the success of similar actions elsewhere.

18.5 Research and Monitoring Needs

Research on and monitoring of the Aral Sea and its surrounding region is absolutely essential to understanding the key natural and human processes that are occurring and designing rational strategies and plans and programs to improve the situation. Below are listed recommendations for these research and monitoring activities. This list is updated and revised from "Recommendations for Further Scientific Research" developed at the NATO Advanced Research Workshop, "Critical Scientific Issues of the Aral Sea Basin: State of knowledge and Future Research Needs," Tashkent, Uzbekistan, May 2–5, 1994 (Micklin and Williams 1996, pp. ix–x). Certainly research efforts have been devoted to a number of these issues since the mid-1990s, but much critical work remains to be done.

18.5.1 Hydrologic and Meteorological/Climatic Processes and Phenomena

1. Studies of hydrologic changes in the basin of the Aral Sea since the 1960s and forecasts of future conditions (e.g. glacier and snowfield melt and runoff, river flow, groundwater resources and their potential sustainable use).
2. Assessment of micro, meso, and macro scale climatic change owing to desiccation of the Aral Sea. Micro and meso scale changes in a zone around the sea are clearly apparent and demonstrated. But macro level changes over the Aral Sea Basin are not at all clear and the subject of considerable argument.
3. Studies of the impact of human influenced Climate Change (Global Warming) on the Aral Sea and its basin. This is certainly one of the most important

phenomena impacting both the natural and human environment here and needs much more detailed research.

4. Evaluation of the character, intensity, range, and impacts of salt/dust transfer from the dried -bottom of the Aral Sea.
5. Modeling of key hydrodynamic processes occurring in the residual lakes constituting the modern and future Aral Sea. An international team led by Oceanographer Peter Zavialov of the Shirshov Institute in Moscow has carried out important research on changes in the northern part of the Large Aral since 2002 (Zavialov 2010). This work needs to be continued and expanded to the entire Large Aral as well as the Small Aral Sea.
6. More intense investigation and modeling of groundwater's role in the water balance of the desiccated Aral Sea. As river flow has diminished and ground water flow increased, this water balance parameter has become, and will become ever more, important.
7. Study of the water balances and hydrology of the Western and Eastern Basins of the Large Aral Sea, the Small Aral Sea, and Tshche-bas Gulf as separate water-bodies with their own unique conditions.
8. Determination of the minimum amount of surface and groundwater that needs to be reserved (from consumptive and polluting uses) for ecological sustainability in the Aral Sea Basin.

18.5.2 Ecosystems and Their Changes

1. Continued investigation of biotic (floral and faunal) changes in the Aral Sea, and deltas of the Amu and Syr Darya brought about by drying of the Aral Sea with better integration of research on different aspects of the region's ecology and stress on the employment of contemporary methods of understanding ecosystem dynamics in a holistic framework. Development of computer models of ecosystem changes as a means of integrating and understanding the dynamics of very complicated systems.
2. The team led by N. Aladin and his colleague, I. Plotnikov (associate editors of this book) from the Zoological Institute in St. Petersburg in collaboration with Western scientists and research groups in Kazakhstan and Uzbekistan has done and continues to do exceptionally valuable work on the aquatic biology of the Aral Sea (see Chaps. 3, 6, and 14). This work needs to be better financed and continued.
3. N. Novikova of the Institute of Water Problems in Moscow, collaborating with researchers from the Institute of Geography in Moscow such as A. Ptichnikov and counterpart organizations in Karakalpakstan conducted high quality work on landscape and botanical dynamics in the lower reaches of the Amu Darya based on extensive field surveys (Novikova 1997; Ptichnikov 2002). These efforts have greatly diminished in recent years but need to be reinvigorated.

4. Attention to issues of biodiversity and endangered species loss, particularly in the deltas of the Amu and Syr Darya.
5. Investigation of how best to use the potential natural resources of the residual Aral seas as they are presently constituted and will be in coming years. Of particular interest in this connection is the possibility of using these water bodies for aquacultural purposes (e.g., the heavily salinized Large Aral for production of brine shrimp eggs), either in an extensive or intensive form.

18.5.3 Agricultural Production and Management

1. Studies of land tenure and use in the Aral Sea Basin and how these relate to water use and ecological degradation here.
2. Investigation of the extent and nature of agricultural water use in the Aral Sea Basin and of means effectively to implement water-saving technologies in irrigated agriculture. Evaluation of presently non-utilized and under-utilized sources of water (e.g., groundwater and ephemeral desert lakes) to augment currently fully or over-utilized sources.

18.5.4 Medical, Health, Social, Economic, Cultural, and Demographic Issues

1. Studies of demographic dynamics in the Aral Sea Basin, of how these exacerbate environmental and other regional problems, and of means of alleviation.
2. Investigations of the economic structure of the Aral Sea region and of means for its improvement.
3. Studies of the medical and health situation in the Aral Sea region of "Ecological Calamity" and of means for its improvement, including developing effective means to monitor the health of human populations in the Aral Sea region.
4. Investigation of the inter-nation and intra-nation legal structures in the Aral Sea Basin and their relationship to ameliorating the most serious environmental problems.

18.5.5 Toxic Contaminants (Biocides, Metals, Other Organic and Inorganic Compounds)

1. More intensive study and monitoring of toxic contaminants, including their sources, amounts, environmental pathways, persistence and biological effects and sinks in the Aral Sea region.

2. Development of less harmful substitutes for toxic contaminants and alternative means of controlling pest species of plants and animals (e.g., integrated pest control primarily dependent on natural biological approaches with the limited use of chemicals).

18.5.6 Application of Satellite Remote Sensing and GIS Research and Monitoring Technologies

1. Research on and monitoring of hydrologic processes, landscape and ecosystem dynamics, irrigation characteristics and other appropriate subjects in the Aral Sea Basin employing contemporary satellite-based remote sensing technologies is of vital importance. This field has seen enormous advancements in the last two decades and today (and even more so in the future) can be the basis of near real-time monitoring of critical natural and human systems in the Aral Sea Basin.
2. The MODIS (Moderate Resolution Imaging Spectroradiometer) sensor on the U.S. Earth Observation System satellites (Terra and Aqua) has become particularly important since that programs launch in 2001 (modis.gsfc.nasa.gov/). With a maximum pixel resolution of 250 m and viewing the entire Earth's surface every 1–2 days while acquiring data in 36 spectral bands, is the best existing tool for closely following medium to large-scale environmental changes in the Aral Sea Basin (see Chaps. 10 and 11). Furthermore, this imagery can be downloaded in viewable and also processable format via the Internet by anyone with a broadband connection at no cost.
3. This imagery is complemented by higher resolution products with less frequent coverage from the French Spot satellite and others, including the U.S. Landsat series, which provides downloadable viewable and processable imagery also at no cost (glovis.usgs.gov/).
4. Satellite images in processable format can be combined with other data via GIS (Geographic Information System) software to create sophisticated, computer-based models for analysis, monitoring, and decision support systems for the Aral Sea and Aral Sea Basin. Efforts along these lines are already underway.
5. Radar altimetry, used over the past decade and a half, to accurately determine the levels of the ocean and lakes (see Chap. 11) may in the near future be employed to much more accurately estimate river flows. Work is underway to perfect this application of radar altimetry (Michailovsky et al. 2011). This would be of great use in determining the inflows to the Aral Sea from the Amu and Syr rivers and more reliably determine the water balances for the Aral Sea (to be more precise, for the separated water bodies that now constitute the modern Aral Sea).
6. Research is needed to determine the optimal means for introducing the above described technologies on a broad scale into the Aral Sea Basin research, monitoring and management effort and for training local scientists and technicians in their use. Efforts have been are being made to promote this, but more needs to be done (http://www.cawater-info.net/index_e.htm; Ptichnikov 2002).

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