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The Aral Sea

The Devastation and Partial Rehabilitation of a Great Lake

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ISBN 978-3-642-02355-2 ISBN 978-3-642-02356-9 (eBook)
DOI 10.1007/978-3-642-02356-9
Springer Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

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
October 2013

Philippe Blondel

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

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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P. Micklin et al. (eds.), *The Aral Sea*, Springer Earth System Sciences,
DOI 10.1007/978-3-642-02356-9_1,

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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P. Micklin et al. (eds.), *The Aral Sea*, Springer Earth System Sciences,
DOI 10.1007/978-3-642-02356-9_2, © Springer-Verlag Berlin Heidelberg 2014

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