THE HANDBOOK OF ENVIRONMENTAL CHEMISTRY

07

Volume Editors Andrey G. Kostianoy
Aleksey N. Kosarev

The Aral Sea Environment

Springer

The Handbook of Environmental Chemistry

Founded by Otto Hutzinger

Editors-in-Chief: Damià Barceló • Andrey G. Kostianoy

Volume 7

The Handbook of Environmental Chemistry
Recently Published and Forthcoming Volumes

Polymers – Chances and Risks I: General and Environmental Aspects
Volume Author: P. Eyerer
2010

Polymers – Chances and Risks II: Sustainability, Product Design and Processing
Volume Editors: P. Eyerer, M. Weller, and C. Hübner
2010

Water Scarcity in the Mediterranean: Perspectives Under Global Change
Volume Editors: S. Sabater and D. Barceló
2010

The Aral Sea Environment
Volume Editors: A.G. Kostianoy and A.N. Kosarev
Vol. 7, 2010

Alpine Waters
Volume Editor: U. Bundi
Vol. 6, 2010

Transformation Products of Synthetic Chemicals in the Environment
Volume Editor: A.B.A. Boxall
Vol. 2/P, 2009

Contaminated Sediments
Volume Editors: T.A. Kassim and D. Barceló
Vol. 5/T, 2009

Biosensors for the Environmental Monitoring of Aquatic Systems
Bioanalytical and Chemical Methods for Endocrine Disruptors
Volume Editors: D. Barceló and P.-D. Hansen
Vol. 5/J, 2009

Environmental Consequences of War and Aftermath
Volume Editors: T.A. Kassim and D. Barceló
Vol. 3/U, 2009

The Black Sea Environment
Volume Editors: A. Kostianoy and A. Kosarev
Vol. 5/Q, 2008

Emerging Contaminants from Industrial and Municipal Waste
Removal Technologies
Volume Editors: D. Barceló and M. Petrovic
Vol. 5/S/2, 2008

Fuel Oxygenates
Volume Editor: D. Barceló
Vol. 5/R, 2007

The Rhine
Volume Editor: T. P. Knepper
Vol. 5/L, 2006

Persistent Organic Pollutants in the Great Lakes
Volume Editor: R. A. Hites
Vol. 5/N, 2006

Antifouling Paint Biocides
Volume Editor: I. Konstantinou
Vol. 5/O, 2006

Estuaries
Volume Editor: P. J. Wangersky
Vol. 5/H, 2006

The Caspian Sea Environment
Volume Editors: A. Kostianoy and A. Kosarev
Vol. 5/P, 2005

Marine Organic Matter: Biomarkers, Isotopes and DNA
Volume Editor: J.K. Volkman
Vol. 2/N, 2005

The Aral Sea Environment

Volume Editors: Andrey G. Kostianoy · Aleksey N. Kosarev

With contributions by

E.G. Arashkevich · A.E. Asarin · N.G.O. Boroffka ·
J.-F. Crétaux · A.I. Ginzburg · M.H. Glantz ·
P.S. Ivanishcheva · A.N. Kosarev · A.G. Kostianoy ·
A.V. Kouraev · V.I. Kravtsova · R. Letolle ·
V.N. Mikhailov · A.A. Ni · Ph.V. Sapozhnikov ·
N.A. Sheremet · G.V. Surkova · A.A. Svitoch ·
P.O. Zavialov · I.S. Zonn

Springer

Editors

Prof. Andrey G. Kostianoy
P.P. Shirshov Institute of Oceanology
Russian Academy of Sciences
36, Nakhimovsky Pr.
117997 Moscow
Russia
kostianoy@mail.mipt.ru

Prof. Dr. Aleksey N. Kosarev
Geographic Department
M.V. Lomonosov Moscow State
University
Vorobjovy Gory
119992 Moscow, Russia

The Handbook of Environmental Chemistry
ISSN 1867-979X e-ISSN 1616-864X
ISBN 978-3-540-88276-3 e-ISBN 978-3-540-88277-0
DOI 10.1007/978-3-540-88277-0
Springer Heidelberg Dordrecht London New York

Library of Congress Control Number: 2010921805

Cover design: SPi Publisher Services

Printed on acid-free paper

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

The Handbook of Environmental Chemistry Also Available Electronically

The Handbook of Environmental Chemistry is included in Springer's eBook package *Earth and Environmental Science*. If a library does not opt for the whole package, the book series may be bought on a subscription basis.

For all customers who have a standing order to the print version of *The Handbook of Environmental Chemistry,* we offer the electronic version via Springer Link free of charge. If you do not have access, you can still view the table of contents of each volume and the abstract of each article on SpringerLink (www.springerlink.com/content/110354/).

You will find information about the

– Editorial Board
– Aims and Scope
– Instructions for Authors
– Sample Contribution

at springer.com (www.springer.com/series/698).

All figures submitted in color are published in full color in the electronic version on SpringerLink.

Aims and Scope

Since 1980, *The Handbook of Environmental Chemistry* has provided sound and solid knowledge about environmental topics from a chemical perspective. Presenting a wide spectrum of viewpoints and approaches, the series now covers topics such as local and global changes of natural environment and climate; anthropogenic impact on the environment; water, air and soil pollution; remediation and waste characterization; environmental contaminants; biogeochemistry; geoecology; chemical reactions and processes; chemical and biological transformations as well as physical transport of chemicals in the environment; or environmental modeling. A particular focus of the series lies on methodological advances in environmental analytical chemistry.

Series Preface

With remarkable vision, Prof. Otto Hutzinger initiated *The Handbook of Environmental Chemistry* in 1980 and became the founding Editor-in-Chief. At that time, environmental chemistry was an emerging field, aiming at a complete description of the Earth's environment, encompassing the physical, chemical, biological, and geological transformations of chemical substances occurring on a local as well as a global scale. Environmental chemistry was intended to provide an account of the impact of man's activities on the natural environment by describing observed changes.

While a considerable amount of knowledge has been accumulated over the last three decades, as reflected in the more than 70 volumes of *The Handbook of Environmental Chemistry,* there are still many scientific and policy challenges ahead due to the complexity and interdisciplinary nature of the field. The series will therefore continue to provide compilations of current knowledge. Contributions are written by leading experts with practical experience in their fields. *The Handbook of Environmental Chemistry* grows with the increases in our scientific understanding, and provides a valuable source not only for scientists but also for environmental managers and decision-makers. Today, the series covers a broad range of environmental topics from a chemical perspective, including methodological advances in environmental analytical chemistry.

In recent years, there has been a growing tendency to include subject matter of societal relevance in the broad view of environmental chemistry. Topics include life cycle analysis, environmental management, sustainable development, and socio-economic, legal and even political problems, among others. While these topics are of great importance for the development and acceptance of *The Handbook of Environmental Chemistry,* the publisher and Editors-in-Chief have decided to keep the handbook essentially a source of information on "hard sciences" with a particular emphasis on chemistry, but also covering biology, geology, hydrology and engineering as applied to environmental sciences.

The volumes of the series are written at an advanced level, addressing the needs of both researchers and graduate students, as well as of people outside the field of "pure" chemistry, including those in industry, business, government, research establishments, and public interest groups. It would be very satisfying to see these volumes used as a basis for graduate courses in environmental chemistry. With its high standards of scientific quality and clarity, *The Handbook of*

Environmental Chemistry provides a solid basis from which scientists can share their knowledge on the different aspects of environmental problems, presenting a wide spectrum of viewpoints and approaches.

The Handbook of Environmental Chemistry is available both in print and online via www.springerlink.com/content/110354/. Articles are published online as soon as they have been approved for publication. Authors, Volume Editors and Editors-in-Chief are rewarded by the broad acceptance of *The Handbook of Environmental Chemistry* by the scientific community, from whom suggestions for new topics to the Editors-in-Chief are always very welcome.

Damià Barceló
Andrey G. Kostianoy
Editors-in-Chief

Contents

Introduction

Aleksey N. Kosarev and Andrey G. Kostianoy

Abstract This book presents a systematization and description of the knowledge accumulated to date on the physical oceanography, marine chemistry, and marine biology of the Aral Sea. A special attention is paid to satellite monitoring of the state and different natural parameters of the Aral Sea and its surroundings. Reasons for the progressing environmental crisis and present socio-economic problems in the Aral Sea region are highlighted. The publication is based on numerous observational data, collected by the authors of the chapters during sea and shore expeditions, on the archive data of Moscow State University, P.P. Shirshov Institute of Oceanology, and the Hydroproject Institute (Moscow, Russia), as well as on a wide scientific literature mainly published in Russian editions. These data are complemented by the results of a series of Russian national and international projects, where an extensive research of the Aral Sea was carried out over the past decade. This book is addressed to the specialists working in various fields of physical oceanography, marine chemistry, biology, and environmental problems.

Keywords Amudarya, Aral Sea, Environmental crisis, Syrdarya

Before 1960 the Aral Sea (Fig. 1) was a water-abundant sea-lake that was fourth largest in the world list of lakes after the Caspian Sea (USSR, Iran), Great Lakes (USA, Canada), and Victoria Lake in Africa. This was a real "pearl" among the sands of the largest deserts – Karakums and Kyzylkums. Navigation between the

A.G. Kostianoy (✉)
P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, 36 Nakhimovsky Pr., Moscow 117997, Russia
e-mail: kostianoy@online.ru

A.N. Kosarev
Geographic Department, M.V. Lomonosov Moscow State University, Vorobjovy Gory, Moscow 119992, Russia

A.G. Kostianoy and A.N. Kosarev (eds.), *The Aral Sea Environment*,
Hdb Env Chem (2010) 7: 1–9, DOI 10.1007/698_2009_29,

Fig. 1 A map of Central Asia (http://www.lib.utexas.edu/maps/commonwealth/cis_central_asia_pol_95.jpg)

sea ports Muinak and Aralsk and the fishery – the famous Aral bream, barbell, sturgeon, *Chalkalburnus* and others – were developed here. One could find beautiful recreational zones and beaches here. The deltas of the Amudarya, the major river of Central Asia, and Syrdarya bringing their waters into the Aral Sea were famous for their biodiversity, fishery, muskrat rearing, and reed production. The local population found occupation in the spheres related to the water infrastructure.

This was a natural and stable period of the Aral Sea evolution that since 1960 was followed by the anthropogenic one, which continues till the present day. This land-locked water body existed almost thanks to runoff from the two main rivers of Central Asia – Amudarya and Syrdarya. But since 1960 riverine water resources have been irrationally used for increasing irrigation of agricultural lands and creation of artificial water reservoirs. As a result the Aral Sea water balance was disrupted and irreversible alterations in the sea regime appeared that later escalated into one of the "largest ecological disasters of the twentieth century." During the last 50 years we have observed a progressive degradation of the Aral Sea and its environment. During this time period the sea shrunk in size from 66,100 km^2 (in 1961) to 10,400 km^2 (in 2008), its volume decreased from 1,066 to 110 km^3, the sea level dropped by 24 m, and its salinity (mineralization) rose from 10 to 116 ppt and about 160 ppt in the western and eastern Large Aral Sea, respectively. The decrease in area of the Large Sea occurred mainly through its shallow eastern part, the area of which in 2008 (3,200 km^2) became for the first time less than that of the western part (4,000 km^2) (Fig. 2). The ongoing desiccation, shallowing, and salinization of the Aral Sea have resulted in profound changes in its physical, chemical, and biological regime.

Today at the location of the former Aral Sea there are three remnant water bodies: the Small Aral Sea, Western Large Aral Sea, and Eastern Large Aral Sea (see Fig. 2). In June 2009 the Western and Eastern Large Aral Sea were still connected by a small, shallow, and narrow channel in the northern part of both basins (Fig. 3). The Aral Sea lost its economic importance, and the aftermath of its degradation represents a serious threat to the local population due to a lack of fresh water, water quality loss, salinization of soils, dust and salt storms, climate deterioration, various diseases, etc.

By the mid-1980s the Aral crisis had been acknowledged by the whole world and became one of the most significant environment protection issues. The Aral problem is not global, but nevertheless it stirs global interest. For many years it was used by the scientific and civil societies to stress how quickly man's activities may cause degradation of vast expanses on our planet.

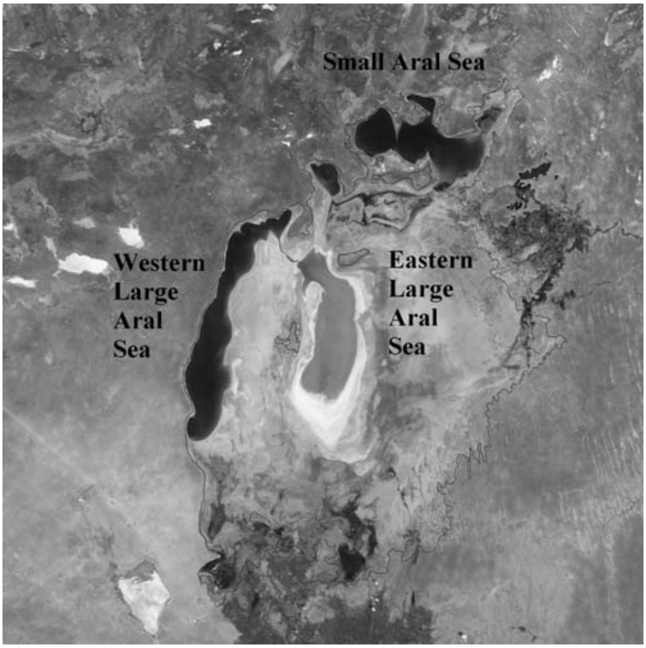


Fig. 2 Satellite image of the Aral Sea from MODIS-Terra on 18 August 2008 adapted from http://earthobservatory.nasa.gov/Features/WorldOfChange/aral_sea.php

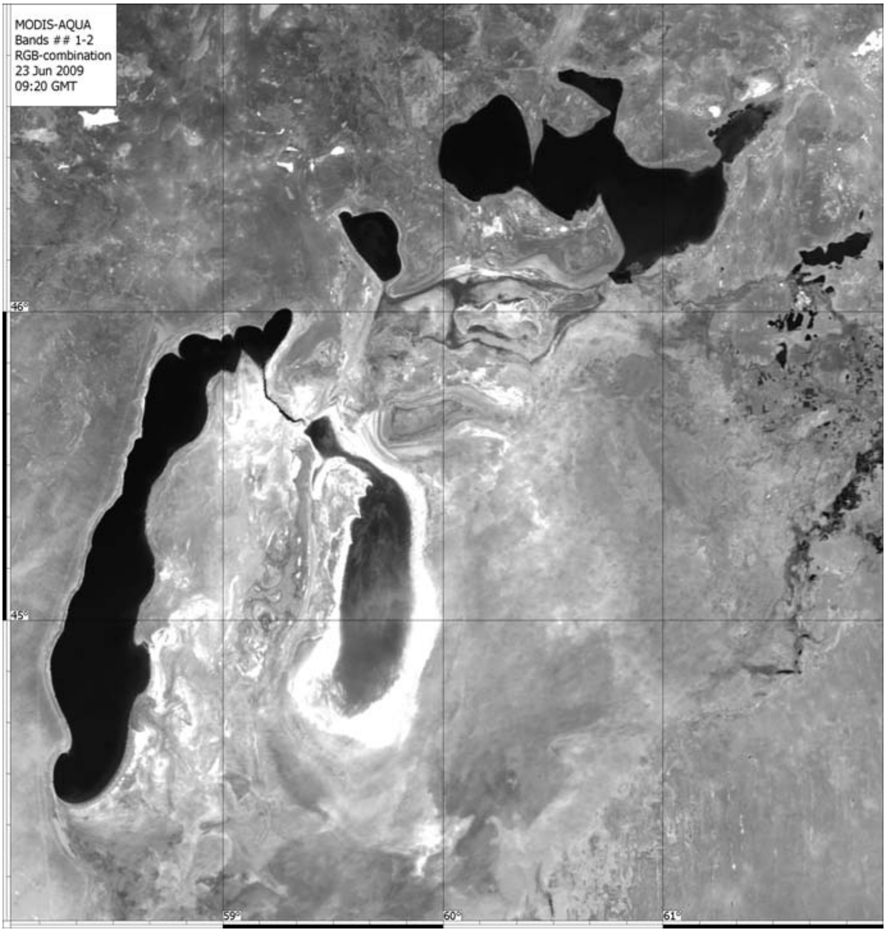


Fig. 3 Satellite image of the Aral Sea from MODIS-Aqua on 23 June 2009. Image courtesy of D.M. Soloviev, Marine Hydrophysical Institute, Sevastopol, Ukraine

In Soviet times the Aral Sea was regularly monitored and investigated: about ten hydrometeorological stations operated on the coasts and islands of the sea, there were regular hydrological and biological observations in the sea in different seasons, as well as geological and geophysical research in the Aral Sea region. A huge data set on the environmental conditions of the sea was collected.

The number of investigations and publications devoted to the Aral Sea problem is enormous. Some of the monographs are listed in the references in chronological order [1–54]. Only in the 1980–1990s it was about 1,000 scientific papers and books, and more than two-thirds of them were published in the late 1990s. Their greater part was collected by J.C.J. Nihoul, A.N. Kosarev, A.G. Kostianoy, and I.S. Zonn and included into the book "The Aral Sea: Selected Bibliography" (2002) [44]. Most of these papers were published in Russian.

The Aral Sea crisis redoubled when after disintegration of the USSR in 1990–1991 the investigations and monitoring of the sea practically ceased. Almost all hydrometeorological stations have been closed, sea expeditions stopped, and assessment of ongoing quick changes in the Aral Sea environment have ceased. At the same time the interest in the Aral Sea problem has risen sharply on the international level. Under the auspices of a number of international organizations and funds a set of important projects on different aspects of the Aral Sea problem have been funded [53, 54].

Many UN organizations (UN University, UNDP, UNESCO, UNEP, UNIDO, FAO, WMO, UN High Commissioner for Refugees, and the International Labor Organization); financial organizations (World Bank, Asian Development Bank, European Bank for Reconstruction and Development, International Monetary Fund, Global Environment Facility); European Union Programs (TACIS, INTAS, INCO-Copernicus, OSCE, TEMPUS); international nongovernmental organizations ("Doctors Without Borders"); regional organizations (International Fund for Saving of the Aral Sea, Interstate Coordination Water Commission, Commission on Sustainable Development, Central Asian Economic Community); and bilateral organizations (US Agency for International Development, Soros Foundation (USA), Konrad Adenauer Foundation, Friedrich Ebert Foundation, Germany Agency for Technical Cooperation (Germany), NOVIB (the Netherlands), NATO Program "Science for Peace," JAIKA, Global Infrastructure Fund Research Foundation (Japan), and others) were involved in the implementation of many hundreds of projects. Apart from these organizations, experts, consultants, scientists, academicians, and others from more than 30 countries took part in the study and preparation of project proposals on the Aral problems. Needless to say, from 2000 more than 30 international projects devoted to various aspects of problems in the Aral Region were elaborated within the framework of the International Programs INTAS and INCO-Copernicus. Dozens of Eastern-European, Russian, and Central Asian institutions and laboratories were also involved in comprehensive investigations. And, of course, ministries, local authorities, institutes of the Academy of Sciences, and national nongovernmental organizations of all Central Asian countries participated in this international cooperation.

The International Fund for Saving the Aral Sea (IFAS) plays a very important role in the international cooperation. IFAS is an interstate organization established in 1993 by the heads of Central Asian states – Uzbekistan, Turkmenistan, Tajikistan, Kazakhstan, and Kyrgyzstan. In 1997, after merging with the Interstate Council for the Aral Sea, the final organizational structure of IFAS was shaped. The main tasks of IFAS are raising funds in the five Central Asian states and through international donors to financially support the Aral Basin Program; implementing joint environmental and research-practical projects on saving the sea and on environmental improvements in the regions affected by the Aral disaster; financing joint fundamental and applied investigations and research-technical developments on restoration of the environment balance; and rational management of natural resources and environmental protection. In December 2008 IFAS received observer status at the UN General Assembly which significantly raises its status and enables it to put forward new initiatives.

On 28 April 2009 a summit of Presidents of the Republics – IFAS founders – was held in Almaty. At the summit it was noted that significant progress in the saving of the Aral Sea was achieved only in Kazakhstan after construction of the Kokaral dam in August 2005. Thus, the Small Aral Sea is now reviving, while the Large Aral Sea continues to disappear. A joint statement of the summit charges the IFAS Executive Committee with the elaboration of a program of actions to render assistance to the countries of the Aral Sea Basin for the period of 2011–2015.

During the last two decades several books devoted to different issues related to the Aral Sea crisis, its reasons, history, and present state of the environment have been published in English. And now, thanks to Springer-Verlag Publishers a new book on the Aral Sea environment has appeared. Naturally, it raises the question: why was this edition undertaken and how does it enrich the very comprehensive bibliography devoted to the Aral Sea? [44].

This monograph is characterized by the following features. First of all, it is multidisciplinary since it deals with the principal processes that govern the Aral Sea's physical, chemical, and biological evolution, and describes the fundamental features of its hydrology, hydrochemistry, and biology, and also considers ecological and socio-economic issues related to the Aral Sea crisis.

Second, the monograph includes a wide range of issues describing the remote past of the Aral Sea region as well as the recent tragic history of the evolution of the sea, and the present state of the Aral Sea environment. To the best of our knowledge, such a collection of high-quality chapters over such a range of topics relating to the Aral crisis has been absent in the scientific literature until now.

Another particular feature of the monograph lies in the combination of different methods used for analysis and calculations. The publication is based mainly on numerous observational data, collected by the authors of the chapters during sea and shore expeditions, on the archive data of Moscow State University, P.P. Shirshov Institute of Oceanology, and the Hydroproject Institute (Moscow, Russia), as well as on a wide scientific literature mainly published in Russian editions. These data are complemented by the results of a series of recent Russian national and international projects, where an extensive research of the Aral Sea was carried out over the past decade. Special attention is paid within the book to satellite monitoring of the state and different natural parameters of the Aral Sea and its surroundings. Reasons for the progressing environmental crisis and present socio-economic problems in the Aral Sea region are also highlighted.

This book combines the work of a group of Russian, Uzbek, French, German, and American authors – specialists in different fields of the earth sciences and the Aral Sea problem. Thanks to the efforts of the editors the results obtained by different scientists are correlated among themselves.

The book is addressed to specialists working in various fields of physical oceanography, marine chemistry, biology, and environmental science studying the cascade of problems related to the Aral Sea: from regional climate change to distribution of benthic and pelagic organisms, and from remote sensing of the sea to archaeology of its coasts. It may also be useful to students and postgraduates specializing in the research of inland seas and lakes. The editors and authors expect that this monograph will help the readers complement the information on the nature of the changing Aral Sea, especially in relation to the present-day conditions of this extremely interesting and unique water body with a tragic history, to assess the alterations that have occurred over the last 50 years, and to establish new strategies for its conservation and recovery.

More detailed information on the special issues of the Aral Sea may be derived from the reference lists at the end of each chapter, as well as in the book "The Aral Sea: Selected Bibliography" [44].

The editors are grateful to colleagues from the P.P. Shirshov Institute of Oceanology (Moscow, Russia), Moscow State University (Moscow, Russia), and the Marine Hydrophysical Institute (Sevastopol, Ukraine) for their long-term fruitful cooperation on the Aral Sea studies.

This book may be regarded as a follow-up volume to our first two books in "The Handbook of Environmental Chemistry" series published by Springer-Verlag entitled "The Caspian Sea Environment" (2005) [55] and "The Black Sea Environment" (2008) [56]. On behalf of the authors, we would like to thank Springer-Verlag Publishers for their timely interest in the environment of the Black, Caspian and Aral seas and their support of the publication presented.

References

1. Barthold V (1902) Information on the Aral Sea and lowers of Amudarya from ancient times till XVII century. Izv Turkestanskago Otd Imp Rus Geogr Obshchestva. Tashkent, p 120 (in Russian)
2. Berg LS (1908) The Aral Sea. An experience of physics-geographic monography. Izv Turkestanskogo Otd Russk Geogr Obshchestva. St.-Petersburg 5: 9, p 580 (in Russian)
3. Malinin A (1921) Brief pilot of the Aral Sea and the Amu Darya delta. Voyennaya Mysl', No 1 (in Russian)
4. Nikol'sky GV (1940) Fish in the Aral Sea. In: Materialy k poznaniyu flory I fauny SSSR (Materials to knowledge of flora and fauna of the USSR). MOIP, Otd Oolog, Moscow, No 1 (XVI), p 115 (in Russian)
5. Blinov LK (1956) Hydrochemistry of the Aral Sea. Gidrometeoizdat, Leningrad, p 52 (in Russian)
6. Rogov MM (1957) Hydrology of the Amudarya delta. Gidrometeoizdat, Leningrad, p 255 (in Russian)
7. Lopatin GV, Den'gina RS, Egorov VV (1958) The Amu Darya delta. AN SSSR, Moscow, p 158 (in Russian)
8. Aral Sea Pilot (Sailing Directions) (1963) Moscow (in Russian)
9. Complex Hydrometeorological Atlases of the Caspian and Aral Seas (1963) Leningrad (in Russian)
10. Dreyer AA, Shamenkova GA (1963) Waves and wind regime of the Aral Sea. GUGMS SM SSSR, GOIN, UGMS Uz SSR, Moscow, Tashkent, p 59 (in Russian)
11. Zenkevich LA (1963) Biology of the seas of the USSR. Izd AN SSSR, Moscow, pp 507–524 (in Russian)

12. Oceanological Tables for the Caspian, Aral and Azov Seas (1964) Gidrometeoizdat, Moscow, p 140 (in Russian)
13. Shul'ts VL (1965) The rivers of Central Asia. Gidrometeoizdat, Leningrad, p 692 (in Russian)
14. Lymarev VI (1967) Shores of the Aral Sea – the enclosed water body of the arid zone. Nauka, Leningrad, p 252 (in Russian)
15. Rogov MM, Khodkin SS, Revina SK (1968) Hydrology of the Amudarya delta region. Trudy GOIN 94: 268 (in Russian)
16. Shnitnikov AV (1969) Intrasecular variability of total humidification components. Essays. Nauka, Leningrad, p 245 (in Russian)
17. Atlas of the Aral Sea Ice (1970) UGMS Uz SSR, Tashkent, p 64 (in Russian)
18. Klyukanova IA (1971) Suspended drifts of Amu Darya and their roles in the irrigation. Nauka, Moscow, p 112 (in Russian)
19. Novozhilova MN (1973) The microbiology of the Aral Sea. Nauka, Alma-Ata, p 160 (in Russian)
20. Kosarev AN (1975) Hydrology of the Caspian and Aral Seas. Moscow University, Moscow, p 272 (in Russian)
21. Shul'ts VL (1965) Water balance of the Aral Sea. Trudy SANIGMI 23: 3–28 (in Russian)
22. Khrustalev YuP, Reznikov SA, Turovsky DS (1977) Lithology and geochemistry of bottom sediments of the Aral Sea. Rostov State University, Rostov-na-Donu, p 154 (in Russian)
23. Pichkily LO (1981) Phytoplankton of the Aral Sea under the anthropogenic influence (1957–1980). Naukova Dumka, Kiev (in Russian)
24. Rafikov AA, Tetyukhin GF (1981) Lowering of the Aral Sea level and changes of natural conditions of the Amu Darya lower. FAN, Tashkent, p 199 (in Russian)
25. Rafikov AA (1982) Natural conditions of drying Southern coastal of the Aral Sea. FAN, Tashkent, p 148 (in Russian)
26. Pinkhasov BI (1984) Neogene-quaternary sediments and neotectonics of the Southern Aral region and Western Kyzylkum desert. Fan, Tashkent, p 115 (in Russian)
27. Molosnova TI, Subbotina GI, Chanysheva SG (1987) Climatic consequences of economic activity in the Aral Sea zone. Gidrometeoizdat, Moscow, p 119 (in Russian)
28. Rubanov IV, Ishniyazov DP, Baskakova MA, Chistyakov PA (1987) Geology of the Aral Sea. FAN, Tashkent, p 248 (in Russian)
29. Akramov ZM, Rafikov AA (1990) The past, present and future of the Aral Sea. Mekhnat, Tashkent, p 144 (in Russian)
30. Bortnik VN, Chistyaeva SP (eds) (1990) Hydrometeorology and hydrochemistry of the USSR Seas. V. VII – The Aral Sea. Gidrometeoizdat, Leningrad, p 196 (in Russian)
31. Glazovsky NF (1990) The Aral crisis. Causative factors and means of solution. Nauka, Moscow, p 136 (in Russian)
32. Popov VA (1990) Problems of the Aral and landscapes of the Amu Darya delta. FAN, Tashkent, p 109 (in Russian)
33. Razakov R (1991) Using and conservation of water resources in the Central Asia. Mehnat, Tashkent, p 203 (in Russian)
34. Razakov RM (1992) The Aral Sea and Aral Sea zone: problems and solutions. Mehnat, Tashkent, p 170 (in Russian)
35. Letolle R, Mainguet M (1993) Aral. Springer, Paris, p 357
36. Kuksa VI (1994) The Southern Sea (Aral, Caspian, Azov and Black) under conditions of the anthropogenic stress. Gidrometeoizdat, St. Petersburg, p 319 (in Russian)
37. Glantz MH (ed) (1995) Creeping environmental problems and sustainable development in the Aral Sea basin. Cambridge University Press, Cambridge, UK, p 291
38. Bos MG (ed) (1996) The inter-relationship between irrigation, drainage and the environment in the Aral Sea basin. In: Proceedings of the NATO advanced research workshop on drainage and development in arid zones, Wageningen, the Netherlands, 4–8 January 1995. NATO science partnership sub-series: 2, vol 22. Springer, p 256
39. Létolle R, Mainguet M (1996) Der Aralsee. Eine ökologische Katastrophe. Springer, Berlin (in German)

40. Micklin PhP, Williams WD (eds) (1996) The Aral Sea basin. Springer, Berlin, p 186 Published in cooperation with NATO Scientific Affairs Division
41. Aladin NV, Filippov AA, Plotnikov IS (2000) Zoobenthos and zooplankton of the Aral Sea. Tr Zool Inst:200 (in Russian)
42. Chub VE (2000) Climate change and its impact on the natural resources potential of the Republic of Uzbekistan. SANIGMI, Tashkent, p 252 (in Russian)
43. Umarov U, Karimov A (2000) Water resources, problems of Aral Sea and environment. Universitet, Tashkent, p 398 (in Russian)
44. Nihoul JCJ, Kosarev AN, Kostianoy AG, Zonn IS (eds) (2002) The Aral Sea: selected bibliography. Noosphere, Moscow, p 232
45. Kostianoy AG, Wiseman W (eds) (2004) The dying Aral Sea. Special issue of J Mar Syst, vol 47(1–4), p 152
46. Nihoul JCJ, Zavialov PO, Micklin PP (eds) (2004) Dying and dead seas. NATO science series. IV. Earth and environmental sciences. Kluwer, The Netherlands, p 36
47. Glantz MH, Zonn IS (2005) The Aral Sea: water, climate and environmental change in Central Asia. WMO, Geneva, No 982
48. Zavialov PO (2005) Physical oceanography of the dying Aral Sea, Springer Praxis Books. Praxis, UK, p 146
49. Alamanov SK, Lelevkin VM, Podrezov OA, Podrezov AO (2006) Climate changes and water problems in Central Asia. UNEP, Moscow (in Russian)
50. Wouters P, Dukhovny V, Allan A (eds) (2007) Implementing integrated water resources management in Central Asia. In: Proceedings of the NATO advanced research workshop on integrated water resources management in transboundary basins – an interstate and intersectoral approach, Bishkek, Kyrgyzstan, 23–28 Feb 2004. NATO science series: IV: Earth and environmental sciences, vol 77. Springer, p 180
51. Dukhovny VA, Navratila P, Ruzieva I, Stulina G, Roshenko E (eds) (2008) Integrated remote sensing and ground investigations of the dried Aral Sea bottom. Scientific-Information Center of Intergovernment Coordination Water Commission, Tashkent (in Russian)
52. Létolle R (2008) La mer d'Aral. l'Harmattan, Paris, p 313 (in French)
53. Zonn IS, Glantz M (2008) The Aral Sea Encyclopedia (eds) Kostianoy AG and Kosarev AN, Moscow: Mezhdunarodnye otnosheniya, 2008, p 252 (in Russian)
54. Zonn IS, Glantz M, Kostianoy AG, Kosarev AN (2009) The Aral Sea Encyclopedia. Springer-Verlag, Berlin, Heidelberg, New York, p 292
55. Kostianoy AG, Kosarev AN (eds) (2005) The Caspian Sea Environment. The handbook of environmental chemistry. vol 5: Water pollution, Part 5P. Springer-Verlag, Berlin, Heidelberg, New York, p 271
56. Kostianoy AG, Kosarev AN (eds) (2008) The Black Sea environment. The handbook of environmental chemistry. vol 5: Water pollution, Part 5Q. Springer-Verlag, Berlin, Heidelberg, New York, p 457

History of Investigation and Exploration of the Aral Sea

Igor S. Zonn and Aleksey N. Kosarev

Abstract The Aral Sea is the unique inland water body located on the border of the Central Asian major deserts – Karakum, Kyzylkum, and Plateau Usturt. Its origin dates back to the first half of the first millennium BC. It was the world's fourth water body by area after the Caspian, and the Superior and Victoria lakes. The history of its investigation spans the period from the origin to development of scientific and cartographic knowledge about the Aral Sea and from ancient times to the present.

Keywords Aral Sea, Cartography, History, Investigations

Contents

I.S. Zonn (✉)
Engineering Research Production Center on Water Management, Land Reclamation and Ecology, 43/1, Baumanskaya ul., Moscow, 105005, Russia
e-mail: igorzonn@mtu-net.ru

A.N. Kosarev
Geographic Department, M.V. Lomonosov Moscow State University, Vorobjovy Gory, Moscow, 119992, Russia

A.G. Kostianoy and A.N. Kosarev (eds.), *The Aral Sea Environment*,
Hdb Env Chem (2010) 7: 11–23, DOI 10.1007/698_2009_5,

1 Introduction

Because of its natural features the Aral Sea represents a unique natural object that for many centuries of its history has been the focus of attention of researchers and scientists. And this is proved by numerous historical data, cartographic documents, and treatises of authors who lived in different times beginning from Ancient Greece. Unfortunately, today we must say that within a lifespan of only one generation this sea as a single natural object practically ceased to exist, and the main reason for this should be sought in man's economic activities. Now the Aral Sea exists in the form of three surviving water bodies. This process caused irreparable damage to ecosystems in this region and to sea-based economic industries.

The exploration of the Aral Sea as a natural object has a long history. It comprises not only the geographical discoveries and mapping, activities of various organizations and individual researchers, but also numerous projects focusing on the sea's preservation and restoration. And this enables us to present a general exposition of this issue, which is referred to in the publications as the "Aral crisis."

2 Antique and Medieval Notions of the Aral Sea

First notions about the Aral Sea may be found in Ancient Greece and Rome. The treatises of the Antique scholars contain the first written allusions to the rivers of Central Asia that flow into the sea. But these data were very fragmental, confused and, at times, even fantastic.

Greek authors made assumptions concerning the existence of the Aral Sea. Strabo (64/63 BC to 23/24 AD) noted that the nomadic tribes of the *Daev* people, who came from the country "behind Tanais and Meotid" meaning here the Syrdarya and the Aral Sea, inhabited the territories to the east of the Caspian Sea. In the same period findings about the Oxian freshwater lake that was located near the Caspian Sea started appearing. The first data about the Aral Sea were obtained in 138 BC by Chjan Cyan who was delegated by the Chinese government as an ambassador to Central Asia and who wrote about finding there "a big lake without high shores." Additionally, in 97 BC Chinese troops commanded by Ban Chao came out to the Aral Sea, while the ambassador of Byzantine who was directed to Turkey in 568 also brought information about the Aral Sea. The map of Ptolemy prepared in the second century, but published in Europe only in 1490 showed that the Oxus (Amudarya) and Yaksart (Syrdarya) flowed into the Caspian. The Oxus had a right tributary in the middle reaches of which there was the Oxis Lake (Oxian). This is the Sarykamysh Depression. So it becomes clear why the first attempts of the Russians in the eighteenth century to map accurately the territory to the east of the Caspian were focused, primarily, on identification of the places of inflow of the major Central Asian rivers.

The Greek historian of the fourth century AD Ammian Marcellin was "the first and only of the ancient scholars who clearly pointed to the existence of the Aral Sea."

Mostly correct data about the Aral Sea can be found in the treatises of the Arab scholars of the ninth to tenth centuries, which contained data about the sea's size and described its shores. In the mid-tenth century the Arab author Ibn Ruste mentioned the Aral Sea in his works. At the same time the first cartographic presentation of the "Khorezm Sea," Istarkhi, had appeared. The map of Istarkhi, descriptions of Ibn Ruste, Al-Biruni and other Medieval explorers prove that at those times the Aral Sea had the same size and outline as in the early tenth century [1].

Among the data about this region received at that time the most interesting is the map of Ibn Khaukal, the Arab traveler of the tenth century. It shows the whole territory of Central Asia with the Aral (Khorezm) Sea and the Amudarya (Djeikhun) and Syrdarya (Sukhun or Shash) rivers.

The world map of Fra Mauro (1457) from Venetia showed a lake to the east of the Caspian Sea, but this lake had no name. Until the sixteenth century there was no new information about the Aral Sea.

In 1552 Ivan the Terrible ordered subjects "to measure the land and to make a drawing of the state." This spurred the development of mapping not only in Rus', but in nearby territories. With time the "drawing" contemplated by the tsar was gradually improved upon. Finally, in 1627 the accompanying book to the map was prepared; it was named "Book to the Great Drawing." In this Book the Aral was referred to as the "Blue Sea."

Scholars from Western Europe knew nothing of the Aral Sea until the late seventeenth century. The sea under the name of "Since" first appeared on the map of Vitzen (Ides) in 1704. The map had been prepared using the materials of the Russian explorers.

3 Early Period in Geographical Investigation of the Aral

In the late seventeenth to early eighteenth centuries, outstanding Russian geographer and historian S.U. Remezov prepared the formidable book "Drawing Book of Siberia" where on one of the drawings he depicted quite accurately the Aral Sea with its inflowing rivers – the Amudarya and Syrdarya.

Presumably during the reign of Peter I (the early 1700s) the color map "Drawing of the Waterway from Astrakhan to the Chinese State" was prepared; the map presented the whole of Central Asia with the Aral Sea, Syrdarya, Amudarya, and Zarafshan rivers, the cities located on them and the irrigation system comprising nine canals in the Amudarya delta. The Aral Sea was named "*Osoby mortse*" (Special Sea).

Further exploration in the Aral region began in 1715 with the expedition led by A. Bekovich-Cherkassky that was directed to the eastern shores of the Caspian Sea by Peter I. The expedition found that the Amudarya flowed into the Aral Sea. Present-day cartographers praise highly the results of this expedition, which made it possible to prepare a map on which the Aral Sea is depicted accurately. In 1716 Peter I ordered A. Bekovich-Cherkassky to go on a new expedition, this time to study the Amudarya. Unfortunately the members of this expedition met a tragic death there. In the order that Peter I handed to A. Bekovich-Cherkassky before the expedition the sea into which the Amudarya flowed was called “Aral” for the first time. In the Turk languages “Aral” means “island.” The most probable explanation of this fact may be the following: the sea is like a Blue island in a boundless sandy desert. . . .

In the 1720s it was thanks to Russia that Western European cartography obtained so much new data about the vast Aral–Caspian area. Meanwhile, further verification of the Aral Sea maps was undertaken. The first accurate topographical and geodetic data about its northern coasts was obtained in 1731 by a Russian mission that was sent to Khazakh Khan, who ruled over the Aral shores and among the members of this mission were two officers – land surveyors. During this period nearly a third of the Aral coastal area remained unsurveyed and it was marked on the map on the basis of data received from local people.

In the mid-eighteenth century after much improvement in the relationship between Russia and Kazakhstan, targeted surveys of the Central Asian territory began. In 1740–1741 on the initiative of F.I. Soimonov and P.I. Rachkov the Russian government directed a hydrographic expedition to the Aral. The members of this expedition studied the eastern shore of the Aral Sea including the Syrdarya delta and on the basis of instrumental surveys they prepared a landscape map of the sea.

In 1744 the “Atlas of the Orenburg Province” was prepared that comprised 13 maps, one of which was the “Land Map of the Khiva and Aral Territories,” which gave a schematic presentation of the Aral Sea.

4 Hydrographic and Cartographic Investigations in the Aral Region

After the mid-eighteenth century there was quite a long interval before further studies on the Aral Sea were undertaken. This interval lasted until 1825 when an expedition headed by Colonel F.F. Berg went to the western coast for preparation of its description and to carry out a leveling survey of the Ustyurt Plateau.

In the 1830s the Aral Sea coast was investigated by a well-known zoologist, professor of the Kazan University E.A. Eversman. His detailed description is now of great value because it helps us to reconstruct ecosystems in the area about 180 years ago. E.A. Eversman’s work included geological and physiographical characteristics of the Aral coast, and offered a suggestion about desiccation of the sea.

In 1831 A. Levshin produced a map of the Aral Sea on the basis of data from the archive of the Orenburg Frontier Guard Commission and “data obtained from Russian engineers or and officers who were in the Circum-Aral in 1820–1826.”

In the history of Aral Sea investigations a considerable contribution was made in the 1840s by the Khiva expedition led by G.I. Danilevsky and F.I. Baziner. The

Expedition Report entitled “Description of the Khiva Khanate” published in 1851 contained detailed information about the climate, relief, and geography of the Usturt and Aral Sea regions. The large-scale map of the Aral Sea and the Khiva Khanate prepared by F.I. Baziner was included by A. Humboldt into his book “Central Asia.”

In 1848–1849 the first marine expedition was organized with the schooner “Konstantin” commanded by naval officer and investigator A.I. Butakov. The members of this expedition conducted general reconnaissance surveys of the sea, its coasts and the Barsakelmes Island. The eastern coast and islands were described and their geographical coordinates were determined. The depth measurements were made over a vast area and as a result the maximum (69 m) sea depth was determined; the currents were also studied. A group of islands was discovered that later were named the islands of Vozrozhdenia and Komsomolsky. Butakov’s investigations in the Aral Sea and in the Syrdarya lower reaches had very important practical results for the organization of shipping over the sea and river. However, there were difficulties in publishing the results of this expedition and the full text of the report was published only 100 years later.

In 1855 A.I. Butakov continued his studies and described the lower reaches of the Syrdarya River and in 1859, the whole delta of the Amudarya River. In 1857 he published his work entitled “Brief Description of the Syrdarya River from Perovsky Fort to the Mouth” where he noted the northward displacement of the delta arms. For his investigations Butakov was awarded the Demidov Prize of the Russian Geographical Society. In 1853 he was elected an Honorary Member of the Berlin Geographical Society and in 1867 the London Geographical Society conferred upon him the medal of the society’s founder.

By the mid-nineteenth century thanks to the efforts of A.I. Butakov and his predecessors the hydrography of the Aral Sea had already been rather well studied. However, at that time the hydrological knowledge of the Aral Sea was still poor. Only K. Sharngorst in 1871, J. Grimm in 1873, and E. Pratz in 1874 took in the summertime a few water samples of the surface water and measured its temperature.

Investigations of the Circum-Aral area and Aral Sea were reanimated to a great extent in 1873 when Khiva joined Russia. Already in the following year two expeditions were working in this region: the Aral–Caspian Expedition organized by the Petersburg Society of Natural Scientists investigated the western and northern Aral coast, while the Amudarya Expedition sent by the Russian Geographical Society studied the southern and southeastern coast. In 1874 a member of the second expedition, well-known land surveyor A.A. Tillo carried out accurate measurements of the sea level and placed a benchmark on the north-western coast that was used as the datum in further determinations of its level.

From 1874 occasional level-gauge observations were carried out on the sea shores. Soon it was found that its level was subject to perceptible fluctuations: after a very low level in the 1880s it rose rather sharply and quickly (during 10–15 years by nearly 3 m) until it stabilized in the 1960s.

In 1874 and 1889 I.A. Strelbitsky determined the morphometric characteristics of the Aral Sea using the maps of Asian Russia. At the same time the biological investigations of the Aral were initiated. The expeditions organized in the nineteenth century provided the first data concerning the flora and fauna of this water body.

5 Regular Research on the Aral Sea

In 1897 the Turkestan Branch of the Russian Geographical Society was set up in Tashkent and this event was very important for further studies of the Aral Sea. A great contribution to the activities of this society and into investigations of the sea was made by L.S. Berg who later became an outstanding Russian scientist, geographer, and zoologist. In 1900–1903 he organized the Aral expedition that conducted geographical and hydrologic surveys of the sea and nearby territories and leveling surveys of the sea surface.

In 1900 L.S. Berg organized instrumental observations of the sea level by a level-gauge in the Greater Sarychaganak Bay on the northern coast of the Aral Sea. In 1904 in the same region the sea level recorder was installed, but it operated unreliably. Regular instrumental observations of the sea level by level-gauge were initiated in 1911 at the hydrometeorological station “Aral Sea,” which had opened in 1884 near the city of Aralsk.

The results of the multipurpose investigations of L.S. Berg were collected in the monograph “Aral Sea” (1908) [1], which provided a comprehensive climatic and physiographical description of the sea, and the basic features of its hydrologic regime such as water level variations, water temperature, salinity, color, and transparency. Such phenomena as seiche were witnessed for the first time in the Aral Sea. The relationship between the sea water level and climate was revealed. The paleoclimatic investigations of L.S. Berg enabled him to challenge the opinion that was widespread at that time concerning the progressive desiccation of Central Asia. The conclusions concerning the fluctuations of the Aral Sea level through its history were very important for the theory of hydrometeorological processes. This monograph immediately received wide publicity and was translated into many languages. The investigations carried out by L.S. Berg present even now a creditable example of a comprehensive analysis of natural events.

Construction in 1905 of the Tashkent railroad spurred further development of the circum-Aral area and the Aral Sea proper. The settlement of Aralsk was established on a seaside stretch of this railroad. Some investigations were conducted in the circum-Aral area in 1905–1915 on an order from the resettlement department. In 1914 the Turkestan branch of the Russian Geographical Society carried out leveling surveys of the sea level that revealed that it was rising. In the period from 1912 to 1915 AD Arkhangelsky and others carried out soil and geological surveys in the Aral area. Later in 1931 the first geological map of this area was published. In the early 1920s with the formulation of tougher requirements for navigation over the Aral Sea it became evident that the Aral Sea had no appropriate coastal pilot. In order to cover this gap, already during the 1921 navigation season hydrographic works were conducted in the Aral Sea, Syrdarya, and Amudarya delta. The obtained data enabled A. Malinin to prepare and publish within a short time the "Brief Pilot of the Aral Sea and the Amudarya Delta" [2].

Another important sphere of development of the Aral Sea was connected with the study and use of its fish resources. In the 1930s fish catches were about 40–50 thousand tons a year. The opening in 1929 of the Aral Research Fishery Station facilitated hydrobiological and ichthyologic investigations that were conducted by V.Ya. Nikitinsky, A.L. Bening, G.V. Nikol'sky, and others. The results of these researches were published in the treatises of the Aral Research Station and in the monograph of Nikol'sky called "Fish of the Aral Sea" (1940) [3] that generalized the materials on fish ichthyology and water regime in the Aral Sea that had been collected after the investigations of Berg.

In the mid-1930–1940s a network of hydrometeorological stations (nine by the late 1940s) was operating in the Aral region. Regular observations of the sea water level, water temperature and salinity, waves, and ice phenomena were conducted. In 1936–1937 regular observations of currents were carried out by the hydrometeorological station "Aral Sea." The obtained results were generalized in the work of Zhdanko entitled "Currents in the Aral Sea" (1940) [4]. Data from coastal observations and hydrological surveys conducted in the open sea since 1941 were included into Nautical Almanacs and publications of the USSR Water Cadastre. During World War II observations on the Aral Sea were still conducted, but episodically. Nevertheless, in 1943 a fishery expedition investigated the spawning water bodies in the Syrdarya and Amudarya. Much time was given to interpretation of the prewar materials. As a result, in 1946 the work of Zaikov "The present and future water balance of the Aral Sea" [5] was published.

In the postwar years due to construction of the Karakum canal and after governmental resolutions on irrigation development in the Amudarya and Syrdarya river basins there was a need for wider-scale research of the sea conducted by the Aral Scientific Fishery Station, State Oceanographic Institute (GOIN), and other organizations. They studied the water and salt balance of the sea, its hydrometeorological and hydrochemical regimes, biology of fish multiplication, adaptation of fish from other basins etc. Studies of the Amudary and Syrdarya deltas became scaly.

The results of comprehensive investigations of the hydrochemical regime of the Aral Sea were incorporated into the monograph of Blinov entitled "Hydrochemistry of the Aral Sea" (1956) [6]. It focused on specific features of the chemical composition and physical–chemical properties of the sea waters, its salt balance, and the regime of nutrients defining its productivity. For the first time a valid evaluation of the future changes of the hydrochemical conditions in the sea (in connection with the contemplated water management activities in its basin) was conducted. As the salt composition of waters of the Aral Sea (as well as the Caspian) differed from that of the ocean, special "Oceanological Tables" (1964) [7] were published.

In 1958–1960 as a result of the wide-scale hydrographic surveys the new "Pilot of the Aral Sea" [8] was published. In the early 1960s the standard network of "century" oceanographic stations of the open sea was introduced that conducted seasonal surveys of its water body including a plethora of standard hydrometeorological and hydrochemical observations. In winter ice air-borne surveys were conducted systematically.

The water level drop in the Aral Sea that started in the 1960s attracted the attention of many researchers from various organizations. And there was an urgent need to analyze and generalize the materials on natural conditions of the sea for the time of its "natural" existence and to assess the likely future changes caused by anthropogenic factors. During 1960–1990 the following monographs describing the hydrological and hydrochemical regimes of the Aral Sea were published, among them Kosarev's "Hydrology of the Caspian and Aral Seas" (1975) [9], and "The Aral Sea" edited by Bortnik and Chistyaev [10]. The nature and structure of the coasts of the Aral Sea are considered in the book of Lymarev (1967) [11]; the basic stages of the sea's development are considered in the book of Kes' (1969) [12]. Other aspects of the sea's nature, i.e., climate and related water availability in the Aral–Caspian basin, were studied by L'vov (1959, 1965) [13, 14] and Shnitnikov (1961–1969) [15, 16]. They attributed the fluctuations of the water levels in the Caspian and Aral seas to the effect of large-scale geleogeophysical and atmospheric processes. This enabled conclusions to be drawn on cyclic wetting rhythms over the century and many-century timescales for this region. A more detailed study of water resources in the Aral basin and a water balance of the sea were conducted by Shul'ts (1965, 1975) [17, 18]. At the same time reference books and practical aids were published containing information about characteristics of the sea's regime ("The Catalog of Level Observations," 1965–1987; "The Reference Book of Basic Hydrological Characteristics," 1972, 1974; "Complex Hydrometeorological Atlases of the Caspian and Aral Seas," 1963 [19], "The Atlas of the Aral Sea Ice," 1970 [20]). By this time the specific features of the Aral natural regime had been studied rather well in general.

The Aral investigations attracted even more attention in the 1960s in connection with the economic development and irrigation of large land areas in the Amudarya and Syrdarya basins, construction of unique main canals and reservoirs with large storage capacity and, as a result, the dropping water level due to intensive water intake from the Amudarya and Syrdarya for irrigation. In his work A.Ye. Asarin (1964) [53] forecasted the drop of the Aral Sea level to 1980.

6 Exploration of Environmental Changes in the Aral Region and the Aral Sea

By the 1980s it became clear that there was not a single component of the natural environmental conditions and not a single branch of agriculture and industry in the circum-Aral area that in the future could develop independently of the Aral Sea level drop and man-made desertification of the nearby territory. That is why the key research and design-survey works on the Aral issue included study of the changes in the natural environment in this region and development of the scientific basis for the actions aimed at alleviation and liquidation of negative consequences of man-made desertification.

The investigations of various aspects of the present state and changes in the natural environment of the Aral and circum-Aral region were conducted quite purposefully. These investigations encompassed geographical and ecological factors [21, 22], natural-reclamation [23, 24], suspended sediments, changes in the cycle of nutrients, carbonates and humus in the “Basin-Aral Sea” system [25, 26], ecological-geobotanical [27–30], geological [31], and climatic [32] studies. Later remote methods for natural studies and monitoring found wide application in special landscape investigations in the circum-Aral area [33–37].

In the 1990s wide-scale investigations were carried out of the consequences of the Aral Sea desiccation, assessing factors such as desertification [38, 39], effect of climate variations on the natural resources [40], salt and dust transfer [41, 42], and the salt balance [43]. At the same time the Zoological Institute of the Russian Academy of Sciences carried out studies of zoobenthos and zooplankton as well as looking at general variations of the sea’s ecosystems and the effects of man’s activities in the Aral region [44, 45]. In 1993 UNEP undertook a diagnostic study of the Aral Sea basin the results of which stirred great interest. From this time on many thematic projects were proposed whose implementation involved many international organizations (UNEP, TACIS, NATO, WMO, World Bank, GTZ, INTAS, and others) as well as experts from the world’s leading countries. Unfortunately, many of these projects were not implemented. At times scientists, researchers, and designers could not come to a consensus on the strategy for Aral preservation and restoration. In the late 1990s Uzbekistan started to use the Amudarya residual flow for creation of polder systems in the river delta. Kazakhstan became involved with restoration of the Small Aral, its northern part, and it can be stated that they succeeded in this.

A considerable contribution to the development of project proposals on protection of the environment, conservation, and restoration of the Aral Sea was made by scientists of SANIIRI and then NIC MKVK headed by V.A. Dukhovny (1990–2000).

A plethora of issues related to the situation in the Aral region is addressed in the book written by a team of authors from Uzbekistan entitled “Water Resources, Problems of the Aral and Environment” [46]. The book provides a detailed description of the water resources of Central Asia, their variations, and the environmental situation of the water basin and the Aral problem. Also included are works reflecting various views on optimization of the Aral region regime.

The M.V. Lomonosov Moscow State University continued study of the causes and dynamics of the sea level drop, and changes in hydrology and coastline of the Aral Sea [47].

From 2000 to 2006 under the supervision of A.G. Kostianoy (P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences) and S.V. Stanichny (Marine Hydrophysical Institute, National Academy of Sciences of Ukraine) the integrated satellite monitoring of the Aral Sea (Large and Small Aral) and the nearby region was carried out. During monitoring the following parameters were recorded: surface and volume of the sea, sea surface temperature, sea level, ice cover, vegetation index, among others.

From 2002 P.O. Zavialov (P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences) organized a series of integrated sea expeditions in the Aral Sea using motor boats that included hydrological, hydrobiological, and hydrochemical surveys (see the work by Zavialov [48–50]).

A certain contribution to the Aral Sea studies, more precisely into generalization of the available investigation materials, and suggestion of their own vision of the problem which has improved awareness among the international scientific community about the Aral environmental crisis has been made by the following scientists: from USA – Ph. Miklin (1991–1996), M. Glantz (1993–2006); from France – M. Mainguet, R. Létolle (1992–1994); from Japan – Ishida (1995–1996), Ogino (1995–1996), Tsutsui (1992–1996); from Australia – W. Williams (1993–1996).

The number of investigations devoted to the Aral problem is enormous. During the 1980–1990s there were about 1,000 scientific publications alone, and more than two-thirds of them were published in the late 1990s, which is shown in Fig. 1. The majority of these publications were collected by J.C.J. Nihoul, A.N. Kosarev, A.G. Kostianoy, and I.S. Zonn and included in the book "The Aral Sea: Selected Bibliography" (2002) [51].

In 2009 "The Aral Sea Encyclopedia" authored by Zonn, Glantz, Kostianoy, and Kosarev was published by Springer [52]. The encyclopedia presents environmental issues, national and international programs, prominent historical figures, a history of research and studies carried out on the sea, and includes a chronology of events

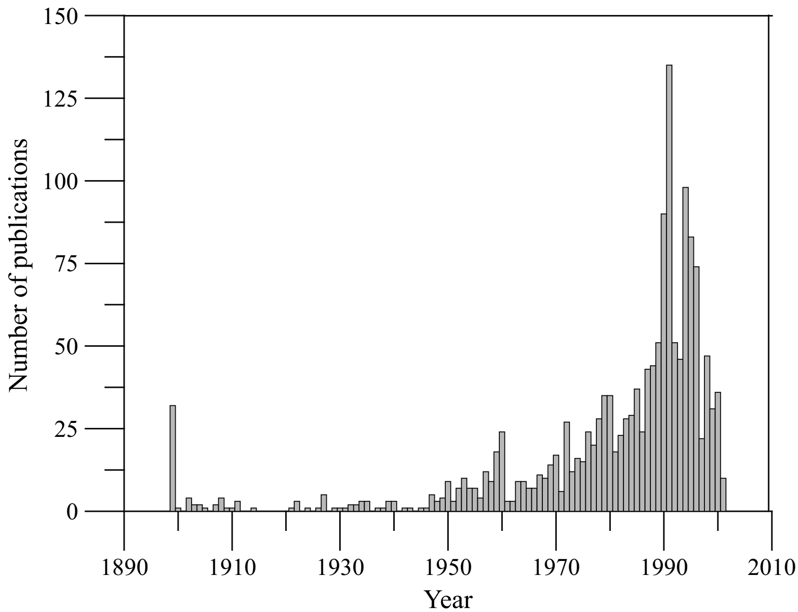


Fig. 1 Number of scientific publications devoted to the Aral Sea [51]. The peak ascribed to the last year of the nineteenth century represents an accumulative number of all the previous publications

during the past five centuries which formed milestones in the history of the development of the Aral Sea and its subsequent disappearance.

As can be seen herein, many issues related to the study of the Aral Sea and nearby territories are permanently in the focus of attention of scientific and practical organizations. Many-year investigations of the Aral Sea issue have provided very interesting information about the present state and changes of natural conditions in this unique water body, and enabled assessment of man-made effects. Nevertheless, due to further rapid changes in the Aral regime, and development and design of water management and engineering actions related to regime regulation in some of its regions, it is still necessary to continue work on integrated monitoring of the sea environment aimed at possible optimization of its regime and environmental protection.

References

1. Berg LS (1908) The Aral Sea. An experience of physics-geographic monography. Izv Turkestanskogo Otd Russk Geogr Obshchestva 5(9):580 (in Russian)
2. Malinin A (1921) Brief pilot of the Aral Sea and the Amu Darya Delta. Voyennaya Mysl', No. 1 (in Russian)
3. Nikol'sky GV (1940) Fish in the Aral Sea. In: Materialy k poznaniyu flory I fauny SSSR (Materials to knowledge of flora and fauna of the USSR) No. 1 (XVI). MOIP, Otd Oolog, Moscow, p 115 (in Russian)
4. Zhdanko SM (1940) Currents in the Aral Sea. Meteorol Hydrol 1–2:78–82 (in Russian)
5. Zaikov BD (1946) The present and future water balance of the Aral Sea. Trudy NIU GUGMS SSSR 4(39):25–59 (in Russian)
6. Blinov LK (1956) Hydrochemistry of the Aral Sea. Gidrometeoizdat, Leningrad, p 52 (in Russian)
7. Oceanological Tables for the Caspian, Aral and Azov Seas (1964) Gidrometeoizdat, Moscow, p 140 (in Russian)
8. Aral Sea Pilot (Sailing Directions) (1963). Moscow (in Russian)
9. Kosarev AN (1975) Hydrology of the Caspian and Aral Seas. Mosk. Univ., Moscow, p 272 (in Russian)
10. Bortnik VN, Chistyaeva SP (eds) (1990) Hydrometeorology and hydrochemistry of the USSR Seas. V. VII – The Aral Sea. Gidrometeoizdat, Leningrad, p 196 (in Russian)
11. Lymarev VI (1967) Shores of the Aral Sea – the enclosed water body of the arid zone. Nauka, Leningrad, p 252 (in Russian)
12. Kes' AS (1969) The main steps of the Aral Sea development. In: Problema Aralskogo Morya (Problem of the Aral Sea), Nauka, Moscow, pp 160–172 (in Russian)
13. L'vov VP (1959) The Aral Sea level fluctuations in the last hundred years. Trudy GOIN 46:80–114 (in Russian)
14. L'vov VP (1965) The Aral Sea and solar activity. Trudy GOIN 85:91–172 (in Russian)
15. Shnitnikov AV (1961) Dynamics of water resources of the Aral Sea Basin in the context of its climatic transgression. Trudy Lab. Ozerovedeniya AN SSSR 14:10–88 (in Russian)
16. Shnitnikov AV (1969) Intrasecular variability of total humidification components. Essays. Nauka, Leningrad, p 245 (in Russian)
17. Shul'ts VL (1965) The Rivers of Central Asia. Gidrometeoizdat, Leningrad, p 692 (in Russian)
18. Shul'ts VL (1975) Water balance of the Aral Sea. Trudy SANIGMI 23 (in Russian)
19. Samoilenko VS, Sachkova AI (eds) (1963) Complex Hydrometeorological Atlases of the Caspian and Aral Seas. Hydrometeoizdat, Leningrad (in Russian)
20. Atlas of the Aral Sea Ice (1970) UGMS Uz. SSR, Tashkent, 64 pp (in Russian)

21. Kuznetsov NT (1980) The preliminary results and some directions of future investigations on the Aral Sea problem. Problemy Osvoeniya Pustyn' 5:10–17 (in Russia)
22. Kuznetsov NT (1991) Geographical-ecological aspects of hydrological functions of the Aral Sea. Izv. AN SSSR, Ser Geogr 4:82–88 (in Russian)
23. Rafikov AA (1982) Natural conditions of drying Southern Coastal of the Aral Sea. FAN, Tashkent, p 148 (in Russian)
24. Rafikov AA, Tetyukhin GF (1981) Lowering of the Aral Sea level and changes of natural conditions of the Amu Darya Lower. FAN, Tashkent, p 199 (in Russian)
25. Klyukanova IA (1971) Suspended drifts of Amy Darya and their roles in the irrigation. Nauka, Moscow, p 112 (in Russian)
26. Klyukanova IA, Nikolayeva RV (1979) Man-induced changes in overall runoff in the Aral Sea Basin. Sov Geogr 20(9):551–559 (in Russian)
27. Kurochkina LYa (1979) The botanic studies in the Aral Sea Basin. Problemy Osvoeniya Pustyn' 3:9–17 (in Russian)
28. Kurochkina LYa, Vukhrer VV, Makulbekova GB, Dimeeva LA (1991) The state of vegetation on the dried bottom and on the shores of the Aral Sea. Izv AN SSSR, Ser Geogr 4:76–81 (in Russian)
29. Novikova NM (1996) Current changes in the vegetation of the Amu Dar'ya delta. In: Micklin PhP, Williams WD (eds) The Aral Sea Basin. Springer, Berlin, Heidelberg, Published in cooperation with NATO Scientific Affairs Division, pp 69–78
30. Novikova NM (2000) Ecological basis for botanical diversity conservation within Amudarya and Syrdarya river deltas. In: Breckle S-W, Veste V, Wucherer W (eds) Sustainable land use in deserts. Springer, Berlin, Heidelberg, pp 84–94
31. Rubanov IV, Ishniyazov DP, Baskakova MA, Chistyakov PA (1987) Geology of the Aral Sea. FAN, Tashkent, p 248 (in Russian)
32. Molosnova TI, Subbotina GI, Chanysheva SG (1987) Climatic consequences of economic activity in the Aral Sea Zone. Gidrometeoizdat, Moscow, p 119 (in Russian)
33. Popov VA (1990) Problems of the Aral and landscapes of the Amu Darya Delta. FAN, Tashkent, p 109 (in Russian)
34. Ptichnikov AV (1994) Space imagery in the studies of landscape dynamics (on the example of Amu Darya Delta) in the Aral Sea region. Issled. Zemli iz Kosmosa 3:76–83 (in Russian)
35. Ptichnikov AV (1996) Environmental and landscape changes in the aral sea region as detected from remote sensing. In: Micklin Ph P, Willams WD (eds) The Aral Sea Basin. Springer, Berlin, Heidelberg, Published in cooperation with NATO Scientific Affairs Division, pp 141–148
36. Glushko EV (1991) Integrated geoecological mapping of Priaralie and Kyzylkum Desert by space images. Vestnik Mosk Univ, Ser Geogr 3:21–30 (in Russian)
37. Glushko EV, Ptichnikov AV, Tikunov VS (1996) Using geoinformation system and space imagery to monitor environment changes in the Aral Sea ecological disaster area. In: Stein TI (ed) IGARSS'96. 1966 International Geoscience and Remote Sensing Symposium, Remote sensing for a sustainable future. Lincoln. NE USA 27–31 May, 1996, IEEE, NY, USA, Vol 4, pp 2324–2325
38. Rafikov AA (1994) Main stages of development of anthropogenic desertification in the Southern Priaralie. Problemy Osvoeniya Pustyn' 3:17–25 (in Russian)
39. Kust GS (1996) Soil evolution in conditions of anthropogenic desertification of the Aral Sea coastal region. Eurasian Soil Sci 29(6):680–686
40. Chub VE (2000) Climate change and its impact on the natural resources potential of the Republic of Uzbekistan. SANIGMI, Tashkent, p 252 (in Russian)
41. Razakov R (1991) Using and conservation of water resources in Central Asia. Tashkent, p 203 (in Russian)
42. Razakov RM (1992) The Aral Sea and Aral Sea Zone: problems and solutions. Mekhnat, Tashkent, p 170 (in Russian)
43. Glazovsky NF (1995) Aral Sea. In: Mandych AF (ed) Enclosed seas and large lakes of Eastern Europe and Middle Asia. SPB, Amsterdam, pp 119–154

44. Aladin NV, Potts WTW (1992) Changes in the Aral Sea ecosystems during the period 1960–1990. Hydrobiologia 237(2):67–79
45. Aladin NV, Filippov AA, Plotnikov IS (2000) Zoobenthos and zooplankton of the Aral Sea. Trudy Zool. Inst:200 (in Russian)
46. Umarov U, Karimov A (2000) Water resources, Problems of Aral Sea and environment, University, Tashkent (in Russian)
47. Kravtsova VI, Lur'ye IK, Markov DV (2001) Cartography of the coastal line changes of the Aral Sea based on satellite imagery. Geod i Kartografiya 4:32–38 (in Russian)
48. Zavialov PO, Ni AA (2009) Chemistry of the large Aral Sea. Handb Environ Chem. doi: 10.1007/698_2009_3
49. Zavialov PO (2009) Physical oceanography of the large Aral Sea. Handb Environ Chem. doi: 10.1007/698_2009_4
50. Zavialov PO (2005) Physical oceanography of the dying Aral Sea. Springer Praxis Books, 146 pp
51. Nihoul JCJ, Kosarev AN, Kostianoy AG, Zonn IS (eds) (2002) The Aral Sea: selected bibliography. Noosphere, Moscow, 232 pp
52. Zonn IS, Glantz M, Kostianoy AG, Kosarev AN (2009) The Aral Sea Encyclopedia. Springer, Berlin, 292 pp
53. Asarin AE (1964) The level regime of the Aral Sea at growing water consumption in Syrdarya and Amudarya river basins. Trudy Gidroproject, N11 (in Russian)

Paleogeographical History of the Aral Sea

Alexander A. Svitoch

Abstract The Aral Sea basin formed as a result of joint action of tectonic subsidence and processes of arid denudation. The basin itself features rather irregular bottom topography, with depressions divided by an elongated elevation trending from north to south. Fragments of marine terraces occur locally at 54–72 m a.s.l. on the sea coasts. In the marine series infilling the basin there have been distinguished sediments attributable to the Akchagylian and Apsheronian transgressions of the Caspian Sea and those of the Khorezmian suite (Holocene) deposited during the last marine stage of the Aral Sea. The lower portion of the sequence is represented by diversified lacustrine formations containing occasional interlayers of gypsum and shells of brackish-water and freshwater mollusks. The upper part of the sedimentary sequence consists of alternating layers corresponding to transgressive and regressive phases of the Aral Sea; shells of *Cerastoderma glaucum* (*Cardium edule*) are typically present.

The history of the Aral Sea may be divided into two unequal parts – a prolonged prehistory and a short epoch of the modern (pre-1961) sea basin. The first stage of the Aral dates back to the Late Pliocene when its basin was filled with water of the Akchagylian and Apsheronian seas; this was followed by long periods in the Pleistocene when subaerial environments persisted in the basin.

The recent marine stage is rather short spanning only the Holocene. It began with a lacustrine-brackish water phase. At that time, lakes of varying salinity existed within the basin; occasionally they dried up and were replaced by solonchak desert. In the mid-Holocene water from the Amudarya turned from the Sarykamysh depression and began to flow into the Aral basin via the Akchadarya channel, thus starting the recent (last) stage of the Aral Sea's history. At that time the Aral was a vast freshened brackish water body of marine type subjected to drastic fluctuations of sea level (within 20 m) and noticeable changes of salinity (up to 10‰) and was inhabited by the mollusk *C. glaucum*.

A.A. Svitoch
Faculty of Geography, M.V. Lomonosov Moscow State University, Vorobjovy Gory, Moscow, 119992, Russia
e-mail: geography@inbox.ru

A.G. Kostianoy and A.N. Kosarev (eds.), *The Aral Sea Environment*,
Hdb Env Chem (2010) 7: 25–44, DOI 10.1007/698_2009_7,

The onset and further evolution of the Aral Sea basin were controlled by a number of factors, including climate, hydrology, tectonics, and human impact. It seems, however, that climate was of primary significance, as it controls the hydrologic cycle within the Aral drainage basin, evaporation from the sea surface, and runoff from the Syrdarya and Amudarya rivers; the latter was of prime importance in turning the poorly inundated Aral depression into a large lacustrine–marine basin.

Keywords Aral Sea, Evolution, History, Geological setting, Holocene, Paleogeography, Relief

Contents

1 Introduction

The Aral Sea located in Central Asia represents the last link in the chain of Eurasian inland water bodies. It differs considerably from other seas in its history and size. Being relatively small in area (66,000 km^2 as of 1960) and young, it is noteworthy for dramatic fluctuations of its level, changes of salinity and environments of sedimentation. In spite of the growing interest in the Aral due to the recent environmental disaster and many papers on the subject [1], the history of its evolution is still insufficiently known. Herein we discuss the natural evolution of the Aral Sea which came to an end around 1961, when increasing human impact resulted in a dramatic sea level drop. Since then, the Aral Sea has practically ceased to exist as a single water body and historically it advanced into its latest – modern stage; that stage is considered in subsequent sections herein.

2 Historical Evolution of the Aral Sea

Two paleogeographic epochs are recognizable in the history of the Aral Sea: first, a very long (late Pliocene–Pleistocene) prehistory when the Aral depression was filled with water of the late Pliocene seas which dried up subsequently, and second, a rather short stage representing the modern existence of the Aral Sea, which lasted over the Holocene (Table 1).

2.1 Prehistory of the Aral Sea Basin

The Aral Sea prehistory dates from the late Pliocene; this was the first stage of marine water penetration into the basin. At that time the lowlands of the Aral region were flooded by the Akchagylian and Apsheronian transgressions of the Caspian Sea. The Akchagylian and Apsheronian seas existed in the Caspian basin during the Late Pliocene. They were relicts of the Eastern Parathetys ocean (Paleogene), and featured an endemic mollusk fauna. The Akchagylian Sea was connected to the ocean, while the Apsheronian basin was an isolated water body. The Aral depression came into being somewhat earlier, during the middle Pliocene [2–4]. The Aral region featured arid environments marked by intensive processes of subaerial denudation. Wind erosion of weakly cemented Neogene rock formed systems of closed deflation depressions, the largest one being located in place of the modern Aral Sea; it consisted of several basins separated by elevations [2].

During the Late Pliocene the Aral basin and adjoining lowlands were repeatedly flooded by the transgressions of the Caspian Sea forming vast marine gulfs with regimes noticeably different from the central parts of those late Pliocene seas. Periodically, when sea level dropped, they transformed into a system of isolated water bodies, some of them freshened, other saline. Lower Akchagylian sediments are found in the region at altitudes up to 140 m a.s.l., while their base varies in altitude within 60 m; the latter fact suggests a deeply dissected Pre-Akchagylian topography, and/or certain tectonic deformations of the sea floor. Judging from rather poor species composition of the Akchagylian fauna and the presence of freshwater species, the gulfs were freshened to a considerable degree by incoming river water. There are two series of salt deposits 85 m thick altogether [5]; they consist of mirabilite, sodium chloride (halite), astrakhanite, glauberite, and epsomite deposited during a regressive stage of the Akchagylian sea. As the area of the sea was dramatically reduced and salinity increased up to 100–150 g l^{-1}, mirabilite was first to precipitate; later, as salinity rose to 230–250 g l^{-1}, it was followed by halite, then astrakhanite, and finally epsomite [6]. The process of chemical sedimentation during the Akchagylian was rather short and interrupted by prolonged intervals of terrigenous deposition. During those intervals clays and silts accumulated over the larger part of the sea and sands were deposited on its periphery.

Unlike the Akchagylian sea – a typical marine basin connected to the ocean, the Apsheronian basin was a large isolated brackish-water sea. Its gulf covering the Aral region was freshened to a considerable degree as indicated by the abundance of freshwater ostracods [7], its individual parts (the Aral, Khorezmian, and Sarykamysh basins) differing noticeably in water salinity [3]. The highest stand of water level in the Sarykamysh basin was recorded at the beginning of the Apsheronian transgression (80 m a.s.l.), later it dropped to 40–50 m a.s.l., and to 0 m by the end of the period [8]. According to [9], the Syrdarya and Amudarya rivers did not reach the Aral region in the late Pliocene, the Amudarya flowed into the Central Karakum desert and the Syrdarya drained the Golodnaya ("Hungry") Steppe and Kyzylkum regions.

It may be safely concluded that the first sea water invasion into the Aral basin led to a long-term (>3 million years) existence of a marine water body distinct for its highly variable salinity and hydrodynamic regimes; the variations depended both on general dynamics of the Akchagylian and Apsheronian sea basins, as well as on changes of climate and runoff of rivers entering the Aral gulf. Undoubtedly, tectonic movements were also of importance, as they predetermined the basin origin and controlled the ways the Late Pliocene seas penetrated into it.

The regression of the Apsheronian sea was followed by a long continental period that lasted through the entire Pleistocene. During that interval, three large transgressions (Bakinian, early Khazarian, and early Khvalynian) are known to have occurred in the Caspian Sea, the water level rising as high as 40 m a.s.l. and more. The Khvalynian sea formed an estuary protruding far eastwards along the Uzboi valley; the water, however, did not penetrate into the Sarykamysh and Aral depressions where subaerial, essentially arid, environments persisted during the Pleistocene. Under those conditions, eolian processes, including wind erosion, produced a series of closed depressions on the dried bottom of the Aral Sea and sand ridges at its eastern periphery [3]. Sometimes the depressions could be filled with river water and form lakes. Freshwater deposits discovered in the Aral basin suggest the appearance of rivers and lakes there as early as the Early Pleistocene. According to [9], they persisted through the Middle Pleistocene. There is no conclusive evidence, however, that rivers flowed into the Aral basin during the Early–Middle Pleistocene. At that time the Amudarya flowed through the lower Kara Kum region into the Caspian Sea accumulating sands of the Kara Kum suite there. The Syrdarya drained the adjacent areas of the Khorezmian basin and Kyzyl-Orda trough and could occasionally reach the Aral [3]. It is a well-documented fact that in the Late Pleistocene the Central Asian rivers flowed into the Aral basin [2]. The Syrdarya was the first to flow into it, while the Amudarya turned to the north at the very end of the Late Pleistocene, the majority of its runoff being directed to the Sarykamysh depression and further via the Uzboi channel into the Khvalynian (Caspian) Sea. It was not before the Holocene that a river water inflow into the Aral basin became steady; that resulted in the appearance of the sea by the Middle Holocene.

2.2 History of the Aral Sea

Two stages are distinguishable in the evolution of the Aral Sea, namely lacustrine-solonchak and marine stages [10] (see Table 1).

The *lacustrine-solonchak stage* is dated to the beginning of the Holocene. The lower limit of its age is drawn at the top of the Upper Pleistocene layers, while the upper one corresponds to the time of *Cerastoderma glaucum* (*Cardium edule*) mollusk penetration into the Aral Sea (about 5 ka BP). An analysis of the bottom

Table 1 Paleogeographical scheme of the Aral Sea

AGE		Systematics of events: Epoch	Systematics of events: Stage	Systematics of events: Transgressive stage	Transgressive (t) and regressive (r) rhytms		^{14}C dats (years)	Sea-level (abs. h., m)	Salinity, ‰	Paleogeographical situation
HOLOCENE	Late	Marine Aral Sea	Marine	recent	T			53	11.3	Inland freshened sea with sharp sea-level oscillations and salinity changes, during regression fragments info a system of salt and freshwater lakes, terrigenous and chemical sedimentation
					P		MGU 734 970±140	43–44		
				late	T			53–53.5	~8–12	
					P	max	MGU 778 1590±140	до 30		
				middle	T			54.5	~8–9	
					P		MGU 742 3600±140	35–40		
				early	T P T	max	MGU 741 4850±90	under 57	~11.3	Penetration and settling *Cerastoderma glaucum* (*Cardium edule*)
	Early		Lacustrine-solonchak				MGU 740 4960±100			System of periodically draining lakes. Active salt accumulation.
PLEISTOCENE	900 thousand	Pre-history	Terrestrial							Drainage, Holocene subaerieal processes
LATE PLIOCENE			Marine: Apsheronian							Freshened bay of a big inland brackishwater basin
	3.0 mln.		Marine: Akchagylian							Freshened bay of a big marine basin connected to the ocean

sediment sequence in the central part of the Aral Sea suggests environments with numerous lakes of varying salinity in topographic depressions; occasionally they dried up and turned into solonchaks. The deposits of that stage contain gypsum and shells of ultra-euryhaline and freshwater mollusks indicative of an unstable sedimentation regime and drastic changes of salinity in periodically drying-up water bodies [10].

The *marine stage of the Aral Sea* was of short duration (late Holocene) and marked by a rather complicated pattern in natural processes. That is especially true in regard to wide fluctuations of the sea level, its salinity, environments, and type of sedimentation.

The sediments attributable to the lacustrine-solonchak stage grade without a noticeable gap into those of the marine stage which are similar to the underlying series in texture and composition. They are different, however, in that interlayers of chemical sediments become less common upwards and *Cerastoderma* shells appear. To date it has not been fully explained how the mollusk could migrate from the Black Sea to the Caspian and later to the Aral Sea. In the mid-Holocene it appeared in the Caspian Sea, which had no visible connection with the Azov–Black Sea basin at that time. It seems that the event took place not at the beginning of the New Caspian transgression (contrary to the opinion of many specialists), but somewhat later. About 5.0–4.5 ka BP *Cerastoderma* penetrated into the Aral Sea in the same (still unexplained) way [11]. It seems most likely that the mollusks during their larval stage could be carried by waterfowl during seasonal migrations. It is also known that *Cardium* larvae may persist for a rather long time under unfavorable conditions, including freshened or increasingly saline water habitats. The appearance and colonization of *C. glaucum* (*C. edule*) in the Aral Sea suggest that the salinity was favorable for acclimatization of the mollusk as early as the Middle Holocene.

The Aral Sea level underwent dramatic changes. On the basis of altitudes of marine terraces on the coasts and submarine constructional forms, as well as on the composition of bottom sediments [12] and palynological data [13], there may be distinguished four stages of high sea level separated by three intervals of low stands [14], the range of sea level changes being equal to or exceeding 20 m. The lithology of the marine sedimentary sequence containing *Cerastoderma* allows one to identify five transgressive–regressive stages (rhythms) [12]. The oxygen isotope analysis of carbonates in the Aral mollusk shells revealed even more rhythms (Fig. 1) [15]. During transgressions, when the sea level reached 58 m a.s.l. or higher, fine silts and clays were deposited over the basin except for the coastal zone where sediments were dominated by sand and gravel. The water salinity did not exceed 10‰ anywhere, and euryhaline brackish water and freshwater mollusks and ostracods became widespread. Marine erosion was active along the coasts, with traces of active coastal destruction found at 56–57 m a.s.l. [14]. During intervals of stabilized sea level, large constructional landforms were formed on low coasts.

During regressive epochs (coinciding with intervals of hot arid climate) the level of the Aral dropped by 20 m and more. The sea grew shallow and broke into separate highly mineralized lakes (with salinity 100‰ and more), or into freshened shallow areas (“plavni”). Regressive sediments are highly diversified in lithology. Most often they are of sand and silt composition with chemical deposits (gypsum, mirabilite, etc.) and lenses of shell debris (coquina). Worth mentioning is the

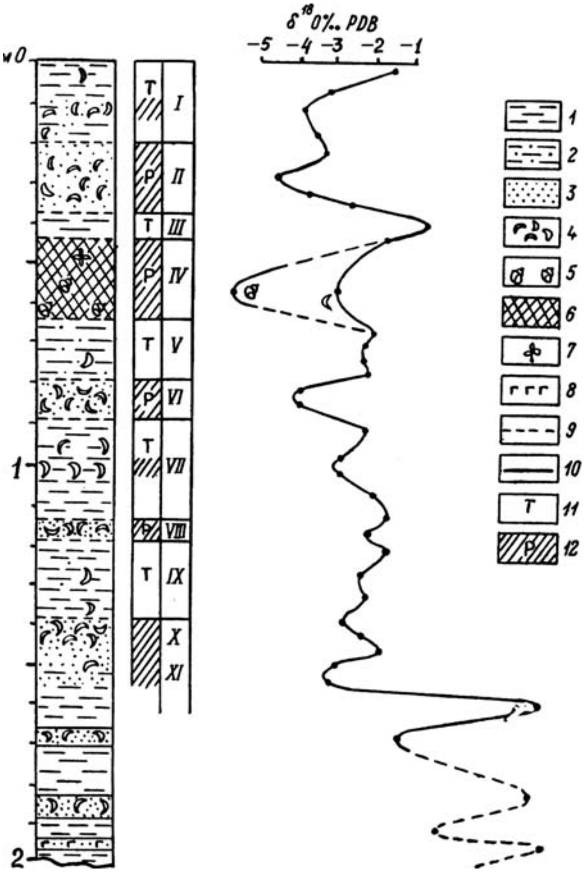


Fig. 1 The oxygen isotopic composition of carbonate mollusk shells from the Aral Sea [15]. (1) clayey mud; (2) clayey–silty mud; (3) sand; (4) marine shell debris; (5) freshwater shell debris; (6) peat; (7) plant debris; (8) gypsum; (9–10) boundaries [(9) gradual; (10) sharp)]; (11–12) stages [(11) transgressive; (12) regressive)]

presence of peat layers. One of them is found in the central part of the Aral depression; it appeared to abound with freshwater mollusk shells (*Armiger*, *Limnaea*, *Anisis*, *Planorbis*, and others) and dated to the maximum regressive stage of the Aral Sea. The sea level at that time dropped to 30–32 m a.s.l., its central depression presented freshened (to a few per mille [10]) shallow water extending far southwards (Fig. 2). At that time chemogenic deposits actively accumulated in the isolated Little Sea, and solonchak landscapes dominated in the coastal regions. At present the dry bottom of the Aral Sea is exposed to subaerial processes similar to those of the past, when the sea level declined; so, the present-day situation offers a clue to environments of the past (Holocene) regressive phases. The latter were marked by an active development of deflation depressions, sors and solonchaks, saline wetlands and large massifs of barkhan

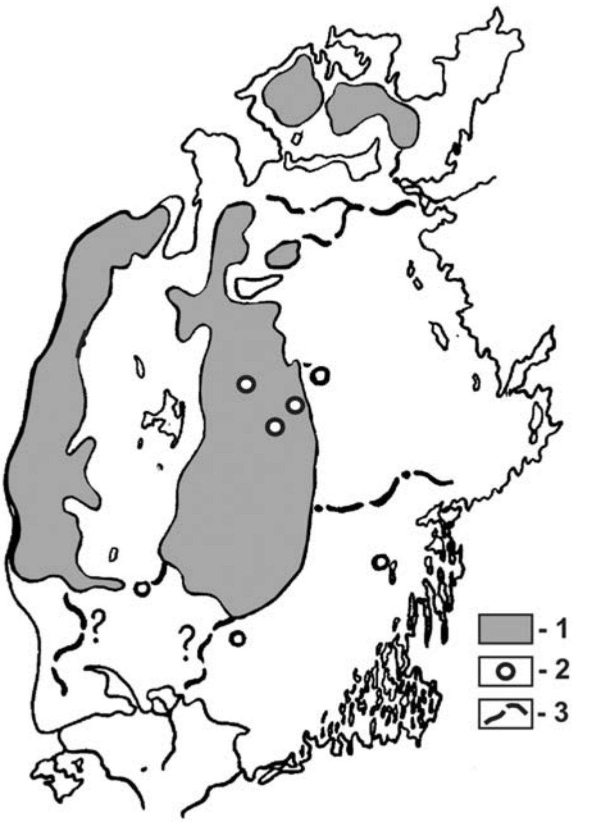


Fig. 2 Paleogeographical scheme of the Aral Sea during regressive lowstand (~1,600 years BP [15]). (1) Basin limits; (2) sediment cores subject to oxygen isotope studies; (3) paleoriver channels

sands. Along with general deterioration of climate, it became dryer and more contrasting, dust storms and dry hot winds gained in frequency. The storms carried silt and salts (sulfates and chlorides) from the dry sea floor onto coastal regions, which resulted in soil salinization.

On the whole, three large transgressive stages separated by regressions have been recognized within the marine Holocene of the Aral Sea [3, 9, 14, 16].

The earliest stage (known as Old Aralian according to [10] and Early Aralian according to [16]) was the longest (from ~4.9 to 3.6 ka BP), with the sea level as high as 56–57 m a.s.l. and salinity close to that of today (before 1961).

The middle stage (Aralian by [10], Old Aralian by [16]) with sea level at 54.5 m [16], and salinity as low as 8–9‰ [10], is dated to the 3.0–1.6 ka BP interval. The low salinity accounts for generally impoverished species composition of mollusks and increasing proportion of euryhaline species (*Hypanis minima*, *Theodoxus pallasi*, and others).

During the late (New Aralian) stage (1.5–1.0 ka BP) the sea level rose to 53.0–53.5 m a.s.l. Mollusk fauna was dominated by brackish-water species indicative of salinity between 8 and 12‰ (*T. pallasi*, *T. zhykovi*, *Pyrgulla conica*, *H. minima*) [10].

The listed transgressive stages of the Aral Sea alternated with regressions, their radiocarbon age (year BP) and sea level altitudes being defined as follows: 3,610 ± 140, ~40–35 m a.s.l.; 1,590 ± 140, ~40–41 m; 970 ± 140, ~ 43–44 m [12].

As indicated by palynological data, the transgressive stages in the history of the Aral featured a noticeably wetter climate. This is suggested by a higher proportion of grass pollen in the NAP group and of fern among spores, by the presence of aquatic and riparian plants, together with a perceptible participation of arboreal pollen. There is also a distinct tendency for a decrease of climate humidity from older stages to younger ones. In the course of the last few thousand years the annual rainfall amount varied between 100 and 150–200 mm [13].

Considerable fluctuations of the level and salinity of the Aral marine basin may be inferred from diatom data. Transgressive marine sediments typically abound in brackish-water species (87%), such as *Thalassiosira*, *Actinocyclus*, *Cyclotella*, *Navicula*, *Diploneis* [17], while freshwater diatoms (*Fragilaria*, *Eunotia*, *Cymbella*, and others) are present copiously in the regressive marine sediments.

As the Aral Sea is a receiving basin for the largest rivers of central Asia – the Amudarya and Syrdarya rivers, its origin and evolution were to a considerable degree controlled by the regime of those two rivers. The rivers themselves developed since the end of the Paleogene under conditions of active tectonic uplift in their upper reaches. During the Pliocene and Pleistocene the rivers' catchment areas were repeatedly subjected to alpine glaciations, while pluvial and arid phases alternated in the middle and lower reaches of the rivers [18]. A characteristic feature of the river regime was repeated changes of flow direction. This could be attributed to a number of factors, the most important of which were the great volumes of bedload sediments. The latter could occasionally block river channels and force the river to migrate over the Central Asian deserts in search of new paths. We can estimate the amount of bedload sediment on the basis of annual input into the Aral Sea before 1961: 94.3 million tons came from the Amudarya, and 32.2 million tons – from the Syrdarya [9].

The river water inflow to the Aral Sea became noticeable from the Late Pleistocene, when the Syrdarya began to flow to the southeastern part of the Aral depression through the Zhanadarya channel. The Amudarya was still flowing to the Khorezmian lake at that time; after the lake had been filled it turned westward and flowed into the Sarykamysh depression. As the water level rose to +58 m a.s.l. the water began to flow through the Uzboi channel into the Caspian Sea (at the time of the Khvalynian transgression). During the existence of the lake in the Sarykamysh depression, part of the Amudarya flow was occasionally diverted towards the Aral basin via the Akchadarya channel; it was not until the beginning of the Holocene that the main part of the river water began to flow steadily into the Aral. At first, when the basin was constantly fed by the Syrdarya only, there existed only some highly mineralized lakes in the central and western parts of the Aral basin. A continuous inflow of the Amudarya water into the Aral basin (by way of the Akchadarya delta) resulted in a young sea coming into being and persisting until recently; according to [19], its appearance took place in the second to beginning of the first millennium BC, the radiocarbon dates [9] put it at about 4.5 ka BP.

The history of early people in the Aral region was closely related to the Amudarya and Syrdarya river systems. Monuments of ancient material cultures have been found in abundance on the Aral Sea coasts. There are numerous campsites of early man, as well as ruins of buildings dated to classical antiquity or to the medieval period found along the tributaries and lakes in the Amudarya and Syrdarya deltas. The oldest monuments are camps of Neolithic hunters and fishermen located on the periphery of the Sarykamysh delta of the Amudarya. In the fourth and third millennia BC early man was willingly settling down on sands around the Akchadarya delta and on slopes of adjoining uplands. Numerous campsites of the Kelteminar culture found along the coastline attributed to the maximum transgression of the Aral Sea (ancient Aral, according to [11]) enable us to date the epoch at the third millennium BC.

At the time of high standing sea level the early inhabitants of the area began to practice irrigated agriculture in the river deltas [19]. Construction of irrigation systems in the Amudarya delta noticeably intensified in the sixth to fifth centuries BC, with development of a slave state in Khorezm, and reached its fullest development in the first centuries of the New Era. A network of canals and dams covered an area of 3.5–3.8 million ha in the Aral region. About 1,500–1,600 years BC the sea level dropped to 30 m a.s.l., which resulted in decay of irrigated farming. A new expansion of irrigation system construction occurred in the seventh to eighth centuries and continued until the Mongolian invasion and conquest of Khorezm by Tamerlan. Protective dams in the Amudarya delta were destroyed, the river was diverted again to the Sarykamysh depression, and the water began to flow to the Caspian Sea via the Uzboi channel. The entire volume of Amudarya water began to enter the Aral Sea again by the early eighteenth century; the Sarykamysh lake dried up and its bottom became a solonchak desert.

3 Geological Setting

3.1 Structural Setting

The Aral Sea is positioned in the zone where geological structures of the Urals join those of Tien-Shan. The Aral depression is bordered on the west by Precambrian crystalline basement, and on the northeast – by the Central Kazakhstan massif [9]. Pre-Mesozoic rocks are highly metamorphosed, heavily distorted and broken by faults into mosaic block systems of varying altitudes.

The sedimentary cover is stratified and consists mostly of calcareous–terrigenous rocks of Mesozoic and Cenozoic age up to 3–4 km thick. They form gentle folds broken by faults. There are three elevated structures within the Aral basin, namely the Aral-Kyzylkum swell (Arkhangelsky's swell), Central Aral and East Aral rises; all of them are quite distinctly pronounced in the sea floor morphology.

3.2 Stratigraphy of the Upper Pliocene and Quaternary Sequences

In the Aral basin the upper Pliocene (Akchagylian and Apsheronian) and Quaternary (Holocene) sequences are represented mostly by marine sediments.

There are only a few outcrops of Akchagylian and Apsheronian series in the coastal scarps of the Aral Sea, the sediments are better known from adjacent areas. Marls, clays, silts, quartz sands and sandstones of the Kushkanataus suite are found at the base of Akchagylian sediments; they are overlain by sandstones and clayey–silty sediments of the Denchizkul suite [9]. On the southern Aral coasts there are sediments attributed to the Zair suite (Late Akchagylian) – gray and greenish-gray clays and silts with interlayers of sands and sandstones. The Akchagylian sediments described in the Amydarya delta region contain mollusk shells determined as *Avimactra subcaspia*, *Potamidus caspinus*, and *Clessiniola polejevi* [3].

At the base of Apsheronian sediments there are gray and gray–yellow sands and sandstones of the Sadyvar suite [20]. The major part of the Apsheronian sequence consists of silts and clays, though detrital limestones are found in the Little Sea and on Lazarev Island, and calcareous conglomerates – in the Sarykamysh depression. Brackish-water mollusks (*Cythereis pseudoconvexa*, *Cythere variabietuberculata*) and freshwater ostracods (*Limnocythere tenuireticulata*) have been found in Apsheronian sands and soft sandstones in the Amudarya lower reaches [7]. Apsheronian sands and clays with *Dreissena* and *Adacna* shells are found on the northern coasts of the Aral at 54–62 m altitude [9]. Total thickness of the upper Pliocene series is up to 500 m.

No reliably dated sediments of Early and Middle Quaternary age are known as yet in the Aral region. Lacustrine variegated clays and silts are believed to have accumulated at that time within the Aral and Sarykamysh depressions, along the Ustyurt scarps ("chinks") and at the modern delta of the Amudarya [7].

The upper Quaternary (the end of the Late Pleistocene) and Holocene deposits occur widely over the Aral basin. They have been penetrated by wells and described in the coastal scarps. In spite of various factual material obtained, there is still no consensus among geologists on its interpretation, and there are still discrepancies between the suggested stratigraphic schemes [6, 10, 14, 16].

The upper Quaternary and Holocene sediments of the Aral Sea may be roughly divided into two series. The lower one found in the cores of the central Aral basin (Fig. 3) was tentatively determined as continental formations of the final Late Pleistocene. It is composed of chocolate clays overlain by sands, its total thickness exceeding 1.5 m. The pollen spectra recovered from the bottom sediments

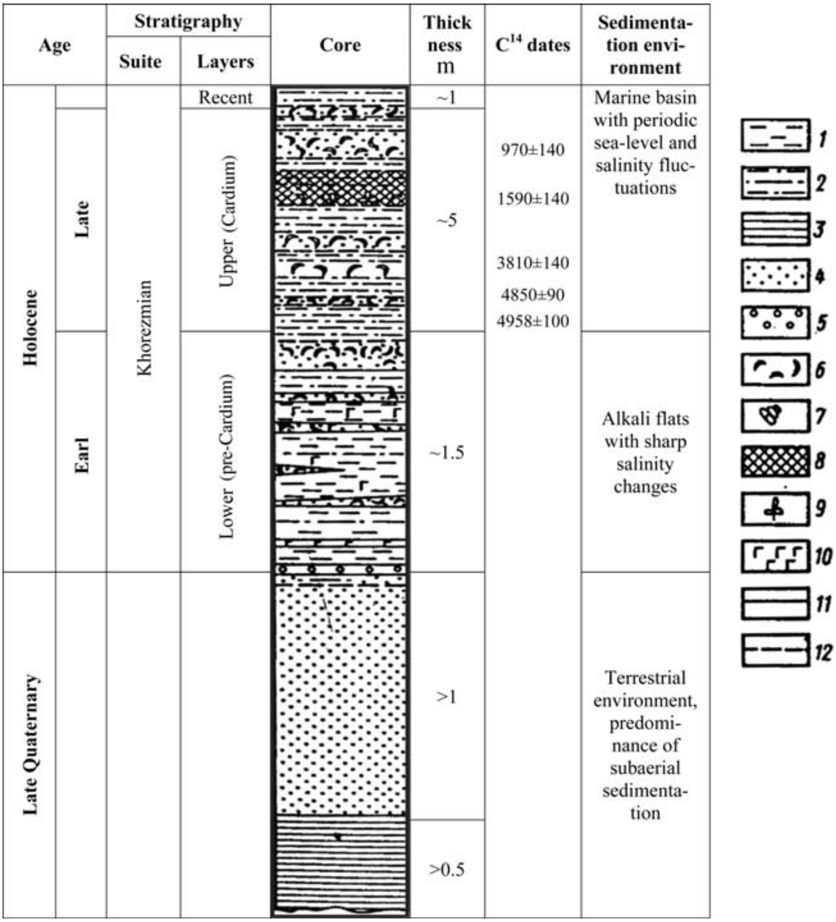


Fig. 3 Stratigraphic scheme of the upper Quaternary and Holocene deposits of the Aral Sea (according to [16]). (1) Clayey mud; (2) silty–clayey mud; (3) clay; (4) sand; (5) rubble; (6) marine shell debris; (7) freshwater shell debris; (8) peat; (9) plant debris; (10) gypsum; (11) sharp contacts; (12) gradual contacts

(Paskevich series) contain abundant spores of true mosses (*Bryales*) indicative of late glacial age [14]. Such a suggestion, however, is disproved by the presence of *C. glaucum* (*C. edule*) shells.

The upper series attributed to the Holocene in its lower part consists of diversified lacustrine sediments (pre-*Cardium* layers) – interstratified layers of clayey and silty mud, poorly sorted sands, shell debris, and gypsum. There are shells of euryhaline (*Caspiohydrobia* ex gr. *grimmi courica*) and freshwater (*Dreissena polymorpha*) mollusks in the series. Their presence permits us to assign the sediments to the lacustrine-solonchak stage of the evolution of the Aral [15]. On the basis of stratigraphic setting the series is dated to Early Holocene.

In the uppermost part of the Holocene series there are marine sediments of various lithology and facies composition. They are 5 m thick (or more) and marked by two characteristic features: first, an abundance of bivalve mollusk shells *C. glaucum* (*C. edule*) and, second, alternating layers of different lithology belonging to transgressive and regressive stages of the Aral.

Besides *Cerastoderma*, 13 more species of brackish water and freshwater mollusks have been recovered from the upper part of the Holocene sequence, as well as various foraminifera, numerous diatoms, spores and pollen [13, 17].

A distinctive characteristic of the marine Holocene lithology is thin bedding, with alternating beds different in substance and size of grains; they reflect fluctuations of the sea level and changes of its salinity. The layers formed at high stands are typically muddy or silty–clayey in composition, and contain only rare shells of marine or freshwater mollusks. Sediments of regressive phases are highly diversified in composition and structure. They are coarser, most often sandy, with interlayers and lenses of shell debris, often enriched in plant remains, occasionally with peat; also present are interbeds of gypsum and carbonates of chemical and terrigenous origin. The sediments show a considerable variability of facies over the area indicative of spatial variations in depositional environments during the Holocene. This is clearly visible when comparing different parts of the basin, such as the Little Sea, northern bays, relatively deep troughs in the west and in the central part, eastern shallows and delta areas of the Amudarya and Syrdarya rivers [8]; in most cases sandy littoral formations give way to fine clayey and silty deposits within a short distance.

Plant remains and mollusk shells from marine Holocene layers in the central depression (layers containing *Cerastoderma*, station 15) have been dated by radiocarbon methods [16]. The results provided evidence of marine sedimentation being confined to the second half of the Holocene and permitted us to date some large regressive phases in the history of the Aral. Other studies have been performed in the central basin, including oxygen isotope analysis of carbonates in mollusk shells [15] (see Fig. 1); in this way it was possible to reconstruct the rhythmicity of the Holocene transgressive and regressive sediments in greater detail.

The recent marine sediments have been studied comprehensively enough [10, 21, 22 and others]. They are highly variable in their lithology and facies, including sands, silts, clayey–calcareous mud, with admixtures of shell debris and plant remains in varying proportions (Fig. 4). Genetically, they may be classified as terrigenous, chemical, and biogenic formations. The terrigenous material is mainly supplied by the rivers and marine erosion (abrasion) of the coasts. Before 1961, the yearly solid runoff from the Amudarya amounted to ~74 million tons, that of the Syrdarya – ~8 million tons, while coastal abrasion produced about 7 million tons. Input of eolian dust is estimated at 22 million tons per year, and biogenic material adds more than 5 million tons. Chemical sedimentation was rather active and produced more than 13 million tons per year [10]. Spatial distribution of the recent sediments is controlled by sea floor morphology, coastline configuration, and hydrodynamic regime of the water body. Sands prevailing in the nearshore zone give way to silts with distance from the coast and are replaced by silty–clayey mud

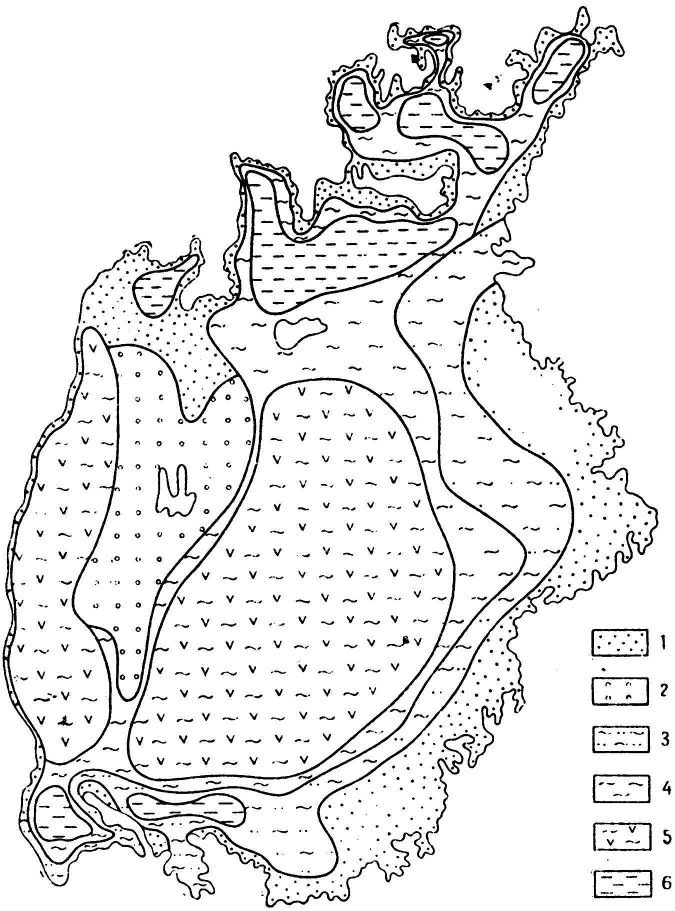


Fig. 4 Scheme of the bottom sediments of the Aral Sea [10]. (1) Sand; (2) oolitic–calcareous sand; (3) coarse silt; (4) fine silt; (5) clayey–calcareous mud; (6) deltaic clayey mud of the northern bays and small Sea

in depressions of the floor. Terrigenous deposits are dominant near the Amudarya and Syrdarya mouths, in the northern bays and within the Little Sea [22].

Bottom sediments in the depressions of the Aral Sea are clayey–calcareous mud – a homogeneous mineral mass enriched with diatoms frustules, with inclusions of hydrotroilite and pyrite. There are areas of oolitic calcareous sands along the eastern sea coast.

The recent sediments of the Aral Sea yielded pollen and spores, diatom algae, foraminifers, and ostracods. Mollusk shells are found in abundance, especially those of *C. glaucum*, *D. polymorpha*, *Dreisssena caspia*, *T. pallasi*, *Hydrobia pusilla*, and *Adacna minima*.

From the stratigraphic point of view, the Holocene formations of the Aral Sea and its coasts form a single series of continental and marine layers similar in structure to each other; it is identified as the Khorezmian suite (after the ancient name of the Aral Sea – Khorezmian) [23]. The suite is subdivided into three units. The lower one (pre-Cardium layers [16]) is represented by stratified lacustrine-solonchak deposits dated to the Early Holocene. The middle unit is composed of essentially marine sediments with *Cerastoderma* shells; the sediments are distinguished by alternating layers different in lithology and corresponding to different stands of the sea level. Radiocarbon dates enable us to date the layers to the second half of the Holocene. The third layer is formed by recent marine sediments of insignificant thickness accumulated during the few last centuries.

4 Topography of the Sea Bottom and Coasts

The modern landforms of the sea bottom and coasts resulted from a joint action of arid erosion, marine, lacustrine, and fluvial processes, as well as tectonics.

4.1 Topography of the Aral Depression

The Aral Sea bottom topography is rather irregular, showing distinct asymmetry (Fig. 5). It is most shallow in its southern part and deepest in the west. The Central depression (the so-called Major Sea) is rather shallow on the whole (about 10–20 m). Its eastern – shallow-water – portion deepens westwards to the central deep. A chain of small islands borders it on the west; structurally it corresponds to a large tectonic uplift trending from south to north (Arkhangelsky's swell). The maximum depths are confined to a deep trough in the west, close to the Ustyurt scarp. As for the bottom relief formation, deposition distinctly prevailed over erosion. Various constructional landforms occur all over the sea bottom, while abrasion landforms are mostly found along steeper western and northern coasts of the Aral. Another distinctive feature of the sea floor morphology is that relict subaerial landforms are usually well preserved and only slightly modified by marine processes [20].

4.2 Morphology of Coasts

The coastline of the Aral Sea was first described by Berg [24]. Before 1961, its total length amounted to 3,420 km. The northern coast is elevated, irregular in outline, with deep bays alternating with large headlands. The western coast adjoining the Ustyurt scarps is straight, precipitous, with a few open bights.

The eastern coast is low and sandy, with small sinuous inlets. The southern coast is of complicated structure, graded sandy segments alternating with protruding fans of individual deltaic channels in the Amudarya delta.

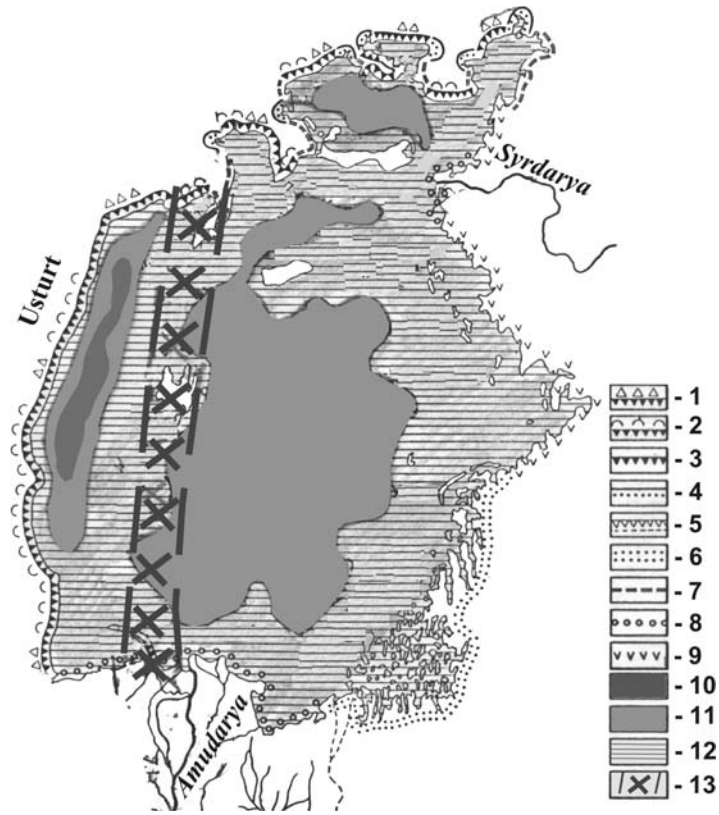


Fig. 5 Coastal and bottom topography of the Aral Sea (according to [2, 24, 25]). Types of coasts: (1) abrasion–denudation coasts; (2) abrasion coasts with slumps; (3) graded abrasion coasts; (4) embayed coasts with accumulative landforms; (5) graded complex coasts; (6) embayed ingression coasts; (7) graded accumulative coasts; (8) deltaic coasts; (9) reed coasts; (10) near-shore shallow (0–20 m); (11) central depression (20–40 m); (12) central deep (40–68 m); (13) submarine ridge (Arkhangel'skii Ridge)

Genetically, the Aralian coasts may be classified into three types, namely, abrasion coasts (modeled by marine erosion), depositional and abrasion-depositional ones [25]. Coasts of the first type (abrasion) are most common at the western, northern and part of the southern margins of the sea. They are built of compact calcareous marls and sandy–clayey Paleogene and Neogene rocks. Typically, they form high (up to 200 m) abrasion cliffs with wave-cut notches and a narrow strip of sandy beach. In areas where loose rocks occur, coasts are rather low, with a shallow notch and broader beach. There exist varieties of abrasion coasts, such as abrasion–denudation ones and abrasion coasts with slumps, with material from screes, rockfalls, and slumps present in the nearshore zone in abundance.

Abrasion-depositional coasts form a transitional type; they are widely distributed at the northern and south-eastern margins of the sea. They are distinct because of a wide occurrence of bights and bays with shores composed of Paleogene and Neogene sands and clays. Abandoned cliffs in bays are often fringed by constructional sandy terraces. Abraded headlands between the bays serve as the main source of sediments which form various constructional landforms in the bays.

The south-eastern coast of the Aral Sea bears distinct traces of eolian landforms inundated by the sea (Aralian type, according to [24]; under natural conditions, it resembled a cluster of low wave-eroded islets alternating with lagoons (limans).

Deposition (aggradational) coasts are the most common type occurring at the southern and eastern margins of the Aral. They are usually low (1.0–1.5 m), and built of loose marine and fluvial deposits (quartz sands with shell debris). The lowest parts are flooded and form channels between the low islets, locally bearing eolian dunes.

Since 1961, the shallowing of the Aral Sea noticeably changed its outlines, especially in the east, south-east, and south. Some shallow bays and inlets dried up, new islets appeared in place of low banks, while older islands became part of the desert land. In its rear part the emerged sea floor became covered with saxaul (*Haloxylon*), tamarisk, saltwort; some massifs of wind-blown sands appeared. There are zones of terrigenous, calcareous, and gypsum soils distinguished on the former sea floor [2].

4.3 Terraces of the Aral Sea

There are old marine terraces traced locally on the sea coasts indicative of a higher sea level in the past. Berg [24] was the first to identify them at altitudes of around 54.0 a.s.l. Some *Cerastoderma* shells were recovered from their sediments. Later Yanshin [26] established that terrace sediments with shells of this mollusk occur at 62.0–64.0 m altitudes and even higher (up to 72.0 m); he explained it by young tectonic uplifts. Later, many investigators described the terraces [3, 14, 16, 25, 27]. The terraces vary between altitudes of 54–80 m and usually contain *C. glaucum* shells.

Most specialists recognize with confidence two Holocene terraces in the Aral coastal regions. The lower one (termed Aral-Caspian by [24] and New Aralian by [25]) has been found in many places on the western, northern, and eastern coasts at 54–55 m a.s.l. It bears a thin sedimentary cover of sand and gravel with shell debris. Some unbroken mollusk shells are also present, including abundant *C. glaucum* and less common *Dreissena caspia*, *D. polymorpha*, *T. pallasi*, *Hydrobia ventrosa*, and *Micromelania elegant* [27]. On the eastern coast the terrace is composed of light-blue marl loam abounding with *Cerastoderma* and *Caspia* shells. The terrace is dated from the middle of the first millennia BC to the twelfth to beginning of the thirteenth centuries AD [10]. Mollusk shells from the terrace sediments were radiocarbon dated to 920 ± 120 [21] and 2,860 ± 80 [14].

The higher (Old Aralian by [26]) terrace found at altitudes of 58–60 m and more occurs more rarely than the lower one. It has been established with certainty on the south-eastern, south-western, and north-eastern coasts of the Major Sea as well as on the Little Sea coasts. In sections on the north-eastern coast the terrace sedimentary cover is up to 7 m thick. The sediments are mostly sands with gravel and pebbles, with occasional silty interlayers; they contain shells of *C. glaucum*, *D. polymorpha*, and *Monodacna* sp. [27]. On the basis of archeological monuments, A.L. Yanshin estimated the terrace's age at five thousand years. Later, using geomorphological and archeological data [3] it was dated to 2.5 ka BP.

On the Aral coasts there are fragments of a higher terrace (Aral-Sarykamysh, according to [27]) at 68–72 m, though not all specialists agree on the subject [3, 16]. Some *C. glaucum* shells recovered from the terrace seem to rule out its pre-Holocene age.

Evidence of regressive phases of the basin has been found on the Aral Sea bottom – submerged beach ridges composed of sands with *Cerastoderma* shells [14]. They occur at depths of 43.0–44.5, 40–41, and 35–36 m and may be dated to the Late Holocene on the basis of the presence of *C. glaucum*.

5 Conclusions

In the evolution of the Aral Sea there may be distinguished two marine stages (see Table 1) separated by a long continental interval that lasted through the entire Pleistocene. During that interval the sea disappeared and subaerial processes were active on its dry floor. The first marine stage (the Aral Sea prehistory) lasted from the Late Pliocene up to the Pleistocene. The depression was already in existence and in the Late Pliocene was subsequently flooded by Akchagylian and Apsheronian transgressions of the Caspian Sea forming vast marine bays with essentially freshened water.

The second stage was rather short and limited to the Holocene. At its initial phase (lacustrine-solonchak) the Aral Sea basin was occupied by a system of water bodies with variable salinity; time and again they dried up and turned into solonchaks. Since the mid-Holocene, a dramatic increase in the volume of water entering the sea due to the Amudarya turning to the Aral resulted in the basin being filled with water. In this way a brackish-water marine basin was formed and populated by *C. glaucum*. The sea basin itself was repeatedly subjected to fluctuations of various duration and range (up to 20 m). The most pronounced high stands of the sea marked by terraces are known as Old Aralian, Aralian, and New Aralian transgressions.

The marine Aral stage was distinguished by noticeable variations of salinity (from a few to tens of per mille) inferred from the lithology and isotopic composition of sediments and species of fossil flora and fauna (mollusks, ostracods, foraminifers, diatom algae). Sedimentary layers associated with the sea transgressions consist mostly of silts and clays and contain relatively poor assemblages of freshwater and brackish-water mollusks. Regressive layers are more diversified in composition; they are primarily terrigenous, with abundant chemical (gypsum and other salts) and calcareous inclusions indicative of the sea level dropping and the single basin being broken down into smaller supersaline or fresh water bodies.

The bottom sedimentary sequences show as many as five and more transgressive–regressive stages of different duration; this hampers their direct correlation with the existing notion of long-term variability of moisture supply on continents [19].

The Holocene history of the Aral Sea marked by dramatic level fluctuations, diversified composition of bottom sediments and fossil faunal assemblages has been undoubtedly controlled by a number of climatic, hydrological, tectonic factors, as well as by human impact. The tectonic influence is seen in deformations of terraces and the sea floor topography. The anthropogenic factor is of primary significance for the modern environmental degradation; in the past, it exerted some influence on redistribution of the river water input and was significant, though not crucial. Hydrological [2, 5, 28] and climatic [10, 14] factors were of much more importance.

Hydrological factors – that is, inflow of water from the Syrdarya and Amudarya – played the major part in the flooding of the Aral depression, in origination and subsistence of a freshened marine basin there. This process dates back to the very beginning of the second half of the Holocene, when the Amudarya river, having formed the Sarykamysh and Akchadarya deltas turned to the north, forced its way to the Aral and began to fill the depression formerly occupied by a number of lakes [5]. Climate controlled the river runoff and, above all, evaporation from the water surface, which was the main control on water loss; rhythmicity of the sea level fluctuations primarily depended on changes in evaporation from the water area.

The natural evolution of the Aral Sea, which started about 4,800 years ago, has undergone dramatic changes in the course of the last near to half a century due to shrinkage of the marine basin and decay since 1960; that date marks the beginning of the new – Anthropogene – stage.

References

1 Nihoul JCJ, Kosarev AN, Kostianoy AG, Zonn IS (eds) (2002) The Aral Sea: selected bibliography. Noosphere, Moscow
2 Maev EG (2000) Vestnik Moskovskogo Universiteta. Geography 2:57–62 (in Russian)
3 Kes AG (1969) Problems of the Aral Sea. Nauka, Moscow, pp 160–172 (in Russian)
4 Kleiner YuM, Kravchuk VN (1966) Izvestiya VUZ. Geol Prospect 19:45–57 (in Russian)
5 Gramm MN (1958) Doklady AN SSSR 120(1):859–862 (in Russian)
6 Rubanov IV (1980) In: Andrianov BV, Zorin LV, Nikolaeva RV (eds) Fluctuations of moisture supply in the Aral-Caspian region during the Holocene. Nauka, Moscow, pp 204–209 (in Russian)
7 Pinkhasov BI (1984) Neogene-quaternary sediments and neotectonics of the Southern Aral region and Western Kyzylkum desert. Fan, Tashkent, 115 p (in Russian)
8 Eberzin AG (1956) Proceedings of the Institute of Geology. Turkmenian Academy of Sciences, 1, Ashkhabad, 150 p (in Russian)
9 Rubanov IV, Ishniyazov DP, Baskakova MA, Chistyakov PA (1987) Geology of the Aral Sea. Fan, Tashkent, 247 p (in Russian)

10 Khrustalev YuP, Reznikov SA, Turovsky DS (1977) Lithology and geochemistry of bottom sediments of the Aral Sea. Rostov-na-Donu, Izd. RGU, 154 p (in Russian)
11 Kiryukhin LG, Kravchuk VP, Fedorov PV (1960) Izvestiya AN SSSR. Geography 1:68–72 (in Russian)
12 Maev EG, Mayeva SA, Nikolaev SD, et al (1983) In: Paleogeography of the Caspian and Aral Seas in the Cenozoic, vol 2. Moscow University Press, Moscow, pp 133–143 (in Russian)
13 Vronsky VA (1975) In: History of lakes and inland seas of the arid zone, vol 4. Nauka, Leningrad, pp 64–68 (in Russian)
14 Veinbergs IG, Ulst VG, Roze VK (1972) Voprosy Chetvertichnoi Geologii 2:69–89 (in Russian)
15 Nikolaev SD (1995) Isotope paleogeography of Inland Seas. VNIRO, Moscow, 125 p (in Russian)
16 Maev EG, Mayeva SA, Nikolaev SD, et al (1983) Cenozoic sediment sequence of the Aral Sea. In: Paleogeography of the Caspian and Aral Seas in the Cenozoic, vol 2. pp 119–132 (in Russian)
17 Aleshinskaya ZV (1991) In: History of lakes Sevan, Issyk-Kul, Balkhash, Zaisan, and Aral. Nauka, Leningrad, pp 243–245 (in Russian)
18 Kes AS, Andrianov VV, Itina MA (1980) Fluctuations of moisture supply in the Arak-Caspian region during the Holocene. Nauka, Moscow, pp 185–197 (in Russian)
19 Shnitnikov AV (1983) Paleogeography of the Caspian and Aral Seas in the Cenozoic, vol 2. Moscow University Press, Moscow, pp 106–118 (in Russian)
20 Vishnyakov AS (1978) Geology of ground waters in Neogene sediments on the palins of Uzbekistan. Fan, Tashkent, 247 p (in Russian)
21 Maev EG, Mayeva SA (1991) History of lakes Sevan, Issyk-Kul, Balkhash, Zaisan, and Aral. Nauka, Leningrad, pp 239–242 (in Russian)
22 Brodskaya NG (1952) Proceedings of the Institute of Geological Sciences, AN SSSR, vol 115. Institute of Geological Sciences, 217 p (in Russian)
23 Zonn IS, Glantz MH (2008) The Aral encyclopedia. Mezhdunaridnye Otnosheniya, Moscow, 251 p (in Russian)
24 Berg LS (1908) The Aral Sea. Izvestiya Turkestanskogo Russkogo Geograficheskogo Obshchestva, vol 5. St-Petersburg, 580 p (in Russian)
25 Lymarev VN (1967) Coasts of the Aral Sea – an inland water body in the arid zone. Nauka, Leningrad, 252 p (in Russian)
26 Yanshin AL (1953) Geology of the Northern Caspian region. Materials on the geological setting of the USSR. Moscow, MOIP, new series, vol. 15(19) 370 p (in Russian)
27 Gorodnitskaya ML (1978) Geomorfologiya 1:46–55 (in Russian)
28 Rubanov IV (1991) History of lakes Sevan, Issyk-Kul, Balkhash, Zaisan, and Aral. Nauka, Leningrad, pp 259–267 (in Russian)

The Aral Sea Under Natural Conditions (Till 1960)

Aleksey N. Kosarev and Andrey G. Kostianoy

Abstract The main hydrological peculiarities of the Aral Sea during the natural period of its life (before 1960) are discussed based on the multiyear data of in-situ observations and scientific publications. General information on the morphometry, hydrological and meteorological characteristics, water balance, sea level, and currents of the sea is provided. The main hydrological conditions of the sea: temperature and salinity distribution, convective mixing, and deep water formation are analyzed. The section on marine chemistry includes general information on the salinity, salt content and balance, dissolved oxygen, and nutrient concentration in the Aral Sea. Distinctive features that are specific to the Aral Sea as a special water body type – a lake-sea – are presented.

Keywords Amudarya, Aral Sea, Convective mixing, Hydrochemical characteristics, Physico-geographical conditions, Sea level, Syrdarya, Water salinity, Water temperature

Contents

A.G. Kostianoy (✉)
P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, 36, Nakhimovsky Pr., Moscow 117997, Russia
e-mail: kostianoy@online.ru

A.N. Kosarev
Geographic Department, M.V. Lomonosov Moscow State University, Vorobjovy Gory, Moscow 119992, Russia

A.G. Kostianoy and A.N. Kosarev (eds.), *The Aral Sea Environment*,
Hdb Env Chem (2010) 7: 45–63, DOI 10.1007/698_2009_26,

1 Introduction

The Aral Sea being a land-locked water basin having no connection with the World Ocean is, in fact, a lake. However, it can also be referred to as a sea if we take into account its size and oceanographic conditions. Not long ago (up to the 1960s) this was a unique natural feature: blue water in the midst of yellow desert sands. River deltas and sea waters filled this area with life, the sea abounded with seiners that left the ports of Aralsk and Muinak for fishing.

The Aral Sea is often compared with the Caspian Sea. The main feature that makes them alike is their land-locked nature, their isolation from the World Ocean. However, paleogeographic studies revealed their cardinal differences both in terms of genesis and age. The Caspian is the relict of the ancient ocean Tethys and its age is about 10 million years. The Aral is approximately 2,000 times younger; it was formed only about 5,000 years ago and came into existence solely due to river flow. During several millennia the inflow of river waters into the Aral desert erosional depression, their metamophization in the course of the water–salt exchange with the atmosphere and ground waters led to the formation of a lake-sea basin having no other analogs on Earth. The evolution of the Aral was a function of geomorphological (formation of the sea depression) and hydrological (its filling with river waters) processes. Numerous migrations of the Amudarya riverbed and related intermittent watering and drying of the Sarykamysh depression and the Uzboi ancient channel played an important role in the Aral paleohistory.

The Aral Sea depression appeared due to exogenous factors, such as erosion, salt drift, and deflation (wind weathering of mountain rocks). About 2 million years ago these factors shaped its relief as well as the relief of the nearby Aral–Sarykamysh depression. The original Aral depression was much larger than the modern one and represented a system of deep (150–200 m) deflated depressions worked by wind in the Upper Pliocene time. Wind erosion was the main factor in the formation of the Aral depression and the volume of eolian drift was 15,000 km^3. Through its whole, at times very complicated, geological history the Aral changed more than once its configuration and size, was filled with water and desiccated in turns. About 15,000–20,000 years ago (in the Late Pleistocene) the Amudarya River that headed westward to the Caspian Sea turned to the north. This was the time of watering of the Aral–Sarykamysh depression and formation of the Aral Sea. From this time onwards the Aral history witnessed several major transgressions and regressions during which variation in water level ranged within dozens of meters.

And the Aral lived its natural life, practically undisturbed by man’s interference, until 1960. Because of the quasistationary regime in the Aral area a specific sea-oriented economic structure (fishing, muskrat farming, maritime transport) was established. The sea produced an alleviating effect on the climate of the nearby territories. Its mere existence was favorable for the environmental and socioeconomic situation in the region. One could hardly imagine so speedy development of dramatic events related to the Aral’s fate.

2 Physico-Geographical Conditions

The Aral Sea is located deep inside the Eurasian continent among the sandy deserts of Central Asia and Kazakhstan at altitudes several dozens of meters above the level of the World Ocean. The history of development of the Aral, and its complete isolation from the World Ocean determined the natural peculiarities of this water body that combined the features of a sea and a lake.

The Aral Sea basin extends from the Turgai plateau in the north to the mountains of Hindu Kush and Pamir–Altai in the south and southeast and from the Ustyurt plateau in the west to Central Tien-Shan in the east. The area of the basin with the Amudarya and Syrdarya River basins is about 1.83 million km^2, which exceeds many times the area of the sea proper.

The Aral was replenished by the waters of the Amudarya (3/4 from the total runoff) and Syrdarya (1/4)(in average). No other permanent water streams were found in its coastal area.

The sea had rather high and cliffy shores in the west and northwest and was low and flat in the east and south. The floor relief of the Aral Sea was rather rugged. In its western part the underwater Arkhangelsky Ridge stretched meridionally. Some of its parts rose above water forming the islands of Vozrozhdenia, Lazareva, and others. More westward of this ridge a narrow and deep trench being the deepest place in the Aral ran along the coast.

At the water level of 53.0 m above sea level the total area of the Aral together with the islands was 68,320 km^2, the maximum depth being 69 m and the average being 16.1 m. The area of the sea water surface was 66,100 km^2 and the volume of water – 1,060 km^3. The coastline length (without islands) was more than 4,430 km. The sea width along the parallel 45°N was equal to 292 km, the maximum length (along the sea midline) – 424 km. There were about 1,100 islands in the Aral with a total area of 2,235 km^2. The largest were Kokaral, Barsakelmes, and Vozrozhdenia [1].

The smaller northeastern part of the Aral Sea of about 6,000 km^2 in area was isolated to the south by Kokaral Island and was called the Small Aral Sea. Its depth did not exceed 28 m, being on the average 10–20 m. The part of the Aral Sea to the south of Kokaral Island was called the Large Aral Sea. The underwater ridge divided the Large Sea into two basins with sharply differing physico-geographical conditions. To the west of the ridge there was a narrow (about 20 km) belt of maximum sea depths (over 30 m). The eastern part of the Large Sea was occupied by an asymmetric depression with prevailing depths of 20–25 m.

A specific feature of the Aral Sea was the presence in its southeastern part of the Akpetkinsky Archipelago consisting of over 500 islands, numerous kultuks, and bays. In kultuks the depths were not more than 8 m with the prevailing depths of 2–3 m.

3 Hydrometeorology

The location of the Aral Sea being not large in size in the zone of nontropic deserts explained the sharp continentality of the climate and high seasonal variability of the hydrometeorological conditions here.

The Aral Sea warmed well during spring and summer and cooled in autumn and winter.

Weak winds blowing over a sea with shallow depths usually generate not high (to 1 m), but short and steep waves. Waves of 1–2 points prevailed in the sea. Winds blowing along the large axis of the sea sometimes generated seiches that did not attenuate for long.

The input to the Aral water balance included mostly the flow of the Amudarya and Syrdarya rivers that brought their waters into the sea as well as a small quantity of precipitation falling on the sea surface. The output part of the water balance consisted of intensive evaporation from the sea surface.

From the early twentieth century when instrumental observations were started and till the mid-1960s the water balance of the Aral Sea was quasistationary. The annual inflow of river waters (52–56 km^3) and atmospheric precipitation (8–10 km^3) managed to compensate for the evaporative water losses (62–66 km^3). Small fluctuations of the sea level around 53 m over the ocean level were observed and this level was assumed to be average over a many-year period.

The sea existed for many centuries in this natural regime and had certain contours and stable natural conditions.

During the long evolution of the enclosed Aral Sea considerable volume fluctuations of the sea level were determined. They had different periodicity: geological epochs, centuries, and shorter fluctuations that occurred due to climatic factors.

In the periodical fluctuations of the Aral water level in the recent 4,000–4,500 years climatologist Shnitnikov [2] identified three long water-abundant periods that were replaced with relatively low-water periods. Every time when the Sarykamysh depression was filled with water the flow via the now dry channel of the Uzboi River going to the Caspian Sea was appeared. The range of water level fluctuations in the Aral Sea reached 6 m.

Fluctuations in the water level of the Aral Sea during the recent 200 years were restored by Berg [3] and L’vov [4] (Fig. 1). In the late eighteenth century the water level was high – at about 53 m. Then there was a period of quick drawdown and by the early 1820s it had dropped to nearly 50 m. In the mid-nineteenth century the water level rose by approximately 2 m and by the 1880s it again dropped to 50 m. In the period from 1895 to 1905 the sea water level increased rather quickly by nearly 3 m and reached elevations close to 53 m. This water level rise in the Aral Sea at the turn of the twentieth century was the result of cyclic climatic changes in the whole Northern Hemisphere which led to gradual increases in river flow. Therefore, the range of century-wise fluctuations of the Aral Sea level was in this period about 3 m.

The instrumental observations of the Aral Sea level were started in 1911, but they became regular only from 1923. In 1950 the so-called Baltic System was adopted for the Aral Sea and the unified elevation of 51.494 m was taken as a zero in all its foot gauges [1]. From the long-term fluctuations of the Aral Sea level were distinguished the natural (till 1960) and modern or anthropogenic, sharply nonstationary periods. During the natural period the sea level was rather stable and varied within no more

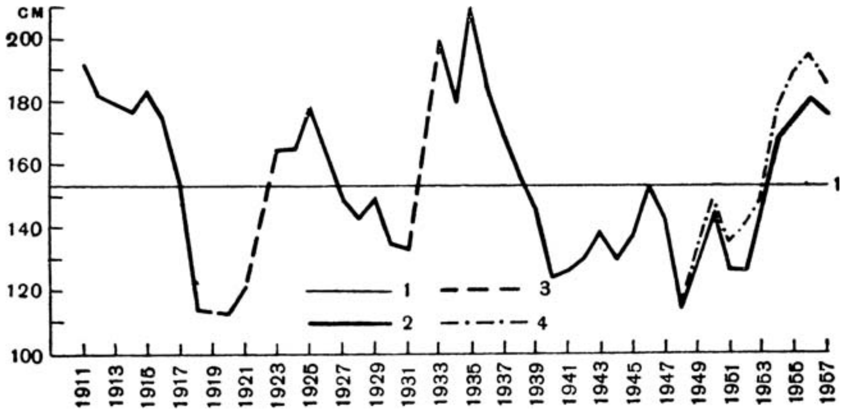


Fig. 1 Fluctuations of the Aral Sea level in 1911–1957 [4]: (1) is the multiyear averaged sea level (cm), (2) is the yearly mean sea level (cm) at Aralsk station, (3) is the yearly mean sea level (cm) at Aralsk station based on incomplete data, (4) is the yearly mean sea level (cm) at Aktumsuk station

than 1 m around the average many-year elevation of 53 m (see Fig. 1). The process of the persistent drop in the Aral Sea level from 1961 is considered separately.

The seasonal sea level fluctuations had a clear-cut periodicity. The maximum level rise in summer was due to run of the flood flow in the Amudarya and Syrdarya. The level drop in autumn was connected with evaporation from the water surface that reached its maximum after passage of the river floods. During winter when the rivers brought small quantities of water into the sea the sea level was at a minimum.

Although the Aral Sea is situated in the southern latitudes, every year it is covered with ice. First ice was usually formed in the coastal northern areas in the second decade of November and by mid-February the ice cover was the maximum. In late February–early March melting of the ice began. The modern ice conditions in the Aral Sea will be described in more detail in one of the chapters in this book.

The key factors contributing to water circulation in the Aral Sea are winds over the sea and bottom relief. Of certain significance are also the coastal configuration, inhomogeneous density of water, and spreading of river waters in the sea.

Many researchers found that in the Aral, unlike other seas of the Northern Hemisphere, the anticyclonic water circulation was dominating. The most reasonable explanation of such a specific feature was suggested by Simonov [5]. He believes that such anticyclonic water circulation in the Aral is caused by the northern winds and the relief of the sea bottom. In order to prove this assumption he estimated the wind-generated water circulation in the Aral Sea.

Apart from the northern winds blowing from May to October, frequently recurring are also southern winds which also increase the recurrence of cyclonic circulation of waters. But this does not change, in principle, Simonov's theory about the factors that induce anticyclonic circulation of water in the sea.

The patterns of resultant currents received on the basis of observations conducted during summer in the period from 1949 to 1969 enabled two basic types of water circulation in the Aral Sea to be revealed: anticyclonic when northern winds were blowing and cyclonic when southern winds were blowing. The maximum current velocities were recorded in the Berg Strait (40–60 cm s^{-1}) and in the areas near the river mouths (20–25 cm s^{-1}). In the central part of the sea currents of 5–10 cm s^{-1} prevailed. The currents near the sea bottom were still weaker – 3 to 7 cm s^{-1} [6].

4 Hydrology

The analysis of the water temperature distribution during the natural period of the life of the Aral was made on the basis of the observation data for 1957–1967 (most complete data is for 1957–1958) [6].

In January–February the sea surface temperature in the coastal area that was covered with ice was close to the freezing temperature characteristic for salinity of about 10 ppt observed in the 1950s (−0.5 to −0.6°C), while in the open sea it was 1–2°C. In April the warming of waters begins. In the open sea the low water temperatures were still maintained (4–5°C, on the average), while in shallow areas the water was heated to 6–10°C, on the average.

In May the water was intensively warmed, in particular in shallow areas. The surface water temperature increased to 14–15°C in the south and east and to 11–12°C in the north of the sea (Fig. 2). In spring the formation of a thermocline began (Fig. 3).

The summer is characterized by high air temperatures (up to 35°C) and sea waters are warmed intensively. The water temperature on the sea surface was more or less homogeneous and it changed only with depth. In August the sea surface temperature varied from 23°C in the Small Sea to 25°C in the southern part of the Large Aral Sea (Figs. 3b and 4a) with the top water layer being heated to a depth of 15 m. In the central part of the sea the upper limit of a thermocline occurred at 15–20 m depths and significant gradients were observed as far as the sea bottom. In the western deepwater area the lower limit of a thermocline – an isotherm of 5°C was found at 30 m depth. In the eastern and southern regions of the sea where the depths were less than 15 m the water was heated to the bottom and a thermocline was not found.

Concerning the vertical temperature distribution, in August differences appeared between the colder and more stratified waters of the western and northern areas and the warm, well-mixed waters of the shallow eastern and southern areas of the sea.

Autumn on the Aral Sea was characterized by a sharp drop of air and water temperatures. The sea surface temperature decreased in the shallow eastern part of the sea from 24°C in August to 20°C in September and to 10–11°C in October (Fig. 4c). At the same time an area of relatively warm waters with a temperature above 15°C in September was maintained in the western deepwater part of the sea (Figs. 3c and 4c). The spatial differences in water temperatures became most vivid in November when temperatures up to 12°C were still recorded in the area of a deepwater trench, while in the eastern region the surface temperature dropped to

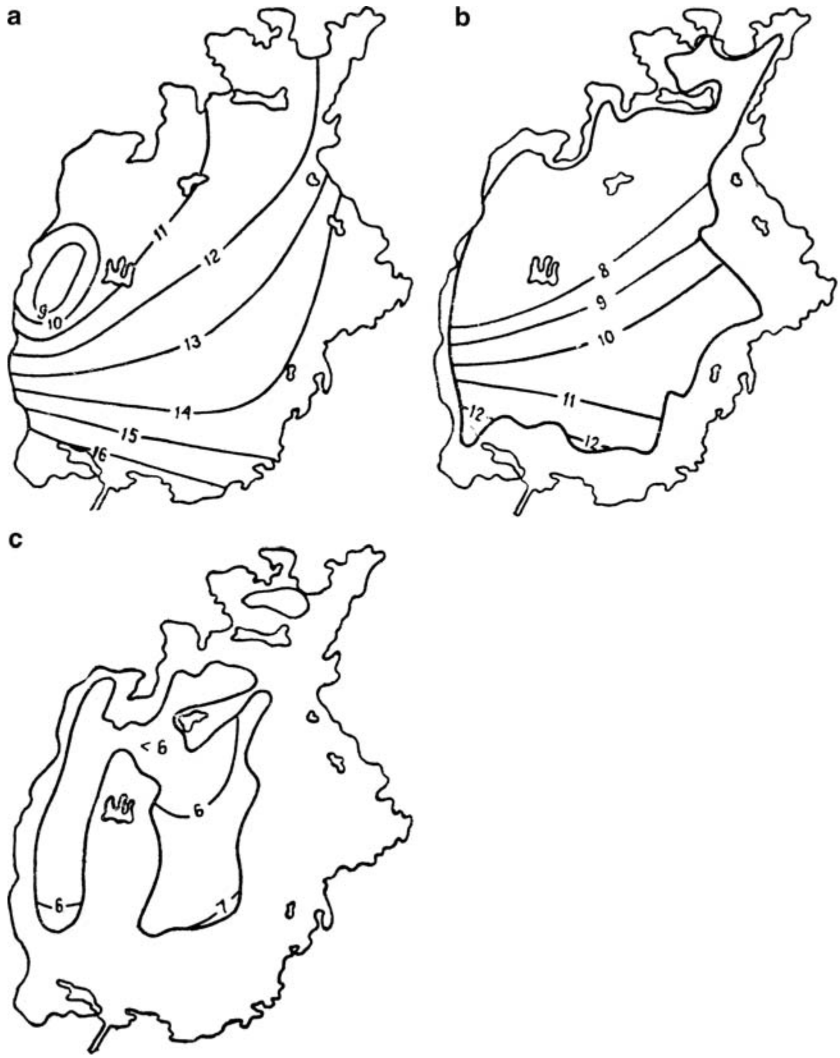


Fig. 2 Spatial distribution of water temperature (°C) in May at depths 0 m (**a**), 10 m (**b**) and 20 m (**c**) [6]

2–3°C. The specific feature of temperature distribution in autumn was homothermia, which was observed in October in all regions of the sea except for the deepwater trench. In some cases a depth-related temperature growth was revealed which is indicative of intensive cooling of the upper layers and near beginning of a convective mixing.

In November the water layer down to 20 m was already well mixed and practically no temperature gradient was observed. The western deepwater part kept its warmth for longer and the water cooled here only in February. The in-situ data

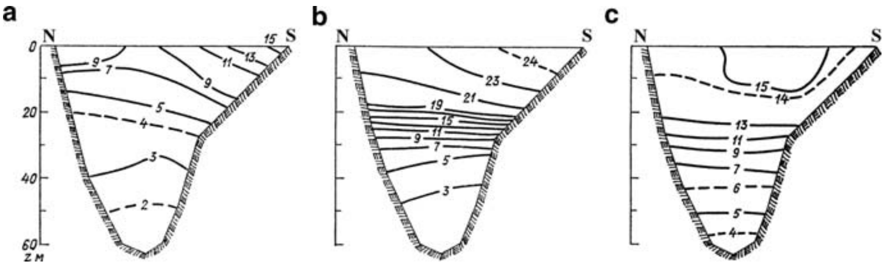


Fig. 3 Mean-annual (1950–1960) vertical distribution of water temperature (°C) on the meridional section along the western part of the Aral Sea in spring (**a**), summer (**b**), and autumn (**c**) [1]

showed that with depth the annual changes of the temperature became less. In the vicinity of the western deepwater trench at 30 m depth the water temperature from April to October changed by approximately 6°C; the maximum temperature in October was 8.8°C. At 50 m depth the water temperature increased from 1.5°C in April to 4.1°C in November.

The thermocline in the Aral Sea was formed nearly everywhere in June and existed till August. Only in the western trench it was maintained within the 20–30 m layer till October.

In the Small Sea the thermal conditions of waters had their specific characteristics. In summer and autumn the deep water layers were 1–2°C colder than in the Large Sea. This can be attributed to considerable cooling of the Northern Aral in winter and impeded water exchange with the central part.

The seasonal changes of water temperature are observed in all water layers; their values vary from 23 to 24°C on the surface to 2.5°C at a depth of 60 m. The occurrence of annual maximums changes with depth and in the bottom layer of the deepwater trench the temperature maximum was registered in December–early January.

The observations of water temperature conducted by coastal hydrometeorological stations throughout a year showed that the minimum water temperature was recorded in January–February and from April the intensive water heating began. In July the water temperature was at a maximum, and from September to December the water was cooled quickly. In the north of the sea (at Aralskoye more meteo station) the water temperature from December to March was negative and on average equal to −0.5°C. In winter the air temperature here dropped to −25°C, thus, the water temperature was always close to freezing point. The maximum temperature was observed in July and was on the average 24°C. In the southwest of the sea (at Tigrovyi meteo station) in January–February the temperature was about 0°C, while in July it rose to 26–27°C, higher than registered by other hydrometeorological stations.

Comparison of the data on water temperature distribution in the Aral Sea in the 1950s and 1960s has indicated that the last of these decades revealed a temperature decrease by 1°C, on the average, in the coastal areas of the sea which may be attributed to greater cooling during the autumn–winter period.

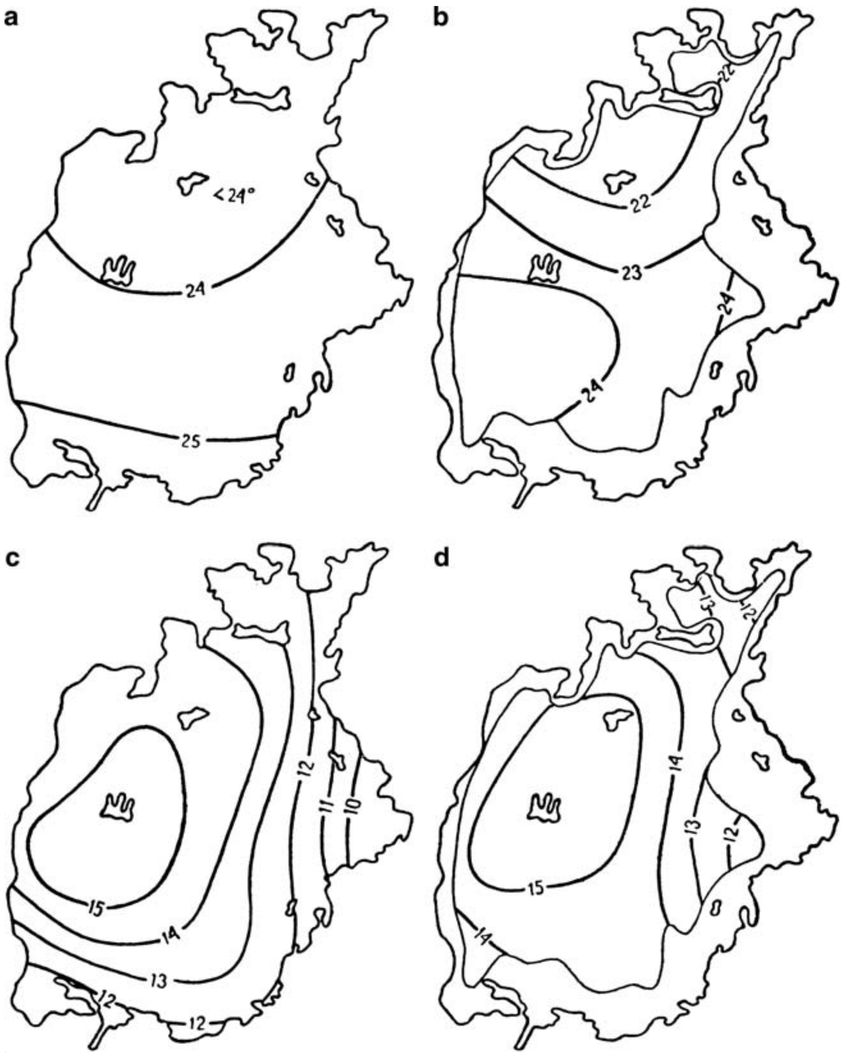


Fig. 4 Spatial distribution of water temperature (°C) in August at depths 0 m (**a**) and 10 m (**b**) and in October at depths 0 m (**c**) and 10 m (**d**) [6]

The essential fluctuations of the mean monthly water temperature were observed at all depths of the Aral Sea. In deeper layers this happened due to the effect of winter convection which, in turn, is connected with the severity of winters. Low temperatures in the bottom layers were registered most often after cold winters with much ice, and higher temperatures – after warm winters. The severity and duration of winters also influence the annual mean temperature of air and water.

The characteristics of the salinity fields in the Aral Sea are dependent on the volume and distribution of the river flow, evaporation processes, ice formation and melting, and also the pattern of water circulation in the sea. Variations of these factors affect the salt balance of the sea as well as seasonal and long-term salinity dynamics. Considerable freshening of the southern part of the sea with the Amudarya waters and the northern part – with the Syrdarya waters influenced greatly the salinity distribution. Beginning from the 1960s due to reduction of the river water inflow into the sea the effect of this factor was progressively diminishing. Wind and convective mixing made the vertical distribution of salinity over the whole sea area homogeneous.

Sea surface salinity was growing with distance from the river mouths where it was low the whole year. The lowest values of salinity were recorded near the mouths of rivers in summer during floods. The central and eastern parts of the Aral Sea featured rather constant salinity in the surface layer.

Kultuks that occurred near the eastern coast had a specific salinity regime. Small depths, impeded water exchange with the open sea, high evaporation in summer and intensive ice formation in winter were facilitating the development of high water salinity. In 1951–1953 the water salinity in some kultuks reached 80–150 ppt.

The vertical salinity distribution in the open sea in summer was characterized by slight growth from the surface downwards to the sea bottom. This increase was more significant in the southwestern and western parts of the sea where in July–August a halocline was formed in the surface layer that coincided with the thermocline, which made the vertical mixing much more difficult.

Until 1960 the sea surface salinity in the sea had been growing from 9.7–9.9 to 10.6–10.8 ppt in the direction from southwest to northeast. In the western deepwater trough the water salinity increased by approximately 0.4 ppt from the surface to the sea bottom. In the northern part of the sea, which featured severe ice conditions, the sea surface salinity was lower due to ice melting (Fig. 5).

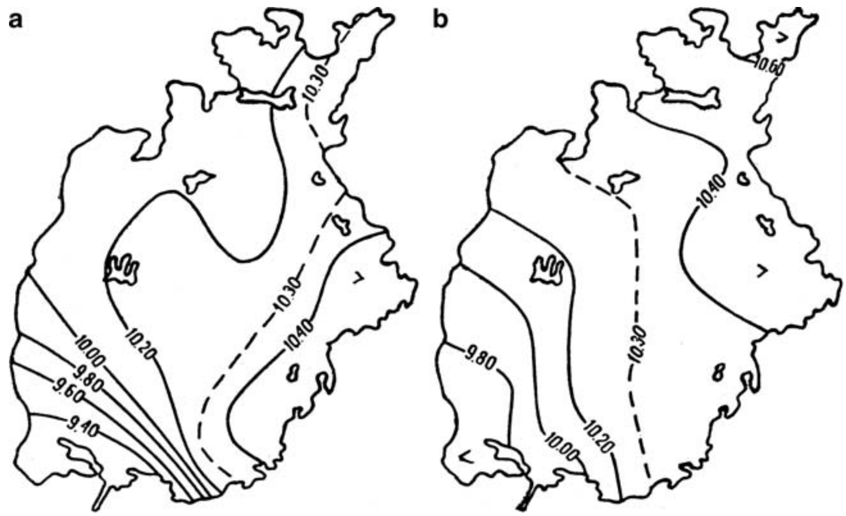


Fig. 5 Spatial distribution of sea surface salinity (ppt) in August (**a**) and October (**b**) [6]

In August the desalting effect of river flow was rather prominent and could be traced in salinity distribution over the sea. The lowest water salinity of 9.3–9.5 ppt was recorded in the southwestern part of the sea (see Fig. 5). In the central part it increased on the surface to 10.4 ppt. High salinity of surface waters was observed in August (10.5–10.6 ppt) in the eastern shallow part where the evaporation was most intensive. In summer, due to the growing effect of the river flow, the vertical salinity gradients also increased. Near the bottom it was 10.2–10.6 ppt practically over the whole sea (Fig. 6). The maximum salinity near the sea bottom – 10.7 ppt was recorded in the central and western parts which could be attributed to saline water creeping from the eastern shallow areas.

In October, the salinity distribution was more even than in August (see Fig. 5). Decrease of the river flow was accompanied by growing water salinity in the southwestern part of the sea where its values varied from 9.6 to 10.2 ppt. In other sea areas the water salinity was 10.3–10.6 ppt. With the water cooling and development of convection the vertical salinity distribution in October became rather uniform in all regions of the sea except for the western trough (Fig. 6).

In general, from spring to autumn the salinity changes over the greater part of the Aral Sea did not exceed 0.2–0.3 ppt and in the most freshened southwestern region – could reach 0.5 ppt. Salinity growth with depth was most significant in the western deepwater region that received saline waters from the eastern shallow part of the sea. Seasonal variations of salinity could be traced in all water layers.

The greatest seasonal variations of salinity occurred in the northern part of the sea (at Aralskoye more meteo station) that was characterized by the most severe ice conditions. In the annual salinity dynamics the minimum was clearly registered in March or April due to ice melting. The average salinity figures may decrease to 6.0–8.0 ppt. The highest salinity was recorded in January–February because of salinization during ice formation. In the 1960s it was 12.5 ppt, on the average. In summer and autumn the salinity was also high – 11.4–12.2 ppt.

From the early 1960s the water salinity in the Aral started growing, especially from 1964–1967. These changes covered all water layers, but they were manifested in different regions variously. From the beginning of observations on the Aral such a general rise of salinity was observed for the first time.

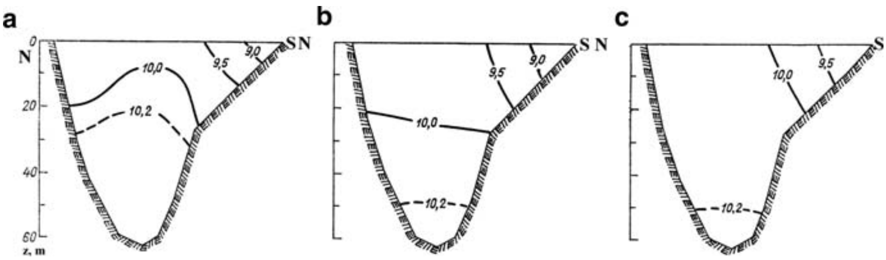


Fig. 6 Mean-annual (1956–1960) vertical distribution of water salinity (ppt) on the meridional section along the western part of the Aral Sea in spring (**a**), summer (**b**), and autumn (**c**) [1]

The most important process forming the hydrological structure of waters in the Aral Sea before its desiccation was a convective mixing in autumn and winter. Regardless of the fact that the Aral Sea locates in the southern latitudes the winter convection here was developing over the whole water area of the sea and engaged all water layers.

The results of observations conducted in 1957–1970 were used for study of the conditions of winter convection development. Analysis included estimates of convection parameters applying the well-known method of Zubov [7] at more than 600 hydrological stations and comparison of the estimates with the results of hydrometeorological observations.

The estimates and analysis of distribution of the hydrological data provided the following pattern of winter convection development in the Aral Sea (Fig. 7). In late August–early September the convection process reached the sea bottom in the eastern and southern regions in shallow areas (depths down to 10 m). After this the eastern region was characterized by intensive cooling of the whole water column, and it was greater here than in most western regions. In the east the convection development was facilitated not only by early ice formation, but also by salinity growth. As a result, the water density here became higher than in the nearby water areas. Cold and saline waters in the eastern region slid westward over the bottom slope spurring the process of winter vertical circulation. Judging by water temperature and salinity in October convection reached the sea bottom in all regions of the Aral Sea except for the western deepwater trough. In November the colder and denser waters from the eastern regions caused acceleration of convection in the western trough. After the waters from the eastern shallow areas penetrate into the deepwater trough the water temperature in its bottom layers in January–February dropped significantly.

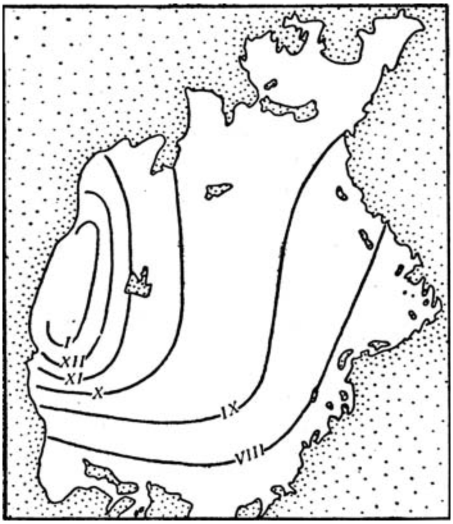


Fig. 7 Time of spreading of the winter vertical circulation to the sea bottom (months) [6]

The fact that convection really reached the bottom of the deepwater trough was confirmed by the data on oxygen distribution by season. Its maximum through the whole water column was observed in spring, after oxygen enrichment of the whole water layer.

Therefore, the deep waters in the western trough were formed as a result of the combined effect of local waters going down during winter convection and advection of waters from the eastern and central parts of the sea in the bottom layer.

The effect of waters from eastern shallow areas on the formation of bottom layers in the western trough was felt practically the whole year. In the warm season, mostly in August, the waters with added salinity due to evaporation penetrated into the trough. Beginning from November the waters from eastern shallow areas, cooled and later salinized during ice formation, started moving westward. These waters reached the trough in late January–February, although this did not happen every year. Formation of the bottom waters in the western trough was one of the most interesting peculiarities of formation of the hydrological structure in the Aral Sea.

Severity of winters on the Aral Sea influenced greatly the hydrological conditions, including development of convective mixing.

5 Marine Chemistry

The results of expeditions of 1951–1954 were mainly used in preparation for the fundamental monograph by Blinov [8] that describes principal hydrochemical peculiarities of the Aral Sea. Blinov identified specific features of the hydrochemical regime of the Aral Sea. The monograph analyzed the basic salt composition and most important physico-chemical properties of the Aral Sea waters, the salt balance of the sea and the hydrochemical factors of biological productivity of this water body. In the conclusion of this publication the readers may find the general hydrochemical characteristics of the sea at the time of the publication and in the future.

The Aral Sea presents a specific water body – a lake-sea. In terms of salt composition the Aral Sea waters may be described as highly metamorphized waters of the river flow feeding the sea. As a result of metamorphization processes the waters of the Aral Sea took an intermediate position between the hydrocarbonate–calcium waters of the mainland and chloride–sodium waters of the ocean. But, nevertheless, by correlation of the salt-forming ions the Aral waters were closer to the mainland waters. Moreover, the bromine content in Aral waters was low which is indicative of the dominating effect of the mainland waters. Because of well-developed hydrodynamic processes the Aral Sea featured highly homogeneous salt composition through the whole water area. It was noted that in the 1950s the salt mass of the sea made approximately 10.5 billion tons, while the average water salinity was 10.5 ppt.

Very interesting are the ideas of Blinov about the salt balance of the Aral waters that unveil “the paradox of the Aral Sea.” Regardless of considerable input of salts and the absence of visible forms of output the water salinity in the sea was not high and was practically unchanged with time (during the stationary regime). By Berg estimates the whole salt mass of the Aral Sea can be created during 320 years. Analysis of the elements of the salt and water balances of the Aral Sea conducted by Blinov has shown that despite the absence of visible forms of salt removal from the sea there was a balance of elements on its output side that contributed to limitation of salinity growth in time. The loss of salts from the sea occurred due to the following factors: filtration into the ground, sedimentation, and wind drift. According to the author's estimates, the wind drift of salts removed less than 0.1% of the salts brought into the sea with the river flow. A more important factor in the eastern part of the sea was filtration of sea salts into sandy shores surrounding the vast shallow areas (the "Aral type" of shore). Every year the filtration managed to compensate fully for salt input from river flow, thus, ensuring stability of sea water salinity [8].

The oxygen content in the Aral Sea reflected well the peculiarities of its hydrological structure. The oxygen regime in the Aral Sea was very favorable – a high oxygen content in water was recorded at all depths during the whole year. In spring the highest oxygen concentration was observed in the north of the sea where it was equal to 9.5–10.5 ml l^{-1} and in the central and western parts – 8.0–10.0 ml l^{-1}. In spring the water saturation with oxygen was usually higher than 100% and may even reach 120%.

In summer, due to intensive heating of the sea the oxygen content dropped to 6.0–7.5 ml l^{-1}. Saturation with oxygen of the surface layer was close to 100%, i.e. being in equilibrium with the atmosphere.

The specific feature of the oxygen distribution in the Aral Sea in summer was maintenance of its maximum in the deeper layers, below the thermocline. The oxygen was accumulated in the bottom layer due to photosynthesis of the bottom flora that was well developed in the Aral and this created oversaturation with oxygen near the sea floor that might reach 140–150% and even more. The presence of the thermocline prevents exchange with the upper layers and leads to homogenization of the oxygen concentration. Only in the western trough was the relative oxygen content in the bottom layer decreasing, but it never dropped below 80% anywhere.

In autumn, when the water starts cooling the oxygen content in the sea water increased once more and in October its values were close to the spring ones. During this season the oxygen spatial and vertical distributions over the water area were rather homogeneous and made 6.7–7.7 ml l^{-1}. Only in the bottom layer of the western deepwater trough was some excessive oxygen content found. In general, the seasonal variations of the oxygen values in surface waters are a function of the water temperature. This may be seen in the graphs of seasonal distribution. In shallow areas photosynthesis is the key factor for saturation of the bottom waters with oxygen, while at great depths this is the convective mixing. The existing thermocline separated the lower, oxygen-oversaturated layer from the upper layer where the oxygen content was in equilibrium with the atmosphere.

One more specific feature of the natural regime of the Aral Sea was insufficiency of nutrients in the water column.

Thus, this water body is poor in phosphates, which is the key reason for its low biological productivity. Very typical is the vertical distribution of phosphates. Unlike other seas where the phosphate content grows with depth, in the Aral Sea the phosphate concentration decreases from the surface towards the sea bottom (to analytical zero). And this phenomenon may be explained by the fact that the Aral has no zone of deep accumulation of phosphates as is the case, say, in the Caspian Sea. Small depths and high water transparency of the Aral ensure high intensity of photosynthesis through the whole water column. Some higher values of phosphates in the surface waters are related to spreading of freshened waters in the sea. The river flow is the main, but not copious source of the phosphate input into the sea.

The average content of phosphates varied in some years from 1.0 to 4.2 mg m^{-3} and, in some cases, dropped even to analytical zero. During the whole observation period their maximum content was registered in August 1949 in the southeastern part of the sea – over 20 mg m^{-3} [8]. The Small Sea was one of the areas with the higher phosphate content (1.0–4.6 mg m^{-3}) as well as the mouth areas of the Amudarya and Syrdarya. The low level of phosphates was recorded in the western area and in the eastern shallow part of the sea – from 0 to 1.0 mg m^{-3}. The highest values of phosphate content were usually observed in the surface layer, but with depth it sometimes dropped even to analytical zero (at 10–20 m depths). Some enrichment of the surface water layer with phosphates occurred, thanks to the river flow. The seasonal variations in the phosphate content in the Aral Sea, unlike other seas, were revealed rather weakly. On a year-to-year scale the average phosphate values increased in the water abundant years and dropped with the decrease of flow from the rivers.

As is known, fixed nitrogen is present in seas and lakes in several forms. Nitrates produce the greatest influence on biotic productivity. They, similar to phosphates, are present in the Aral Sea in very low concentrations. Thus, the nitrate nitrogen content in the open part of the Large Sea never exceeded 5 mg m^{-3} and only in the mouth areas of rivers was it somewhat higher. The nitrate values in the Small Sea were higher. Their content in the surface waters varied from 7.0 to 15.0 mg m^{-3} and in the bottom layer – from 1.0 to 3.0 mg m^{-3}.

Distribution and seasonal variations of the silicate content in the Aral Sea waters were subject to the effect of two key factors: a river flow that imported dissolved silicic acid and a biological silicate cycle in the sea proper. In general, the content of silicic acid in the Aral Sea is not high compared to other seas.

The average silicate content in the Aral Sea waters was only 250 mg m^{-3}. Its minimum making 120–140 mg m^{-3} was observed in the central and eastern parts of the sea, while its maximum making 800 mg m^{-3} was observed in the southern part that was influenced by the Amudarya waters.

In the vertical distribution of silicate its highest level was registered in the surface waters above the thermocline as silicate was imported here with the river flow (the main source of silicate for the sea). No accumulations of silicate in the bottom layer were observed (except for the western trough) because it was intensively consumed in all water layers from the top to the bottom over the whole sea area. Its seasonal distribution was quite specific: the silicate content increased generally from spring to autumn, and its minimum occurred not in summer, but in late September–October.

6 Conclusions

The most important factors producing the greatest effect on formation of the hydrological structure of waters in the Aral Sea are thermal exchange with the atmosphere and river flow. Small depths prevailing in the sea that facilitate quicker heating and cooling of waters also play their role. In the winter time the processes of ice formation and melting were very important for hydrological conditions of the sea. The combination of the mentioned factors created the specific features of the hydrological conditions in different parts of the sea.

Much heat coming to the sea surface in spring and summer and small depths create conditions for intensive heating of the surface waters in spring. Already in May a thermocline was being formed on the lower limit of the wind mixing layer and it reached its maximum development in July–August. The upper limit of the thermocline was located at 10–15 m depth and the high temperature gradients (0.4–1.4°C m^{-1}) were observed to the sea bottom over the greater part of the sea. The hottest month is July. In late August the water started cooling and its minimum temperatures were registered in January–February. The seasonal variations of the water temperature were observed in all water layers, but its values decreased from 23–24°C on the sea surface to 2.5°C at a depth of 60 m.

Many-year variations of the water temperature in the deepwater trough occurred due to convective mixing. Low temperatures in deep layers of the trough were recorded mostly after cold winters with much ice, while the higher temperatures – after warm winters with a small ice cover.

The output part of the salt balance included wind salt drift (mechanical evaporation), filtration of sea water into the shores and bottom, and sedimentation of low-solubility salts (carbonates). Apart from the wind drift (its share is not large, in fact) the most significant path for the loss of sea salts was via continuous filtration of saline waters in the eastern shallow areas into the shores and bottom of the sea.

Distribution of salinity over the sea and its seasonal variations were dependent, largely, on the river water inflow and evaporation. Lower salinity was found in the Amudarya and Syrdarya mouth offshore areas. The greater part of fresh waters came with the Amudarya flow into the southern part of the sea and spread with the anticyclonic circulation along the western coast. High salinity was observed in shallow areas near the eastern coast with their impeded water exchange with the sea. The salinity field in the open sea was rather monotonous. The vertical distribution of salinity did not reveal significant gradients. In view of the small depths the convection in autumn and winter covered all water layers and created homohalinity. In summer with the progressing freshening of the surface waters the vertical gradients of salinity were created.

The changes in water salinity in the period from spring to autumn did not exceed 0.2–0.3 ppt in the greater part of the open sea and 0.5 ppt in the southwestern part. In the northern and central parts of the sea the seasonal dynamics of salinity revealed its growth in winter, the clear-cut spring minimum and an even dynamics during the rest of the time.

In autumn, with the beginning of water cooling and less prominent stratification of water layers the convective mixing processes started developing in the sea. By late September the convection reached the bottom in the vast shallow areas in the eastern and southern parts. This facilitated considerable cooling and later salinization of shallow waters in the eastern part of the sea. Sliding of high-density waters from the shallow areas accelerated the convection processes in the sea. In November the winter circulation covered the central part of the sea and in January–February reached the bottom of the western trough, although this did not happen in all years. The bottom waters in the western trough were formed, largely, by the waters of high-density penetrating here from the shallow eastern regions.

The specific feature of the oxygen regime of the Aral Sea is maintenance of the permanently high oxygen content in space and time. Oversaturation with oxygen in deeper layers might reach 120–150%. Oxygen content below 80% was never registered. The increase of the relative oxygen concentration was usually observed below the thermocline, i.e. at a depth of 10–15 m from the surface. Such high concentration of dissolved oxygen in waters of the Aral Sea may be attributed, on the one hand, to high water transparency and small depths creating good conditions for benthos development and, on the other, relative insufficiency of pelagic organisms and organic matter which restricts consumption of dissolved oxygen for oxidation.

Waters of the Aral Sea are characterized by low concentrations of nutrients – phosphorus, nitrogen, and silicate which suppress photosynthetic activity of bioorganisms. The greater part of the Aral possesses the features of the typical oligotrophic water body. Insufficiency of nutritive mineral substances in the sea waters may be explained both by the nature of input and cycling of these substances in the water body and also by morphological and hydrological peculiarities of the sea. High transparency of water, small depths ensured sufficient illumination of all water layers and development of photosynthesis in all water layers from top to bottom, in particular, development of the higher underwater vegetation consuming the regenerated mineral nutritive salts. Therefore, there were no morphological conditions for accumulation of nutrients in the sea proper. The "biological filters" of deltas, including higher benthos and overwater vegetation well developed in river mouths consuming the greater part of nutrients from river waters, played a rather significant role in restricting the input of nutritive salts into the sea.

One of the factors describing the content of nutrients in the land-locked shallow seas is the quantity of this matter that is imported annually with the river flow per a unit of the sea volume. Under the natural regime of the Aral Sea (till the 1960s) the flow of nutrients was 2.5 times less than in the Sea of Azov and 4 times less than in the Northern Caspian [8].

The Aral Sea was always relatively poor in flora and fauna. This happened due to isolation of this water body and specific features of its regime. The Aral did not have many groups of animals that lived in other inland seas, e.g. in the Caspian and Azov seas. Many fish species of the Aral that originated in fresh and slightly saline waters were not adapted to essential changes of their habitat.

According to various sources, the phytoplankton of the Aral Sea comprised only 40–70 species (in the Caspian and Azov seas they numbered more than 180). Dominating were diatom and flagellate species. The zooplankton comprised 25 species, but more than 70% of this was taken by diatomic copepods. This restricted the use of food resources of the sea. Zoobenthos comprised 48 species, of which 20 were widespread bivalves. Although the zoobenthos biomass was rather considerable (about 20 g m^{-2}, on the average), it was still less than in the Northern Caspian and in the Sea of Azov.

The Aral Sea was populated with 20 species of fish of freshwater genesis. These were mostly carp (12 species) and perch (three species). Under natural conditions the total fish catches were up to 40,000–45,000 tons yr^{-1} (in 1957–1960) [9].

There were numerous projects for improvement of the fishery productivity of the Aral Sea due to introduction of mass species of zooplankton, zoobenthos, and fish. In the 1940–1950s the fries of the Caspian stellate sturgeon, bullhead, and Baltic herring were released into the sea. After this the consumption of zooplankton increased sharply, while its resources shrank.

Under the quasistationary regime in the Aral Sea region a specific sea-oriented economic pattern (fishing, muskrat farming, marine transport) was practiced. The sea produced an alleviating effect on the climate of nearby territories. The very existence of the sea was favorable for the environmental and socioeconomic situation in the region.

Hydrological and hydrochemical conditions of the Aral Sea in the present anthropogenic period on the basis of expeditions conducted in the 2000s are considered elsewhere in this volume.

References

1. Bortnik VN, Chistyaeva SP (eds) (1990) Hydrometeorology and hydrochemistry of the USSR Seas. The Aral Sea, vols V–VII. Leningrad, Gidrometeoizdat, p 196 (in Russian)
2. Shnitnikov AV (1959) The Aral Sea past and present in the context of large scale climate rhythms. Proceeding of 3rd All-Russian Hydrological Congress, vol 7. Gidrometeoizdat, Leningrad, pp 47–57 (in Russian)
3. Berg LS (1908) The Aral Sea. An experience of physico-geographical monograph. Izv Turkestanskogo Otd Russ Geogr Obshchestvo, St Petersburg 5(9):580 (in Russian)
4. L'vov VP (1959) The Aral Sea level fluctuations in the last hundred years. Trudy GOINa 46:80–114 (in Russian)
5. Simonov AI (1954) To the question of the reasons of anticyclonic circulation of the Aral Sea waters. Meteorologia i Gidrologiya 2:50–52 (in Russian)
6. Kosarev AN (1975) Hydrology of the Caspian and Aral Seas. Moscow University, Moscow, p 272 (in Russian)

7. Zubov NN (1947) Dynamical oceanology. Gidrometeoizdat, Leningrad, p 430 (in Russian)
8. Blinov LK (1956) Hydrochemistry of the Aral Sea. Gidrometeoizdat, Leningrad, p 52 (in Russian)
9. Zonn IS, Glantz M, Kostianoy AG, Kosarev AN (2009) The Aral Sea Encyclopedia. Springer, Berlin Heidelberg, New York, p 292

Socio-Economic Conditions of the Aral Sea Region Before 1960

Igor S. Zonn

Abstract The paper presents a study of the socio-economic conditions of the Aral Sea and Amydarya and Syrdarya deltas (water supply, diseases, fishery, water transport) that existed before 1960, the time of desiccation of the sea and degradation of the deltas. In this period the life and welfare of the local population was closely connected with the sea and depended on fishery and navigation.

Keywords Diseases, Fishery, Water supply, Water transport

Contents

1 Introduction

There is hardly any other example of the degradation of a sea (one of the largest lakes on the Earth) within one generation; but this really is what happened to the Aral Sea. We can recollect cases of desiccation of small lakes, such as Lon-Nor in China.

I.S. Zonn
Engineering Research Production Center on Water Management, Land Reclamation and Ecology
43/1, Baumanskaya ul., 105005 Moscow, Russia
e-mail: igorzonn@mtu-net.ru

A.G. Kostianoy and A.N. Kosarev (eds.), *The Aral Sea Environment*,
Hdb Env Chem (2010) 7: 65–73, DOI 10.1007/698_2009_6,

We can also give examples of water volume reduction in lakes or fluctuations of their water level such as, for example, that which occurred with the Mono Lake, a salt lake in the USA; the Chad Lake in Africa; the Dead Sea in Israel, etc. But degradation of the sea – this can be referred to as a real regional disaster.

The changes in the Aral were related not so much to natural causes but more, to a significant extent, to anthropogenic impacts related to the growing economic activities of man. The main natural factors influencing the course of evolution of the Aral (climate, specific runoff from watersheds, morphology of sea depressions) do not have such a high dynamic as man-made factors that are capable of rapid and irreversible changes to the Aral ecosystem [1].

During the history of the Aral there were periods of considerable regression associated with intensive development of irrigation systems in the Amudarya and Syrdarya basins. But they, most probably, were not of the same magnitude, did not proceed so intensively, and did not result in such devastative consequences as we witness in the Aral basin at present.

In order to understand what we have lost as a result of desiccation of the Aral Sea we must restore the natural and socio-economic situation that existed before 1960 – the beginning of degradation of the Aral.

2 Socio-Economic Conditions in the Aral Area

Leaving aside the socio-economic activities of the population in the Aral area we cannot neglect conditions of everyday life. Living near water is always convenient and favorable for man’s health.

The main occupations of the population in the Aral Sea area were fishing and fish processing, servicing of ships, navigation both within the sea and along the full-flowing – at that time – mouths of rivers and their numerous arms.

The coast of the Aral Sea was populated but very sparsely. The coastal areas were used mostly as pastures and part of the land used was under cotton. The largest settlement was the city of Aralsk located on the northeastern coast of the sea. At this location the railroad ran closest to the sea. The second important transport outlet to the sea was in the south via the Amudarya River – the city of Muinak. Located in the deserts these cities have always faced problems of water supply.

2.1 Medico-Biological Situation

Before 1960 the growth of water consumption in the circum-Aral region did not significantly affect the water balance of the Aral Sea and the quality of river water. The biosanitary capacity of the natural environment and its natural coagulation facilitated the process of water self-purification in sources. Moreover, there was also a free flow reserve which was disposed of into the Aral Sea that compensated for evaporative losses, and as a result, the water level in the sea was maintained [2].

Before 1960 inadequate attention was drawn to the medico-biological situation in the circum-Aral territories – in the Karakalpak Autonomous Republic of Uzbek SSR and Kzyl-Orda Region of Kazakh SSR. These territories were always densely populated and the people settled mostly in the delta areas of the Amudarya and Syrdarya. In the circum-Aral region and for Central Asia, in general, the ethno-demographic situation has always been distinguished by a high birthrate among the native population (a traditional willful tendency towards large families). And this, to a great extent, was responsible for the problems arising here in relation to provision of the growing population with adequate food resources, water supply, and medical services. Before 1960 these reserves depended largely on the Aral Sea, which was the natural and economic basis of this region. The level of health of people living in the circum-Aral region is closely dependent on the condition of water resources. The circum-Aral regions had the lowest consumption of water per inhabitant compared to other republics, while the rural population was not actually provided with drinking water complying with state standards. The salinity of drinking water here was always $1.5–2.5\,g\,l^{-1}$. The diet of the people lacked adequate quantities of vitamins and proteins. Poor medical services were a result of insufficient allocations to social needs. Despite a free-of-charge medical service its quality lagged significantly behind other republics. And this was especially true of the rural regions where not all villages – scattered over large expanses – had even medical stations for treatment of the people. According to statistics, people living in the lower reaches of rivers are affected to a greater extent by specific diseases than people living upstream. It should be noted that the weak point with the circum-Aral region was always poor water supply and wastewater disposal in settlements. And there were two basic reasons for this – lack of adequate freshwater sources, both surface and underground, and lack of adequate finance for construction of centralized water supply systems and water ducts from the regions where these sources were available. The main sources of water supply for the people of the circum-Aral region were turbid, contaminated, and brackish waters of the Amudarya and Surdarya rivers. In some places remote from the Amudarya and Surdarya the population had to take water directly from irrigation and drainage canals and even from aryks for domestic purposes. Such poor sanitary conditions of water use in the circum-Aral region were due to the acute water deficit. The shortage of quality drinking water causes deterioration of the population's health that reveals itself in physiological dysfunctions, negative genetic consequences, etc. Because of the poor development and low capacity of centralized water supplies and periodical water shortages in the available sources the people used brackish and underground waters for domestic and drinking purposes. The scarce treatment facilities mostly of standard configuration (settling, coagulation, filtration, chlorination) failed to ensure adequate treatment and bacterial purity of water.

This fact and the inadequate level of medical care even in those times were responsible for a high sickness rate. The most widespread were urolithiasis, gastro-intestinal, and cardiac diseases [2].

2.2 Fishery

The Aral fishery region comprised the Aral Sea basin with the mouths of the Syrdarya and Amudarya rivers. The composition of commercial fish species included common carp, sabrefish, roach, bream, perch, pike perch, and catfish and one species of the sturgeon family – bastard sturgeon. Other fish were not of commercial significance. The main spawning grounds were located in the marine parts of the Amudarya and Syrdarya deltas, thus, the share of river fishing was only 10%, while 90% of fish were caught in the sea. The second specific feature was the even run of fish that made the fishery less seasonal.

The most intensive development of the fishery in the delta area and in the Aral Sea, in general, was observed after the construction of the Central Asian railway (at the beginning of the 1890s) which made it easier to sell fish products to the inland regions of the country.

Soon after the 1917 October Revolution, some private capitalist enterprises that still existed in the Aral Sea area were affected by the destructive civil war, which meant fishing in the delta was considerably reduced. An intensive rise of the fishing industry started approximately in the 1930s. At that time all fishing industry enterprises in the Aral Sea area were integrated in the system of state fishing and fishery collective farms.

During the ensuing years the volume of fishing in the delta and adjoining areas (in general, in the southern part of the Aral Sea area) increased to such an extent that the area produced on average two-thirds of the total amount of fish caught in the entire Aral Sea fishery basin.

It should be mentioned that the annual fluctuation of yields of most whitefish was typical of the fishery in the Aral Sea. This fact could be explained not only by the intensity of fishing, but by some other reasons. The dynamics of the Aral whitefish stock were found to be defined by the efficiency of reproduction processes, which were directly dependent on the flow of the Aral Sea tributaries and on the periodical change of the structure of the Amudarya delta, hydrological peculiarities and biological conditions of the spawning pools. The combination of the above optimum conditions contributed to maintaining the Aral Sea fish resource base at a high level. Since the fishery in the Amudarya delta was mainly based on marine fluvial anadromous fish periodically coming to this area for spawning or wintering, it was quite natural that the fluctuations in whitefish yields were also observed here.

In the period of the quasistationary regime the Aral Sea played a significant role in USSR economics. At that time the Aral's share in the total inland fish catches was 5–7%, in the catches of valuable fish species (sturgeons, bream, common carp, sea roach, pike perch, asp) 11–13%. The average annual fish catch was 30–40 thousand tons (in some years it provided up to 58 thousand tons of valuable freshwater food fish). Muinak and Aralsk had fish processing plants of great significance to the country.

Muinak was called the capital of the Aral fishermen. It is located on the Tokmak-Ata Island separated from the mainland only by a narrow and shallow strait. The main pride of Muinak was the fish canning plant which in those times was considered one of the largest enterprises in the Soviet Union. It was constructed in 1941 for manufacturing fish and meat products – canned beef and canned terrapin. This lasted till 1956 when it became a fish canning plant. The plant manufactured various products: smoked, dried, salted, live, and frozen fish, but the main produce was canned fish (in 1958 it produced 21.5 million cans) [3].

Fishery in the delta was practically concentrated in the foreshore delta and sea bays (Kazakhdaryinsky, Abbassky, Sarbassky, Muinaksky, Adzhibaisky) and in water bodies of the northern seaside part of the delta connected with the foreshore delta areas. The lakes located in the central and southern parts of the delta were of local fishery significance.

Fishery in the delta and foreshore delta of the Amudarya River was based on fishing of bream, carp, roach, Cahlcalburnus, Aral barbel, asp, redeye, etc. whose share made 86% of the total fish yield in this area.

Three species of fish gave the maximum yields, i.e., bream, carp, and roach, and they were equal to 40, 23, and 13%, respectively, of the total fish yield in the delta; summed they reached 73% of the total fish yields. The roach species (Cahlcalburnus, Aral barbel, asp, redeye, etc.) were of minor fishery importance. Their fish yields taken together were approximately 13% of the total fish yield in the delta [4].

Among other fish species of commercial significance in the delta mention should be made of sheatfish which yielded 4.5% of the total fish yield and pike whose catch reached 4.5% of the total yield. As for the perch species only sander was regularly found in the fish yields, but it was of minor fishery importance equaling at least 2% of the total fish yield.

At that time the spineback was not fished either in the delta or in the sea. Spineback resources in the Aral Sea were largely exhausted in the prewar years as a result of epizootia (in 1936) caused by suckling parasites and intensive fish catches before the river mouths. To ensure preservation of the spineback population, which was one of the most valuable fish species in the Aral Sea, its fishing was prohibited and it was caught only occasionally by seines in the delta.

The new inhabitant of the Aral Sea, i.e., the Caspian stellate sturgeon, propagated extensively; however, it was not fished at this time.

The catches of most important fish species and fish species of minor importance differed greatly. This was due to the greater or lesser concentration of various fish stocks in any region of the delta. The main area of bream fishing in the delta was the northwestern part, partially the Adzhibay and Muinak bays. The largest quantities of carp were fished in the Adzhibay bay and in the northeastern part. Chalcalburnus prevailed in the area of Porly-Tau. Similarly, the maximum yields of barbel were in the Porly-Tau area while the minimum yields were in Urga. The maximum catches of asp were in the Urga area. In the Adzhibay, Sarbassky, and Muinak bays its quantity in fish catches was insignificant.

The share of predatory fish in the fish catches was the greatest in the inner regions of the delta. In quantitative terms the pike catches were the largest. The maximum sheatfish catches were obtained in the northeastern and central parts of the delta.

The fishery fleet in the delta area comprised sail-rowing and motor vessels. The sail-rowing vessels were provided with nets, seines, and hoop nets. In relation to fish catches per fisherman the stationary and hoop nets ranked the first in this respect among the passive fishing tools.

During the Soviet time the fishery industry was subject to radical retrofitting. The greatest fish yields were provided by the fishery kolkhozes (collective farms): in the northern part of the Aral Sea 19 kolkhozes were serviced by the North-Aral and Kuvandarya motor fishery stations (MFS), in the southern part ten kolkhozes – the Muinak MFS a major one in the Soviet southern water bodies.

Of the average annual fish catches reaching about 35 thousand tons the share for the Northern Aral Sea was about 40% and the Southern – about 60%. The fishing leaders were carp – about 28% of the total catch (the Aral Sea had the second highest carp catches in the USSR), bream – to 29% (third highest in the USSR), sea roach – 16%, others – 27%.

For fishery development in the Aral Sea area two refrigerating plants were constructed, a fish canning plant, 11 fish-salting plants, and accessory facilities, such as shipyards, repair and container-making workshops. As a result, the manufacture of frozen, cooled, and canned fish products increased, while the salted fish output decreased.

2.3 Musk Rat Farming

Commercial musk rat farming was organized in the Amudarya delta in 1941. In the period from autumn 1943 to spring 1944 about 335 musk rats from the Balkhash musk rat farm were resettled here into the reed strip [5]. The animals that originated from Canada acclimatized and propagated rather quickly and from 1946 catches had already reached commercial scale. About 1,000 specialists took part in musk rat hunting. The musk rat farm created in the Amudarya delta delivered to the state more than one million pelts a year and there was great demand for the pelts on the international fur market.

High-quality pelts were used for the manufacture of various fur clothes: coats, hats, collars, muffs. Musk rat pelts were often dyed for imitation of mink, sable, and fur seal. The hair was shaved from low-quality pelts and used in felt manufacture. Musk glands were a rather valuable raw material for making long-lasting fragrance.

It should also be mentioned that the musk rat farms failed to be used to their full potential. In particular, after pelt removal the carcasses were often thrown into water bodies.

Musk rats were hunted with the help of small traps. And quite often not only mature animals, but small ones having low commercial value were trapped. To avoid the death in traps of musk rats with low-quality fur, pregnant females, and females with sucklings and also young animals it would be appropriate to use trap designs that would not threaten the life of the animals. In this case the entire catch of low-value animals (in commercial terms) could be released, thus, increasing the population of musk rats. Traps of this kind were gradually put into use.

The activity of the must rat farms was not limited to hunting and delivery of pelts to the state. The workers of these farms performed from time-to-time cleaning of water "passes" connecting the inland water bodies. In some cases new canals-passes were made in the reedy banks. They facilitated spreading of the musk rats over the delta area and made easier their hunting. Sometimes special short canals were constructed to divert river water from the functioning channels of the delta arms to the nearby lowlands. Without this many water bodies would suffer from water shortage and later they could not be used as a habitat for musk rats. In musk rat farming much attention is paid to the arrangement of artificial musk rat huts or special foundations for them. In the late 1950s in addition to musk rat farming the farming of silver foxes was initiated.

2.4 Water Transport

Prior to the 1960s the Aral being an inland water body shared by Kazakhstan and Uzbekistan was the main link connecting ports Aralsk and Muinak and the cargo traffic between was as large as 250 thousand tons a year. The main transported commodities were cotton, grains, salt, fish, chemicals, and others. The most important commodities, such as fish and cotton, were transported to the north from the regions located in the Amudarya lower reaches and mostly from the Karakalpak ASSR, while the south received food and industrial products.

Not long ago water transport was the only means of cargo transit to the Amudarya delta and from this area to the railroad. In spite of construction of the new railroad Chardjou–Nukus–Kungrad water transport still remained most important for this region.

From the south cargo was transported via the Amudarya River from the city of Chardjou, which at that time was also a station on the railroad Tashkent–Ashkhabad. Notwithstanding a rather long navigation period (about 7 months) the communication through the Amudarya had some disadvantages and among them rather high flow velocities in the river and considerable and unexpected variations of the river channel configuration.

In the north the Amudarya delta was connected with the railroad Orenburg–Tashkent via the Aral Sea shipping line from the city of Aralsk to the city of Muinak (to be precise, to the village of Uch-Sai located on the Tokmak-Ata Island, 18 km northward of Muinak). The disadvantage of this line was the lack of a suitable and well-equipped port in the delta that would ensure quick unloading and loading of ships.

The construction of the railroad from Chardjou to Nukus running along the left bank of the Amudarya River and further on to Kungrad improved considerably transport communication between the delta cities and administrative and industrial centers of the Republics of Central Asia. The proposed extension of this railroad in the northwesterly direction through Ustyurt and as far as railroad station Makat would connect cities in the Amudarya delta directly with the main railroads of the European USSR.

Simultaneously with the construction of this railroad (Nukus–Makat) it was necessary to address the most important local problems for the delta area associated with construction of roads designed for cargo transportation from certain parts of the delta to the railroad and vice versa.

The industries existing in the lower delta (fishery and musk rat farming) required maintenance and improvement of the local waterways used for transportation of people, food products, building materials, fishing, and hunting products. At the same time development of other branches of the national economy were planned in the delta area. Among such branches were animal husbandry, cotton growing, and organization of local industries based on the use of reeds in the manufacture of paper, building materials for houses, fuel bricks, etc. It was also possible to use weeds harvested in the water bodies in the course of cleaning the passes as fertilizers for cultivated crops and in kitchen gardens. Harvested weeds could also be used in compost preparation.

The local water transport in the delta constituted motor vessels owned by different organizations. These motor vessels with a draught of 3 m ran along certain routes. In the seashore part of the delta motor vessels of fishery organizations represented the main transportation mode. In the inner parts of the delta the navigation was mostly developed in the main river channel and its main branches, such as Kipchakdarya and Akdarya and also in the largest arm Raushan [4].

For heat supply to enterprises and residential houses coal was delivered by railroad to the station Aral Sea from where it was reloaded onto barges and transported further to coastal settlements.

2.5 Recreation

Even in the late 1950s the Aral coasts (in particular the western and northern coasts of the Muinak Peninsula) were considered as very good regions for the construction of resorts, balneological complexes, and recreation zones for the local population. A recreation zone was created that required several dozen million rubles in investments for its construction. Several pioneer camps and rest houses belonging to different ministries and departments were built here. They functioned on the basis of the Aral Sea possessing a complex of factors – curative water, temperature, solar radiation, salinity, and gas concentrations. The warm season here lasted from April through October and the bathing season lasted for 5 months [3]. These places abounded in natural sandy beaches, transparent sea waters, springs of mineral water and curative mud, largely sulfide and silty, with high balneological properties. On the eastern coast of the Muinak Peninsula children's resorts were organized. Here one could find many beautiful natural sandy beaches, the sea water was very clear, and mineral waters and curative muds were also found in this area.

3 Conclusions

During the 1960s the governments of the Central Asian republics were posed a very serious problem in relation to intensive development of irrigated farming; which was more beneficial – the Aral Sea with its transport, fish, fur animals, and recreational possibilities or guaranteed yields of valuable agricultural crops (cotton, rice, grape, and others) in areas that in the future would require the whole total flow of the Amudarya and Syrdarya rivers. The latter won. As a result, 50 years later the Aral depredated. With the loss of the sea and the severe environmental disturbances that ensued man failed to receive the expected affluence.

References

1. Kuksa VI (1994) The Southern Sea (Aral, Caspian, Azov and Black) under conditions of anthropogenic stress. Gidrometeoizdat, St.-Petersburg, p 319 (in Russian)
2. Socio-Economic Problems of the Aral and the Aral Sea Region (1990) Academy of Sciences of Uzbekistan. Council for the research of productive forces. FAN, Tashkent, p 143 (in Russian)
3. Akramov ZM, Rafikov AA (1990) The past, present and future of the Aral Sea. Mekhnat, Tashkent, p 144 (in Russian)
4. Lopatin GV, Den'gina RS, Egorov VV (1958) The Amu Darya Delta. AN SSSR, Moscow, Leningrad, p 158 (in Russian)
5. Uzbekistan Guidebook (1963) Tashkent. Gosizdat UzSSR (in Russian)

Reasons for the Environmental and Socio-Economic Crisis

Igor S. Zonn

Abstract The causes of the Aral crisis should be sought in the mismatch between economic structures prevailing in the Central Asian republics and factors related to the possibilities provided by and condition of the circum-Aral ecosystems. Economic development in the region was determined by the political ideology of the Soviet Union with its administrative command system, which led to unwise management of water, land, and other resources.

Keywords Cotton, Irrigation expansion, Political decisions, Water resources management

Contents

1 Introduction

No other natural feature has received so much attention as the Aral Sea. However, only few have dared to write honestly about the causes of its death. Many scientists were guided by time-serving, while lower-rank bureaucrats were shielded from the

I.S. Zonn
Engineering Research Production Center on Water Management, Land Reclamation and Ecology
43/1, Baumanskaya ul, 105005, Moscow, Russia
e-mail: igorzonn@mtu-net.ru

A.G. Kostianoy and A.N. Kosarev (eds.), *The Aral Sea Environment*,
Hdb Env Chem (2010) 7: 75–82, DOI 10.1007/698_2009_20,

problem by strictly following economic plans. Unfortunately, the mass media while presenting the emotional disputes concerning the Aral issue seldom, if ever invited for discussion those specialists for whom the fate of the Aral was more than simply a topic of discussion but a key issue in their daily research.

Today one can hardly find a single scientist who still doubts that the Aral Sea crisis, involving also the coastal territories of Uzbekistan, Kazakhstan and Turkmenistan which were directly affected by the desiccation of the sea, emerged primarily as a result of political decisions sanctioning wide-scale development of irrigated farming which increased the anthropogenic load not only on the sea proper, but on the watershed basins of the Amudarya and Syrdarya flowing into it [1–3].

2 Inherited Ideology of Land Development

In his work Kosarev describes the situation in the Aral and circum-Aral area prior to 1960, when this unique natural body was a lake-sea that was referred to as "the Central Asian pearl." The Aral had important fishery, hunting, transport, and recreational significance. It influenced favorably the climatic and hydrological conditions in this region and many water fowl and near-water birds stopped here for propagation and rest on their migration routes. The Amudarya and Syrdarya rivers flowing into the Aral Sea helped to maintain the dynamic equilibrium of the Aral biosystems. The extensive development of irrigation and related growing application of chemicals in agriculture with a view to alleviate negative natural environmental factors such as climate aridity and lower soil fertility, spurred the "creeping destabilization" of the Aral Sea geosystem which finally led to the ecological disaster that is termed most often the "Aral crisis."

Beginning from the 1960s the government of the USSR formulated tasks for the Central Asian republics requiring them to place new irrigated lands into agricultural use to increase agricultural output, first of all, of cotton and rice. At that time over 4 million ha were irrigated in this region and they were used for cotton growing (Table 1). However, to meet the required targets it was necessary to increase the irrigated areas to 7 million ha.

Such tasks were formulated in special resolutions by the administrative command system and were adopted, in fact, over five-year periods. The resolutions not only fueled the growth of irrigated and drained lands, but, at the same time, cut the input of the Amudarya and Syrdarya waters into the Aral Sea and, as a result,

Table 1 Dynamics of water and land resources utilization in the Aral Sea basin [4]

Indicators	Measurement unit	1960	1970	1980	1990	2000	2006
Population	Million people	14.1	20.0	26.8	33.6	41.5	44.96
Irrigated area	1000 ha	4,510	5,150	6,920	7,600	7,990	8,456
Total water intake	$km^3 yr^{-1}$	60.61	94.56	120.69	116.27	105.0	106.30
Incl. for irrigation	$km^3 yr^{-1}$	56.15	86.84	106.79	106.4	94.66	95.97
Specific water intake	$m^3 yr^{-1}$	12,450	16,860	15,430	14,000	11,850	11,650

Table 2 Party (CPSU CC) and Government (CM) Resolutions on land improvement in Central Asia and their consequences for the Amudarya and Syrdarya flows and the Aral Sea [2]

Year	Irrigated lands in the Aral Sea basin (×1000 ha)	Aral Sea level drop (m)	Average input of the Amudarya and Syrdarya to the sea (km^3)	Resolutions of the governmental authorities
1960–1965	4,241	0.91	42.8	October 1961. XXII Congress of CPSU. Adoption of the CPSU Program which included land reclamation
1965–1970	4,698	1.56	43.7	May 1966. "On the wide-scale development of land reclamation to obtain high and stable yields of cereals and other agricultural crops"
1970–1975	5,350	3.91	26.9	July 1970. "On the perspective land development in 1971–1985, regulation and redistribution of river flow"
1975–1980	6,125	7.14	12.3	
1980–1985	6,895	11.03	4.8	May 1982. USSR Food Program until 1990 which included the problems of land reclamation development October 1984. "On long-term program of land improvement, increase of reclaimed land use efficiency for the stable increment of food stocks of the country"
1985–1990	7,403	14.9	9.5	August 1986. CPSU Politburo Resolution "On the cessation of the work on the partial flow transfer of Northern and Siberian rivers" September 1988. "On measures for fundamental improvement of the environmental and sanitary conditions in the utilization, strengthening and safeguarding of water and land resources in this basin" November 1989. USSR SC Resolution "Concerning urgent measures for improving the environmental conditions of the country"
1990–1991	–	16.6	–	March 1991. USSR SC Resolution "Concerning the implementation of the Resolution of the Supreme Council of the USSR concerning urgent measures for improving the environmental condition of the country related to the problem of the Aral Sea"

All Resolutions are limited to the period of the USSR existence
CPSU CC the Central Committee of the Communist Party of the Soviet Union; *CM* the Council of Ministers

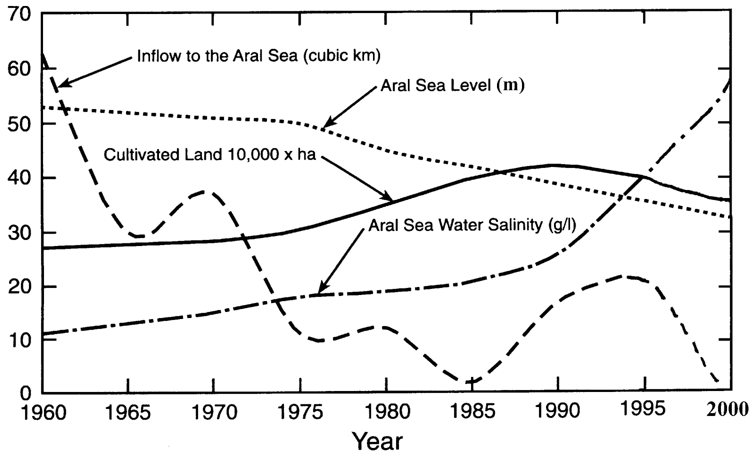


Fig. 1 Environmental conditions of the Aral Sea in 1960–2000

caused the drop of the water level in the sea (Table 2, Fig. 1). Such consequences as well as growing soil salinity, loss of biodiversity, which were later called "the environmental consequences," were not taken into account in these resolutions or decisions. And no alternative plans for Aral region development were considered. The state pursued the main targets to ensure by all means cotton independence, and a further increase of cotton production for the domestic market and for supply to the allies of the USSR – the East European countries. State and local authorities were also interested in irrigation extension because they could then count, and not without reason, on receiving subsidies and material resources that could be used also for other, often quite selfish purposes. At the same time, as a positive factor we should mention the increase in new workplaces in the age-old sphere of farming for the quickly growing population in Central Asia.

Domination of one type of land use, i.e., irrigated farming oriented to monoculture of cotton in the Central Asian republics led to maximum simplification of the structure of the regional socio-economic system, to enhanced dependence on the functioning of one factor – water resources, while almost completely neglecting social dependence on environmental conditions.

The decisions relating to the need and possibility of further wide extension of irrigated farming in the region should be scientifically validated. And, naturally, such ideological scientific validation was provided in spite of the fact that its objectivity stirred great doubts. By the early twentieth century the area of lands potentially suitable for irrigated farming in Central Asia was evaluated at 7.5–8 million ha. In the early 1960s this area was already much greater – 14.1 million ha [5]. In the late 1960s–early 1970s using the land reclamation classification for lands of Central Asia and Kazakhstan it was determined that more than 27 million ha in the Aral basin were suitable for irrigation, therefore, the area of irrigable lands exceeded several times the irrigation capacity of rivers and ground waters of the region.

Therefore, among the political and economic causes of the death of the Aral Sea we can name some interrelated elements: centralized planning, enlargement of agricultural farms, quick development of land irrigation and drainage and water management, agricultural mismanagement and militarization.

3 Cottonization

In 1960 Uzbekistan produced 1 million tons of raw cotton and Turkmenistan – 122,000 tons, and by 1990 the cotton crops had increased to 1.7 million tons and 423,000 tons, respectively. Over these three decades cotton production in the Aral region, in general, had sustained a nearly twofold growth, i.e., from 1.4 million to 2.5 million tons.

In the USSR the Aral region provided 90% of cotton and 40% of rice. The country became cotton-independent. This was achieved, primarily, through extensive irrigated farming ignoring herewith the likely consequences of such agricultural practices.

Such extensive irrigated farming led to unwise development of enormous territories, to development not only of the lands that were suitable, in principle, for irrigated farming, but also lands for which irrigation improvement was not easy due to high salinity or heavy soil texture, unfavorable hydrogeological conditions, etc. And irrigation improvements on these lands brought many negative environmental consequences: secondary soil salinization and formation of large saline drainage flow.

Monoculture farming demanded great quantities of mineral fertilizers and wide application of herbicides, thus, the planned targets for cotton and rice were achieved through application of enormous quantities of mineral fertilizers (up to 600 kg ha^{-1} which is 20 times more than the norm) as well as chemicals and defoliants (15 times more than the norm). Moreover, crop rotations were not observed: from year to year cotton was grown on the same lands, and the situation with rice was the same. As a result, the quality of the cotton and nutritive value of the rice were incessantly deteriorating.

For rectification of such a situation the water application rates were increased three to fourfold everywhere. It should be said here that production of 1 ton of cotton requires 3,000–4,000 m^3 of water, while 1 ton of rice – requires more than 5,000 m^3. And the applied irrigation rates that were not fully scientifically validated ignored many peculiarities of soils and agricultural crops. They were often estimated for the maximum and not most efficient yields and experience had shown that they were, generally, excessive.

It is also a known fact that leaching of saline soils making about 60% of the cultivated lands requires 4,000–5,000 m^3 of water, on the average. Assuming transit water losses from irrigation sources to the field being 30% of the withdrawn water, then the actual water use exceeds twice the needed quantity of water. The result of such practices was a drastic distortion of the environmental equilibrium on irrigated lands.

In 1966 a new idea for organization of large rice-growing plantations in the Lower Amudarya was taking shape. Its realization demanded construction of engineering irrigation systems. Rice being a water-loving plant required for growth a significant increase in water intake and this was in the face of an emerging water deficit due to cotton cultivation. The increase of water intake in the upper and middle reaches of the Amudarya aggravated still more the situation with water in its lower reaches where rice farming was developing. Therefore, certain efforts were made to resolve the problem of water deficit.

It should be noted that certain mistakes were made in the development of new irrigated lands for rice growing. Quite often the construction of engineering systems lagged behind the pace of extension of sowing areas and rice-growing farms seeking to fulfill the planned targets had to cultivate rice on primitively developed lands. And, moreover, many rice-growing systems failed to meet modern requirements. A terraced relief demanded excessive irrigation water use, while small sizes of rice checks lowered the efficiency of machinery, labor, and water resources which affected yields. As a result, the irrigation and drainage conditions of lands deteriorated drastically. By the late 1980s the area under cotton was about 75% with the norm being 70%, the area under rice was 68% with the norm being 85%.

4 Water Problems

In the Soviet Union the management of water resources was based on the following principles: a notion of practically inexhaustible water resources that can be put into use; free-of-charge withdrawal of water from the sources and disposal there of waste waters; centralized control of water use throughout the country where the norms and rules of water use and the related facilities were identical. The chosen strategy targeted towards priority cultivation of water-intensive monocultures – cotton and rice resulted in quicker intake of river flow for irrigation. The situation in some cases became even worse due to irrigation and drainage development of nonsuitable lands and poor design, construction and operation of irrigation systems which was inevitable if one takes into account such a high pace of extension of irrigated areas which had never before been witnessed in the world. The plans for the increased production of cotton and rice demanded extension of irrigated lands which could be attained only through construction of new waterworks and water-management facilities. From 1966 to 1990 the construction of water-management projects and commissioning of the largest irrigation canals in Central Asia, such as Karakum, Karshi, Amu-Bukhara and others whose head water intake varied from 200 to 500 m^3s^{-1} and more, were conducted at a high pace. Large reservoirs such as Andizhan, Charvak, Chardara, Tyuyamuyun, Nurek and others were put into operation and enabled regulation of the flow of rivers in this region. The regulation of the Syrdarya and Amudarya flow reached 94 and 86%, respectively. This caused a nearly doubled water intake from irrigation sources.

By this time due to the applied water use practices the water resources in the region were practically exhausted. The developing water crisis caused by excessive and uncontrolled water intake from rivers was somewhat disguised by disposal of return and drainage waters into rivers that deteriorated the water quality in rivers. In some low-flow years the excess of water intake over disposed waters was as high as 40% giving in 1980 an average of 15–20% over the region. Comparison of water consumption figures with changes in the irrigated land area indicated that the water taken for irrigation was used mostly not for extension of irrigated lands, but for increase of water application rates and these rates were growing not only on newly developed lands, but in the zones of old irrigation, too. The greater application rates caused the groundwater to rise in all territories. The groundwater level rose and varied from 1 to 2 m above the critical level. More than 70% of the irrigated lands were characterized by medium to heavy soil salinity. For this reason the raw cotton yields here were 50–80% lower than on nonsaline lands. This urged construction of artificial drainage systems, collecting-drainage networks. By volume of earth-moving works and unit costs this program was comparable with that of the irrigation systems. The problem of utilization of return flow was resolved, but rather inefficiently, by construction of artificial salinizing lakes. Disposal of their waters into the rivers caused an increase in river water salinity which demanded a further increase in irrigation rates. By 1970 the collecting-drainage waters became the key factor controlling the water–salt regime of the river flow. Therefore, the circle of problems was closed: the problems of money-intensive methods of development of irrigated farming applied under conditions of the socialist economy when the unit cost of the final product – cotton – was, in fact, neglected. Construction took a great deal of time and many systems were not completed, the land commissioning lagged behind the targeted figures. One of the reasons for such a situation was underestimation of the natural factors of the newly irrigated lands. Thus, in particular, the soil conditions turned out to be more problematic than was assumed in the projects that proceeded from analogy with the lands that had already been irrigated. In addition, "sovietization" changed, to some extent, the mentality of the local people who developed a less reverend attitude to water compared with their remote ancestors. Farming became unprofitable and required subsidies. The declared programs on water management improvement, development of water-saving technologies, saving of water resources and others were not implemented because they were not realizable under the political and economic conditions that existed at that time.

5 Conclusions

In an attempt to formulate the causes of the Aral crisis most scientists and specialists agree that the main cause was the wrong strategy for location of water-intensive production forces. Attributing key significance to irrigation together with wider application of chemicals in agriculture and other kinds of anthropogenic impact led to radical changes in the natural environment and economy of this vast region. The Aral crisis differs from other major environmental disasters that occurred quite quickly (Bhopal, India, 1984; Chernobyl, former USSR, 1986). It was and remains still a "creeping" environmental problem, that is, a complex of slowly growing and accruing changes in the natural environment. Over time changes that seemed fairly insignificant developed into a real crisis [6, 7].

The Aral Sea which previously was the climate-regulating factor in the region turned into a dead water body and lost its economic significance. The main consequences of desiccation of the Aral Sea were negative changes in microclimate in the circum-Aral region (a vast territory of the dried sea became a source of hazardous aerosols that drifted for hundreds of kilometers poisoning everything alive on their path), degradation of the sea and delta ecosystems, loss of biodiversity, withdrawal of large areas in the river deltas from agricultural use (due to insufficient fresh water and progressing soil salinization), and greater difficulties obtaining drinking water of good quality (due to growing water salinity and pollution). These negative factors reduced drastically the occupational opportunities for the local population in the Aral region and, thus, intensified migration and worsened the people's health. Today we should not address the issue of saving the Aral, but the issue of saving the Amudarya delta. In other words, we should shift the focus of our attention from the Aral to coping with the problem of international water management. And the fate of the people living in the Aral Sea zone depends on how successfully we can address this challenge.

References

1. Glazovsky NF (1990) Aral crisis. Nauka, Moscow in Russian
2. Zonn IS (1999) The impact of political ideology on creeping environmental changes in the Aral Sea basin. In: Glantz MH (ed) Creeping environmental problems and sustainable development in the Aral Sea basin. Cambridge University Press, Cambridge
3. Saiko TA (1998) Geographical and socio-economic dimensions of the Aral Sea crisis and their impact on the potential for community action. J Arid Environ 39:225–238
4. Atalyev KH, Saparov UB (2007) Control of transborder drainage waters in the Aral Sea basin. Problems of desert development, No 4 (in Russian)
5. Letunov PA (1962) Land stocks and problem of agricultural development of new irrigated lands in the republics of Central Asia and Kazakhstan. In: Integrated utilization of land and water resources in the republics of Central Asia and Southern Kazakhstan. Tashkent
6. Glantz MH, Zonn IS (2005) The Aral Sea: water, climate and environmental change in Central Asia. WMO Publication, Geneva, Switzerland No 982
7. Glantz MH (2003) Water, climate affairs. Island Press, Washington, DC

Regional Climate Variability

Galina V. Surkova

Abstract Climate variations have been registered in the Aral Sea area time and again. In recent decades the anthropogenic effect has become a significant contributing factor. It became prominent, firstly, due to global changes caused, in particular, by the growing level of greenhouse gases in the atmosphere, and, secondly, due to regional variations – shrinking of the Aral Sea area. The latter fact leads to growing continentality of the local climate. During the last century the mean annual air temperature in the Aral region has risen by more than 1°C. The most perceptible warming is recorded in the transitional seasons. Long-term data on precipitation have revealed their great year-to-year variability and some increase of the annual precipitation due to the growing precipitation in the cold season.

Keywords Atmospheric circulation, Climate, Climate variations, Weather

Contents

G.V. Surkova (✉)
Geographical Faculty, Lomonosov Moscow State University, Vorob'evy Gory 119991, Moscow, Russia
e-mail: galina.surkova@gmail.com

A.G. Kostianoy and A.N. Kosarev (eds.), *The Aral Sea Environment*,
Hdb Env Chem (2010) 7: 83–100, DOI 10.1007/698_2009_2,

Abbreviations

HMS	Hydrometeorological station
IPCC	Intergovernmental panel on climate change
PCMDI	Program for climate model diagnosis and intercomparison

1 Introduction

The climate of the Aral region is moderate with the strong continentality revealing itself in the greater seasonal and daily variability of air temperatures and atmospheric precipitation. The flat relief makes the region open to the intrusion of cold air from the north and northeast through Western Siberia. The region is located in the "heart" of Eurasia, quite far from the oceans and this factor results in the lower concentration of water vapor in the atmosphere and, consequently, less precipitation. Because of the aridity of the climate the prevailing landscape forms around the Aral are semideserts and deserts [1–3]. Long-term hydrometeorological observations and historical materials prove the recurrence of climate variations in the Aral region. The response to the global climate events here has its region-specific features caused by peculiarity of its geographical position and shrinking of the Aral Sea area. Related to global atmospheric processes recent decades have witnessed growing air temperature and changes in the water budget of rivers in the Aral Sea basin and the water budget of the sea proper. In addition the anthropogenic factor plays a key role in these variations [4].

2 Present-Day Climate

2.1 Solar Radiation

The quantity of solar radiation received on the Earth's surface depends on two groups of factors: external and internal. The external group may include astronomical factors, such as day duration and sun height. One of the key internal factors is atmospheric circulation. It influences the cloudiness and transparency of the atmosphere and has a large influence on the transfer of energy within the atmosphere.

In the formation of the Aral region climate the radiation factor plays a key role. This refers especially to the warm period when, thanks to clear weather, the incoming solar radiation flux is so strong (Fig. 1a) that the other important climate-forming factor – atmospheric circulation – makes only a minor contribution. The annual duration of sunshine here is as high as 3,000 h, which is 65–70% of that possible. This factor in the Aral region is greater than in the Mediterranean and California which are located on the same latitudes.

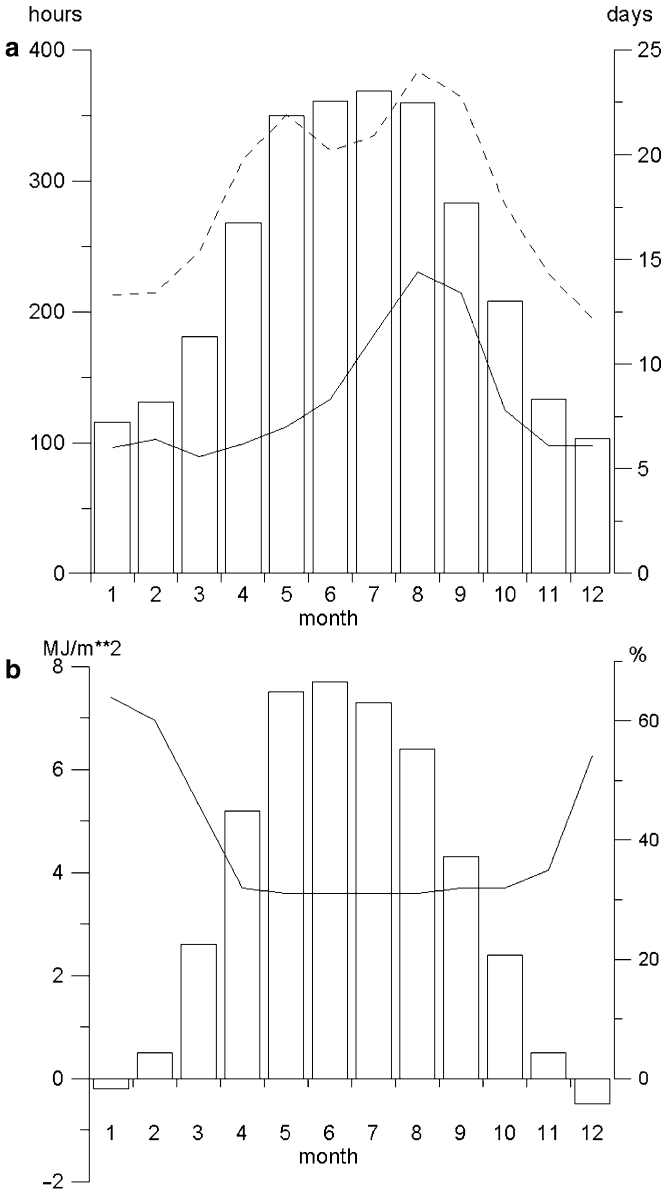


Fig. 1 Annual dynamics of (**a**) the time of sunshine in hours (*columns*) and the number of clear days by the general (*firm line*) and lower (*dotted line*) cloudiness; (**b**) radiation balance (MJ m^{-2}, *columns*) and albedo of the land surface (%, *firm line*), HMS Aral Sea

Such conditions are formed due to frequent recurrence of weather with a small cloud fraction. The number of cloud-free days is the greatest in summer months (Fig. 1a). In the coastal zone of the Aral Sea compared to inland regions the frequency of low-level clouds is greater and may reach 35–40%. During a year the recurrence of totally clear sky has its maximum in August–September (60–65%) and one minimum in December–January and a second minimum in March (34–40%). For sky free from low-level clouds the recurrence at the end of summer is as high as 80–85% and in winter it drops to 50% and less. The number of days without low-level clouds over the Aral is equal to 200–240, and without any clouds – 80 to 100 days.

The monthly radiation budget is negative only in December–January (Fig. 1b) when the effective radiation from the Earth's surface exceeds the short-wave radiation influx, while the albedo of the surface, especially covered with snow, grows drastically. During the rest of the year the surface is intensely warmed-up facilitating formation of hot and dry air.

The types of clouds depend on the season. During the cold season with its frequent inversions and low moisture content in air stratus clouds with small vertical thickness prevail. In the summer over the heated land convection processes are developing, thus, facilitating cumuli formation.

2.2 Atmospheric Circulation

The large Aral Sea in the center of Asia significantly influences weather processes. At present with the decrease of the sea area this influence is gradually weakening.

Northeasterly flows prevail throughout the year in the Aral region. The pressure fields determining the atmospheric circulation regime in the warm and cold seasons of a year differ. In the cold season this region is affected by the wedge of the Asian anticyclone. In the summer in the center of a vast heated mainland in the atmospheric pressure field the effect of the inland thermal depression is great. During summer wind directions are more variable than in winter, but the prevailing effect of the northeasterly transfer is maintained and even tends to grow (Fig. 2a, b). Westerly and southwesterly winds are more seldom observed here. During the transitional seasons the role of the western air mass transfer increases.

Wind velocities in winter markedly exceed the summer ones (Fig. 2d). Practically everywhere in the Aral region their mean monthly values exceed 3 ms^{-1} reaching in some places even 5 ms^{-1} and more, which makes these territories rather attractive in terms of small-scale wind energy development. Strong winds and loose soils – the consequence of the Aral desiccation – create a serious environmental problem as salt and sand drift from the exposed seabed in addition to transfer of chemicals that were once brought into the sea from the fields with river waters. Every year from coastal areas that were up to quite recently at the bottom of the Aral Sea the wind puts adrift more then 75,000 tons of sand and salts [5] and transports them hundreds of kilometers. This causes progressive soil salinization in the Aral Region.

Because of the small depths of the Aral Sea winds blowing even with small velocities create short, but steep waves. Over the flat territories of the Aral region and over the sea surface the wind velocities often reach storm magnitudes. In the

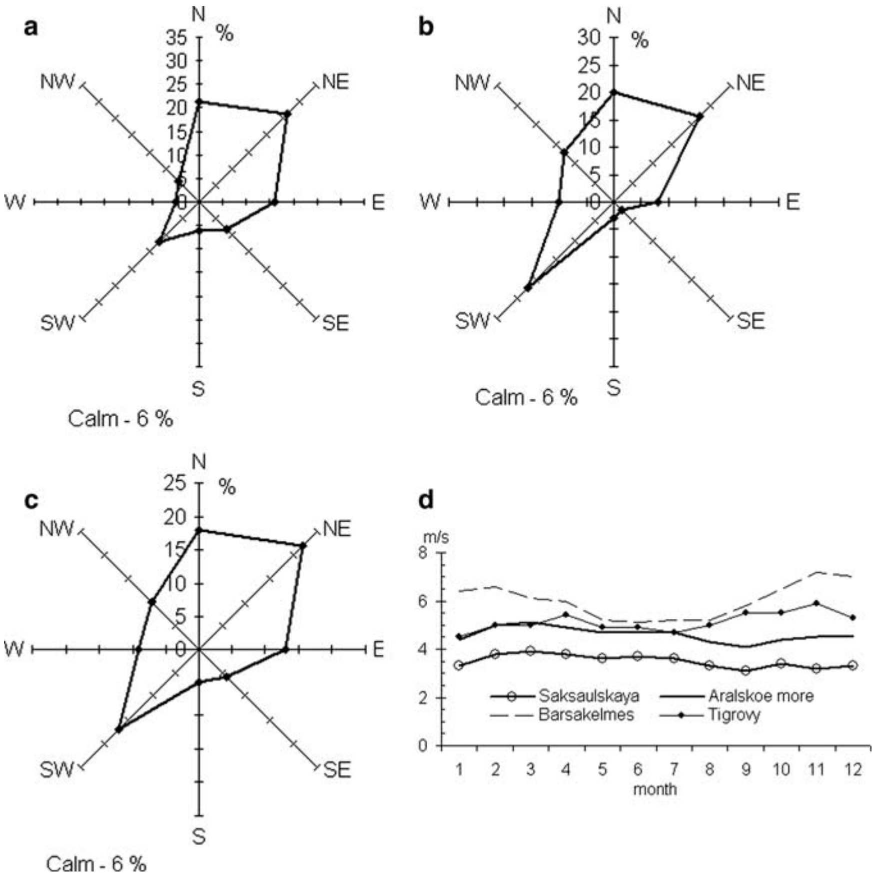


Fig. 2 Frequency of wind directions (%), (**a**) in February, (**b**) in August, (**c**) during a year, HMS Aral Sea; (**d**) mean monthly wind velocity (ms^{-1}), names of HMS are given in the figure

times when navigation and fishing in the Aral were important economic activities the frequent storms were a serious threat to vessels. In the ice-free period there were more than 70 days a year with storm winds. The storm conditions are observed most often during transitional seasons – 8 or 9 days a month and more. In summer the average number of stormy days is about six in a month [6].

Among a variety of synoptic processes typical for Central Asia and the Aral region we can distinguish 11 basic types [7]. Five of them are responsible for about 80% of storm recurrence [6]. Let us consider these types.

Breakthrough of the South-Caspian cyclone (7–8% of storms). In this situation the cyclone which originated in the south of the Caspian Sea moves quickly towards the Aral where it slows its pace and then goes further on to the east or grows weak and sometimes even regenerates. Under such a scenario the systems of atmospheric fronts connected with the cyclone extend sublatitudinally over the Aral Sea. The zones of front passage are characterized by short-term wind outbursts to storm scale. More extensive storm zones are associated with the warm front and a warm sector of a cyclone. In such a situation the wind direction depends on the cyclone's trajectory and on what part of the cyclone is located over the Aral Sea. The easterlies are prevailing.

Northwestern cold anticyclone intrusion (24–25% of storms). The cold anticyclone formed in the Arctic or middle-latitude air masses over the northwestern part of European Russia comes to the Aral region through the Caspian Lowland and Western Kazakhstan. Storm winds are connected here with the approach of the high-pressure ridge and passage of a cold front that draws in cold air masses. The winds lull in the center of the anticyclone and with leveling of the pressure horizontal gradients. The wind direction depends on the location of the anticyclone ridge axis.

Northern cold anticyclone intrusion (7–8% of storms). Cold air from the Arctic or from temperate latitudes over the Urals, Western Siberia, and Kazakhstan rushes southward to the atmospheric depression zone over Turkmenistan. The passage of the sublatitudinally extending atmospheric front over the Aral Sea causes strengthening of northern and northeasterly winds to storm magnitudes.

Southwestern periphery of the anticyclone (26% of storms). Spreading of the Asian high over the Aral region leads to development of high-pressure gradients between this region and the low-pressure zone over Turkmenistan and, as a result, to the increase of wind velocities. The wind direction depends on the position taken by the anticyclone ridge. Northeasterly and southwesterly winds prevail. The specific feature of such a synoptic situation is high stability of wind direction over several days.

Western anticyclone intrusion (21–22% of storms). When in the south of Central Asia the pressure is high, while over the Aral Sea active cyclogenesis or growth of the existing cyclone occurs, the air from temperate latitudes rushes from the west through the Caucasus and Caspian Sea into the Aral region in the rear of the meridionally oriented and quickly moving cold front. These winds bring dust storms that cover vast territories. The passage of the cold front is accompanied by especially sharp wind intensification with wind gusts reaching squally magnitudes.

Concerning *local atmospheric circulations* the most important are breezes that develop in the warm season of a year over the Aral coasts and which contribute much to the formation of weather and climate of the region. The breezes determine the wind direction in the lower atmosphere – onshore in the daytime and seaward at night. The intrusion of the sea breeze in the coastal zone makes the climate milder which is expressed by a lowering of temperature and cloud formation. Desiccation of the Aral Sea has resulted in a weakening of breeze winds and therefore there is less influence of the sea on the temperature and humidity regime in the surrounding territories and, consequently, there is an increase of climate continentality leading to growth of temperatures and higher aridity. Dry winds and dust storms become more frequent here.

2.3 Air Temperature

The temperature regime of the Aral Sea and coastal regions is influenced by radiation factors. This influence is most pronounced in the summertime with its prevailing slightly cloudy weather, long daylight period, and the considerable height of the Sun. In winter the effect of atmospheric circulation on the air temperature is more prominent. Sharp cooling and warming periods may be observed due to alternating cold air intrusions from the north and heat transfer from the southwest. Interannual variability of the air temperature is most significant in the wintertime (Fig. 3a). Great are also the interlatitudinal differences – the mean monthly temperature in January ranges from −12°C in the north of the Aral to −6°C in the south. In the cold season a considerable effect is produced by the Asian anticyclone ridge responsible for intrusion of the cold Arctic or moderate continental air from the northwest, north, and northeast and steady frosty weather. The greatest waves of cold air are associated with the northeastern ultrapolar intrusions. Breakthroughs of southern cyclones cause sharp variations of weather. In winter such cyclones bring with them the intensive efflux of warm air masses and thawing periods. In the rear of southern cyclones the cold-air intrusions cause sharp temperature drops. In spring the thermal regime is unstable – quite often there is recurrence of cold weather and even late frost periods.

The rise of the air mean daily temperature above 0°C occurs in the late decade of March over the whole Aral Sea coast. In the north the return of negative temperatures is marked in the first decade of November, in the south in the first decade of December. In spring the rise of the air daily temperature above 5°C occurs everywhere in late March–early April. In autumn this temperature barrier (5°C) is overcome in late September in the northern part of the sea and in the second decade of December on the southern coast. The frost-free period lasts 220 days in the north and 260 days in the south of the Aral Sea coast.

In summer the heating of the mainland leads to formation of a vast thermal depression in the baric field after hot weather with a few clouds becomes established. Winds formed under low-gradient pressure field are rather weak. This fact and almost cloudless weather lead to strong heating of the surface and air. Cold intrusions from the north are quite probable in summer, but they do not lead to such drastic temperature drops as in winter. Thanks to high values of the radiation balance and the slightly cloudy weather the cold air becomes heated rather quickly. This time the spatial contrasts of the temperature over the sea are smoothed and its mean monthly values are equal to 26–28°C over the whole seashore. In autumn the weather in the Aral region may remain warm for rather a long time period due to prevailing anticyclonic processes. Quite often the winter comes very quickly and this is accompanied by a sharp temperature drop. The mean annual air temperature is positive varying from +7°C in the north to +10°C in the south of the Aral Sea. As the size and depth of the Aral Sea are not large, its effect on the air temperature is minor. Therefore, the shift of the air temperature maximum to August does not occur and the hottest month even in the coastal regions is July.

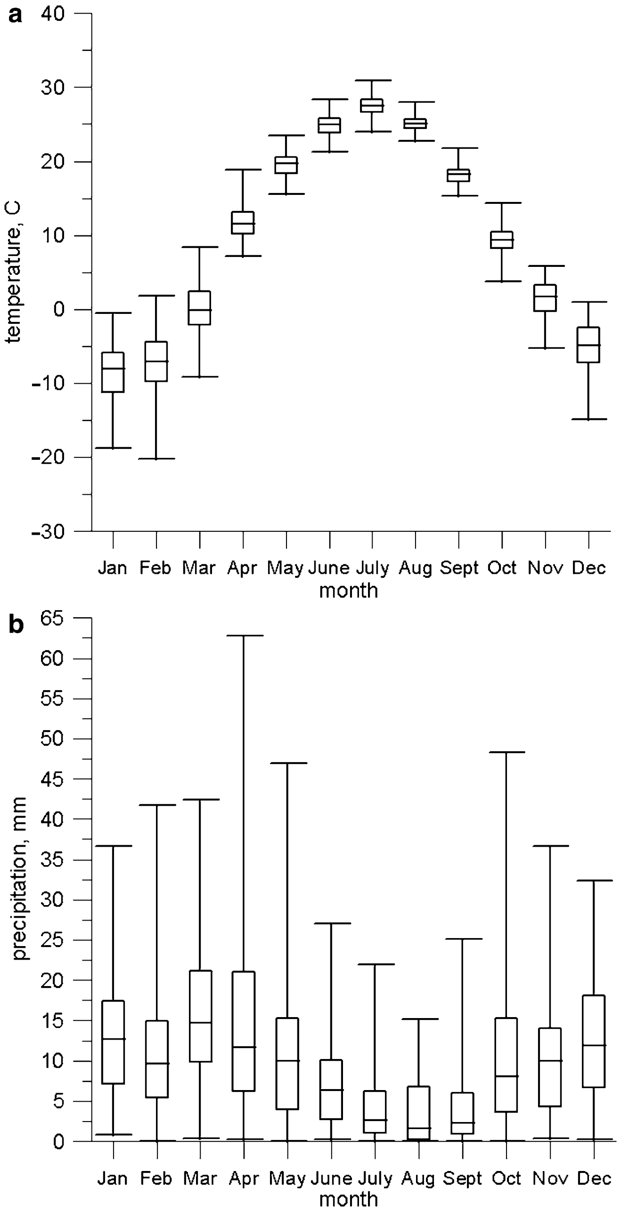


Fig. 3 Annual dynamics of (**a**) mean monthly air temperature and (**b**) precipitation sum in the form of "*box-whiskers*," HMS Aral Sea. A *horizontal line inside the "box"* is a median, *top* and *bottom borders* of the "*box*" – 1st and 3rd quartiles, *ends of a vertical section* – minimum and maximum values

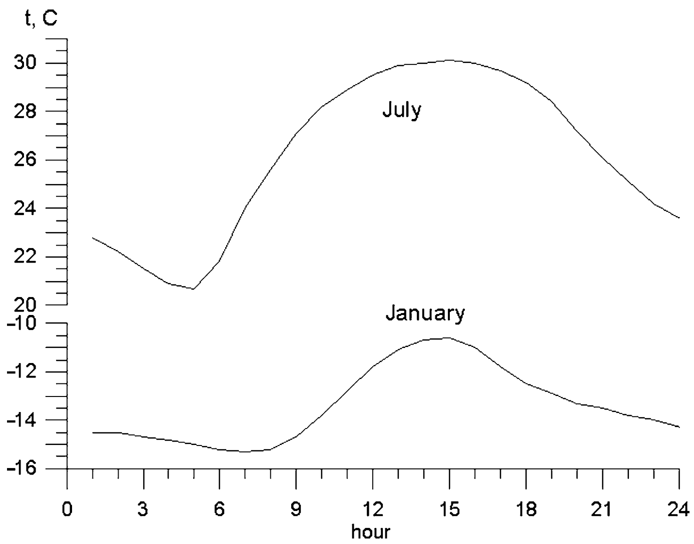


Fig. 4 Daily air temperature course, °C, in January and July, HMS Aral Sea

As a result of intensive heating of air in summer and its significant cooling in winter under conditions of anticyclonic weather or during intrusions of icy air from the north the great temperature variations during a year are observed. But under the conditions of a sharply continental climate there is a great range of not only seasonal, but daily temperature variations (difference between the day and night temperatures), in particular in summer (Fig. 4). On the Aral Sea coast this effect is somehow weakened. In the last decades the shrinking of the sea area has led to the greater spread of extreme values, thus, intensifying the effect of the climate continentality.

2.4 Air Humidity

Air humidity is dependent on many factors – circulation specifics in the atmosphere, evaporation intensity, soil and air temperature. During a year the quantity of water vapor in air as well as the temperature are lowest in winter and highest in summer. Beginning from April the partial pressure of water vapor sharply increases and this tendency is maintained till July (Fig. 5a).

In summer over the heated expanse of deserts continental tropical air is formed which is characterized by high aridity. The humidifying effect of the Aral Sea is felt only within a narrow coastal strip and is most prominent in the midsummer (Fig. 5b). Some increase of air humidity is observed on the banks of the Amudarya and in its delta, but this does not affect the amount of precipitation. In the cold

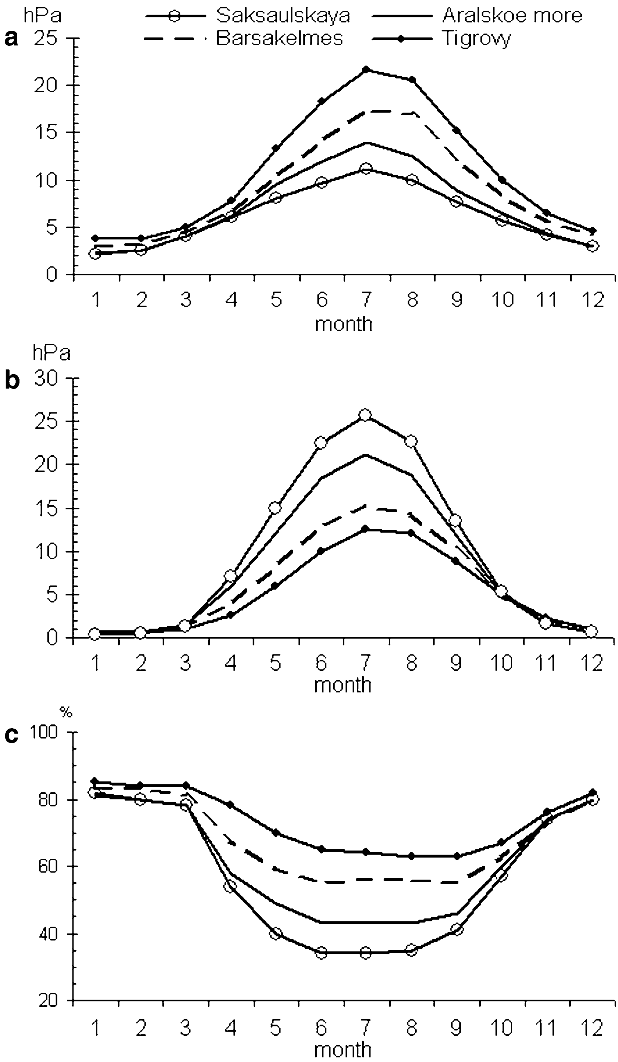


Fig. 5 Annual dynamics of (**a**) partial pressure of water vapor (gPa), (**b**) saturation deficit (gPa), and (**c**) relative humidity (%). Names of HMS are given in the figure

season the cyclonic activity in the Aral region becomes more intensive. This results in increasing precipitation and growth of the absolute and relative air humidity.

The annual and daily dynamics of relative humidity characterizing the air saturation with moisture depends, to a great extent, on the air temperature. The daily dynamics of relative humidity is most prominent in summer when its amplitude combined with a considerable temperature drop during a day may be as high as 15–20%.

On the Aral Sea coast the number of days with relative humidity lower than 30% is much less than in the deserts. There may be only 5–10 such days in a year, while at a distance of 60–65 km from the sea their number may already reach 130–140 days in a year, and at 120–130 km – 190 days in a year. The greatest number of dry days is recorded in May. As a result of Aral desiccation the air humidity in recent years has been reducing significantly.

2.5 *Precipitation*

The Aral Sea coast is characterized by very scanty atmospheric precipitation. The Atlantic air masses, being the main humidifying factor, become desiccated while moving inside the continent or they fail to reach the Aral Sea at all. The sum of precipitation over the Aral Sea is less compared to the coast which is seen in Fig. 6, on Barsakelmes island less precipitation occurs then at coastal hydrometeorological stations.

The cold season is rather dry. During this time the intrusion of cold and low-humidity Arctic air masses or the air masses formed over the continent prevails. In summer the condensation level in the heated air is so high that convectional precipitation is not formed. Atmospheric fronts are the main reason for precipitation in this region. There are two maximums in the annual dynamics of precipitation – the main in spring and the second in autumn. Both are connected with the intensification of cyclonic activities at that time. Interannual variability of precipitation change significantly from year to year (see Fig. 3). In this context the characteristics of monthly sums of various probability become very important. The annual precipitation in the Aral region reaches 90–120 mm. Over the Aral Sea basin as well as in the middle and upper streams of the Amudarya and Syrdarya rivers the precipitation tends to increase to 150–200 mm per year and more in mountainous regions.

The inland location of the Aral basin determines the strong cooling of the water surface and air in winter. This is also caused by a higher reflecting capacity of the semidesert and desert landscapes compared to the coasts of the Black Sea and Azov

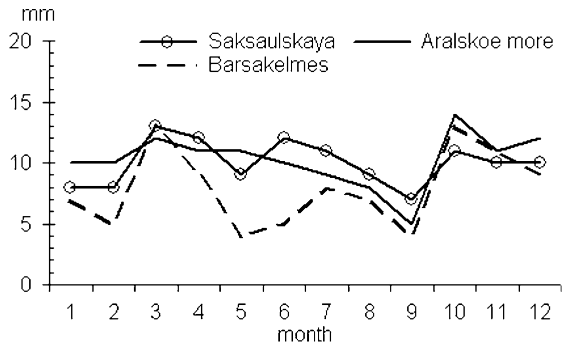


Fig. 6 Annual dynamics of the monthly sums of atmospheric precipitation (mm)

Sea where on the same latitudes the vegetation cover is better developed and more incoming solar radiation is absorbed. In the Aral region the radiation budget in late autumn becomes negative, the temperature decreases below zero and snow is the main form of precipitation. In the Aral region the snow cover starts to be observed usually since 1–15 December and remains solid to early February. The number of days with solid snow cover averages 30–50 a year. Its thickness is not large; the average of the maximum decade values is equal to 5 cm. Last snow usually melts by the first decade of March. At that time snowstorms may occur on the sea coasts – 5 to 10 days a year. Most frequently this event is observed with northeasterly winds.

Among climate phenomena we should mention mists, dust storms, thunderstorms, and hail. Mists are most often observed over the Aral Sea in winter, lasting, on the average, 6 days a month. They are connected with the activity of the Asian anticyclone that facilitates formation of inversions under which the condensation products accumulate. In summer practically no mists occur. Dust storms are recorded, on the average, about 10 days a year [4]. They usually originate at wind velocities of 10–14 ms^{-1}. The visibility in this case may become nearly zero, although more often it drops to 3–4 km. Thunderstorms and hails are rare events in the Aral region, their number decreases from north to south.

3 Climate Variations

Present-day researches have shown that the climate of Central Asia varied rather widely. The proxy paleoclimatic data (sporo-pollen analysis, reconstruction of the levels of ancient lakes, fossil soils, archeological materials) prove that in different time periods essential changes in the water and heat balance were recorded on the territory of the modern Aral basin. The major global climate events, the response to which is detected also in the climate of Central Asia, were Eemian (about 125,000 years ago), the Last Glacial Maximum (about 21,000 yeas ago), and the mid-Holocene optimum (about 6,000 years ago).

Changes in the moistening and temperature regime were fixed during the last millennium. The most prominent events were the so-called Middle Age optimum (about 600–1200 AD) and Little Ice Age (about 1400–1800 AD).[1]

According to paleoreconstructions [8, 9], during the Eemian the air temperature in the Aral Sea area was 2°C higher than at present, while the annual sum of precipitation exceeded the modern values by 100 mm, i.e., more than twofold. It is assumed that the increase in precipitation occurred mainly in winter due to intensification of the western transfer and cyclonic activity.

The response to the Last Glacial Maximum in Eurasia (21,000 years ago) was lowering of the summer temperatures in Central Asia by 2–4°C compared to the

[1]The chronology of these periods is given according to climate events in Europe. But proxy paleodata show climate changes in Central Asia too.

modern ones [10]. At that time the annual precipitation in the Aral region differed insignificantly from the modern one, over the greater part of the Aral watershed it was a dryer climate than now.

In the subsequent millennia the air temperature in the Northern Hemisphere gradually increased. This growth was uneven; in the period 14,000–10,000 years ago it was interrupted more than once by cooling periods. In the mid Holocene 9,000–5,000 years ago the summer temperature in middle latitudes became comparable to the modern one, climate in Central Asia at that time was not as dry as it is now. The bottom sediments in numerous ancient lakes existing at that time in Central Asia alternate with salt deposits, which is indicative of multiple periods of watering and desiccation of these territories. In the mid Holocene the territories of modern deserts were composed of soils typical of steppe landscapes that at present may be found only in regions where the annual sum of precipitation is no less than 200–250 mm. This is approximately twice as large as the precipitation amount at present in deserts and semideserts. Human settlements in these regions also suggest the notion of relative comfort of climatic conditions at that time. The last "wet" period in Central Asia is related to the time of the Middle Age optimum. Archeological excavations have provided evidence of numerous human settlements in the regions that are presently desert and of the development of grain growing at that time.

Therefore, over the whole territory of Central Asia the improvement of humidity conditions occurred during warming in the Holocene, while aridization occurred in the cooling epochs. It is assumed that considerable precipitation changes in the Holocene took place in piedmont and mountain regions of Central Asia which could affect the river flow in the Aral basin. The sporo-pollen analysis has shown that in the periods of global warming the wetting of these regions increased – in the mid-mountain belt the wooden vegetation increased and in the valleys the areas under meadows widened.

Reconstruction of the paleoclimates of the Late Pleistocene and Holocene on the basis of numerical models [11] proves the important role of feedback between vegetation and characteristics of the lower atmosphere in formation of temperature and precipitation regimes in arid regions of Central Asia. Thus, the increased density of the vegetation cover and its changed species composition in the Aral region in that epoch led to reduction of the reflecting capacity of the surface (albedo) and so to the increase of the amount of heat spent on evaporation and transpiration by plants. As a result, there was a change in the ratio between the components of the radiation and heat budget of the surface and lowering of the summer surface air temperature against the global warming. In fact, the direct and proxy paleoclimate data [12] prove that in the global warming epochs the climate in arid zones of Central Asia became milder – the amount of precipitation increased (in particular, in winter) and the summer temperature was lower.

Climatic variations in the Aral region and in its watershed basin are revealed even within smaller time scales [4, 5, 13, 14]. Observations carried out in the twentieth century have shown that the temperature and precipitation regimes were not stable (Figs. 7, 8). The lowest mean annual temperature was recorded in this region in the early 1930s as a result of cold winters. From the mid century the annual temperature was on the rise mostly because the spring months became warmer. Beginning from the 1980s the growth of autumn temperature became obvious. In other seasons the temperature trend was less pronounced than in the transitional seasons. According to estimates of the Intergovernmental Panel on Climate Change (IPCC), the trend of the mean annual air temperatures in the Aral region in 1901–2005 was 1.1–1.7°C per 100 years and only in 1979–2005 it was 0.3–0.7°C per 100 years [16]. Because of the reduction of the mitigating effect of the desiccated sea, the daily positive air temperature in spring sets in later then before [4].

Analysis of temporal variability of the mean annual air temperatures in the Aral region in the twentieth century has not revealed any clear-cut periodicity. On the contrary, the interannual variability of the mean monthly air temperature for months with the same names enabled us to disclose some hidden periodicity. The spectra of a century series of the mean monthly temperature of July and October are rather close and the variation period of 9–10 years is easily discernible. Somewhat different, but similar kinds of spectra were found for winter and spring months. The period of variations for these months is equal to 2–3 years. In the spectrum of the January air temperature the maximums were also recorded in 4, 5–6, and 26–27 years. Similarity of the spectra of the winter–spring and summer–autumn months is a result of inertia in the heating and cooling of the surface.

According to estimates of the IPCC [16] and regional studies [4, 5], in Central Asia in the past century the amount of atmospheric precipitation over the Aral Sea has changed quite insignificantly, its average sums within a century even increased.

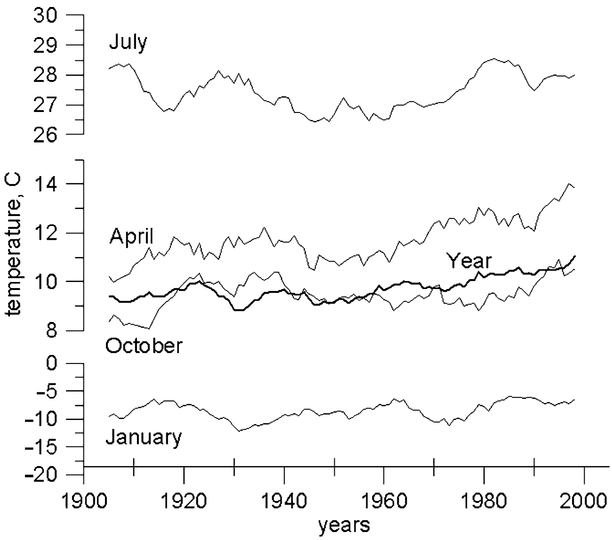


Fig. 7 Variations of air temperature, °C, over the Aral Sea, moving average, averaging "window" 9 years. Estimates were made on the basis of data from [15]

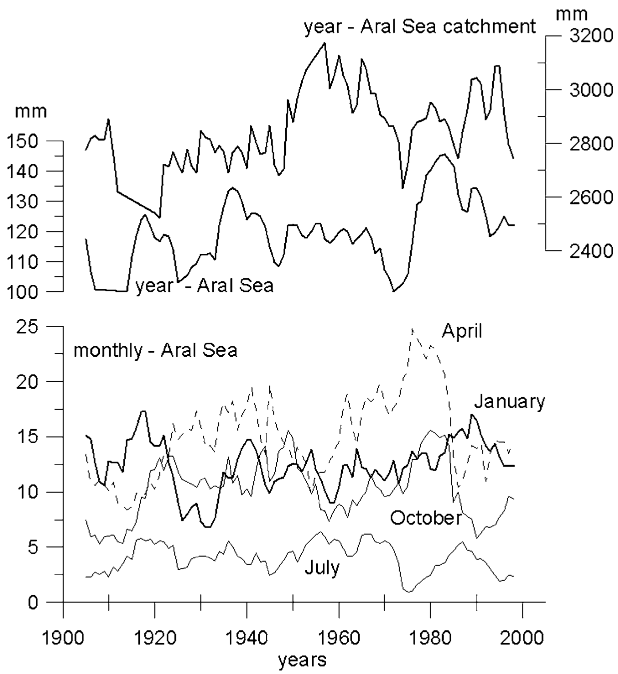


Fig. 8 Variations of precipitation (mm) over the Aral Sea (*left vertical axis*) and over its watershed basin (*right vertical axis*, the averaging territory 37–63 N° and 65–70 E°), moving average, averaging "window" 9 years. Estimates were made on the basis of data from [15]

Thus, during the past century in the Aral basin the annual precipitation increased by 10–20% compared to the mean values estimated for 1961–1990 (the reference period at climate changes studies). The tendency for precipitation variation in different periods of the twentieth century had different signs, and not always were they coherent over the sea and a watershed basin. These nonsynchronous variations may be attributed to the fact that the mechanisms of precipitation formation over the Aral Sea and its coastal zone differ from those acting in the Pamir and Tien-Shan mountains where the major part of the flow of the Amudarya and Syrdarya feeding the Aral Sea is formed. Investigations have shown (for example [17]) that variations of the water level in the Aral Sea are harmonious with the run-off variations of these rivers. The increase of precipitation in the Aral Sea basin may lead to run-off increasing. However, it should be taken into account at what time of year this increase occurs and how the ratio of solid and liquid types of precipitation changes and also how the water consumption in the countries using the water of these rivers changes.

The nature of temporal changes in precipitation is rather complicated. The spectral analysis has shown that the greatest input into interannual variability of the annual sums of precipitation is made by variations with the intervals of 2–3, 6–7, and 20 years.

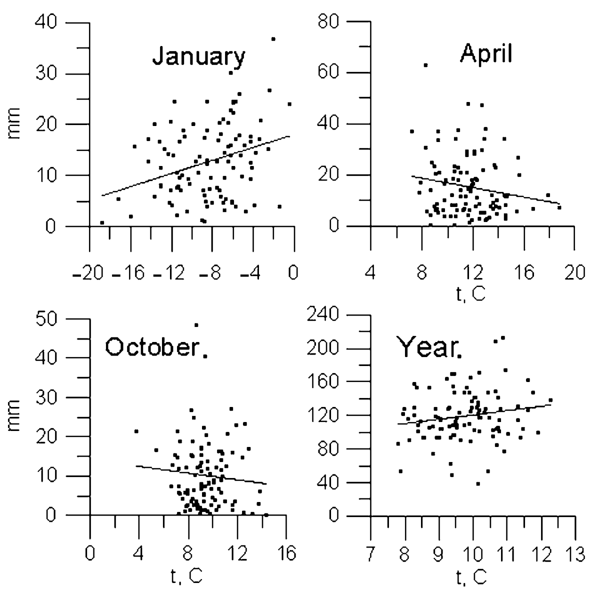


Fig. 9 Comparison of the mean monthly and annual air temperature, (°C, *horizontal axes*), with precipitation sum (mm, *vertical axes*). Estimates were made on the basis of data from [15]

It is difficult to call the changes of air temperature and quantity of atmospheric precipitation in the Aral region in the twentieth century (Fig. 9) harmonious. The spread of their values is rather great. But all the same it is seen that the increase of the January temperature was accompanied, in general, by the increase of atmospheric precipitation. The same regularity, although less pronounced, may be traced in the annual values. In the transitional seasons no unambiguous relationship between the temperature and precipitation may be found. In the summer months the effect is usually opposite to the winter situation – a temperature growth is combined with smaller precipitation.

The Program for Climate Model Diagnosis and Intercomparison (PCMDI) united the efforts of the leading scientific teams for addressing the problem of the global climate forecast. In accordance with the PCMDI plan, the forecast of climatic changes was prepared on the basis of an ensemble of numerical general circulation models of the atmosphere and ocean (21 models) for several scenarios of pollutant and greenhouse gas emissions into the atmosphere [18]. The results of these estimates presented in the last report of the Intergovernmental Panel on Climate Change [16] have indicated that by the late twenty-first century the air temperature in the Aral region depending on the emission scenarios may become 2–7°C higher compared to 1981–2000. According to the forecast, by this time the annual precipitation over the Aral Sea and the Syrdarya and Amudarya basins may increase by 10%. In this case the amount of precipitation in winter will grow by 10–30%, but in summer it will be 10–20% less than in the late twentieth century. Changes in the precipitation regime and rising of the air temperatures may result in redistribution of the effect of the rain, snow and glacier components in the basins of the rivers feeding the Aral Sea.

4 Conclusion

The climate in the Aral region has been subjected to many variations. In the last decade the local climatic changes in the Aral region were connected, on the one hand, with the global processes in the climate system, and, on the other, with shrinking of the sea area and also the geographically related specifics of the regional response to the global climate changes. The reduced mitigating effect of the sea influenced the cloudiness and precipitation regimes, caused the wider range of daily and annual air temperature variations recorded by the coastal stations and also the lowering of the absolute and relative air humidity. Reduction of the sea water mass led to weaker breeze circulation. Exposure of the vast area of the sea bottom due to sea recession caused a greater number of dust storms and the salinization of soils over vast terrains. During the past century the mean annual air temperature in the region has been growing, this is especially pronounced in the transitional seasons. The precipitation amount has somewhat increased mostly in the wintertime. According to a climatic forecast this tendency may be maintained in the next decades.

References

1. Oliver JE (ed) (2005) Encyclopedia of world climatology. Springer, Heidelberg
2. Letolle R, Mainguet M (1993) Aral. Springer, France
3. Sorokina VN, Gushchina D Yu (2006) Climatology, climate geography. Faculty of Geography, MSU, Moscow (in Russian)
4. Chub VE (2000) Climate change and its impact on the natural resources potential of the Republic of Uzbekistan. SANIGMI, Tashkent (in Russian)
5. Alamanov SK, Lelevkin VM, Podrezov OA, Podrezov AO (2006) Climate changes and water problems in Central Asia. UNEP, WWF, Moscow-Bishkek (in Russian)
6. Drejer AA, Shamenkova GA (1963) Waves and wind regime of the Aral Sea. GUGMS SM SSSR, GOIN, UGMS Uz.SSR, Moscow-Tashkent (in Russian)
7. Bugaev VA, Giorgio VA, Kozik EM, Petrossiants MA, Pshenichny A, Ya S, Romanov NN, Chernyshova ON (1957) Synoptic processes in Central Asia. AN UzSSR, Tashkent (in Russian)
8. CLIMAP Project Members (1984) The last interglacial ocean. Quatern Res 21(2):123–224
9. Velichko AA, Grichuk VP, Gurtovaya EE, Zelikson EM (1983) Palaeoclimate of the USSR in Eemian. Izv AN SSSR. Geography 6:30–45 (in Russian)
10. Borzenkova II (1992) Climate changes in Cenozoic. Hydrometeoizdat, St. Petersburg (in Russian)
11. Kislov AV, Surkova GV (1998) Simulation of the Caspian Sea level during the late 20000 years. In: Benito G, Baker VR, Gregory KJ (eds) Palaeohydrology and environmental changes. Wiley, New York

12. Velichko AA, Klimanov VA (1990) Climate of the Northern hemisphere 5–6 ka. Izvestia of the Russian Academy of Science. Geography 5:38–52 (in Russian)
13. Chub VE, Ivanov YN, Subbotina OI, Tolkacheva GA, Toryannikova RW (1996) Review of the scientific and environmental issues of the Aral Sea basin. The Aral Sea basin – NATO ASI, Series, Partnership Sub-series 2, Environment, vol 12. Springer, Berlin, pp 9–21
14. Zolotokrylin AN, Tokarenko AA (1991) About variations of climate in the Aral Region during the last 40 years. Izv AN SSSR. Geography 4:69–76 (in Russian)
15. Mitchell TD, Jones PD (2005) An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int J Climatol 25:693–712
16. IPCC (2007) In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge
17. Nezlin NP, Kostianoy AG, Lebedev SA (2004) Interannual variations of the discharge of Amu Darya and Syr Darya estimated from global atmospheric precipitation. J Mar Syst 47:67–75
18. Nakicenovic N, Swart R (eds) (2000) Emission scenarios. Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Amudarya and Syrdarya Rivers and Their Deltas

Alexander E. Asarin, Valentina I. Kravtsova, and Vadim N. Mikhailov

Abstract Characteristics of the annual flow of the Amudarya and Syrdarya rivers, which determines the water inflow to the Aral Sea and its level regime, are presented herein. On the basis of hydrological observations on the mentioned rivers and their tributaries the annual flow of the Amudarya and Syrdarya rivers in the zones of its formation (natural water resources), inflow to the delta summits and to the Aral Sea is presented over a 75-year timescale. For the same period information concerning water withdrawal from the rivers of the Amudarya and Syrdarya watersheds for economic reasons, including irrigation, is summarized. For the Amudarya and Syrdarya rivers natural flow variations for separate decades in the 75-year (1932–2006) period have been compared with the inflow to the delta summits which covers all kinds of anthropogenic influence in the catchment areas of these rivers. Up to the 1960s the deltas of the Amudarya and Syrdarya rivers, which had received a lot of water and sediments, were among the most dynamic in the world. These azonal objects resisted the deserts of Central Asia and were notable for their high biodiversity and biological productivity. As a result of dramatic man-induced reduction of river's water inflow and a drop of Aral Sea level the deltas of the Amudarya and Syrdarya rivers, their hydrographic network and landscapes have undergone severe degradation. In many respects these deltas have lost their specific "deltaic" natural complex. At present they are artificially flooded only in part. After isolation of the Small Sea in 1987 its water was partly transferred to the Large Sea through the channel in the former Berg Strait. An earth-filled cross-dike was constructed in a channel in 1996 to maintain the level of the Small Sea; in 1999 it was destroyed, and in 2006 replaced with a solid dam. After this the level of the

A.E. Asarin (✉)
Institute Hydroproject, 2 Volokolamskoye shosse, 125993, Moscow, Russia
e-mail: hydro@hydroproject.ru

V.I. Kravtsova and V.N. Mikhailov
Moscow State University, Vorobievy Gory, 119899, Moscow, Russia
e-mail: vik@lakm.geogr.msu.su, vmikh@hydro.geogr.msu.su

A.G. Kostianoy and A.N. Kosarev (eds.), *The Aral Sea Environment*,
Hdb Env Chem (2010) 7: 101–121, DOI 10.1007/698_2009_8,

Small Sea began to depend on the inflow from the Syrdarya river. The level became stable at about 39.5 m (1990)–37.8 m (1991). It was even higher in some years, and the sea area increased (2003, 2005). Recently (in 2006–2008) the level of the Small Sea fluctuated within 41.2–41.7 m. Stabilization of the sea level due to rather small river water inflow was reflected on 2003–2006 space images: the growing mouth cape of the main channel of the Syrdarya river delta can be clearly seen. Thus, one could argue that restoration of delta-forming processes in the mouth of this river is quite possible. It has been established that the statistical parameters of natural river flow variation in the zones of flow formation during the period of stability of the Aral Sea level (until 1961) and during its very strong decrease (1971–2006) are practically invariable. The volumes of annual inflow to the delta summits and to the Aral Sea during different periods in the last 45 years are critically less than those before 1961. The functional relationship between the Aral Sea level variation and the water inflow to the Sea has been revealed. The dynamics of the Amudarya delta in different geological epochs and the Syrdarya delta during the last 70 years have been analyzed.

Keywords Amudarya, Delta, River channel flow losses, River flow, Syrdarya, Water consumption

Contents

1 Introduction

The water budget, level, and salinity regimes of the Aral Sea are practically determined by the value and variation of the Amudarya and Syrdarya water inflow. The fall in water level of the Aral in the last 45 years by more than 20 m and its surface reduction by approximately 3.5 times (from 66,000 to 19,000 km^2) was caused by considerable decrease in the river water inflow. The salinity of the sea water increased from 11‰ in the stable period to 100‰ and more in last decades [1].

During the first 60 years of the past century evaporation from the Aral Sea water plane was equilibrated by inflow from the Amudarya and Syrdarya rivers, and the range of fluctuation of water level around an elevation of 53 m did not exceed 0.5 m [2]. In the second half of 1960 the Aral Sea water level decrease began; it was especially intensive during 1975–1990 and the process is presently ongoing.

According to the references [3–5] and recent investigations the total river inflow to the Amudarya and Syrdarya river deltas, as an average over the period 1931–1960, was equal to 61.7 km^3 per year. During the last four decades because of the growth of irrigated areas and resulting water withdrawals from the catchment basins of the Amudarya and Syrdarya rivers, the inflow to the deltas decreased. During the decade 1961–1970 the average annual inflow volume reduced to 45.9 km^3, in 1970–1980 to 28 km^3, and in 1981–1990 to 19 km^3.

Herein is described the natural fluctuations of the Amudarya and Syrdarya annual flow, the variations in the river inflow to the deltas and to the Aral Sea that occurred (and are still in progress) as a result of economic activities in the drainage basins of the abovementioned rivers. This process is a crucial factor leading to the shallowing and division of the Aral Sea into two parts: the Large Sea and Small Sea.

The 75-year series of annual flow of the Aral Sea catchment rivers has been formed on the basis of the official publications of the Hydrometeorological Service of USSR [6–12], the data on water withdrawal reported by Basin Water Organization "Amudarya," Basin Water Organization "Syrdarya," and the Scientific-Information Center Interstate Coordination Water Commission of Central Asia (SIC ICWC) (Internet sites: www.sic.icwc-aral.uz and www.cawater-info.net).

A hydrographic scheme of the Aral Sea catchment area is presented in Fig. 1.

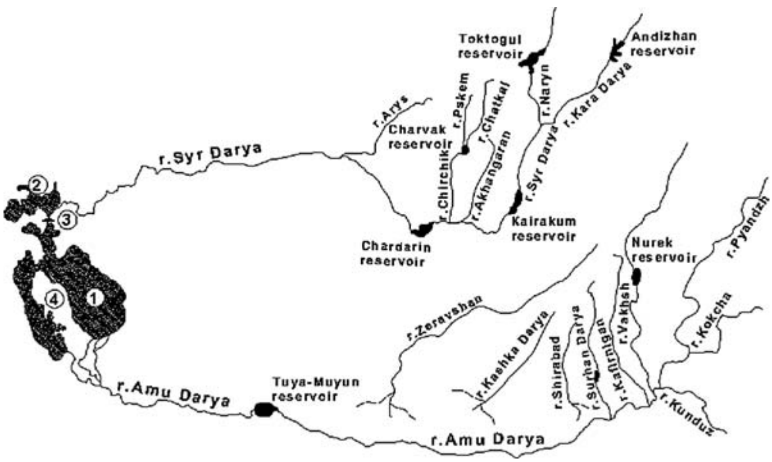


Fig. 1 The Aral Sea catchment area: *1* Large Sea; *2* Small Sea; *3* Dam in the Berg Strait; *4* Peninsula (former island) Vozrozhdeniya

2 Amudarya River

2.1 General Information

The Amudarya, the largest river of Central Asia is formed as a result of confluence of the Pyandzh (catchment area $A = 114{,}000$ km^2) and Vakhsh ($A = 39{,}000$ km^2) rivers. The Amudarya river length is about 1,450 km from the confluence of these rivers to the Aral Sea. The catchment area, including closed drainage zones, is evaluated as 465,000 km^2, the area of the effective drainage basin is 300,000 km^3. The Zeravshan, Kashkadarya, Murgab, Tedjen, and Atrek rivers do not contribute to the Amudarya flow as their water is totally consumed by irrigation.

Downstream of the confluence of the Pyandzh and Vakhsh rivers the following tributaries: Kunduz ($A = 31{,}300$ km^2), Kafirnigan ($A = 11{,}600$ km^2), and Surhandarya ($A = 13{,}600$ km^2) fall into the Amudarya.

The Amudarya flow forms only in the upper, mountainous part of the catchment, more than 60% on Tajikistani territory and about 25% on the territory of Afghanistan [14]. Downstream of v.Kerki its water is consumed due to irrigation and is lost by evaporation in the flooded alluvial plain.

Hydrometric works on the Amudarya river have been conducted since the 1870s [15]. Before the first quarter of the twentieth century the hydrological observations had not been systematic. The longest series of observations are available from the gauging stations of Kerki (1910–1920, 1925–1937, 1952–2006) and Chatli (1913–1917, 1931–1973) [6–10].

Water inflow to the delta summit (discharge sites of Chatli, Samanby, Kizildjar) is much less than the flow values recorded at the Kerki site. On the almost 900-km stretch of Amudarya from Kerki to the delta (and in the delta also) an important volume of water is consumed by irrigation and lost due to evaporation from the flooded alluvial plain and transpiration by hydrofilous plant vegetation.

Amudarya river water is highly mineralized from natural origins (the Pyandzh and Vakhsh rivers bring into the Amudarya about 25 million t per year) and due to anthropogenic factors: discharge of 25 million t of alluvion or sediments saline drainage water from irrigated lands. The main annual salinity of the Amudarya water in the summit of the delta (v.Kysildjar) increased along with irrigated area growth: from 0.5–0.6 g l^{-1} in 1970 to 1.3 g l^{-1} in the 1980s. In the last decade the mineralization has stabilized at 1 g l^{-1}.

The Amudarya water had and has a rather high turbidity: on the average for 1930–1960 42,000 gm^{-3} downstream of the Vakhsh and Pyandzh confluence (v.Kerki) and 2,600 gm^{-3} in the lower course of the Amudarya (v.Chatli). At this point (the delta summit) the mean annual water turbidity changes from 1,900 to 3,300 g m^{-3}, and in some months of the flood period (May–August) the turbidity value may reach 18,000 g m^{-3} being 10,000 g m^{-3} on average. The suspended sediments of the Amudarya have a high mechanical composition: a predominance of particles with a diameter smaller than 0.01 mm.

2.2 Natural Water Resources of the Amudarya

The distribution of drainage basin areas [14] and natural flow of the rivers which reach the Aral Sea according to the authors' estimation is presented in Table 1.

The values of natural flow of the Amudarya for every year in the period 1932–2006 have been determined as a sum of annual volumes of natural flow of rivers whose flow reaches the Amudarya stream. The fluctuation of this flow for the 75-year period is given in Table 7.

As is shown in Table 1 the range of annual flow variation equals 51 km^3 (from 54 km^3 in 1986 to 105 km^3 in 1969). The 5-year period from 1961 to 1965 was very dry with a mean volume of 62.2 km^3 per year i.e., 10% less than the long-term average, very abounding in water was the 8-year period from 1952 to 1959 with a mean annual volume of 74 km^3.

The sampling statistical parameters of the Amudarya annual flow assessed on the basis of the 75-year series are: coefficient of variation $C_V = 0.15$, the coefficient of correlation between flow volumes of adjacent years is close to zero.

2.3 Control and Utilization of Water Resources

The flow of several of the Amudarya tributaries is controlled by the reservoirs. Until 1970 the largest was the South-Surhansky reservoir with an effective storage of 0.71 km^3, the total effective volume of other artificial lakes being 0.1 km^3. In 1975 the Nurek reservoir on the Naryn river, the greatest one in the Amudarya basin (live storage 4.5 km^3), was constructed. The government of Tajikistan plans for the future to construct upstream of Nurek Dam a rockfill dam (the Rogun Dam)—the

Table 1 Characteristics of main tributaries of Amudarya

River	Catchment area (km^2)	Outlet site	Long-time average flow (km^3 per year)
Pyandzh	113,500	Lower Pyandzh	35.9
Vakhsh	39,100	Tiger gully	20.2
Kunduz	37,100	Generalized	4.4
Kafirnigan	11,600	Tartki	5.5
Sukhandarya	13,600	Manguzar	3.4
Kashkadarya	8,780	Khinabad	0.8[a]
Zeravshan	12,300	Dupuli	4.8[a]
Total	235,980		75.0[a]

[a]Incl. 5.6 km^3 which does not reach the Amudarya stream

highest in the world—with a live reservoir volume of 8 km^3. On the Amudarya stream the Tahiatash water intake scheme and Tuyamuyun reservoir with an active storage of 5.2 km^3 are in operation.

From 1956 considerable volumes of the Amudarya flow were transferred by the Karakum canal to arid regions of Turkmenistan. In the last years water delivery by the canal amounts to 10–11 km^3 per year.

2.3.1 Water Consumption

Available information about water withdrawal for irrigation before 1935 is very limited. An indirect assessment of water consumption could be made on the basis of irrigated areas. In 1968–1972 in the Amudarya catchment a large-scale complex of hydrometrical works (during the so-called "Hydrological year") was realized. These works permitted determination of volumes of water diversion from the Amudarya and its tributaries.

Amudarya water resources are and will be expended not only for irrigation purposes but also for industrial and drinking water supply and for pisciculture needs. Annual water consumption for nonirrigation needs in 1970 was 0.5 km^3, and in 1980 and 1990 reached 4 km^3.

The total water consumption and losses in the Amudarya watershed for the period from 1932 to 2006 are shown in Table 2 (according to the data of the State Hydrological Institute in St. Petersburg).

According to data from the Basin Water Organization "Amudarya" web site, in the last years (2001–2007) the volume of water withdrawal from the Amudarya varied from 26 to 44 km^3 per year.

From Table 3 it is clear that the main water user is irrigation. The growth of irrigated areas is presented in Table 3.

It is evident that after 1990 the rate of growth of irrigated areas decreased significantly. New irrigated lands put into operation are located only in Tajikistan and Turkmenistan.

Table 2 Water expenditures in the Amudarya basin

Period	Volumes of water (km^3 per year)			
	Anthropogenic withdrawal		Natural losses (upstream of delta)	Total water consumption and losses
	Total	Including irrigation consumption		
1932–1940	12.1	11.8	15.1	27.2
1941–1950	14.9	14.3	10.3	25.2
1951–1960	18.9	18.0	9.7	28.6
1961–1970	24.0	22.4	8.2	32.2
1971–1980	36.1	32.4	3.3	39.4
1981–1990	51.0	47.0	2.5	53.5

Table 3 Irrigated lands in the Amudarya drainage basin

Country	Irrigated area (thousands of hectares)								
	1950	1960	1965	1970	1975	1980	1990	2000	2005
Uzbekistan	1.06	1.22	1.17	1.28	1.48	1.84	2.30	2.30	2.30
Tajikistan	0.21	0.27	0.29	0.36	0.39	0.42	0.50	0.60	0.65
Kyrgyz republic	–	–	0.01	0.01	0.01	0.02	0.02	0.02	0.02
Turkmenistan	0.35	0.43	0.52	0.67	0.85	0.96	1.30	1.30	1.40
Total	1.62	1.92	1.99	2.32	2.73	3.24	4.12	4.22	4.37

2.4 River Channel Losses

The evaporation loss from the water plane of the channel and flood plain of the Amudarya in the section v. Verkhneamudarynskaya–v. Kerki is 1.5 km^3 per year and on the length of v.Kerki–v.Chatli varies from 10 to 19% of the inflow volume to v. Kerki. The average value of this loss in the period 1932–1970 is equal to 8 km^3 per year.

2.5 Inflow to the Delta Summit and Water Losses in the Delta

The mean values of annual inflow to the summit of the Amudarya delta based on hydrologic observations of gauging stations in v. Chatli (1931–1973), Kyzildjar (1959–1987), and Samambay (1974–1996) for particular time periods are presented in Table 8.

The discharge capacity of the Amudarya channel does not exceed 1,000 m^3 s^{-1}. When discharge is greater submersion of the flood plain begins with water expenditure filling hollows, by evaporation from the water surface of permanent and temporary water bodies, and by transpiration by hydrophilous plants.

During the period of stable Aral Sea levels (before 1961), the total delta area (from v. Chatli to the Sea) made up 9,000 km^2 [11].

Water losses in the Amudarya delta were assessed by several researchers [12–14]. On the grounds of these estimations and data of hydrologic observations recorded in 1956–1970, the authors of this work have shown the water losses in delta depend on the flood magnitude (maximum discharge, water level and inundated area) and annual flow volumes. According to this dependence the volumes of delta losses in the stable Aral Sea period (1926–1960) varied from 1.6 km^3 in 1951 to 15.8 km^3 in 1934 with a mean value of 5.9 km^3. During the decade 1961–1970 the volume of mean annual losses constituted only 3.2 km^3, in spite of the fact that in 1969, the wettest year in 75 years, the water losses in the delta reached 14.3 km^3. During the two last decades outstanding losses were recorded only in a few wet years and their mean value did not exceed 1 km^3 per year.

2.6 Inflow to the Aral Sea

The residual (after all losses) inflow to the Sea gauged on the main water arteries of the delta which reach the sea edge, for the period from 1932 to 1950 was assessed by the authors of this work and by Uzbek Hydrometeorologic Service for 1951–2006. The results of this estimation, which does not contradict the data (shown in Fig. 6) on the water level and the volume of water variations in the Aral Sea changes during 1932–2006, are presented in Table 9.

3 Syrdarya River

3.1 General Information

The Syrdarya, the second largest river in terms of flow volume in Central Asia (catchment area $A = 219{,}000$ km^2) is the result of the confluence of two big rivers: the Naryn ($A = 59{,}900$ km^2) and Karadarya ($A = 30{,}100$ km^2). The Syrdarya is the longest river of Central Asia: its proper length is 2,137 km and the length from the source of the Naryn is 3,019 km. Practically all flow of the Syrdarya forms in the mountains and foothills which border the cotton-growing regions: the Fergana valley, Chrchik-Ahangaran-Keles Irrigation Region (CHAKIR), the Hungry Steppe, and the Dalverzyn steppe. Downstream of v.Chardara the river flow is spent for irrigation needs and evaporation losses from the flood plain. In the 800-km length up to Kazalinsk only one tributary flows into the Syrdarya—the Arys river ($A = 14{,}000$ km^2).

Hydrological observations in the Syrdarya and its tributaries started in the first decade of the twentieth century (from 1900 in Chirchik river at v.Hodjikent, from 1910 in Naryn river at Uch-Kurgan, in Karadarya at v.Kampyr Ravat, and the Syrdarya at v.Begovat). Uninterrupted observations begun in 1926 of most rivers in the Syrdarya watershed [16,17,24].

The salt content of the Syrdarya water at the delta summit (Kazalinsk) over the decade 1961–1970 made up about 1.3 g l^{-1} and with irrigated area growth increased up to 2.2 g l^{-1} in 1985. In the last decades its value has been 1.6 g l^{-1}. The water of the Syrdarya is unfit for drinking both in the middle and lower reaches of the river course.

3.2 Natural Water Resources of the Syrdarya

As mentioned above, the main volume of the Syrdarya water flow forms in the upper part of the watershed. About two thirds of the total water resources of the Syrdarya goes to the Naryn, Karadarya, and Fergana rivers (the flow of the

Table 4 Characteristics of main tributaries of the Syrdarya

River	Catchment area (km^2)	Outlet site	Long-time average flow (km^3 per year)
Naryn	59,110	Uch-Kurgan	13.3
Karadarya	12,400	Kampyr Ravat	4.2
Rivers of Fergana	16,600	Generalized	8.4
Chirchik	11,100	Khodjikent	7.2
Angren (Akhangaran)	5,090	Soldatskoye	0.8
Keles	3,310	Mouth	0.4
Arys	15,100	Mouth	1.5
Total	122,710		36.6[a]

[a]Incl. about 6 km^3 which does not reach the Syrdarya stream

rivers Isfara, Sokh, Akbura, and some others is consumed completely by irrigation and they do not reach the Syrdarya Stream). About ¼ of the Syrdarya flow is provided by the drainage basins of the Chirchik, Angren (Ahangaran), and Keles rivers [14]. The rest of the Syrdarya water flow forms on the southwest slope of Karatau mountain ridge and in the Arys river drainage basin, a considerable part of the flow of these rivers is spent in their proper basins. Roughly 1.6 km^3 per year inflow in the Syrdarya river is the result of groundwater appearance.

The distribution of catchment area of main tributaries of the Syrdarya is shown in Table 4.

The annual long-term average runoff for the 75-year period (1932–2006) is equal to 30.8 km^3, with a coefficient of variation $C_V = 0.23$. The correlation between flows of adjacent years is close to zero.

The annual flow volumes and their mean values for separate decades of the 75-year series are presented in Table 7.

During the 75 years the annual volume of the Syrdarya natural flow varied from 18 km^3 in 1975 to 53 km^3 in 1969. The most water abounding was the decade 1951–1960 with a mean volume of 33.9 km^3, and the most water short decade was 1971–1980 with a mean value of 24.6 km^3.

3.3 Losses of Water in the Channel and in the Delta of the Syrdarya River

Before the substantial growth of water withdrawal by irrigation on the river stretch between v.Kokboulak and Kazalinsk, a considerable volume of water was unproductively spent on evaporation from the water surface of the river channel and the flood plain and by transpiration by hydrofilous vegetation in the flooded and underflooded zones of the river valley. The majority of channel losses were concentrated in the lower course of the river from v. Tumen Aryk and Kazalinsk.

According to the data of simultaneous observations in several sites on the Syrdarya, the wasteful (in addition to irrigation consumption) losses of water before the 1960s made up 6 km^3 per year and varied as a function of volume of inflow to v. Kokbulak. During the last decades during which the majority of Syrdarya flow has been diverted to the irrigated lands the natural losses of water decreased considerably.

Detailed hydrometric works in the Syrdarya delta were realized only in 1963 during the research program named "Hydrological Year." The synchronous observations in six sites, at which 400 water discharges were gauged, have shown that at the section from v. Kara Aryk (45-km downstream of Kazalinsk) to the Aral Sea water losses made up 330 million m^3. However, 1963 was a water short year and the flooded area was insignificant, hence the data for this year are not representative. According to the estimations of different researchers [14,18] based on the flooded areas and evaporation layer the average volume of water losses in the delta is equal to 1.5 km^3 per year.

3.4 Control and Utilization of Water Resources

The flow of the Syrdarya and its main tributaries (Naryn, Chirchik, and Karadarya) is regulated by the Toktogul, Charvak, Andijan, Kayrak-Kum, and Chardara reservoirs, whose parameters are shown in Table 5.

These reservoirs realize the over-year (complete) regulation of the Syrdarya flow, the coefficient of control of total water resources reached a practically boundary value of 0.93. The main regulator of flow is Toktogul reservoir capable of realizing an over-year control of Naryn runoff and the compensated regulation of water resources of the middle and lower stream of the Syrdarya.

In the wet (water abundant) years the excess of inflow to the Chardara reservoir was diverted to the closed drainage Arnasay hollow. In the very high flood of 1969 20.9 km^3 of water was discharged to this water body.

Table 5 Parameters of reservoirs in the Syrdarya catchment

Reservoir	River	FSL (m)	Water plane area (km^2)	Volume (km^3)	
				Total	Effective
Toktogul	Naryn	900	284	19.5	14.0
Charvak	Chirchik	890	40	2.0	1.6
Andijan	Karadarya	905	55	1.9	1.7
Kayrak-Kum	Syrdarya	347.5	513	4.2	2.6
Chardara	Syrdarya	252	900	5.7	4.7

Table 6 Water expenditures in Syrdarya basin

Period	Volumes of water (km^3 per year)			
	Anthropogenic withdrawal		Natural losses (upstream of delta)	Total water consumption and losses
	Total	Including irrigation consumption		
1932–1940	14.0	13.5	6.7	20.7
1941–1950	17.2	16.1	6.0	23.2
1951–1960	21.5	19.6	3.7	25.2
1961–1970	26.3	21.0	2.9	29.2
1971–1980	29.7	25.2	1.7	31.4
1981–1990	35.0	30.0	1.5	36.5

3.4.1 Water Consumption

In the Syrdarya watershed a relatively systematic registration of water abstraction for irrigation and returns into the water drainage system via waste discharge began comparatively recently. The most complete data concerns regions of ancient irrigation—Fergana and CHAKIR where the discharges in the main irrigation canals have been gauged regularly since early 1938. In the period 1940–1950 the registration of the discharges of return water began.

In the process of water consumption and return estimation a 3-year cycle of hydrometrical works realized during 1963–1965 by the program “Hydrological Year in the Syrdarya Watershed” played a very significant role.

Total water expenditure and loss in the Syrdarya catchment over a 59-year period according to the data of the State Hydrological Institute are presented in Table 6.

According to data from the web site of the Basin Water Organization “Syrdarya” in recent years (2001–2007), the volumes of water withdrawal from the rivers of the Syrdarya watershed varied from 14 to 16 km^3 per year, i.e., half of that registered over 1971–1990.

3.5 Inflow to the Delta Summit and to the Aral Sea

The fluctuations of annual inflow to the delta (shown in Table 8), reflecting both the natural variation of river flow and anthropogenic factors (water diversion for economic needs and flow control by reservoirs) are summarized by inflow to Kazalinsk (delta summit) whose annual value is presented in Table 8.

The data in this table shows that the mean 10-year values of the inflow to the Syrdarya delta, which were relatively stable before 1960, started to reduce in the following decades (down to 10.0 km^3 per year in the water abounding decade 1961–1970 and down to 2.3 km^3 per year in 1981–1990. In some years the volume of inflow to the delta dropped to 0.5 km^3. Recently, in a relatively wet period the volume of inflow to Kazalinsk varied from 1.6 to 10.4 km^3 per year with an average (for the last 15 years) value of 8.0 km^3 per year.

Syrdarya water entry into the Aral Sea in the period before 1950 (our estimate) and over 1951–2006 (according to Uzbek Hydrometeorological Service data) are shown in Table 6.

4 Deltas of the Amudarya and Syrdarya Rivers

4.1 Delta of the Amudarya River

The water balance and water level of the Aral Sea are basically controlled by the amount of Amudarya river inflow. Throughout history the sea level has depended on whether the Amudarya river ran into the Aral Sea, the Sarykamysh depression, or the Caspian Sea [19]. In the Late Pleistocene the Amudarya river ran into the Aral Sea and its level was 68–72 m. In the Early and Middle Holocene (up to 2000 BC) water of the Amudarya river went into the Sarykamysh depression and through the Uzboi river to the Caspian Sea. At that time the Aral Sea level was very low (30–35 m). During the Second to First millennia BC the Amudarya river ran again into the Aral Sea and its level rose to 58–60 m. Later, the Amudarya river turned to the west several times which led to a drop of the Aral Sea level (in the middle of the First millennium BC–fourth to sixth centuries AD and in the Middle Ages, in the thirteenth and fourteenth to sixteenth centuries). These were periods of Aral Sea regressions when its level fell to 40–41 m. In the seventh to thirteenth centuries Amudarya river inflow to the Aral Sea occurred again several times and the water level reached 54–55 m. Since the seventeenth century the Amudarya river ran into the Aral Sea and its level became 50–53 m. Further on just stages of higher and lower level were observed. The phase of low level (below 50 m) was characteristic of the beginning of the nineteenth century, and the phase of higher level (about 53 m) for the first half of the twentieth century.

With its high sediment discharge the Amudarya river formed very dynamic deltas in its lower reaches. Repeated changes of the river channel have resulted in formation of at least three large consecutive alluvial-deltaic complexes in its lower reaches [11,20]: the Akchadarya, Sarykamysh, and Aral deltas (Fig. 2). Deposition of Amudarya river sediments has produced an alluvial stratum 80–140 m thick [21].

The latest Aral delta with the summit at the Takhiatash narrow has an area of about 9,000 km^2. Several cycles could be identified in the formation of this delta when catastrophic breaks of the channel into lower parts of the delta took place. In 1937 the Inzhener Uzek by-channel running into the Taldyk Bay of the Aral Sea was formed as a result of such a break. Subsequent sedimentation of the bay and then of the open near shore zone has led to the formation of the so-called Inzhener Uzek delta—the last isolated delta which existed before the modern drop of the Aral Sea level. During the period 1940–1951 its area increased by 152 km^2, i.e., about 13 km^2 per year; it moved 25 km forward into the Aral Sea (an average of 2.1 km per year). During the early phase of Inzhener Uzek delta formation there were

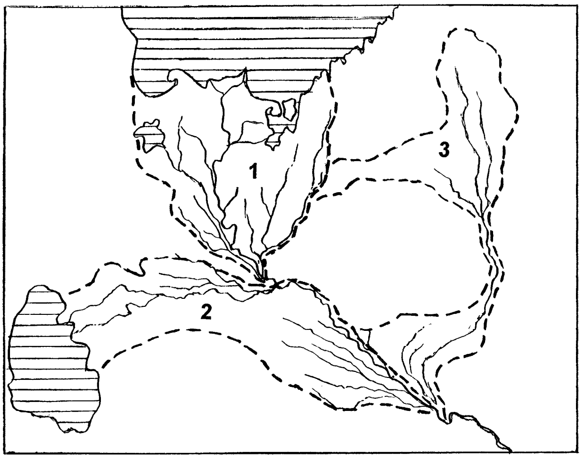


Fig. 2 Ancient deltas of the Amudarya river: *1* Aral; *2* Sarakamysh; *3* Akchadarya

rather numerous by-channels (up to 10–12). By the 1960s their number had reduced to 4–5.

In the beginning of the 1960s the Aral delta of the Amudarya river had active by-channels called Kipchakdarya, Akdarya, Kazakhdarya, Inzhener Uzek, Akkaj, and Urdabai, as well as a network of irrigation canals (Fig. 3). After the decrease of the Aral Sea started in 1961 the number of by-channels was reduced and in the middle of the 1970s there was only one main by-channel branching within the Inzhener Uzek delta. The Inzhener Uzek, Akkai, and Urdabai by-channels were still present until 1975 (Fig. 4). The drop of the Aral Sea level was accompanied by a passive advance of the coastal line into the sea along the edge of the existing delta. The advance of the alluvial cone caused by the sediment flow became less intensive. A rapid drop of the sea level and dramatic reduction of river flow slowed down, and then stopped the formation of the delta; the advance of the coastal line into the sea was mainly passive at that time.

In the 1980s it was only the Urdabai by-channel that carried water to the sea. In 1982 the main channel in the delta was blocked. A fixed fill dam was constructed near the kishlak (village) of Shuak and the residual river water flow coming to the delta was diverted to the left-bank part of the delta for irrigation and watering purposes. According to [13,22,23], the inflow of river water to the Aral Sea was practically zero at that time: in 1982, 1983, 1985,1986, and 1989 there was no inflow of the Amudarya river water to the sea, and in 1984 it did not exceed 4 km^3. According to other sources, the existing water inflow to the Aral Sea was very small during those years (1982 – 0.5 km^3, 1983 – 7 km^3, 1984 – 5 km^3, 1985 – 5 km^3, 1986 – 0.5 km^3, 1987 – 12 km^3, 1988 – 24 km^3, 1989 – 6 km^3, 1990 – 0.7 km^3) [19]. However, the configuration of the coastal line on space images of 1984 and 1989 shows a well-defined cape in the mouth of the former Urdabai by-channel, thus proving a continuing slow advance of the cape into the Aral Sea along with the passive advance of the coastal line. In 1991 the cape was no longer observed, and it

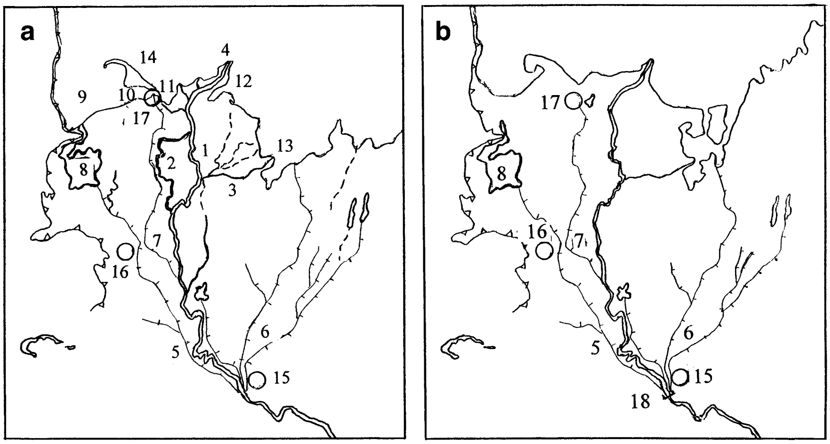


Fig. 3 The Amudarya delta in the beginning of the 1960s (**a**) and in 1974 (**b**). By-channels: *1* Kipchakdarya; *2* Akdarya; *3* Kazakhdarya; *4* Urdabai, canals; *5* named by Lenin; *6* Kyzketken; *7* Raushan; *8* the Sudochie Lake, Bays; *9* Adzhibai; *10* Muinak; *11* Sarbas; *12* Abbas; *13* Dzhaltybas; *14* the Muinak Peninsular, settlements; *15* Nukus; *16* Kungrad; *17* Muinak; *18* The Takhiatash waterworks

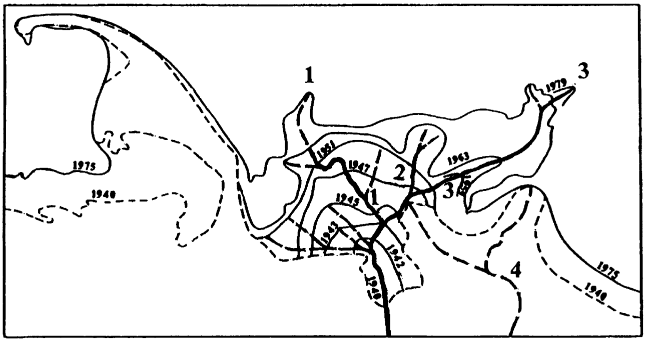


Fig. 4 The Inzhener Uzek delta changes during 1940–1979. Channels: *1* Inzhener Uzek; *2* Akkai; *3* Urdabai; *4* Ulkendarya (in 1890)

has been already partially cut off by coastal processes. Hence, it may be considered that since 1989 the advance of the coastal line of the delta into the sea became passive, and by 2003 it moved 20 km to the north from the latest deltaic cape.

The incision of the main Amudarya river channel, caused by the decrease of the general erosion base, i.e., the Aral Sea level, has led to the disappearance of both by-channels and natural water reservoirs within the delta. The bays of Adzhibai, Muynak, Sabbas, Abbas, and Dzhaltyrbas situated at the edge of the delta have also dried off. Reduced inflow of river waters and their transfer for irrigation needs have principally changed the nature of water inflow to the deltaic lakes [19]. These reservoirs were fed by drainage and exhaust waters with higher amounts of salts

(3–6 g l^{-1}). A large lake area was formed in the delta which blocked the inflow of river and drainage waters into the Aral Sea.

Recently, when the coastal line in the southern part of the Large Sea retreated by 100 km compared with its 1961 position, river waters sometimes came to the reservoir, mainly during overflows over cross dikes and dams of artificial lakes. Fans of such overflow streams could be seen on 2003, 2004, and 2006 space images. The river inflow has slowed the retreat of the sea shoreline which occupied practically the same position in 2005 as in 2004; and the area of the Large Sea was almost the same in 2004 and 2005.

During the period 1950–1960 the Amudarya river delta was a well-watered green oasis between the stony Ustyurt Plateau and the Kyzyl Kum sand desert. The tugai (riparian woodlands) along watercourses, extensive reed stands, lakes and floods were the most typical landscapes of the delta with abundant waterways and reservoirs. Cultural landscapes (irrigated lands) prevailed in the western and eastern periphery of the delta. Rich fauna and flora were characteristic of the delta area and a lot of waterfowl nested or wintered there. Deltaic channels and reservoirs were rich with fish (the annual catch reaching 25,000 t); up to one million muskrats were caught there annually. In the 1930s even Caspian (Turanian) tigers used to live in the tugai.

Dramatic reduction of the amount of water in the delta area as a result of decreasing inflow of the Amudarya river and the drop of the Aral Sea level has brought catastrophic consequences to the deltaic environments. The main effect was the aridization of the delta area, particularly decrease in the ground water table, increase in mineralization, accumulation of salt in the upper soil layer, drainage of lake–marsh complexes and degradation of tugai ecosystems, acceleration of deflation processes, and replacement of hygro- and hydrophytic vegetation by xerophytes and halophytes. Meadow and marsh solonchaks, shors (salt lakes), salt crusts, and barchan sands were formed on the dried bottom of the Aral Sea.

Despite various aridization phenomena the area of lake networks within the delta have undergone just minor changes. Moreover, a lot of cross dikes, dams, and reservoirs were constructed in order to keep water within the delta area. Therefore, the scheme of delta landscape dynamics compiled through comparison of 1975 and 1985 space images (Fig. 5), shows many new water bodies along with vast areas of dried sea bottom within the delta which existed before the drop in sea level. During these 10 years the area of dried lakes was about 190 km^2, while new reservoirs and lakes fed with exhaust waters expanded to over 460 km^2. Accumulation of water in artificial reservoirs could be easily seen on space images of the delta taken in 1991, 2002, and 2003; this became a reason for the cessation of Amudarya river inflow to the Aral Sea.

4.2 Delta of the Syrdarya River

In the lower reaches the Syrdarya river forms a delta the area of which was 6,700 km^2 before 1961. The summit of the delta is near the town of Kazalinsk. The Aksai by-channel breaks away to the left from the main channel 25-km

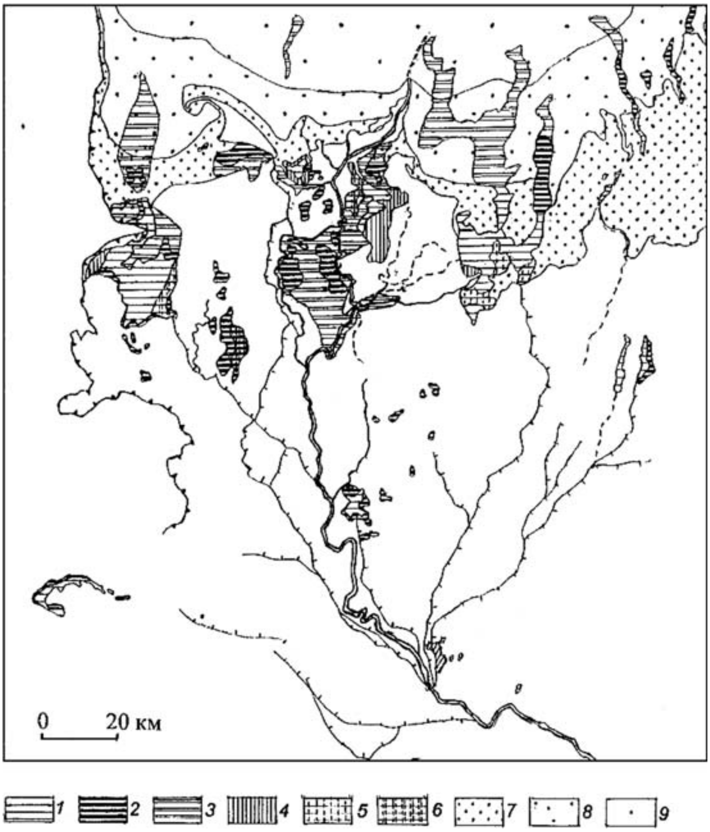


Fig. 5 Transformation of water bodies in the Amudarya river delta. Water bodies of the delta: *1* in 1975; *2* increase of water areas as in 1985; *3* increase of water areas as in 2003; former bottom of water bodies; *4* in 1975; *5* disappearance of water bodies as in 1985; *6* disappearance of water bodies as in 2003. Dried bottom of the sea; *7* as in 1975; *8* as in 1985; *9* as in 2003

upstream of Kazalinsk and goes to the southwest. Till 1960 it ran into the former Bay of Bozkol on the eastern coast of the Aral Sea. 15 km downstream of Kazalinsk several additional channels broke away from the main channel also to the southwest. After turning north the main channel travelled westward and ran into the Aral Sea, forming an advancing delta. Thus, by 1961 the delta of the Syrdarya river included territory between the Aksai channel and the main channel of the river with several channels, irrigation canals, Kamyshlytash, Karakol and other lakes, bogs, reed stands, and irrigated fields.

In the lower reaches the channel of the Syrdarya river ran through its own sediments above the surrounding areas. Therefore, flooding caused by summer high water (the river has mainly snow and glacial sources of water supply), as well as ice jams and zazhors, were frequent during freezing and ice break periods.

The hydrographic network of the Syrdarya river delta was highly variable before the drop in Aral Sea level. Breaking of natural levees during high water periods promoted the rearrangement of the channel network. Water of the Syrdarya river carries a large amount of suspended matter; in the past the sediment runoff in the mouth reached 12 million t per year, 4 million t were deposited within the delta, and it annually moved ahead into the sea by 50–100 m [19].

Retreat of the shoreline caused by the drop in Aral Sea level was particularly rapid on the shallow eastern coast and has changed both the delta itself and its hydrographic network. A wide belt of dried up sea bottom has separated its southwestern by-channels from the main part of the delta. After the retreat of the shoreline the Aksai by-channel went through the former bottom of the Bozkol Bay to the southwest, then turned to the south and formed its own system with lakes–floods. After 1977 the channel went to the west around the plateau scarp and, probably, till 1984 brought water to the Aral Sea. Space images taken in 2001, 2002, and 2003 show the impoundment of the lake network along the Aksai by-channel and ground water inflow to the Aral Sea along the extension of this by-channel. Since isolation of the Small Sea from the Large Sea in 1997 the main (north-westward) channel of the Syrdarya river ran into the Small Sea, thus contributing to the stabilization of its level.

Changes of the environmental situation within the Syrdarya river delta preceded those of the Amudarya river delta. In the second half of the 1970s the inflow of water to the delta summit accounted for only 4% of water resources accumulated within the basin. Since 1971 the spring and summer high waters have not practically occurred. Water of the Syrdarya river was intensively used for irrigation and the inflow to the delta quickly reduced. Since the second half of the 1970s it has not exceed 1–3 km^3 per year. In 1974–1986 the Syrdarya river practically did not reach the Aral Sea [13]. In several places the river channel has been closed by ground dams, and incoming water was used to fill the deltaic lakes and water the pastures. The area of deltaic lakes has decreased from 1,000 to 300 km^2.

Since the end of the 1980s the situation has improved a little due to the increasing river flow and isolation of the Small Sea. In 1990 inflow of river water to the summit of the Syrdarya river delta was 3.4 km^3; about 2 km^3 reached the sea through the main channel, and the rest through lakes and by-channels. In 1991 the inflow of water into the sea was nearly twice that in 1990 [13]. Space images of these years show considerable watering of the delta; the main lake systems are filled with water, and the near-channel meadows are wet.

5 Discussion

Over 75 years of hydrological observations the natural flow of rivers feeding the Aral Sea was relatively stable (Table 7).

The average values (of natural river flow) before and after 1960 coincide practically (101 and 100 km^3 per year), in separate decades of the 75-year period the mean values deviate from the average in the Amudarya by +6% and -12%, in the Syrdarya by $\pm 20\%$, the total water resources of the Aral Sea watershed:

+7% and −11% (in the anomalous 20-year drought period in 1971–1990). Coefficients of variation of total annual flow are practically constant: in 1932–1960 $C_v=0.15$, in 1961–2005 $C_v=0.16$.

In spite of this, the inflow to the delta summits during the first and second half of the 75-year period (and in its separate spaces) differs significantly (Table 8).

From the data of Table 8 it appears that after 1960 the volume of inflow decreased considerably and in the decade 1981–1990 made up 16.6 km^3 per year in the summit of the Amudarya delta and 2.3 km^3 per year in the Syrdarya delta summit. The average value for the last 36 years was 2.3-times smaller than that in 1932–1960.

The decrease of river inflow to the Aral Sea is the result of water withdrawals in drainage basins of the Amudarya and the Syrdarya rivers.

The mean volume of annual inflow to the Aral Sea and the Aral water levels in separate periods are presented in Table 9.

The long-term fluctuations of annual volumes of the natural flow of the Amudarya and Syrdarya rivers (water resources), total inflow to the deltas and to the Aral Sea and main annual water levels of the Large and Small Sea are shown in Fig. 6.

Table 7 Natural flow of the Amudarya and the Syrdarya in the catchment area

Period	Annual flow (km^3)		
	Amudarya	Syrdarya	Total
1932–1940	67.1	28.2	95.3
1941–1950	71.7	29.4	101.1
1951–1960	71.6	33.9	105.5
1932–1960	70.3	30.2	101.0
1961–1970	69.4	31.6	101.0
1971–1980	65.2	24.6	89.8
1981–1990	61.9	27.0	88.9
1991–2000	73.5	34.1	107.6
2001–2006	70.0	37.3	107.3
1961–2006	68.0	30.9	98.9
1932–2006	69.4	30.8	100.2

Table 8 Inflow to the delta summits

Period	Annual volume (km^3 per year)		
	Delta of Amudarya	Delta of Syrdarya	Total
1932–1940	44.9	13.5	58.4
1941–1950	49.2	13.9	63.1
1951–1960	46.0	17.2	63.2
1932–1960	46.7	15.0	61.7
1961–1970	35.9	10.0	46.9
1971–1980	24.5	3.4	27.9
1981–1990	16.6	2.3	18.9
1991–2000	18.9	6.1	25.0
2001–2006	15.6	8.4	23.6
1961–2006	22.9	5.9	28.8

Table 9 River inflow to the Aral Sea and its water level

Period	Inflow to the Aral Sea (km^3 per year)			Water level of the Aral Sea (m)			
	Amudarya	Syrdarya	Total	Large Sea		Small Sea	
				Initial	Final	Initial	Final
1932–1940	36.0	13.4	49.4	53.2	52.7	53.2	52.7
1941–1950	38.9	13.7	52.6	52.6	52.7	52.6	52.7
1951–1960	17.3	16.1	33.4	52.7	53.4	52.7	53.4
1961–1970	10.2	6.5	16.7	53.3	51.4	53.3	51.4
1971–1980	6.9	2.3	9.2	51.0	45.8	51.0	45.8
1981–1990	1.9	1.6	3.5	45.2	38.2	45.2	40.0
1991–2000	7.0	3.7	1.7	37.7	33.6	39.8	39.5
2001–2006	7.6	7.8	14.4	32.6	30.2	41.5	41.5

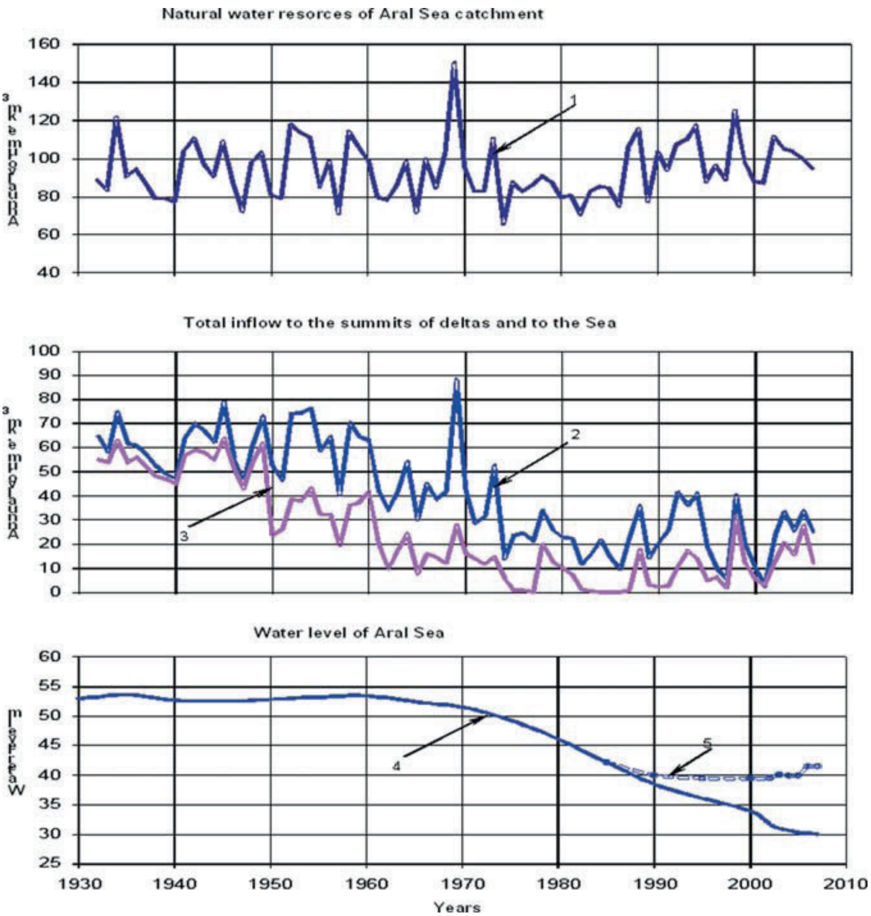


Fig. 6 Total natural flow of the Amudarya and the Syrdarya rivers, inflow to the deltas and to the Aral Sea, water levels in the Aral Sea: *1* natural flow; *2* and *3* inflow to the deltas and to the Sea; *4* water level in the Large Sea; *5* water level in the Small Sea

The analysis of the dynamics of the Amudarya and Syrdarya river deltas over historical time and, particularly, in the twentieth century, indicated that until the 1960s they were among the most changeable deltas in the world. In the first half of the twentieth century the high sedimentary load of the rivers and stable level of the Aral Sea provided for their rapid advance into the sea. The Amudarya river delta was advancing by 2.1 km per year and its area increased by 13 km^2 per year; in this respect it was second only to the Huang He river delta.

A sharp decrease in water and sediment inflow of the Amudarya and Syrdarya rivers to the Aral Sea and the drop of its level has resulted in slow-down and then termination of the active, i.e., through accumulation of river sediments, advance of the deltas into the Aral Sea. Their hydrographic network, landscapes, biological resources have experienced severe degradation. At present only artificial watering is possible for some parts of the deltas.

6 Conclusions

1. Variation of natural water resources forming on the Aral Sea watershed are characterized by moderate variability both during the stable period of the Sea and in the last 45 years. The average volume of the Amudarya annual flow in 1932–1960 and 1961–2006 is equal to 70.3 and 69.4 km^3 per year and $C_V = 0.15$. The analogous Syrdarya flow is 36.2 and 36.8 km^3 per year with $C_V = 0.18$ and 0.20.
2. The volume of water withdrawals increased in the last decades from 12 to 50 km^3 per year in the Amudarya drainage basin and from 14 to 35 km^3 per year in the Syrdarya catchment area. Correspondingly the summary inflow to the delta summits of the mentioned rivers reduced appreciably: from an average value equal to 61.7 km^3 per year in 1932–1960 to 28.8 km^3 per year in 1961–2006.
3. Through an 850-mm layer of effective (minus precipitation) evaporation from the Aral Sea surface the water level of the Sea decreased by 23.3 m from 53.4 m in 1960 to 30.1 m in 2006.
4. Under the actual economic state of the Aral catchment area with the expected variation of total water inflow to the Sea over a range of 5–25 km^3 per year the water level of the Large Sea could vary from 29 to 33 m. The water level of the Small Sea is controlled by the dam in the Berg Strait.

References

1. Mikhailov VN, Kravtsova VI, Gurov FN (2006) Variation of the hydrological state of the shoreline of Aral Sea. In: Sovremennye global'niye izmeneniya prirodoiy sredy (Actual global changes of natural environment), vol 2. Nauchny mir, Moscow (in Russian)

2. Reference book of main hydrological characteristics in the Aral Sea, vol 14. USMS Uzbekskoy SSR (1972) (in Russian)
3. Asarin AE (1964) Level regime of the Aral Sea under development of water consumption in the Syrdarya and Amudarya Basins. Trudy Gidroproekta 12:211–221 in Russian
4. Asarin AE (1973) Components of the Aral Sea water balance and their influence on long-standing fluctuations of its water-level. Vodnye Resursy 5:29–40 in Russian
5. Dunin-Barkovsky LV (1967) Irrigation development and the destiny of Aral Sea. Problemy preobrazovaniya prirody Sredney Azii (Problems of the Central Asia nature transformation). Nauka, Moskow in Russian
6. Surface water resources of the USSR, vol 14, Central Asia, Issue 3. Amudarya River basin. GIMIZ (1971) (in Russian)
7. Annual data on the regime and resources of inland surface water, vol 4. Uzbek SSR. Tashkent (1983–1988) (in Russian)
8. Annual data on the regime and resources of inland surface water, vol 5(3) Kazakh SSR. Obninsk-VNIIGMI-MTsD (1984–1989) (in Russian)
9. Long-term data on the regime and resources of inland surface water, vol 4. Uzbek SSR. Gidrometeoizdat, Leningrad (1987) (in Russian)
10. Principal hydrological parameters, vol 14(3). The Amudarya River basin. Gidrometeoizdat, Leningrad (1967, 1976, 1980) (in Russian)
11. Rogov MM (1957) Hydrology of the Amudarya Delta. Gidrometeoizdat, Leningrad, p 255 in Russian
12. Hydrometeorology and hydrochemistry of USSR's Seas, vol 7. Aral Sea. Gidrometeoizdat, Leningrad, 190 pp (1990) (in Russian)
13. Mikhailov VN (1997) River deltas of the Aral Sea drainage area. Ustya rek Rossii I sopredelnykh stran: proshloe, nastoyashee i budushee (River mouths of Russia and adjacent countries: past, present and future). GEOS, Moskow, pp 361–373 in Russian
14. Shul'ts VL (1965) The Rivers of Central Asia. Gidrometeoizdat, Leningrad, p 692 in Russian
15. Dorand FB (1878) Hydrometrical investigations on the Amudarya. In: Trudy Amudar'inskoy Ekseditsii (Proceedings of the Amudarya expedition), No. 4. Russk Geogr Obshchestvo, St-Petersburg, 150 pp (in Russian)
16. Surface water resources of the USSR, vol 14, Central Asia. Issue 1. Syrdarya River basin. GIMIZ (1969) (in Russian)
17. Principal hydrological parameters, vol 14(1). The Syrdarya River basin. Gidrometeoizdat, Leningrad (1967, 1974, 1978) (in Russian)
18. Korganov AS (1969) Water balance of the lower reaches the Syrdarya (from Chardary to the Aral Sea). Problemy Osvoeniya Pustyn' 5:56–64 in Russian
19. Shekhovtsev AA, Bortnik VN (1991) Present-day geoecological state for the lower Syrdarya and Amudarya and Aral Sea. Meteorolodiya i Gidrologiya 10:112–115 in Russian
20. Kes' AS (1991) Natural history of the Aral Sea and its Region. Izv AN SSSR Ser Geogr 4:36–46 in Russian
21. Rogov MM, Khodkin SS, Revina SK (1968) Hydrology of the Amudarya Delta Region. Trudy GOIN 94:268 in Russian
22. Bortnik VN, Kuksa VI, Tsytsarin AG (1991) Present status and possible future of the Aral Sea. Post Soviet Geography 33(5):315–325 in Russian
23. Basic tenets of conception of conservation and restoration of the Aral Sea, normalization of ecological and socio-economic situation in Aral Sea region. Izv AN SSSR Ser Geogr No 4, 8–12 (1991) (in Russian)
24. Long-term data on the regime and resources of inland surface water, vol 5. Kazakh SSR. Gidrometeoizdat, Leningrad (1987) (in Russian)

Physical Oceanography of the Large Aral Sea

Peter O. Zavialov

Abstract The objective herein is to summarize the present state of knowledge of the hydrological system of the Large Aral Sea and quantify the profound changes to its physical regime that have been witnessed over recent years. The discussion is mainly based on original observations from several field surveys of the sea conducted between 2002 and 2008. The total drop of the Large Aral Sea surface level since 1960 is over 24 m. Compared with the predesiccation state, the salinity increased by a factor of 12 and 21 for the western and the eastern basins, respectively. Starting from the mid-1990s, the penetration of saltier and denser water from the shallow eastern basin into the deeper western basin played a major role in the build-up of the vertical stratification in the sea. The interbasin exchanges, however, tended to become less significant as the strait connecting the basins became shallower and narrower following the continuing level drop. An important finding of the recent field research is the discovered "self-deepening" of the strait, i.e., the formation of a channel the depth of which today is about 5 m, associated with the erosion of the bottom by currents. The surface circulation of the western basin apparently remains anticyclonic, and the deep circulation cyclonic, under the predominant winds. Seiches (both surface and internal) may play an important role in the dynamical regime of today's Aral Sea. In particular, seiches with a period of 48 h and magnitude of up to 10 cm in the surface level and over 10 cm s^{-1} have been observed in the western basin. Internal waves with a wavelength of 15–20 km and amplitude up to 5 m have been documented in the pycnocline, which may constitute an important mixing mechanism.

Keywords: Large Aral Sea, Salinization, Stratification, Thermohaline regime, Internal waves

---

P.O. Zavialov
P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, 36 Nakhimovsky Pr., 117997 Moscow Russia
e-mail: peter@ocean.ru

A.G. Kostianoy and A.N. Kosarev (eds.), *The Aral Sea Environment*, 123
Hdb Env Chem (2010) 7: 123–145, DOI 10.1007/698_2009_4,

Contents

Abbreviations

ppt “Parts per thousand” = grams (of salt) per kilogram (of water)
SST Sea surface temperature
TS temperature–salinity
psu Practical salinity units

1 Introduction

The objective herein is to summarize the present state of knowledge of the hydrological system of the Large Aral Sea and quantify the profound changes to its physical regime that have been witnessed over recent years. The discussion is mainly based on original observations from several field surveys of the sea conducted between 2002 and 2008. The surveys were confined to the principal, southern constituent of the Aral Sea, known as the Large Sea. Accordingly, the scope of what follows is restricted to the Large Sea only. This discussion is intended as a review and contains some recent unpublished data, as well as some data that have been previously published elsewhere (in particular, [1–3]).

In the Introduction, we address the historical background and briefly describe the “initial” physical state of the Aral Sea prior to the onset of desiccation and at the early stages of the contemporary regression. In Sect. 2, we provide details of the field campaigns and data used. In Sect. 3, we focus on the present thermohaline structure of the sea and its variability. The physical mechanisms likely responsible for the observed changes of the thermohaline fields pertain to the sea circulation and exchanges between different parts (hereinafter referred to as the basins) of the Aral Sea. These issues are discussed in Sect. 4. We then draw summarizing conclusions in Sect. 5.

To appropriately evaluate the ongoing changes of the Aral Sea, one must recall its original, predesiccation state. With its 1,066 km^3 of total volume, 66,000 km^2 of area, 64 m of maximum depth, and about 56 km^3 of average annual freshwater supply from rivers, the Aral Sea was a brackish water body. Its salinity spanned around 10 ppt and never exceeded 12 ppt. Generally, the water mass of the sea was amazingly spatially uniform: except for the estuarine areas of the Syrdarya and Amudarya rivers, the difference between the surface and bottom salinities was

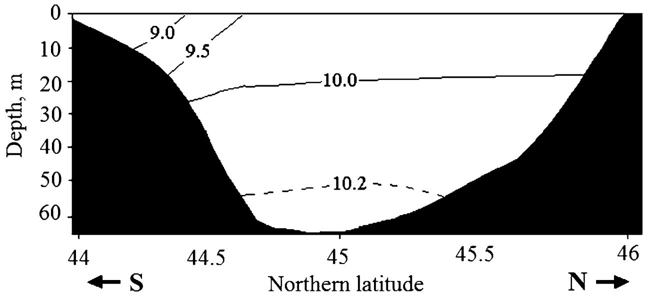


Fig. 1 Salinity (ppt) distribution in summer, typical for the predesiccation Aral Sea. Longitudinal vertical section through the western deep basin, along the track shown by the *dashed line* in Fig. 2. The figure is drawn based on the data presented in [4] and [5]

merely a few tenths of ppt (Fig. 1). Horizontal variability of salinity was also very slim: overall, 2–3 ppt at the very most, and again, the minimum values were mainly associated with the estuarine plumes. The main part of the Aral Sea away from the river mouths exhibited very small spatial variability (Fig. 2). The seasonal cycling of salinity was largely negligible [4]. At the same time, temperature demonstrated rather energetic variability, both spatial and temporal, at different scales. The seasonal range of the SST was over 25°C, and horizontal SST gradients often exceeded 6–8°C per 100 km. The vertical stratification of temperature was also typically strong: in the bottom part of the western trench (depths over 60 m), temperature remained nearly constant at 2–4°C throughout the year, while the near-surface water masses in summer were as warm as 23–25°C, forming a steep thermocline at 20–30 m depths. Hence, not surprisingly, the density fields were mainly governed by temperature rather than salinity (we shall see from what follows that this situation has largely changed during the sea's desiccation). The σ_t density values spanned between some 5 kg m^{-3} in summer and nearly 10 kg m^{-3} in winter and spring, with the surface-to-bottom density differences sometimes attaining 3 kg m^{-3} in summer, but, generally, small in other seasons [5].

In consequence of the mild vertical stratification of the predesiccation Aral Sea, the entire water body of the sea was fully ventilated down to the bottom in all seasons. Moreover, most of the Sea was oversaturated with oxygen. The overall average content of oxygen was 6.27 ml^{-1}, or 101% of the saturation value, but oversaturation up to 180% has been observed near the northeastern shore [6]. The Sea remained well ventilated during the first decades of the desiccation until the late 1980s [5].

The notion of the predesiccation Aral Sea circulation is somewhat speculative, given that extremely few (if any) direct current measurements have been reported. However, already the early researchers [7, 8] perceived the most peculiar feature of the sea's basin-scale circulation, namely, its anticyclonic direction (although there was also a hint of a smaller cyclonic gyre north of Barsakelmes Island [4, 9]). As is well known, the neighboring enclosed seas lying in the same latitude belt, such as the Black Sea, the Sea of Azov, and the Caspian Sea, all exhibit cyclonic

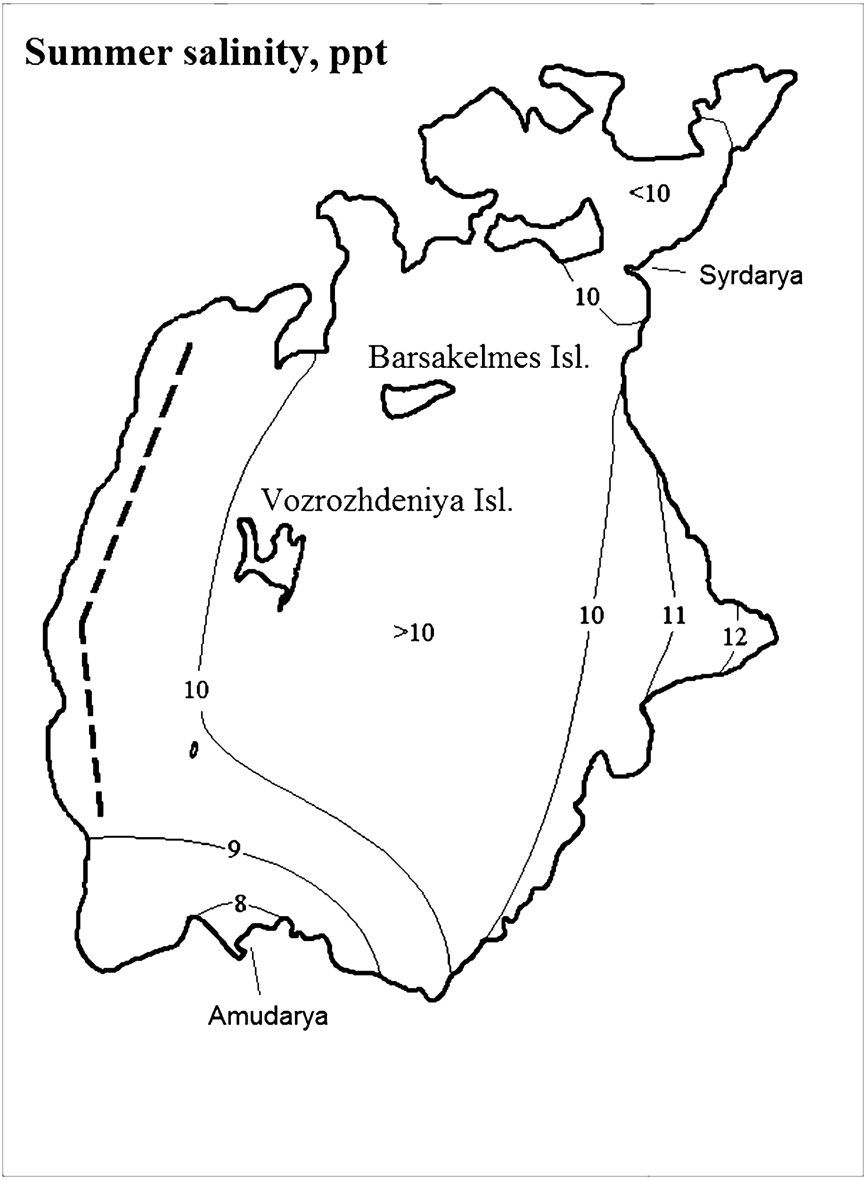


Fig. 2 Surface salinity (ppt) distribution in autumn, typical for the predesiccation Aral Sea. The figure is drawn based on the data presented in [4] and [5]

basin-scale gyres. The opposite sign of the Aral Sea surface circulation has been hypothetically attributed to a combined effect of the regional winds (of which the predominant are the northeasterlies), specifically positioned sources of buoyant river discharges, and the bottom topography of the Aral Sea. The winds led the currents by 12–20 h [10]. There were no measurements of currents in the bottom layer, but some model results suggested that the bottom circulation direction was opposite to that of the near-surface one, mainly because of the barotropic adjustment, with the level of "no motion" located at a depth of 15–25 m [11]. The near-bottom advection of saltier and, hence, denser water from the shallow eastern basin has been suspected to be responsible for the vertical structure in the deep layers of the western trench [12] (it will be shown in what follows that the importance of this mechanism greatly increased during the desiccation). As that in any enclosed basin, the Aral Sea circulation was also characterized by the presence of seiches. The principal seiche was reported to have a period of 23 h and amplitude of 10–20 cm in the terms of the surface level [13].

To summarize the predesiccation state of the Aral Sea, it can be said that many of its physical characteristics were mainly controlled by thermal rather than haline variability. On the other hand, salinity was an important factor driving the vertical and horizontal circulations. The brackish water body was fairly homogeneous spatially; the vertical density stratification was relatively small as well. The sea was always well mixed and fully ventilated, which was perhaps the most generic characteristic of the "old" Aral Sea, largely determining the character of its biological communities. Vertical mixing was partly sustained by thermal and haline convection.

The desiccation began in 1961, and by the date of this writing (September 2008) the total level drop was over 24 m. With its present volume of only about 110 km^3, including 70 km^3 in the Large Sea and 40 km^3 in the Small Sea, the sea has lost nearly 90% of its water. Salinity increased accordingly (see Sect. 2 for quantitative details). We demonstrate in the remainder of this discussion that the ongoing desiccation and shallowing of the Aral Sea have resulted in profound changes to its physical regime.

In the Soviet era, the Aral Sea was one of the best-explored seas of the former USSR. The physical regime of the Sea was subject to extensive monitoring by means of research cruises conducted several times a year, continuous observations at as many as 11 coastal meteorological stations, aircraft surveys, and other methods. Unfortunately, these activities ceased by the early 1990s, and since then field observations in the sea have been sparse. In part, this was because of the economic and political troubles the region faced following the disintegration of the USSR. In addition, by the time navigation in the Aral Sea had stopped completely, and the shoreline had retreated far away from any infrastructure, organization of field work became logistically very difficult. As a result, at the beginning of the millennium, many basic characteristics of the rapidly changing Aral Sea environment were practically unknown.

In 2002, the Shirshov Institute of Oceanology of the Russian Academy of Sciences (SIORAS) in collaboration with a number of institutions in Uzbekistan and Kazakhstan launched a long-term program of field research and monitoring of the Aral Sea. The results presented below are mainly based on the data collected thereby.

2 Data and Methods

A summary of the hydrographic field work accomplished to the date of this writing is given in Table 1, see also the map of stations in Fig. 3. Nine expeditions have been realized from November, 2002, through June, 2008. Some of them were divided into separate legs in different parts of the sea (Table 1). Until 2004, the field campaigns were limited to the western basin, which is technically and logistically easier to work in. However, the measurements were later extended onto the strait area, and then the eastern basin. To date, measurements have been made at a total of 117 hydrographic stations with motor boats delivered to the site by all-terrain vehicles. In addition, nine mooring stations equipped with current meters (either rotational Potok-2M or acoustic Doppler Aquadopp) and pressure gauges were deployed during this period. The locations of the deployments are shown by the white bullets in Fig. 3. Each of the moorings remained in operation for a few days following the deployment, recording the data every 1 min. Simultaneously, the basic meteorological parameters (wind speed and direction, air temperature, absolute and specific humidity, atmospheric pressure) were continuously registered as 20-min averages by a portable automatic meteorological station *HeavyWeather* installed on the shore, at the distance of a few kilometers from the moorings. In addition, a complete set of surface meteorological data was recorded every 6 h at the Aktumsuk meteorological station of the Uzbekistan Hydrometeorological

Table 1 List of hydrographic surveys in which the data used herein were collected

Cruise	Date	Location	CTD	Velocity
1	November 2002	Western basin	SBE19plus, 11 stations	
2	October 2003	Western basin	SBE19plus, 20 stations	Potok-2M, two moorings
3	April 2004	Western basin	SBE19plus, four stations	
4(1)	August 2004	Western basin	YSI6600, 16 stations	
4(2)	August 2004	Strait	SBE19plus, six stations	
5(1)	October 2005	Western basin	SBE19plus, eight stations	Potok-2M + tidal gauge, one mooring
5(2)	October 2005	Strait	SBE19plus, seven stations	Potok-2M + tidal gauges, two moorings
5(3)	October 2005	Eastern basin	SBE19plus, seven stations	
6	March 2006	Western basin	SBE19plus, two stations	
7	September 2006	Western basin	SBE19plus, 18 stations	Aquadopp + tidal gauges, two moorings
8	November 2007	Western basin	SBE19plus, two stations	
9(1)	June 2008	Western basin	SBE19plus, 15 stations	Aquadopp + tidal gauges, two moorings
9(2)	June 2008	Eastern basin	Water collected for salinity, one station	

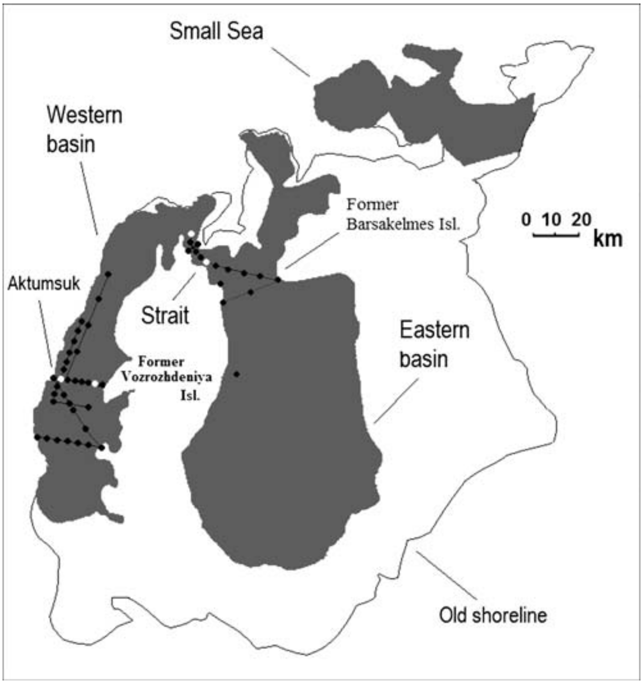


Fig. 3 Map of the Aral Sea and locations of the hydrographic stations (*black bullets*) where the data used in this study were collected in 2002–2008 (many of the stations have been occupied repeatedly). The *white bullets* indicate the locations of moorings

Service, located on Ustyurt Plateau, 8 km west of the sea in the central part of the western basin. Finally, the absolute elevation of the Aral Sea surface above the ocean level was determined during most of the cruises through direct geodesic leveling using a triangulation beacon located near the Aktumsuk site on the western bank of the western basin.

At all hydrographic stations, surface-to-bottom CTD profiling was performed using a manual winch, normally, accompanied by water sampling from standard depth levels (0, 10, 20, 30, 40 m, where applicable) using 5-l Molchanov bottles. The Sea Bird's SBE19plus CTD profiler was used in all expeditions, except the one of summer 2004. In the latter expedition, both salinity and temperature of the water were expected to be high and the electric conductivity could therefore have been beyond the range of the SBE profiler, so we opted for the Yellow Springs YSI6600 instrument designed for a broader range of conductivity.

A major problem with interpreting CTD data collected from the Aral Sea is linked with the salt composition of the water, which is significantly different from that of the ocean water (see [14]). In consequence, the relation between the electric conductivity and salinity is also different. Moreover, the empirical relation once used for the predesiccation Aral [15], is no longer valid because of the ongoing precipitation of salts and corresponding changes in salt composition [1]. No known explicit relation is available at present. Therefore, we applied the following procedure to infer the salinity from the CTD data. First, the true salinities S_{true} of the collected water samples were obtained chemically in the laboratory of the Abdullaev Institute of Geology and Geophysics, Uzbekistan, using the dry residue method [16]. Then, the corresponding "pseudosalinity" values S_{ctd}, i.e., those computed through the standard oceanic relation, were extracted from the CTD data, and linear regression between the chemically obtained and CTD-derived salinity values was constructed. The linear relation obtained thereby was then used to convert the entire set of CTD data to the "true" salinity. As an example, we present here the regression based on 14 chemically analyzed water samples collected in October, 2005:

$$S_{true} = 2.047 S_{ctd} - 44.8 \tag{1}$$

where the units of S_{true} are ppt (g kg^{-1}), and those of S_{ctd} are psu. The regression yielded $R^2 > 0.94$, however, the rms deviation was nearly 2 ppt. Fortunately, the range of the spatial variability characteristic for today's Aral Sea (up to 12 ppt between the surface and the bottom, up to 100 ppt between the western and the eastern basins) is, typically, much larger than the possible uncertainty of the conversion procedure.

3 Thermohaline Structure

The shrinking of the Aral Sea has been accompanied by a continuous salinity build-up. The progress of growth of the surface salinity in the Large Sea is shown in Table 2 (includes data from [17] and original data collected by the author and co-workers). The most recent salinity figures available at the date of this writing (data obtained in June 2008) are 116 ppt for the western basin, and 211 ppt for the eastern basin, constituting respective increases by factors of 12 and 21 since 1960. It is interesting to note that during almost all of the first four decades of desiccation, until the late 1990s, salinity growth was identical in the two basins, but since approximately 1997, the salinization of the eastern basin has started to progress much faster than that of the western basin. It was by that time that the two parts of the sea had become largely separated from each other, with exchange between them restricted to two connecting straits in the north and the south (and, later, since 1999, a single strait in the north). As a much shallower water body, the eastern basin was subjected to stronger evaporation in summer and, consequently, faster salinity growth.

A key feature characteristic of the "new" state of the Aral Sea, in contrast with its regime prior to the onset of desiccation and that at the initial stages of shrinking, is the vertical stratification. The first SIORAS survey of 2002 immediately revealed the salinity difference as high as 12 ppt between the upper mixed layer (82 ppt) and the bottom layer (94 ppt), see Table 3. According to the most recent available hydrographic data collected before 2002, namely, the data of 1990 [5], the Aral Sea was still well mixed at the time. We, therefore, can only conclude that the strong

Table 2 Progressive salinity build-up in the Large Aral Sea. The numbers indicated by one *asterisk* are the data published in [17], those marked by two *asterisks* are the original data by the author and his coworkers

Year	Salinity (ppt)	
	Western basin	Eastern basin
1960	10*	10*
1970	12*	12*
1980	17*	17*
1990	32*	32*
1992	35*	35*
1995	42*	42*
1996	44*	44*
1997	51*	52*
1998	54*	58*
1999	56*	No data
2000	63*	No data
2001	68*	112*
2002	82**	160*
2003	86**	No data
2004	92**	No data
2005	98**	130**
2006	109**	No data
2007	117**	No data
2008	116**	211**

Table 3 Summary of the sea surface level and thermohaline state variability for 2002–2008

Cruise number	When	Where	Sea level (m)	Salinity (ppt)		Temperature (°C)	
				Surface layer	Bottom layer	Surface layer	Bottom layer
1	Nov 2002	Western basin	30.47	82	94	10	15
2	Oct 2003	Western basin	30.50	85	96	14	2
3	Apr 2004	Western basin	–	86	87	5	1
4(1)	Aug 2004	Western basin	30.71	91	87	25	2
4(2)	Aug 2004	Strait	–	100	100	23	23
5(1)	Oct 2005	Western basin	30.12	98	101	18	4
5(2)	Oct 2005	Strait	–	132	132	17	17
5(3)	Oct 2005	Eastern basin	–	130	134	15	15
6	Mar 2006	Western basin	30.20	99	–	−2	–
7	Sep 2006	Western basin	29.60	109	106	18	3
8	Nov 2007	Western basin	29.20	117	127	10	11
9(1)	June 2008	Western basin	29.28	116	118	23	2
9(2)	June 2008	Eastern basin	–	211	–	–	–

vertical stratification first appeared sometime between 1990 and 2002, and the exact dating is unknown. However, there are reasons to believe that this may have happened in 1996–1997, following the appearance of marked horizontal salinity gradients between the two basins (see below). The H_2S contamination of the bottom layers associated with the enhanced stratification (see [14]) is likely to have originated from the same times.

Characteristic vertical profiles of temperature and salinity for the period 2002 through 2008 are shown in Fig. 4 and summarized in Table 3. The archetypal vertical structure in 2002–2003 characterized by enhanced stratification was generally "two-layered," with minimum salinity in the upper mixed layer of 7–23 m followed by a more or less steep halocline where the salinity increased sharply downwards, attaining maximum values at the bottom (Fig. 5). In the fall season when most of the measurements were made, the halocline was typically accompanied by temperature inversions. During those years, we believed that the stratification of the western basin was permanent and the conditions were meromictic.

However, in the spring of 2004, the entire column was nearly uniform in salinity at about 86 ppt (see Table 3), indicating that winter convection was likely to had been able to destroy the meromictic conditions, and the enhanced stratification was an intermittent rather than permanent feature. By the late summer of 2004, a new type of stratification had arisen, which persisted in autumns until the fall of 2006. This stratification was mainly "three-layered," involving two salinity maxima, one at the surface, and the other one at the bottom, separated by a relatively "fresh" intermediate layer (Fig. 6). Despite the salinity inversion just below the upper mixed layer, the column was maintained in a stable state by a steep thermocline. The deeper salinity maximum was best developed in 2005, but a hint of it was also observed in the fall of 2006, when there was a marked bottom mixed layer, indicating the presence of strong currents in the bottom layer (which was also confirmed by direct current measurements).

The hydrographic data from the eastern basin of the Aral Sea are very sparse. The only available data characterizing spatial distributions were collected in the fall of 2005. We note that the basin, despite being very shallow, exhibited significant stratification – up to 1 ppt per meter (Fig. 7).

In November of 2007, the stratification of the western basin was again similar to that characteristic for 2002–2003, with a single salinity maximum at the bottom (127 ppt, the highest ever observed in the western basin to that date), and a temperature inversion in the lower part of the column. The upper mixed layer was also the deepest (32 m) at the time. In June of 2008, the vertical structure demonstrated again two salinity maxima, and a relatively "fresh" layer between them, at about 20 m. However, this time the upper maximum was not at the surface, but at a depth of about 8 m, and the bottom maximum was very weak. The stability of the column was preserved by an extremely steep thermocline (23°C at the surface and only 1°C at 20 m).

What are the physical mechanisms responsible for the variability of the vertical thermohaline structure in the deep western basin? As hypothesized in [1, 18], there are two major concurrent mechanisms, which can be referred to as the convective and advective mechanisms. The former is related to the evaporation from the

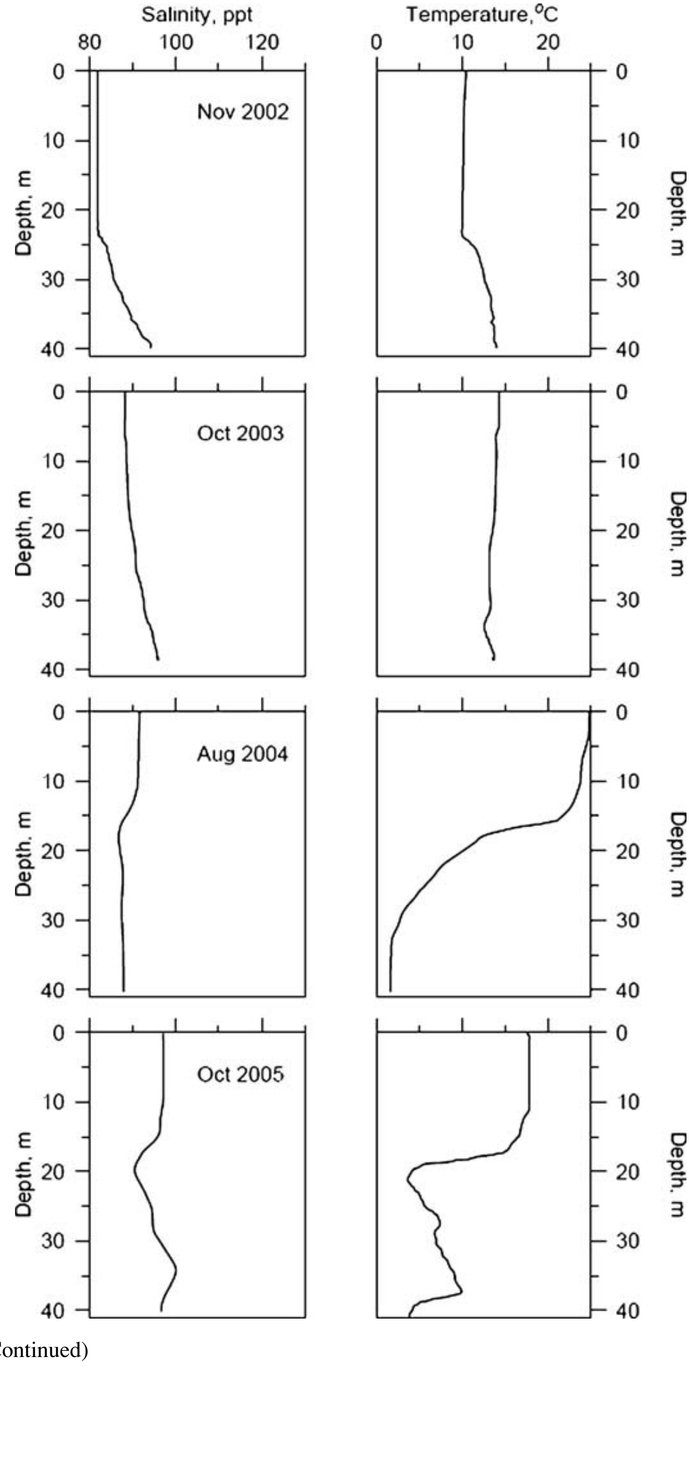


Fig. 4 (Continued)

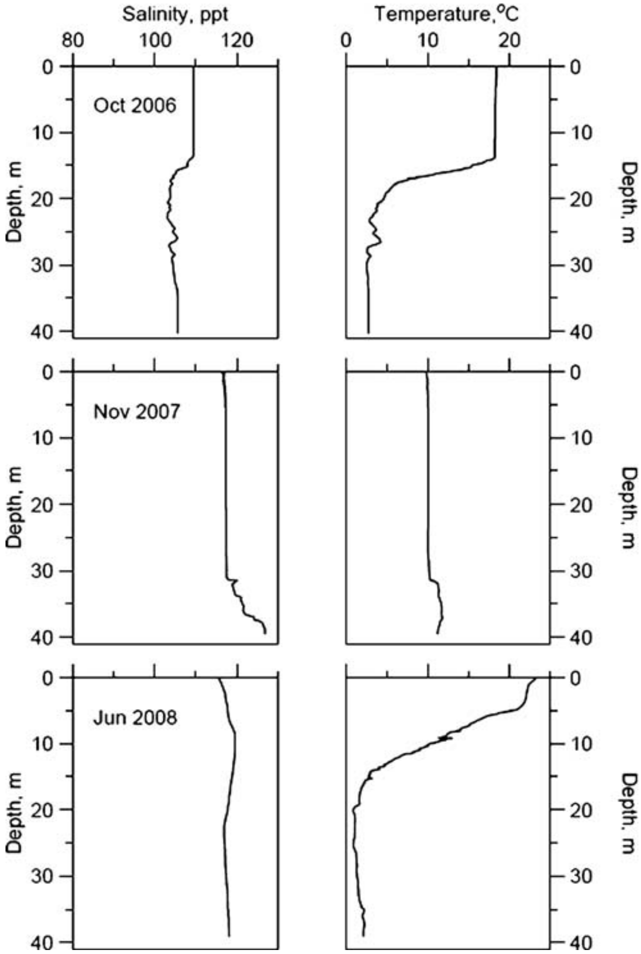


Fig. 4 Vertical profiles of salinity (*left*) and temperature (*right*) observed in 2002–2008. The deepest site of the western basin (Station A2, 45°05.89′N, 58°23.41′E)

surface layer. In summer and fall, intense evaporation should lead to a release of excessive salt in the upper layer and, therefore, a salinity maximum near the surface. The column may remain stable as long as the thermocline is sufficiently steep, but is doomed to convective overturning when winter cooling leads to relaxation of the vertical temperature gradient.

The advective mechanism is associated with the intrusions of saltier water from the eastern basin through the strait connecting the basins. Entering the western basin, the denser eastern water slips downslope and may accumulate in the bottom layer. Therefore, this mechanism tends to create a salinity maximum near the bottom. As the strait narrows and shallows following the continuing shrinking of the sea, the relative importance of the two mechanisms can change. Before 2003, when the strait was quite broad, the advective mechanism is likely to have been dominant, which

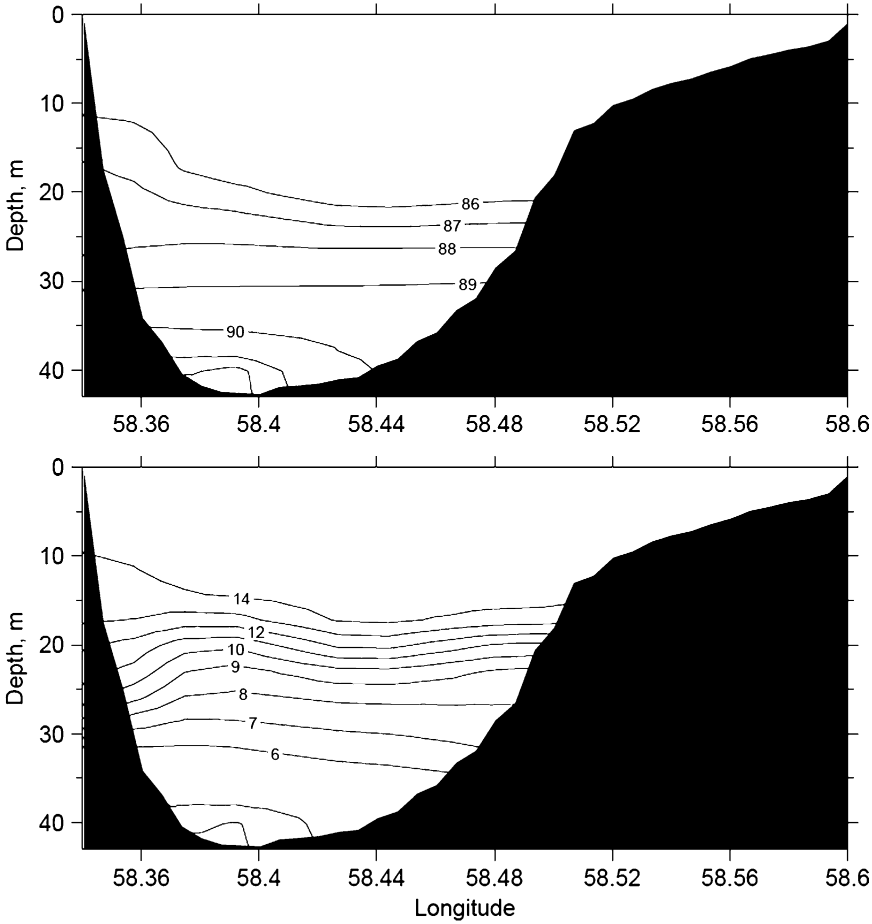


Fig. 5 Zonal vertical distribution of salinity (ppt, *upper panel*) and temperature (°C, *lower panel*) across the central part of the western basin. October, 2003, Survey 2

was manifested in the single salinity maximum at the bottom. Afterwards, the two mechanisms may have been comparable, and the stratification pattern with two salinity maxima developed. As the desiccation progresses further and the interbasin exchanges eventually become insignificant, the bottom maximum vanishes. Some details of the exchanges between the two basins are discussed in the next section.

4 Circulation and Interbasin Exchanges

Some authors have argued that the slightly saltier waters originating from the eastern part of the Sea contributed to the formation of the deep water in the western trench even before the onset of desiccation [12]. At the time, the salinity difference

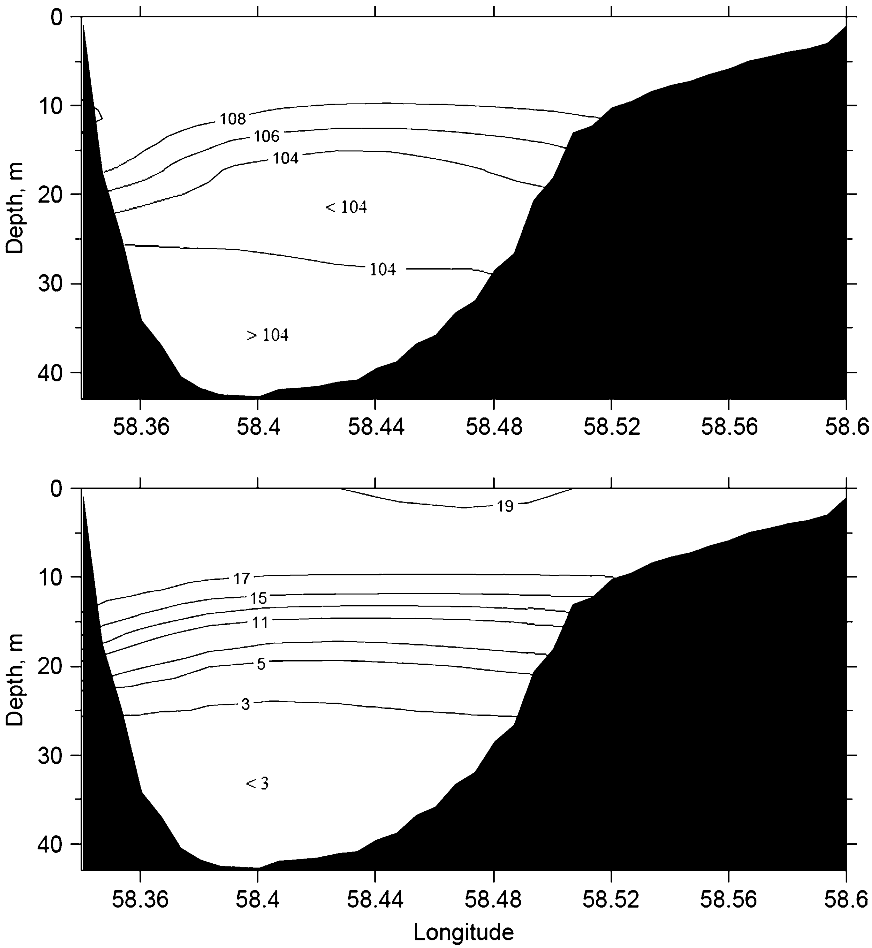


Fig. 6 Zonal vertical distribution of salinity (ppt, *upper panel*) and temperature (°C, *lower panel*) across the central part of the western basin. September, 2006, Survey 7

between the shallow eastern and deep western parts of the Sea never exceeded a few tenths of ppt. Under the new conditions that developed starting from the mid-1990s, when the differences of the salinities in the two basins attained much larger values (see Table 2), the importance of this mechanism must have increased greatly.

Indeed, the eastern basin water intrusions into the western basin can often be clearly identified by means of TS (temperature–salinity) analysis. In many TS diagrams, the eastern basin water (EBW) can be seen as a distinct water type, whose mixing with the local western water type accounts for the observed spanning ranges of temperature and salinity. An illustrative example is shown in Fig. 8, corresponding to the fall of 2003. In this case, the complexity of the thermohaline structure in the western basin can be explained by the intermixing of three basic

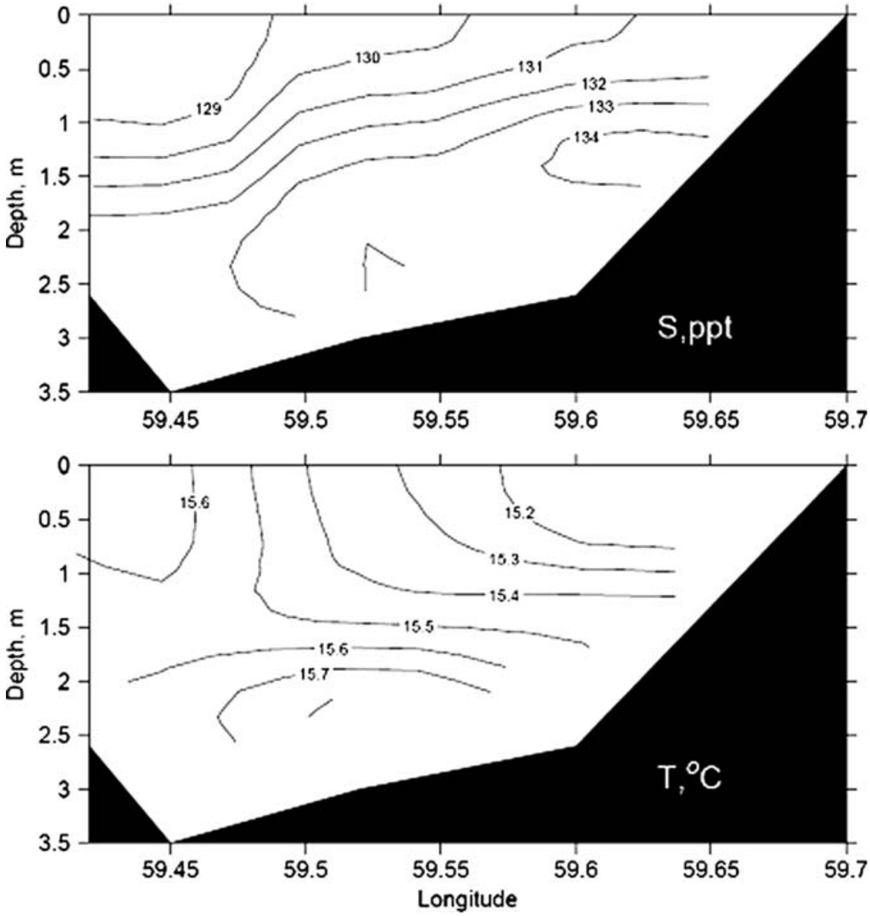


Fig. 7 Zonal vertical distribution of salinity (*upper panel*) and temperature (*lower panel*) across the northern part of the eastern basin, from the eastern outlet of the strait connecting the two basins to the western extremity of the former Barsakelmes Island. October, 2005, Survey 5(3)

water types. The surface type is mainly formed by interactions with the atmosphere; the cold bottom type seen in the southern part of the basin may have resulted from winter convection. On the other hand, the relatively warm and much saltier bottom type characteristic for the northern part of the basin is likely to belong to the eastern basin water which penetrated the western basin through the connecting strait in the north.

A similar EBW intrusion was also documented in the fall of 2002. By means of TS analysis, it was demonstrated [1] that the bottom water of the western basin contained 9–11% admixture of EBW, and estimated that about 900 million tonnes of salt had been advected from the eastern basin into the western basin between 1990 and 2002, or about 70 million tonnes per year on the average. It is worth mentioning

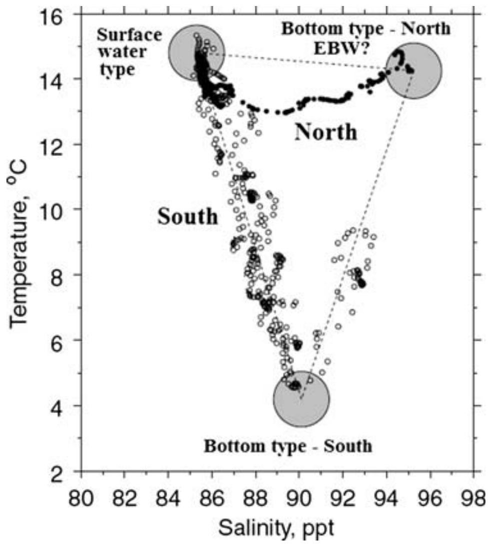


Fig. 8 TS (temperature–salinity) diagram for the western basin waters. "North" and "south" refer to the northern and the southern parts of the western basin. October, 2003, Survey 2

here that the salinity in the western basin continued to grow even in 2002–2005, when there was no level drop. Therefore, the salinity growth in the western basin could only have been due to water exchanges with the saltier eastern basin.

The only available data of direct flow measurements in the strait were collected during 75 h in October of 2005 at a mooring station at the western outlet of the strait. Also recorded were meteorological data and surface level variability (Fig. 9). The measurements corresponded to the conditions of moderate easterly and north-easterly winds. The flow in the strait was directed from the east to the west at up to 20 cms^{-1}. The wind stress led the current for about 6 h. An estimated 0.4 km^3 of water was transported through the strait during this event, leading to an increase of the surface level at the western extremity of the strait by about 50 cm.

The examples above demonstrate the importance of the exchanges through the strait connecting the basins. We note that the very existence of the strait during the last years was unexpected. According to the only available bathymetric maps compiled in the 1950s, the strait should have dried out completely as soon as the sea level dropped below 30.5 m a.o.l., i.e., in 2002. However, the strait is still there in 2008. Moreover, our surveys of 2004 and 2005 revealed a continuous relatively deep "fairway" in the otherwise shallow strait (Fig. 10). We hypothesized that the deep channel must have resulted from the erosion of bottom silts by intense interbasin currents. The depth in the deep channel was up to 6 m in 2005, and should be up to 5 m at the date of this writing (2008), and the basins remain connected and interacting. However, the strait has narrowed drastically over the last few years, leading to about 50% reduction of its cross-sectional area, despite the existence of the deep channel (Fig. 11). Besides, the eastern basin itself has shrunk dramatically. We must assume, therefore, that the importance of the interbasin exchanges decreased significantly in the last few years.

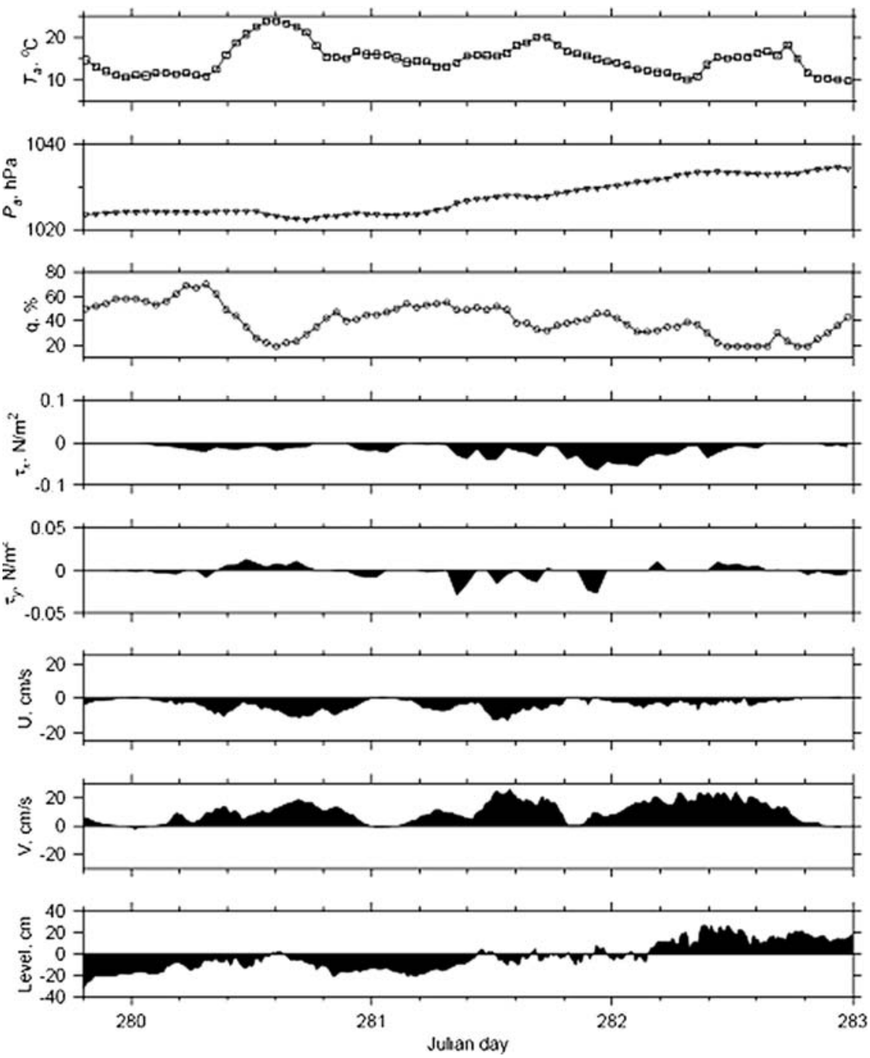


Fig. 9 Data from the mooring station installed in the strait connecting the western and the eastern basins in October, 2005, Survey 5(2). The current meter and the level gauge at the mooring station were deployed at the depth of 4 m, about 1.5 m above the bottom in the deep channel at the western outlet of the strait. The meteorological station was installed at the northern bank of the strait, some 3 km north of the mooring. *From top to bottom*: atmospheric pressure; relative humidity; zonal and meridional wind stress components; zonal and meridional components of the current velocity; surface level anomaly as derived from the pressure gauge

As to present circulation in the western basin itself, few data are available. The first of the recent velocity measurements was made in October, 2003 [1]. The instrument was deployed in the upper mixed layer, near the western shore of the western basin (45°06′N, 58°21′E). A 5.75-day long data series was collected,

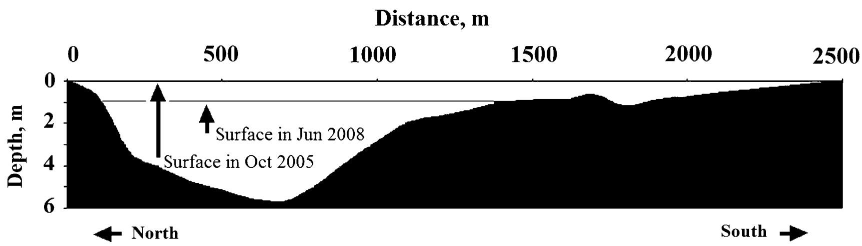


Fig. 10 Bathymetric profile along a cross-section of the strait connecting the western and the eastern basins (the coordinate of the northern extremity of the cross-section is 45°44.82′N, 59°12.96′E). Echo-sounder data collected in October, 2005, Survey 5(2)

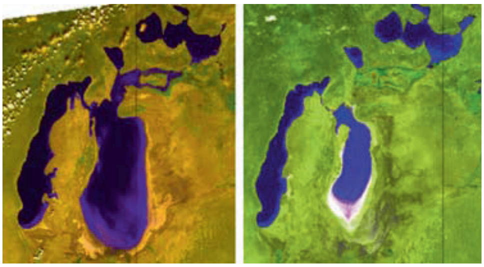


Fig. 11 MODIS AQUA satellite scenes (*visible band, false color*) of the Aral Sea taken on 2 September, 2003 (*left*) and 25 August, 2008 (*right*). Courtesy of S. Stanichny and D. Soloviov. Note the dramatic changes of the eastern basin area and narrowing of the strait

most of which corresponded to the conditions of moderate northeasterly winds, rather close to the climatic average for this region. The current velocity was mainly directed towards the NNE along the coast at 5–10 cms^{-1}.

In June, 2008, a 6.5-day long velocity series was recorded in the bottom layer at two locations, one at the western slope (45°05.21′N, 58°23.03′E, depth 36 m) and the other at the eastern slope of the western basin (45°01.70′N, 58°30.00′E, depth 25 m). The sea surface level anomaly was also recorded at the eastern mooring. These data are depicted in Fig. 12, together with the wind stress. Within the period of the observations, there were two events of strong N and NW wind bursts, each preceded by periods of very weak wind or no wind (Fig. 12). During the NW wind episodes, the sea level at the eastern slope reacted by increasing with the time lag of about 20 h. The bottom layer immediately responded to the surface height increase (correlation over 0.7 with no temporal lag) and a northward barotropic current developed along the eastern slope. An opposite sign, southward current developed in the bottom layer at the western side some 24 h later.

Of course, the episodic series of observations discussed above are too short to allow for any general statements about the character of the present Aral Sea circulation. Nonetheless, they give a hint that under the typical winds, the surface circulation in the western basin remains anticyclonic, and the bottom circulation is cyclonic – as it used to be in the "old" Aral Sea. Some numerical modeling experiments have also confirmed this conclusion (e.g., [1], and Zhurbas, personal communication, 2007).

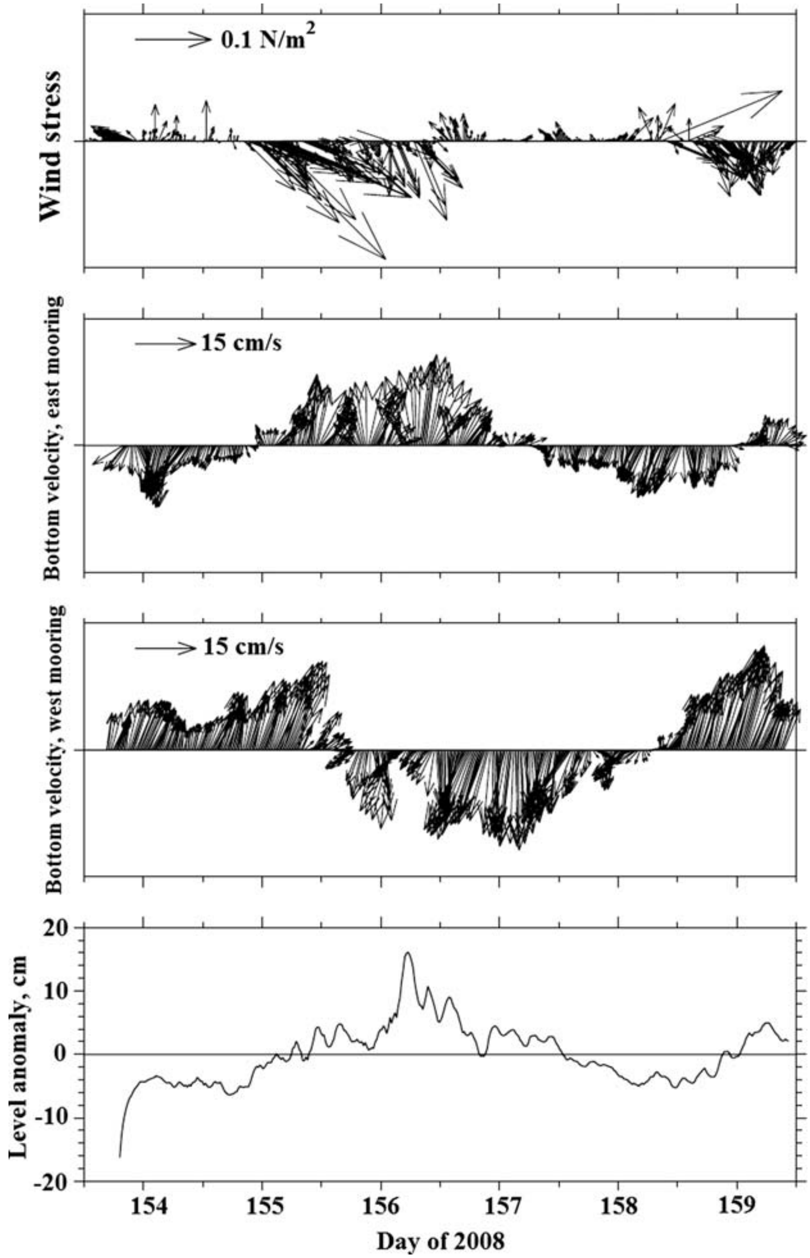


Fig. 12 Data from two mooring stations deployed in June, 2008, Survey 9(1). The west mooring was located at the western slope of the western basin (45°05.21′N, 58°23.03′E, depth 36 m), while the east one was located at the eastern slope of the western basin (45°01.70′N, 58°30.00′E, depth 25 m). *From top to bottom*: wind stress; bottom velocity at the east mooring; bottom velocity at the west mooring; surface level anomaly at the east mooring

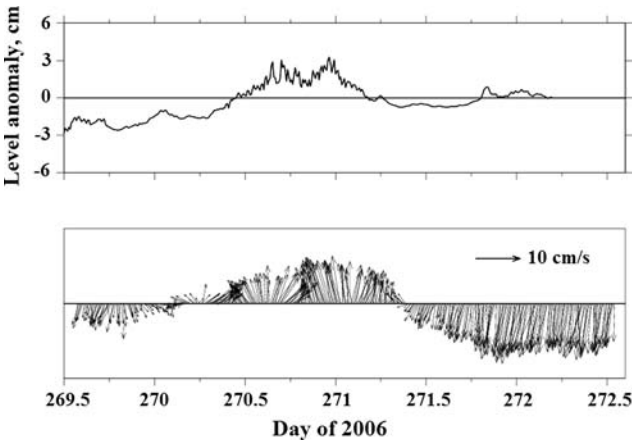


Fig. 13 Data from a mooring station deployed at the A2 site (45°05.89′N, 58°23.41′E, depth 40 m) in September, 2006, Survey 7. Surface level anomaly (cm, *upper panel*) and bottom velocity (cms^{-1}, *lower panel*)

As in any enclosed basin, the Aral Sea is subject to intrinsic standing waves in its water body, i.e., seiches. An example of what is likely to be a four-nodal longitudinal internal seiche in the western basin is shown in Fig. 13. We note that the entire period of these observations was characterized by very weak winds (0–2 ms^{-1}). It can be seen that the period of the wave is about 48 h, and the magnitude of the velocity changes at the bottom is over 20 cms^{-1}. The seiche was manifested in the sea surface height as a wave with amplitude of about 6 cm. In recent numerical experiments with the Princeton Ocean Model, a similar seiche was simulated whose period was 45 h, i.e., rather close to that observed (Roget Armengol, personal communication, 2008).

The vertical distributions of salinity and temperature along the longitudinal axis of the western basin, measured in September, 2007, simultaneously with the observation of the seiche discussed above, are shown in Fig. 14. We note the wave activity in the pycnocline. The characteristic wave length is about 20 km, and the vertical displacements of the isopycnal surfaces are up to 4–5 m.

5 Conclusions

(1) To the date of this writing (November, 2008) the total drop in surface level of the Large Aral Sea since 1960 has been over 24 m. In consequence of the desiccation, the Aral Sea has undergone profound changes to its physical regime, and evolved from a brackish, relatively homogeneous and well-mixed environment into a hyperhaline, strongly stratified residual water body. In the summer of 2008, salinity in the western basin attained values of about 116 ppt, while in the eastern basin salinity exceeded 211 ppt. Compared

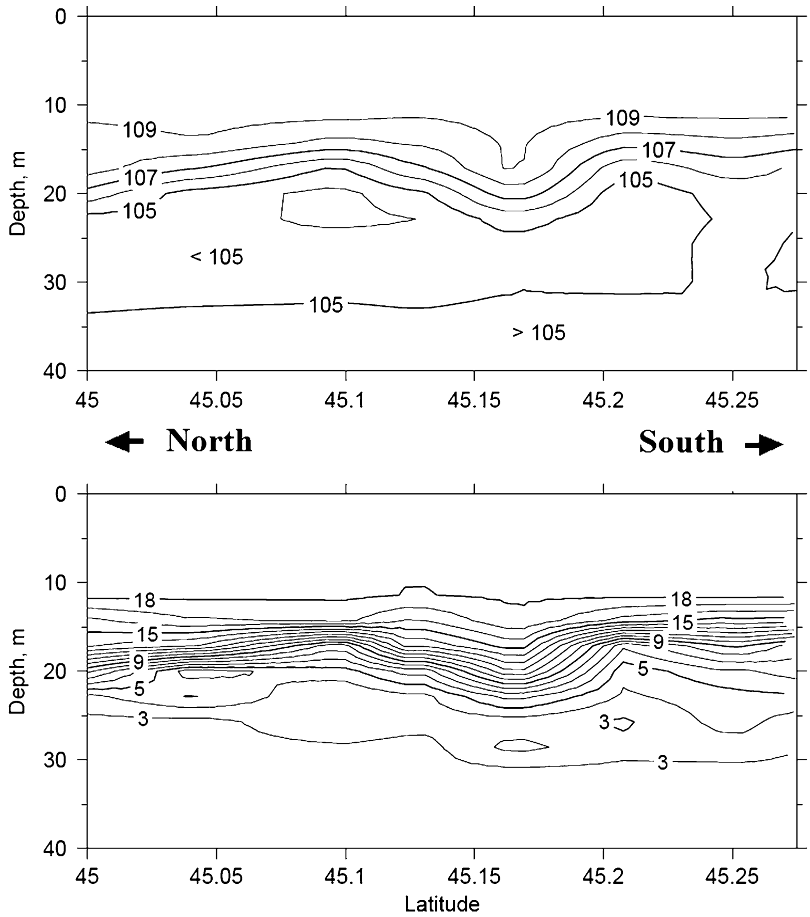


Fig. 14 Longitudinal vertical distribution of salinity (ppt, *upper panel*) and temperature (°C, *lower panel*) in the deepest portion of the western basin, approximately along the isobath 39 m, in September, 2006, Survey 7. Note the intense internal wave activity in the pycnocline

with the predesiccation state, these values constitute an increase by a factor of 12 and 21 for the western and the eastern basins, respectively.

(2) During the first decades of the desiccation, the salinity increase had been nearly equal in all parts of the sea. Then, in the mid-1990s, pronounced differences between the eastern and the western basins began to grow. Probably, at the same time, the penetration of saltier and denser water from the eastern basin into the western basin started to play a major role in the build-up of the vertical stratification in the sea. It is this mechanism that was responsible for extremely high stratification in the western trench and anoxic conditions in the bottom layer in the early 2000s. At that time, the water exchanges between the eastern and the western basins through the connecting strait were of the order of 0.1 km^3 of water per day, and some 70 million tonnes of salt per year.

(3) An important finding of the recent field research is the discovered “self-deepening” of the strait, i.e., the formation of a channel whose depth today is about 5 m, associated with the erosion of the bottom by currents. This means that while the sea’s level drop progresses, the strait itself is unlikely to dry out, although the eastern basin has shrunk dramatically in the last years, and may continue shrinking into a small, hyperhaline residual sea adjacent to the eastern outlet of the strait. The interbasin exchanges, however, tended to become less significant as the strait connecting the basins was shallowing and narrowing following the continuing level drop. Therefore, the western basin is likely to become less stratified.

(4) The surface circulation of the western basin apparently remains anticyclonic, and the deep circulation cyclonic, under the predominant winds. As far as the relatively fast surface currents are concerned, the transversal spatial scale of today’s sea is too small for the Coriollis force to be significant, so that the direct wind drag matters rather than the Ekman transport. On the other hand, the bottom layer circulation seems to immediately follow the sea surface slopes in the classic barotropic manner, so the Coriollis force is still effective for the slower, near-bottom currents.

Although the observational data are sparse, they give a hint that seiches (both surface and internal) may play an important role in the dynamical regime of today’s Aral Sea. In particular, seiches with the period of 48 h and magnitude of up to 10 cm in the surface level and over 10 cms^{-1} in current velocity have been observed in the western basin. Internal waves with the wavelength of 15–20 km and amplitude up to 5 m have been documented in the pycnocline, which may constitute an important mixing mechanism.

Acknowledgments The studies reported herein have been supported by a series of grants from the Russian Academy of Sciences, Russian Foundation for Basic Research, National Geographic Society (USA), and NATO. Special thanks are given to the collaborators from Uzbekistan Academy of Sciences, National University of Uzbekistan, Nukus Educational Institute and Karakalpak State University, and Uzbekistan Hydrometeorological Institute, and, personally, to A. Ni, T. Kudyshkin, A. Kurbaniyazov, Kh. Toychiev, and many other colleagues and friends from the Aral Sea region.

References

1. Zavialov PO (2005) Physical oceanography of the dying Aral Sea. Springer Praxis, Chichester, UK, p 146
2. Zavialov PO, Kostianoy AG, Emelianov SV, Ni AA, Ishniyazov D, Khan VM, Kudyshkin TV (2003) Hydrographic survey in the dying Aral Sea. Geophys Res Lett 30:1659–1662
3. Zavialov PO, Ni AA, Kudyshkin TV, Kurbaniyazov AK, Dikarev SN (2008) Five years of field hydrographic research in the Large Aral Sea (2002–2006). J Mar Syst. 10.1016/j.jmarsys.2008.03.013
4. Kosarev AN (1975) Gidrologiya Kaspiyskogo i Aral’skogo Morey (Hydrology of the Caspian and Aral Seas). Moscow University Publishing, Moscow, Russia, 271 pp (in Russian)

5. Bortnik VN, Chistyaeva SP (eds) (1990) Gidrometeorologiya i Gidrohimiya Morey SSSR. (Hydrometeorology and Hydrochemistry of the Seas of the USSR), Aral Sea, vol. 7 Gidrometeoizdat, Leningrad (in Russian)
6. Blinov LK (1956) Hydrochemistry of the Aral Sea. Leningrad, Gidrometeoizdat, 152 pp (in Russian)
7. Berg LS (1908) The Aral Sea. An Attempt of physical geographic description. Izvestiya Turkestanskogo Otdeleniya. Russian Geographic Society, St. Petersburg, 5, 9, 580 pp (in Russian)
8. Zhdanko SM (1940) Currents in the Aral Sea. Meteorologiya i Gidrologiya 1–2:78–82 (in Russian)
9. Rubanov IV, Ishniyazov DP, Baskakova MA, Chistyakov PA (1987) Geology of the Aral Sea. FAN, Tashkent, 247 pp (in Russian)
10. Simonov AI (1954) On origins of anticyclonic circulation of the Aral Sea waters. Meteorologiya i Gidrologiya 2:50–52
11. Shkudova, Ya G, Kovalev NP (1969) An attempt of implementation of a stationary hydrodynamical model for computing currents in a shallow sea. Meteorologiya i Gidrologiya 10:76–86
12. Simonov AI (1962) The origin of relatively high-salinity water of the Aral Sea western depression. Trudy GOIN 68:103–117 (in Russian)
13. Arsenieva NM, Davydov LK, Dubrovina LN, Konkina NG (1963) Seiches in the Seas of the USSR. LGU, Leningrad, 184 pp (in Russian)
14. Hydrochemistry of the Aral Sea. In: The Handbook of Environmental Chemistry. doi: 698_2009_3
15. Sopach ED (1958) Electric Conductivity as a Means for Determining Salinity of Sea Waters. Gidrometeoizdat, Moscow, 139 pp (in Russian)
16. Ni A, Zavialov P, Ishniyazov D, Kudyshkin T, Kurbaniyazov A, Mukhamedzhanova D, Toychiev Kh, Friedrich J (2005) On hydrochemistry of the Aral Sea. Ekologiya xabarnomasi 2:41–44 (in Russian)
17. Mirabdullaev IM, Joldasova IM, Mustafaeva ZA, et al (2004) Succession of the ecosystems of the Aral Sea during its transition from oligohaline to polyhaline waterbody. J Mar Syst 47 (1–4):101–108
18. Zavialov PO, Kostianoy AG, Sapozhnikov PhV, Scheglov MA, Khan VM, Ni AA, Kudyshkin TV, Pinkhasov BI, Ishniyazov DP, Petrov MA, Kurbaniyazov AK, Abdullaev UR (2003) Modern hydrophysical and hydrobiological state of the western Aral Sea. Okeanologiya 43(2):316–319 (in Russian)

Satellite Monitoring of the Aral Sea Region

Anna I. Ginzburg, Andrey G. Kostianoy, Nickolay A. Sheremet, and Valentina I. Kravtsova

Abstract The efficiency of using satellite information (satellite imagery, measurements from radiometers and altimeters) for tracing the dynamics of various characteristics of the Aral Sea during its desiccation is demonstrated. Interannual variability of morphometric parameters of the sea and its parts is considered (1957–2008), as well as that of sea surface temperature (SST) (1982–2000), sea level (1992–2006), dates of the first and last observations of ice cover (1992–2005), amount of atmospheric precipitation over the catchment areas (1979–2001), and normalized difference vegetation index (NDVI) (1981–2001). Seasonal changes in landscape of a former sea bottom have been analyzed and mapped. Examples of manifestation of various processes in water (coastal upwelling, vortices, wind surges, etc.) and atmosphere (dust/salt storms) on satellite images are presented.

Keywords Aral Sea, Ice cover, Microwave radiometry, River outflow, Satellite altimetry, Sea level, Sea surface temperature

Contents

A.I. Ginzburg, A.G. Kostianoy, and N.A. Sheremet (✉)
P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, 36 Nakhimovsky Pr, 117997, Moscow, Russia
e-mail: sheremet@ocean.ru

V.I. Kravtsova
Faculty of Geography, Lomonosov Moscow State University, Vorobievy Gory, 119992, Moscow, Russia

A.G. Kostianoy and A.N. Kosarev (eds.), *The Aral Sea Environment*,
Hdb Env Chem (2010) 7: 147–179, DOI 10.1007/698_2009_15,

Abbreviations

AVHRR	Advanced very high resolution radiometer
DMSP	Defense meteorological satellite program
GFO	Geosat follow-on
GPCP	Global precipitation climatology project
ISADB	Integrated satellite altimetry database
J1	Jason-1
MCSST	Multichannel sea surface temperature
NASA	National aeronautics and space administration
NDVI	Normalized difference vegetation index
NOAA	National oceanic and atmospheric administration
SMMR	Scanning multichannel microwave radiometer
SSH	Sea surface height
SSM/I	Special sensor microwave/imager
SST	Sea surface temperature
T/P	TOPEX/Poseidon

1 Introduction

Desiccation of the Aral Sea in the so-called anthropogenic period (since 1961) led not only to considerable changes in its morphometric, physical, chemical, biological and other parameters, but to disappearance of the infrastructure in the coastal zone as well, including meteo and sea level gauge stations. The current lack of reliable in situ measurements and time series for sea surface temperature (SST), sea level and ice cover parameters since the mid-1980s may be successfully replaced by using corresponding satellite information available through the world-wide databases. In particular, multichannel sea surface temperature (MCSST) data (since November 1981) and data of the Pathfinder project (a joint NOAA/NASA project devoted to the production of a high-quality global SST dataset from 1985 to the present) can be the basis for tracing of long-term variability of SST in different parts of the Aral Sea. These databases with high spatio-temporal resolution (1 km, daily) and temperature resolution (0.1°C) are based on measurements of advanced very high resolution radiometer (AVHRR) onboard satellites of the National Oceanic and Atmospheric Administration (NOAA). Radar altimeters from the TOPEX/Poseidon (T/P) and Jason-1 (J1) satellites have provided reliable, regular, frequent, and weather-independent data for monitoring of sea level in the Large and Small Aral seas since 1992. Altimeter data as well as data of the special sensor microwave/imager (SSM/I) radiometer enable us to study interannual variability of the ice regime of the Aral Sea. Images from AVHRR NOAA and MODIS (onboard Terra and Aqua satellites) radiometers provide a possibility to follow the changes in the sea's coastline and observe interesting phenomena in water, atmosphere, and on the dried parts of the Aral Sea.

Herein we discuss the dynamics of various parameters of the Aral Sea during its desiccation which was traced with satellite information. The consideration includes changes in morphometric characteristics (shoreline, sea area and volume), sea level, SST, and ice regime. In addition, we look at phenomena associated with changes in the Aral Sea coastline and salinity, such as upwelling along the eastern coast of the western Large Aral Sea formed due to shallowing of the sea, occasional Amudarya water inflow in the eastern Large Aral, freezing of fresh Amudarya runoff over cold and saline Aral water, etc.

2 Morphometric Parameters and Estimating Salinity

Use of satellite information for mapping of the Aral Sea shoreline began in the second half of the 1970s, when changes in morphometric parameters of the sea had already manifested themselves.

Mapping of changes in the Aral Sea shoreline with satellite images was initiated by the Kazakh Aero-geodesy Department. On the basis of space photos from the Resurs-F satellites for 1977, 1984, and 1989 (spatial resolution R~30 m) photographic plans were arranged, the shoreline for these years was annotated and a map of the Aral Sea dynamics from 1957 to 1989 with a prediction to 2000 was issued (in 1990), by which the area of the sea was estimated [1,2]. The mapping of the shoreline of the sea on the basis of satellite images was explored further in the Department of Cartography and Geoinformatics of the Faculty of Geography of Lomonosov Moscow State University (Russia). The following materials were used for these purposes in different years up to 2000: MSU-SK/Resurs-O images (R = 170 m, scan swath of 600 km) for 1989–1998; images obtained with a digital photocamera from the Russian module of the International Space Station (R = 50 m) in 1999. (Procedures for computer processing of satellite images is considered in detail in [3,4].) Ressl and Micklin [5] also used satellite information for monitoring of the Aral Sea desiccation in the following years: Challenger

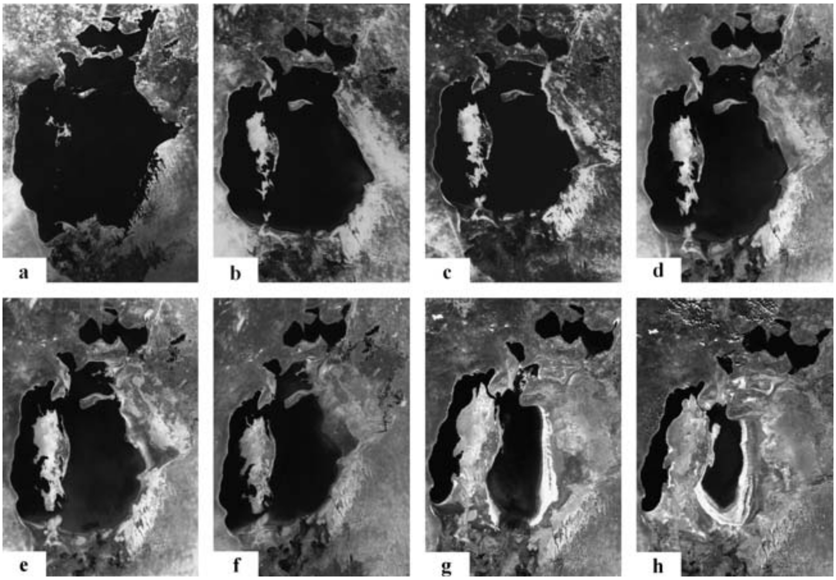


Fig. 1 Aral Sea images from orbital space station Salut-4 (1975), MSU-SK/Resurs-0 (1989–1999), MODIS/Terra (2001–2007): (a) June 1975; (b) April 12, 1989; (c) October 18, 1991; (d) July 18, 1993; (e) October 3, 1996; (f) June 13, 1998; (g) October 13, 2005; (h) November 26, 2007 (in accordance with symbols in the figure)

Hasselblad photograph (1984), satellite imagery of NOAA-9 and NOAA-11 (1985–1992), and MSU-SK/Resurs (from 1996 to 2000).

Since 2000, regular images have been available from the Terra satellite, which performs a daily global survey. MODIS/Terra images in the visible and near-infrared bands ($R = 250$ m) made yearly mapping in the same season possible (in particular, under minimal sea level) and allowed investigation of seasonal changes of the sea's shoreline. Some satellite images of different years obtained with dissimilar facilities and demonstrating gradual shrinking of the Aral Sea are presented in Fig. 1. Dynamics of the shoreline changes during 1957–2008 is shown in Fig. 2.

From yearly satellite images and Fig. 2 one can trace, for example, gradual detachment of the Small Aral Sea from the Large Aral Sea by 1989 (because of transformation of Kokoral island to a peninsula in the west and progradation of land in the east) and separation of the Large Sea into its western and eastern parts by 2001 owing to an increase of the area of shoal around the former Vozrozhdenija and Lazareva islands. Since 1989, the Large and Small Aral seas, which were before connected by the Berg strait (15 km wide) [6], are actually separate basins with their own specific hydrological regimes. It became especially evident after the building of dams in 1992–2005 (dates of successive construction and destruction of dams/ barrages in the former Berg strait are indicated in [7]).

The shoreline of the bay in the north-eastern Large Sea, which was formed as a result of detachment of the Small Sea from the Large Sea and attachment of

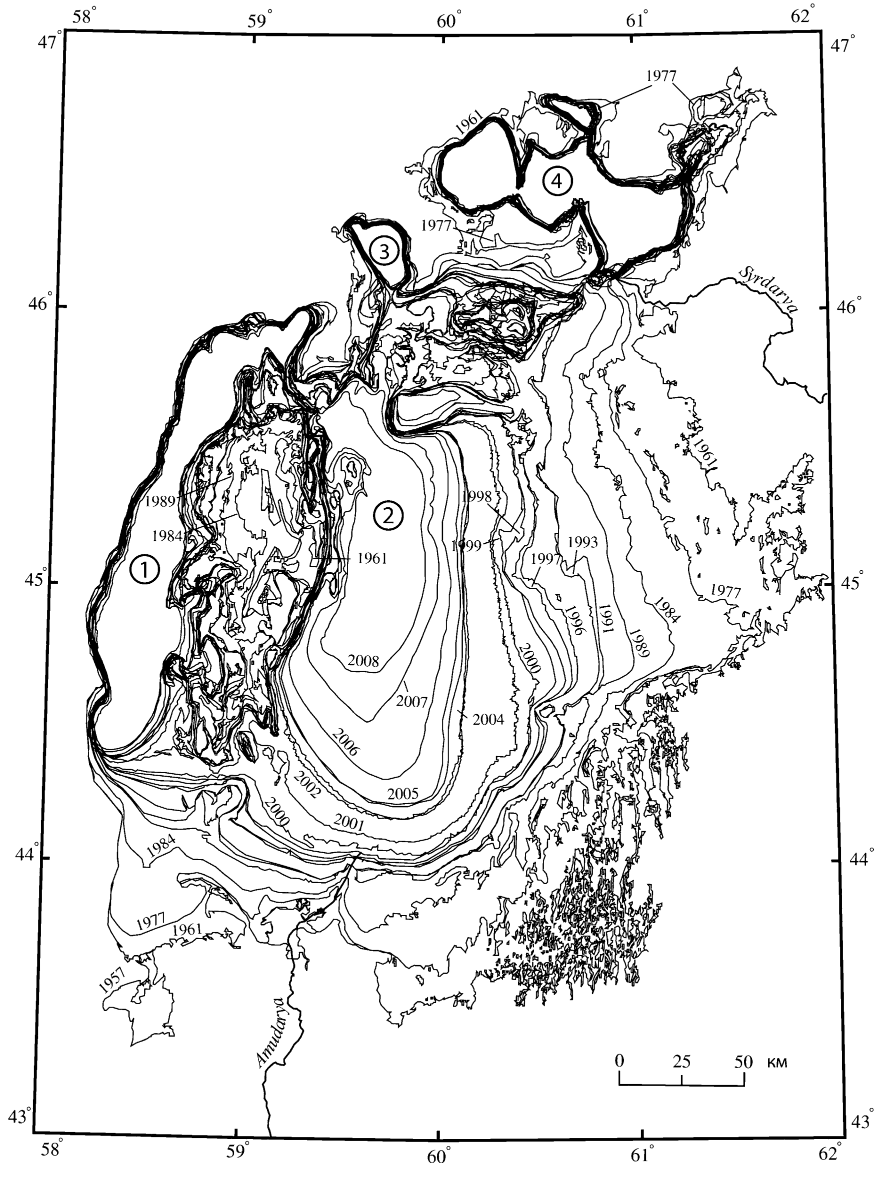


Fig. 2 The map of the Aral Sea coast line changes during 1957–2008. Figures in circles: 1 – western Large Aral Sea, 2 – eastern Large Aral Sea, 3 – bay Tshchebas detached in 2004, 4 – Small Aral Sea

Barsakel'mes island to the land, is most dynamic, its changes being sometimes asynchronous with those of the rest of the Large Sea. With a continuing drop of sea level, the retreat of the shore and shrinkage of the basin area generally, an increase

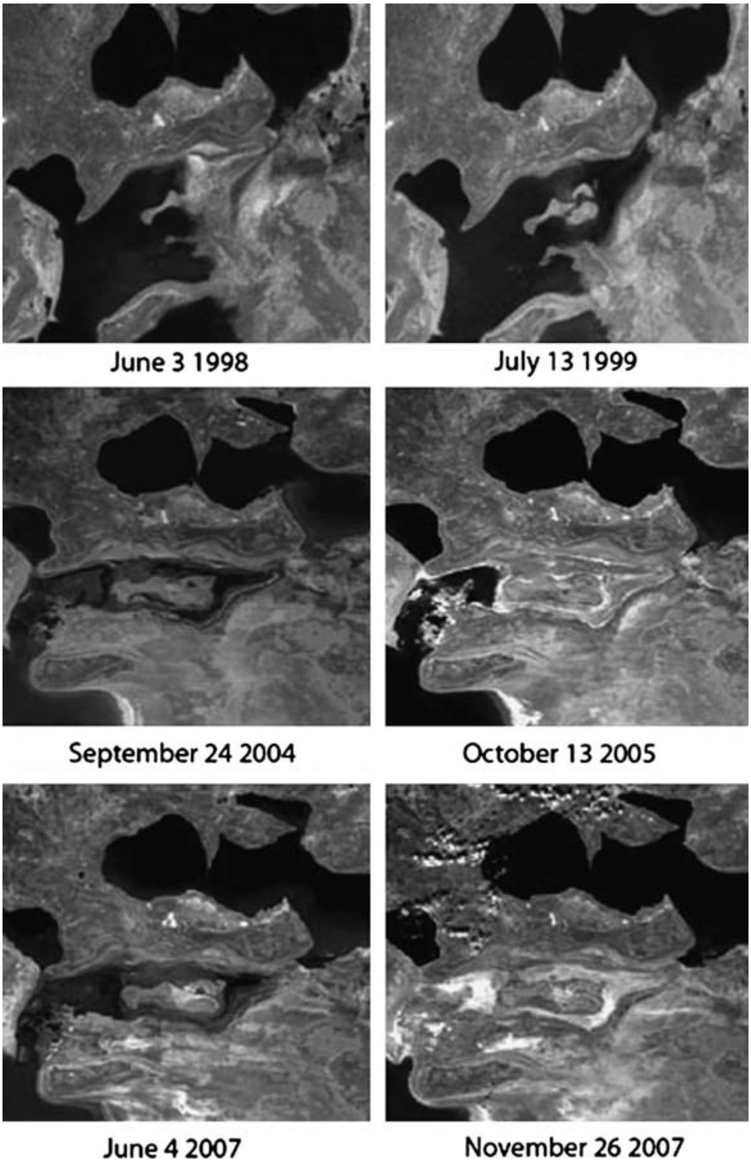


Fig. 3 The view of the north-eastern bay in 1996–2007 on images from satellites Resurs – O/MSU-SK (1996–1999) and Terra/MODIS (2001–2007)

of water supply has been observed there in certain years (Fig. 3) associated with inflow of water from the Small Sea. In the years of moderate inflow or its termination, the bay dried (in 1996, 1998, and 2001), whereas with ample runoff it overflooded (in 1991, 1993, 1997, and 1999). In the years 2002, 2003, and 2005, when

Table 1 Changes of the area of the Aral Sea and its parts (km^2) in 1957–2008

Year	Aral Sea as a whole	Large Sea					Small Sea
		As a whole	Western part	Eastern part			
				As a whole	Basic basin	Detached reservoirs	
1957	**67,100**	61,200					5,900
1961	**66,400**	60,500					5,900
1977	**54,900**	50,600					4,300
1984	**47,400**	43,700					3,700
1989	41,500	**38,400**	9,400	29,000			**3,100**
1991	36,600	**33,800**	8,200	25,600			**2,800**
1993	36,000	**33,000**	7,900	25,100			**3,000**
1996	31,300	**28,600**	7,100	21,500			**2,700**
1997	31,200	**28,100**	7,000	21,100			**3,100**
1998	29,700	**26,500**	6,700	19,800			**3,000**
1999	29,300	**26,300**	6,500	19,800			**3,000**
2000	26,700	**23,900**	6,200	17,700			**2,800**
2001	22,100	**19,400**	5,500	13,900			**2,700**
2002	19,900	**17,000**	5,200	11,800			**2,900**
2003	19,700	**16,800**	5,000	11,800			**2,900**
2004	17,900	**15,100**	4,800	10,300	9,500	*800*	**2,800**
2005	16,900	**14,100**	4,800	9,300	8,700	*600*	**2,800**
2006	15,700	**12,400**	4,600	7,800	6,800	*1,000*	**3,300**
2007	12,200	**8,900**	4,200	4,700	4,400	*300*	**3,300**
2008	10,400	**7,200**	4,000	3,200	2,900	*300*	**3,200**

Setting of numbers in bold reproduces the real separation of the Aral Sea into the Large and Small seas in 1989

water overflow in the sea from artificial water bodies in the Amudarya delta was observed, the north-eastern bay was irrigated. It is quite possible that its regime was determined in these years by income of Amudarya's riverine and post-irrigative waters into the sea as well. Upon construction of the fundamental dam in August 2005, the state of the bay was totally dependent on regulation of inflow from the Small Sea by the dam: the bay was flooded in June 2007, but it dried in November of that year (Fig. 3).

Changes in the area of the Aral Sea as a whole and its individual parts during1957–2008 with consideration for satellite information (see also Fig. 2) are evident from Table 1. Using these estimated areas it is possible, with known detailed bathymetry of the basin, to estimate its level and volume (see [5,8–11]). An example of similar calculations for the Large and Small seas (1986–2006) is given in Table 2, which is taken from [11].

The data of Tables 1 and 2 allow one to trace the changes in rate of shrinkage of the Aral Sea area and drop of its level in different time periods. The annual mean value of reduction in basin area, which was about 700 km^2 yr^{-1} in 1961–1977, increased up to 1,200 km^2 yr^{-1} in 1984–1989, when river inflow into the sea practically stopped in certain years. The rate of area shrinkage was extreme in 1989–1991 (2,300 km^2 yr^{-1}), which was related to a large extent to the extremely dry year 1989. During the 1990s, when the yearly observations were provided by

Table 2 Changes in basic morphometric parameters of the Large and Small seas from 1986 to 2006 (Table 2 from [11])

Years	Large Sea			Small Sea		
	Sea level (m)	Sea area (km^2)	Sea volume (km^3)	Sea level (m)	Sea area (km^2)	Sea volume (km^3)
1986	41.02	38,560	380.63	40.90	2,830	22.47
1987	40.19	37,130	343.17	40.80	2,810	22.39
1988	39.67	36,180	312.65	40.50	2,750	21.84
1989	39.10	35,300	306.92	40.20	2,710	20.28
1990	38.24	33,670	280.44	40.50	2,750	21.84
1991	37.66	32,020	257.16	40.40	2,730	20.92
1992	37.20	31,830	240.17	40.20	2,710	20.28
1993	36.95	31,420	231.70	39.37	2,570	18.43
1994	36.90	31,310	229.87	40.10	2,690	20.01
1995	36.50	30,040	217.25	40.50	2,750	21.84
1996	35.48	28,540	195.63	40.50	2,750	21.84
1997	34.80	26,910	173.44	41.20	2,910	22.67
1998	34.21	25,750	168.43	42.50	3,240	27.03
1999	33.98	24,120	147.62	36.8	2,090	12.03
2000	33.50	22,930	139.53	39.80	2,620	19.26
2001	32.40	21,000	131.16	39.20	2,550	17.97
2002	32.00	18,700	110.84	39.30	2,580	18.44
2003	31.50	17,300	97.23	40.00	2,650	19.77
2004	31.09	16,400	93.46	40.80	2,810	22.39
2005	30.70	15,770	89.79	41.00	2,860	22.52
2006	30.40	13,470	81.35	41.80	2,990	24.01

regular surveys from the Resurs-O satellite, a marked nonuniformity of the area shrinking rate in different years was revealed (this may be partially associated also with forced use of images for different seasons before 2000). During this time, periods with a high area shrinkage rate of about 1,500 km^2 yr^{-1} (1993–1996, 1997–1998) alternated with periods where the rate decreased down to 300–600 km^2 yr^{-1} (1991–1993, 1998–1999) and even to about 50 km^2 yr^{-1} (1997). These sharp variations are reflected in the map (see Fig. 2): the shorelines for 1991 and 1993 as well as for 1996 and 1997 practically merge.

In 2000, the area shrinkage rate increased up to 2,600 km^2 yr^{-1} and in 2001 it was extreme (4,600 km^2 yr^{-1}) due to a joining of shoals of the middle islands to the southern shore of the eastern Large Sea. In the last period 2001–2008, a mean value of the area shrinkage rate was 1,670 km^2 yr^{-1}, but this rate was also nonuniform: it was minimal in the high water years of 2003 and 2005 (200 and 1,000 km^2 yr^{-1}, respectively) and maximal in 2007 (3,500 km^2 yr^{-1}). The total area of the Aral Sea decreased from 66,400 km^2 in 1961 to 10,400 km^2 in 2008 (see Table 1) which is only 15.7% of the sea area in 1961. In this case, the maximal rate of area shrinkage (1,358 km^2 yr^{-1} on the average) during 1989–2008 was observed, in accordance with the data of Table 1, in the eastern part of the Large Sea having flat shores, whereas its western part shrank with a mean rate of 284 km^2 yr^{-1}; the Small Sea's area was not practically changed. The decrease of the area of the Large Sea occurred mainly through its shallow eastern part, the area of which in 2008 (3,200 km^2) became for the first time less than that of the western part (4,000 km^2).

The Small Sea level varied also slightly after 1989, within about 39–42 m (abs. sea level). Its variations were associated with both Syrdarya outflow variations and overflow of the Syrdarya water into the Large Sea. In particular, a sharp level drop in 1999 (see Table 2) was related to destruction of the Kokoral dam in April 1999 [7,8]. At the same time the Large Sea level markedly decreased from 41.02 m in 1986 to 30.4 m in 2006 with an average speed of about 50 cm yr^{-1}.

Please note that values of sea level in Table 2 for some years may be overestimated or underestimated as compared with real ones. For example, the direct measurements made in November 2002 [12,13] and October 2003 [14] (see also [15]) at the point 45°05.6′N, 58°20.2′E, using the geodesic triangulation method, yielded practically the same values - 30.47 and 30.50 m, respectively, which is about 1.5 m less than estimated values in Table 2 for these years. This overestimating of the sea level values can be the result of inaccurate determination of sea area based on satellite images.

A comparison of data in Tables 1 and 2 (see also similar information in [8] for 1960–1995 and in [5] for 1960–2002) shows that differences in estimates of the Large and Small sea's areas by different authors for the same year can exceed sometimes 10%. This can be associated with differences in procedures of satellite data processing and with the use of satellite images relating to different seasons or different wind conditions (short-term changes in shoreline and sea area under the influence of wind are considered below in Sect. 6). Variations of areas of the sea and its parts during 2002 are illustrated by the data of Table 3, which were obtained by processing of the MODIS/Terra images received at different times. It may be seen that a decrease of the basin area occurs irregularly through the year, maximal changes being typical for the shallow eastern Large Sea; they are practically absent in the Small Sea. The Large Sea area slightly increases in March–July, with peaks in April (after clearance of snow cover on plains) and in July (during the peak of discharge of rivers with glacial feeding). The second half of summer and the beginning of autumn (from mid-July to October) are characterized by a sharp decrease of the basin area. In winter, judging from a comparison of autumn

Table 3 Seasonal changes of the area of the Aral Sea and its parts (km^2) during 2002

Date	Aral Sea as a whole	Large Sea			Small Sea
		As a whole	Western part	Eastern part	
13 March	21,490	18,640	5,530	13,110	2,850
16 April	21,690	18,860	5,110	13,750	2,830
18 May	21,570	18,700	5,110	13,590	2,870
10 July	21,740	18,840	5,140	13,700	2,900
28 July	21,020	18,160	5,260	12,900	2,860
14 August	20,500	17,640	5,320	12,320	2,860
19 September	19,320	16,530	4,960	11,570	2,790
7 October	19,240	16,380	5,350	11,030	2,860
5 November	19,210	16,340	5,120	11,220	2,870

and spring images, the area of the ice-covered sea is stable. This stepped course of sea area change correlates with seasonal variability of sea level. Please note that satellite observations of seasonal variations of sea area are indirectly confirmed by sea level measurements in the western Large Aral Sea [15] (30.2 and 29.6 m in March and September of 2006, respectively) and by altimetry measurements (see below).

Data obtained about the area of the Aral Sea and its parts can be used for estimating water salinity in the sea in the absence of in situ measurements [9]. The procedure includes three successive steps: (a) refinement of the linkage curve between sea level, sea area and volume and obtaining their analytic relations; (b) a check on degree of conformity of the Aral Sea areas obtained with satellite images to those calculated from sea level with consideration of the sea area-sea level curve for the period when sea level measurements were still carried out; (c) reconstruction of sea level values for the period when reliable observational data on sea level were already absent using satellite-derived sea area values; basing on the water level the volume of waters was calculated, which in turn was used for water salinity determination. For example, by such calculations, the volume and salinity of the Large Aral Sea in 2001 might be 279 km^3 and about 57 ppt, respectively [9]. These prognostic estimates, however, appeared to be significantly underestimated for both water volume (see Table 2) and salinity, which was 68 ppt in the Aktumsuk region (western part of the Large Sea) already in 1999 [8] (see also [10]).

3 Long-Term Variability of Sea Level

Direct satellite measurements of sea level are possible from radar altimetry, which have provided reliable, regular, and weather-independent data since October 1992, by which time separation of the Aral Sea into two parts had already occurred. Data of altimetry from the T/P and J1 satellites for tracing variation of the Aral Sea level has been used in several research papers [7,16–20]. Ground tracks of T/P (since August 2002 replaced by Jason-1) and J1 over the Aral Sea are shown in Fig. 4.

Note that currently several sources of altimetry series for the Large and Small Aral seas are publicly available online - Hydroweb, USDA Reservoirs database, Lakes and Rivers database, and the integrated satellite altimetry database (ISADB). On the basis of the initial altimetry data each group of researchers uses different methods to estimate the resulting sea level for the given period. Intercomparison of these databases and the reasons for potential differences between them for the Aral Sea case are considered in [7]. Variations of sea level in the Large and Small seas from October 1992 to December 2006 retrieved from the ISADB database developed at the Geophysical Center of the Russian Academy of Sciences [21,22] are shown in Fig. 5. In this case, sea level for the Large Sea was calculated at crossover points 107–142; for the Small Sea, a crossover point 107–218 is too close to the coast to be used for correct analysis, thus a point at 107 ascending pass, which is equidistant from the coastline, was used (see Fig. 4) [7].

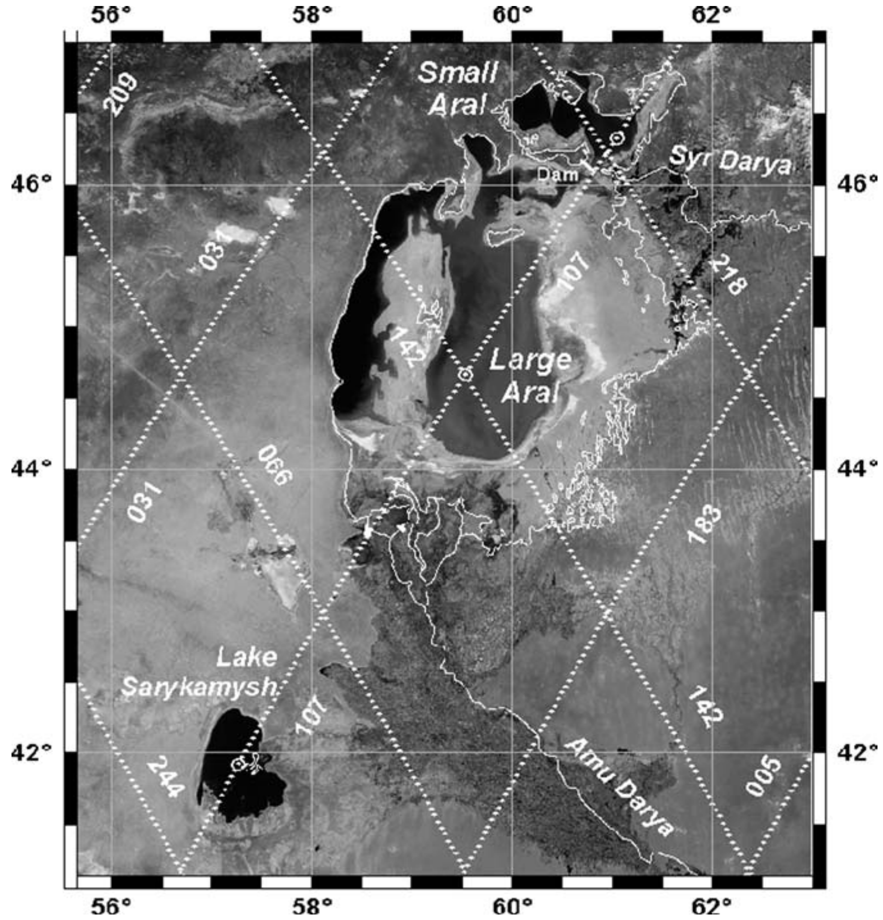


Fig. 4 The T/P and J1 ground tracks (*dotted lines*) imposed on the MODIS image for 18 May 2002 (after [7])

Figure 5a shows a continuous decrease of the Large Sea level [in relative values, sea surface height (SSH)] modulated by seasonal and interannual signals. From 1992 to spring 1995 sea level was relatively stable; since that time we observe a rapid decrease of sea level till summer 2002 with the rate of sea level drop reaching 95 $\mathrm{cm\,yr^{-1}}$ on average. From October 1992 to August 2002 water level decreased by about 6.5 m. During the last years sea level drop has continued, but at a much lower rate: 13.5 $\mathrm{cm\,yr^{-1}}$. Seasonal changes of sea level are usually within 1 m, but in some years they reach about 2 m (see Fig. 5a).

The Small Aral level in general increased after separation of this basin from the Large Sea (see Fig. 5b). A temporary decrease of the Small Sea level in 1994–1996 was associated with the three-year absence of the dam that had collapsed in April

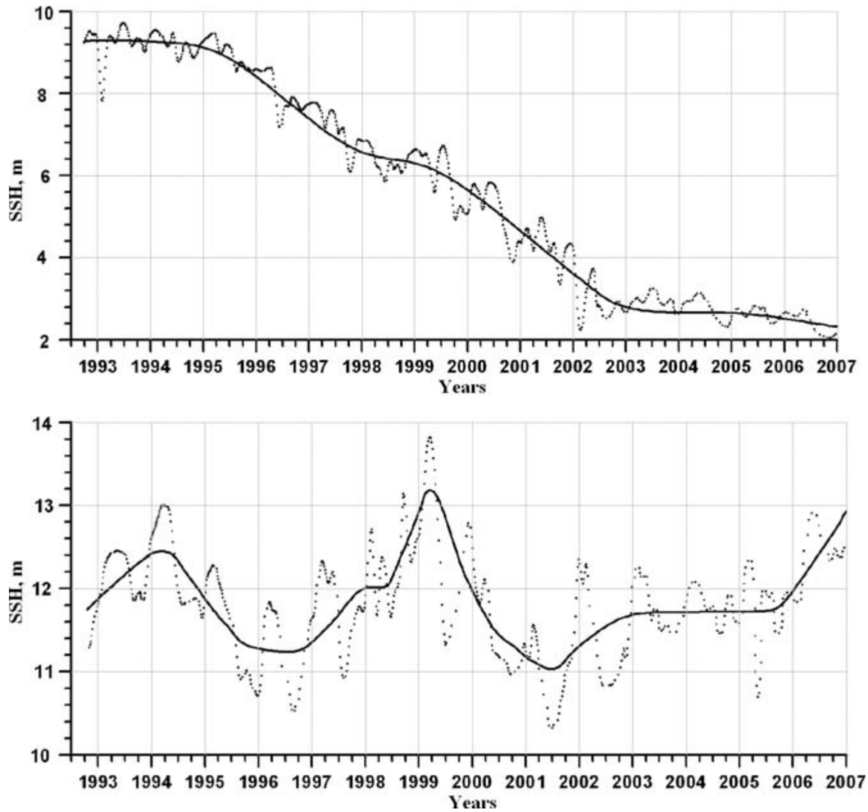


Fig. 5 Variation of sea surface height (SSH) (1992–2006): (**a**) of the Large Sea, (**b**) of the Small Sea (after [7])

1993. A break-up of the next (fourth, see [7]) dam in April 1999 resulted in a new sharp decrease of the level by 2.5 m. Since September 2001, the Small Sea level has increased. The rate of increase of the level since September 2005 (putting in operation of a fifth dam) has been about 95 cm yr^{-1}. The seasonal range of sea level can reach about 2 m (see Fig. 5b).

4 Temporal Variations of SST

Datasets based on satellite AVHRR measurements may be used for investigating interannual and seasonal variability of the Aral Sea SST. Results of such investigations, which were made using MCSST data, are presented, for example, in [23–25]. According to the study of Ginzburg et al. [24] based on nighttime weekly mean MCSST data with spatial and temperature resolution of about 18 km and 0.1°C, respectively, and available in situ measurements of the 1950s, the following changes in temperature regime of the Aral Sea and its three regions (Small Sea, western and eastern Large Sea) occurred during the anthropogenic period 1982–2000 as compared with the conventionally natural period (1911–1960):

By 2000, the monthly mean SST increased in May by about 4–5°C in all the regions of the Aral Sea; in August it increased by about 2.5°C in the Small Sea and central part of the Large Sea and by about 1.5°C in the western Large Sea; in November it decreased by about 1.5–2.5°C in the Large Sea and practically was not changed in the Small Sea. These changes are representative of a shift of the spring and autumn temperature phases (about one month and half of a month in the Large Sea, respectively) toward earlier onset in comparison with the conventionally natural period (see [6]) (Fig. 6). The maximum of summer SSTs displaced on average from Mid-August to the second half of July.

Since 1994, the summer SST maximum of the shallow eastern Large Sea has been higher than that of the "deep" western region as distinct from the preceding period, notably the SST difference between the relatively deep western and shallow eastern parts of the Large Sea had changed sign (see Fig. 6). From about this time (the early 1990s), when the sea level drop in the Large Sea reached about 16 m (see Table 2), an increase of SST differences between the three regions of the Aral Sea began (Fig. 7), which was likely associated with shallowing of the sea (see [24]).

Because of the increased mean-August SST (higher than 25.5°C) and decreased winter SST (lower than −2°C), the seasonal range of SST exceeded 27°C. It did not exceed 24°C during the conventionally natural period.

In 1995–2000, annual mean SST decreased with a mean trend of about 0.1–0.3°C yr^{-1} (the minimum trend was in the western region). Its estimated value for 2000 (about 11.8°C in the eastern Large Sea) appeared to be 0.6°C higher than the predicted one in [6] for this year with regard to the expected desiccation of the sea.

On the whole, the results support the predictions made in 1950–1980s about coming changes in the Aral Sea thermal state with the sea desiccation (see [6,24]). This implies that the revealed changes in the sea temperature regime were determined mainly by the Aral desiccation (decreasing its depth and heat storage). The higher annual mean SST value by 2000 in comparison with the prediction [6] could be associated, in particular, with the large-scale climatic variability because air temperature throughout Central Asia increased by 1.5°C between 1960 and 1991 [23].

It should be noted that the lower artificial limit of the temperature range of the MCSST global data set is about −2°C (with regard to oceanic salinity). However, a processing of AVHRR-SST data for 2002–2004 made it possible to determine current freezing temperature T_{fr} as −7°C and estimate maximum seasonal range of SST for these years as 37°C for the open waters [25]. This value seems to be a world record for the World Ocean and inland seas.

Under such freezing temperature, salinity in the eastern part of the Large Sea should be about 120 ppt [25]. This estimate of salinity based on satellite-derived T_{fr} is quite real because in situ salinity in the surface layer of the deeper (and less saline) western part of the Large Sea in 2004 was 100 ppt [15]. Values of T_{fr} of about −7°C and −8.96°C obtained for the salinity 160 ppt were also reported by Zavialov (see [10]) and Kouraev et al. [26], respectively. (For comparison purposes,

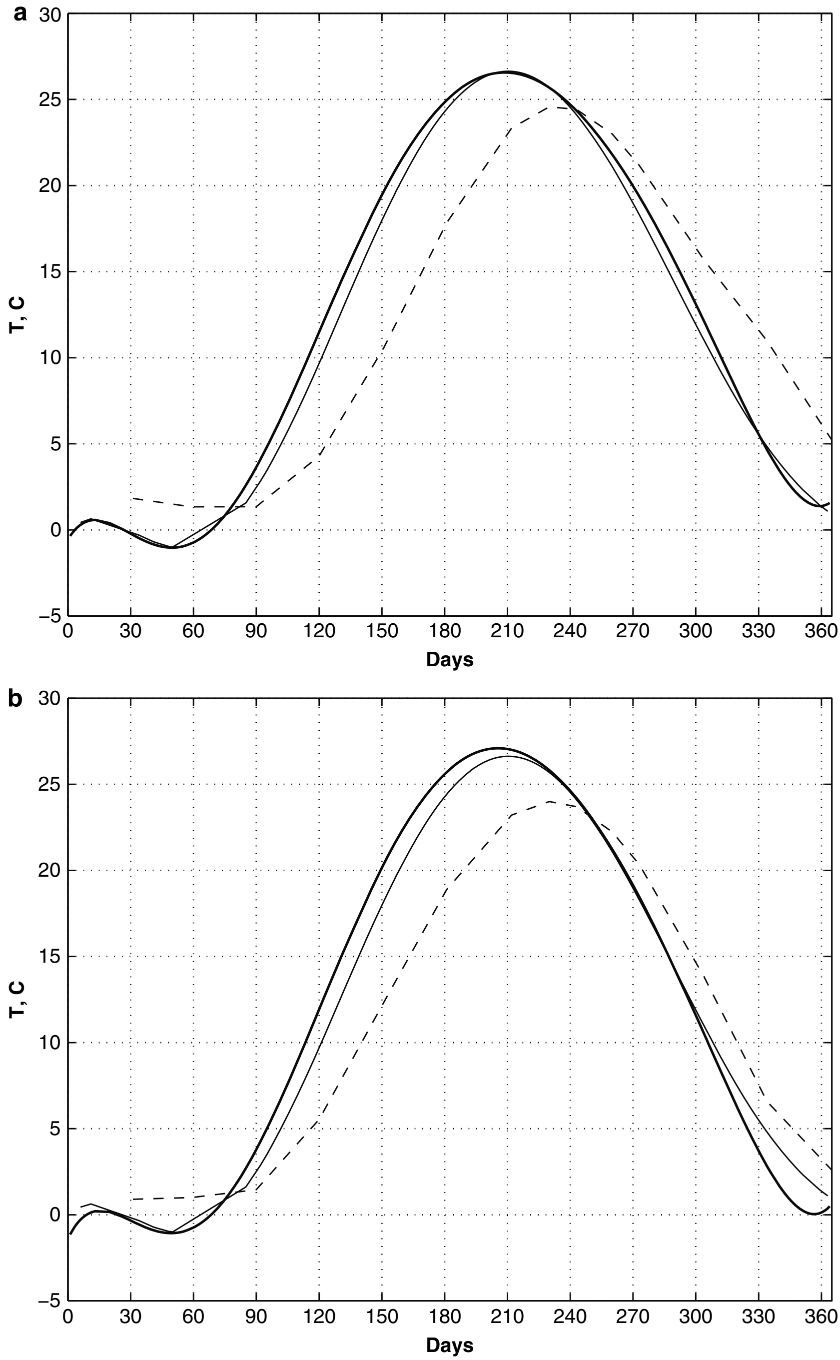


Fig. 6 Seasonal cycles of SST in the Large Sea averaged over the period 1982–2000: (**a**) in the western part, (**b**) in the eastern part. *Thick* (*thin*) solid lines correspond to averaging over 1994–2000 (1982–1993); *dashed lines* correspond to seasonal cycles of SST in the conventionally natural period. This figure is reproduced from [24]

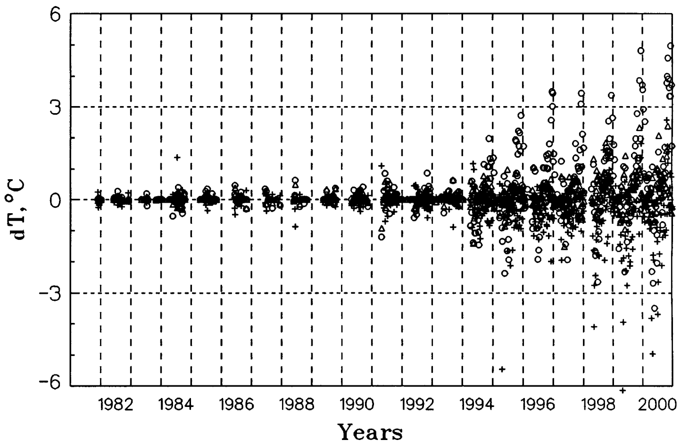


Fig. 7 Deviations of weekly mean SSTs for the Small Sea (*crosses*), western Large Sea (*circles*), and eastern Large Sea (*triangles*) from those for the entire basin. This figure is reproduced from [24]

in the conventionally natural period salinity and T_{fr} in the Aral Sea were about 10 ppt and −0.5–0.7°C, respectively.) Notice also that because of the high water salinity T_{fr} became higher than the maximum density temperature (see [24]). Interestingly, ice appears to be warmer than water in satellite images [25].

5 Ice Cover

The Aral Sea is covered by ice every winter for several months. However, dates of ice formation (appearance of the first ice) and ice break-up (full open water observed) have a significant spatial and temporal variability determined by meteorological conditions (in particular, by severity of winters, wind fields), sea morphology, and water salinity. Changes in regional climate as well as in physico-chemical and morphometric parameters of the Aral Sea itself result in variability of its ice conditions. In the absence of regular studies of ice cover in the Aral with in situ observations at coastal meteorological stations and by means of aerial surveys, which were carried out from about 1941 to the middle of the 1980s [6], satellite information became the basic and effective method of studying this variability.

Satellite imagery gives very pictorial information on ice extent and ice season duration (Fig. 8). However, this kind of data depends on cloud cover and is not regular. A first source of satellite all-weather data was the passive microwave data set from the scanning multichannel microwave radiometer (SMMR, 1979–1987) onboard the NIMBUS-7 satellite and from the SSM/I onboard the defense meteorological satellite program (DMSP) series (since 1987). Regular and all-weather information on ice cover conditions is obtained with a new method based on using

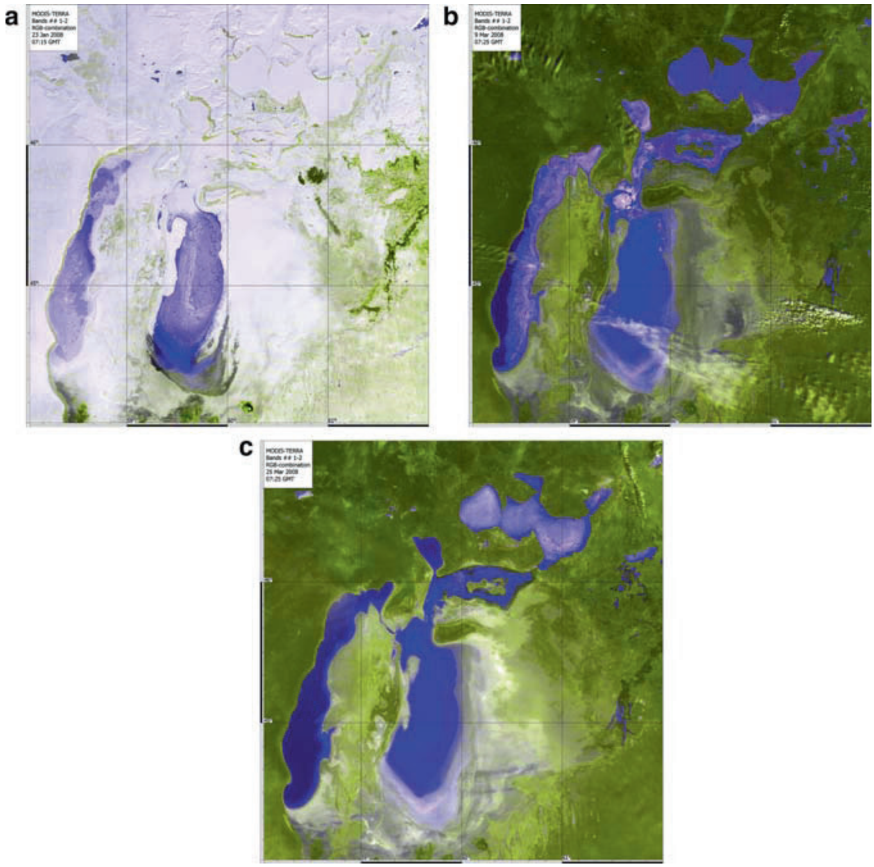


Fig. 8 Ice in the Aral Sea in the winter of 2008. MODIS/Terra satellite images (combination of bands 1 and 2) for 23 January (**a**), 9 March (**b**), and 25 March (**c**) (courtesy of D. Soloviev, Marine Hydrophysical Institute, Sevastopol, Ukraine)

the synergy of simultaneous data from active (radar altimeter) and passive (radiometer) microwave nadir-looking instruments onboard the T/P and other satellites [7,26–28]. Data from the T/P and J1 satellites orbiting on the same ground track have been available since October 1992 and February 2002, respectively.

The synergy of data from SSMR and SSM/I sensors (since 1978) as well as a combination of simultaneous data from active and passive instruments onboard the T/P satellite (since 1992) allowed researchers to obtain series of dates of the first and last observations of ice cover, duration of ice season as well as ice extent for 1979–2002 [26]. In the paper [7], data from the T/P satellite were complemented by observations from radar altimeters onboard the Geosat follow-on (GFO) (operating since January 2000) and ENVISAT (since November 2002) satellites. Ground tracks for these satellites covered the eastern part of the Large Sea and Small Sea

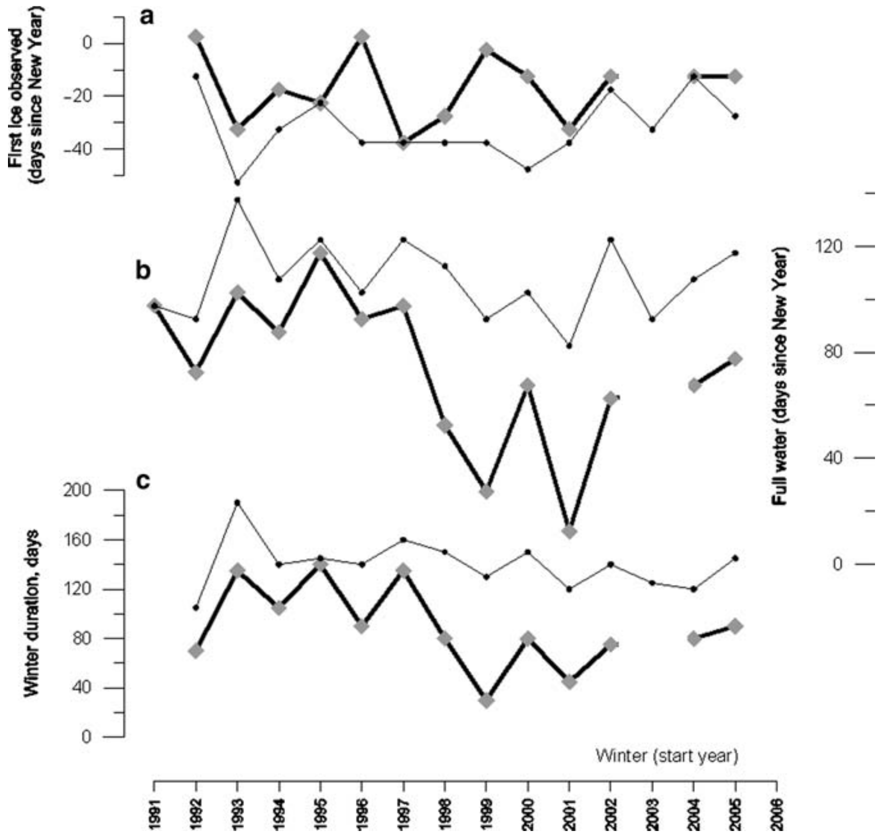


Fig. 9 Interannual variability of ice event dates: (**a**) ice formation, (**b**) ice break-up, and (**c**) winter duration (difference between the two dates) (after [7])

(see [7]). Dates of ice formation and ice break-up have been defined for these areas of the Aral for 1991–2006, except the winter 2002/2003, when due to altimetry data coverage and availability it was difficult to reliably deduce these dates for the Large Sea (Fig. 9).

It may be seen (Fig. 9) that ice in the Small Sea starts to form 15 days earlier (on average) and disappears later (70 days later in the cold winter of 2001/2002) than in the Large Sea, which is also illustrated by Fig. 8. This difference in ice conditions can be associated both with the more northern geographic position of the Small Sea and with its higher freezing temperature as compared with the Large Sea because of the considerable difference in salinity of these regions. Interestingly, interannual variability of dates of ice start/end and ice season duration in the Small Aral did not exhibit a marked trend during 1992–2006, whereas winter duration and especially date of the ice disappearance in the shallow eastern Large Aral had distinct trends of different signs in different periods: a negative trend in 1996–2002 (phase of warming) and a positive one in 2002–2006 (phase of cooling) (see Fig. 9). Notice that an increase of winter duration in 2002–2006 occurred when the Large Sea level varied only slightly (see Fig. 5a) and hence water salinity and freezing temperature values were practically unchanged. This provides support for a supposition (see [10,26]) that changes in the dates of start and end of the ice season as well as in ice extent are related to regional climatic trends rather than to salinization effects.

6 Various Phenomena in the Water and Atmosphere from Satellite Imagery

Satellite images of visible and infrared bands allow one to observe various processes and phenomena in water, atmosphere, and on dried areas of the Aral Sea.

6.1 Ice

As mentioned above, satellite images enable us (in the absence of cloudiness) to determine dates of ice formation and break-up, extension of ice cover, and regional peculiarities of ice distribution, including those under the influence of wind. Because of the low freezing temperature (about -7°C in the eastern part of the Large Sea at the present time, see above), the ice cover in the region is normally only partial (see Fig. 8), even in severe winters (see also the satellite image for 22 February 2003 in Fig. 3.12 of [10]). The MODIS/Aqua image for 22 February 2003 and other satellite images reveal an interesting phenomenon associated with low water temperature in winter in the shallow eastern Large Sea because of its high water salinity: formation of the tongue of ice at the southernmost extremity of the eastern Large Sea adjacent to the principal location of the Amudarya water inflow that is likely due to cooling of fresh riverine water "from below" by colder and saline waters of the sea [10]. One more interesting phenomenon is revealed from satellite observations (see Fig. 8b) that is characteristic of the modern period: the shallow eastern part of the Large Aral becomes free of ice earlier than the western one. This is likely determined by higher salinity of waters of the former part of the sea and their lower freezing temperature.

Snow-covered sites of land are also well seen on satellite images for the winter season (for example, see Fig. 8a).

6.2 Wind Effected Phenomena

Displacement of water in a definite direction (landward or seaward) under the influence of wind (positive or negative surges) on flat sites of a former sea bottom

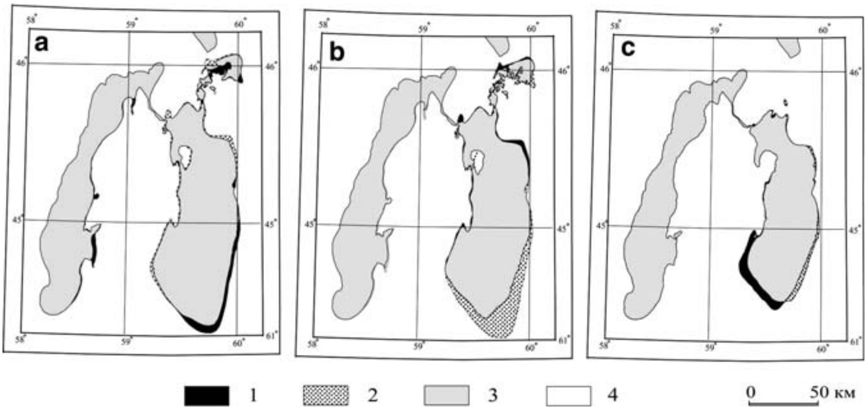


Fig. 10 Wind effected phenomena derived from MODIS/Terra images: (**a**) 1–4 June 2007 (north wind*)*, (**b**) 4–8 June 2007 (south wind), (**c**) 1–3 October 2007 (north-eastern wind). 1 – part of coastal zone area flooded under high level of the surge; 2 – part of coastal zone area free of water under low level of the surge; 3 – water surface; 4 – land

covers large areas. The temporal scale of transition from negative to positive surge can be only a few days. For example, on 4 June 2007 a positive surge took place on the southern and eastern coast of the eastern Large Sea under a northerly wind over an area of 360 km^2 (Fig. 10a), whereas on 8 June 2007 – a very strong negative surge under a southerly wind cleared water from a strip of the southern and southeastern coast 20 km wide with an area of 840 km^2 (Fig. 10b). A northeasterly wind at the beginning of October 2007 resulted in flooding of the zone of the southwestern coast of the eastern Large Sea with a width of about 8 km and an area of 350 km^2. At the same time an extended band of the eastern coast 1–4 km wide with an area of 160 km^2 became free of water (Fig. 10c).

6.3 Upwelling and Mesoscale Circulation

The phenomenon of wind-induced uplift of colder deep water to the sea surface (upwelling) in the Large Sea, in the process of which the water temperature can drop by 10–13°C over a diurnal period, is well known [6,29]. However, the spatial scale of the phenomenon and associated features of mesoscale water dynamics were not known until recently.

An analysis of visible and infrared images from the Terra, Aqua, and NOAA satellites (Stanichny 2005, oral talk in Moscow; [30]) has shown that upwelling manifests itself at the eastern coast of the western Large Sea both in the period of spring warming (April–May) (Fig. 11a) and in autumn (Figs. 11b and c). The band of cold upwelling waters of width several kilometers covers practically all the coast. In this case, cyclonic vortices and features reminiscent of transversal filaments of

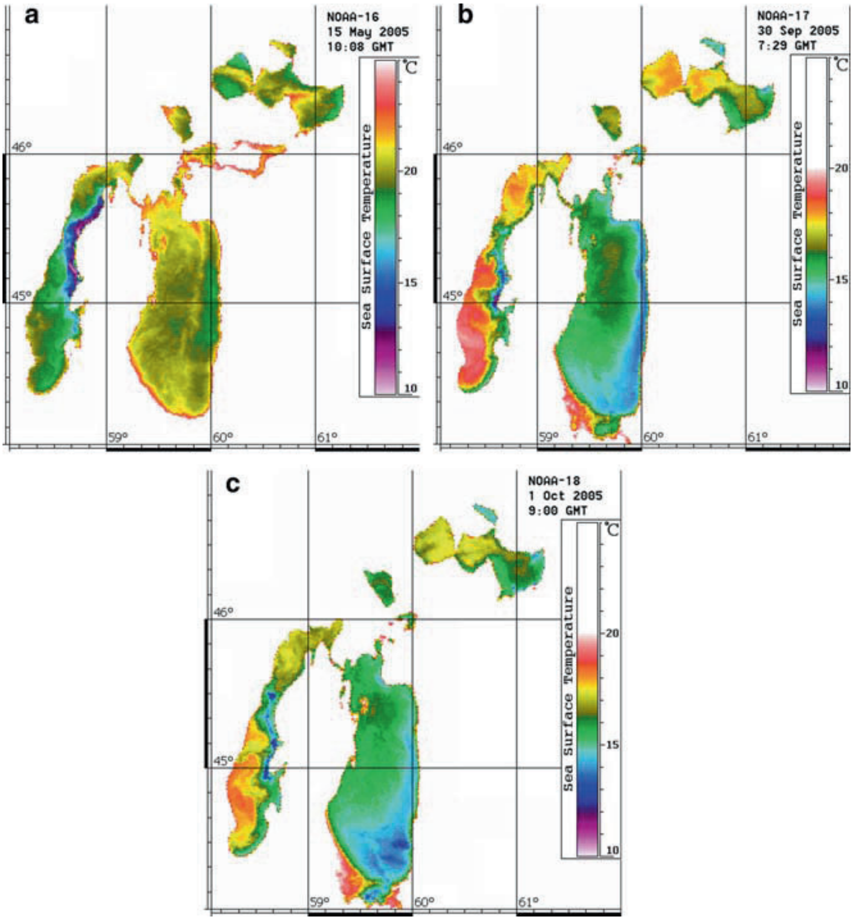


Fig. 11 Infrared images from the NOAA satellites: NOAA-16 image for 15 May 2005 (**a**), NOAA-17 for 30 September 2005 (**b**), and NOAA-18 for 1 October 2005 (**c**) (courtesy of D. Soloviev, Marine Hydrophysical Institute, Sevastopol, Ukraine)

upwelling, which are typical for the ocean and seas [31], terminated by cyclonic vortex (diameter of vortices of 5–10 km) are formed at the seaward boundary of this band. A comparison of Figs. 11b and c shows that the structure of the upwelling zone can markedly change within the time scale of one day.

Interestingly, during the conditionally natural period (prior to separation of the Large Aral into the western and eastern parts, when the eastern coast of the western Large Sea was absent) upwelling was frequently observed in summer at the western coast of the Aral Sea [6,29] which suggested that southerly or westerly winds were the cause. In the case of the images in Fig. 11 upwelling should be related to winds from the north or east. An analysis of maps of ground wind over Asia confirmed the predominance of northeasterly winds in the Aral region at the end of September-beginning of October 2005.

Minimal SSTs in the upwelling zones in Figs. 11a, b, and c were 10.5, 11.5, and 12.5°C, respectively; their temperature contrast with respect to the waters beyond these zones - 8, 6.5, and 5.5°C, respectively (temperature scale is not presented because of the complexity of transmission of temperature gradations in the black and white version). A decrease of SST of about 2°C at the eastern coast of the eastern Large Sea at the same time could be caused by a joint effect of the autumn cooling and the negative surge.

Figure 11c reveals also a cyclonic eddy centered at 45°N with a diameter of 19 km, which is comparable with the local width of the western Large Sea. Entrainment of transformed cold upwelling waters by this eddy as well as vortices at the upwelling front evidently contribute to horizontal water exchange in this part of the sea. Notice that a cyclonic eddy with a horizontal scale of about 30 km centered at 44.8 N is seen on the surface velocity field derived from a pair of satellite images taken on 9 and 10 November 2002, by the Maximum Cross-Correlation technique (see Fig. 3.28 in [10]). This suggests that cyclonic eddies 20–30 km in diameter are a characteristic feature of water circulation in the western basin of the Large Sea, at least in the autumn season. Notice that large-scale circulation in the Large Aral in the conditionally natural period was anticyclonic.

6.4 Dust/Salt Storms

A dry band along the north-eastern and eastern coast formed as a result of the Aral Sea desiccation is the source of salt, which together with dust are transported by wind over a distance up to 450–500 km from the source of generation and accelerate the process of desertification of the Aral region [6,32]. Such dust/salt storms have been observed on satellite images since the mid-1970s [33] (see, for example, Fig. 12). The predominant direction of the salt and dust transport (up to 60%) is southwestward [6]; sometimes these dust/salt flows are traced almost to the eastern coast of the Caspian Sea (see Fig. 12).

6.5 River Inflow into the Aral Sea

Amudarya and Syrdarya outflows, the withdrawal of which for irrigation needs determined the tragic destiny of the Aral Sea, are represented to some extent on satellite images. The volume of Amudarya discharge decreased from 40 km^3 in the 1960s to a few km^3 in the 1980s. Nonetheless the only remaining spill-stream Urdabay continued to come forward to the sea up to 1989. A dam created in the riverbed and the building of barrages to hold water in reservoirs of the delta resulted in termination of direct Amudarya outflow into the sea. However, in the 2000s when

Fig. 12 Dust/salt storm over the Aral Sea: MODIS/Aqua image for 29 April 2008, courtesy of NASA. Black lines show country borders between Kazakhstan, Uzbekistan, and Turkmenistan

these reservoirs overfilled in the years abounding in water, Amudarya waters came into the Large Sea (Fig. 13). Temporary run off (surface or underground) gives rise to wetting of soil and eroding salt crusts easily seen on satellite images and results also in the appearance of reed vegetation on the dry bottom – strips of reed indicate underground continuation of the discharge.

Notice that, as distinct from the situation with overflow of waters from reservoirs in the Amudarya delta into the Aral observed on 13 October 2005 (Fig. 13), the opposite process occurred two weeks before under a north-easterly wind – cold waters from the Aral flowed into artificial reservoirs (unfortunately, this is not seen in the black and white figures (Figs. 11b and c), but is easily seen in the color version).

7 Atmospheric Precipitation over the Rivers' Catchment Areas

Inflow from the two rivers (Amudarya and Syrdarya) is the main income component of the Aral Sea water balance. So, it is important to estimate the amount of water precipitated from the atmosphere over the catchment areas of these rivers, reveal its interannual variability, and compare a tendency of this variability with the changes in the Aral Sea level. Such an estimation for the period 1979–2001 was made by Nezlin et al. [34].

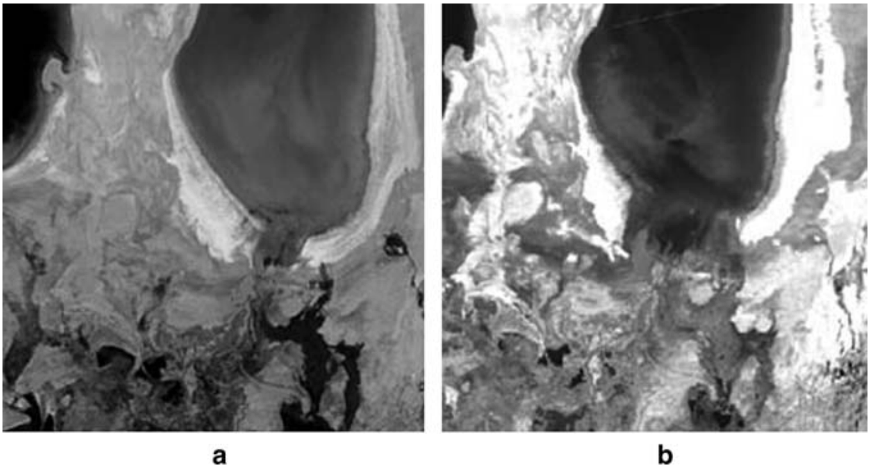


Fig. 13 Water overflow from reservoirs in the regional part of Amudarya delta in MODIS/Terra images for 22 September 2004 (*left*) and 13 October 2005 (*right*)

Two global data arrays of atmospheric precipitation were used: (a) the remotely sensed data produced within the scope of the global precipitation climatology project (GPCP) from the measurements of microwave radiometers and infrared sensors on different satellite platforms collected during 1979–2001 and (b) data derived from the precipitation measured by rain gauges and processed at the Global Precipitation Climatology Center (GPCC) in Germany over 1986–2001. The data on monthly precipitation were integrated over the rivers catchment areas (see [34]). The variations of sea level were obtained with data from the T/P satellite: for the Large Sea, altimetry data in crossover points of satellite tracks 107 and 142 were used, for the Small Sea - those of tracks 107 and 218 (see Fig. 4).

It is seen from Figs. 14 and 15 that the precipitation supplying the Amudarya and Syrdarya rivers exhibits interannual variations of a 5- to 9-year period. Both GPCP and GPCC data on precipitation demonstrate a marked decreasing trend for the Amudarya catchment area (Fig. 14) and almost insignificant decreasing trend (the absence of a trend since 1985) for the Syrdarya case (Fig. 15). These trends correspond well to interannual variability of the sea level of two separated basins of the Aral Sea. So, it may be concluded that not only anthropogenic impact but also natural trends in regional climate changes (changes of the amount of total rain and snow precipitation over the catchment areas) determine the level of the Large and Small seas [34]. Notice that cyclic seasonal variations of atmospheric precipitation do not influence the Large Sea level. In contrast, the level of the Small Sea, whose volume is much less, is sensitive to seasonal variations of atmospheric precipitation. Seasonal maxima of atmospheric precipitation are observed in winter-spring and seasonal minima in summer-autumn. This result is in agreement with the data of Table 3.

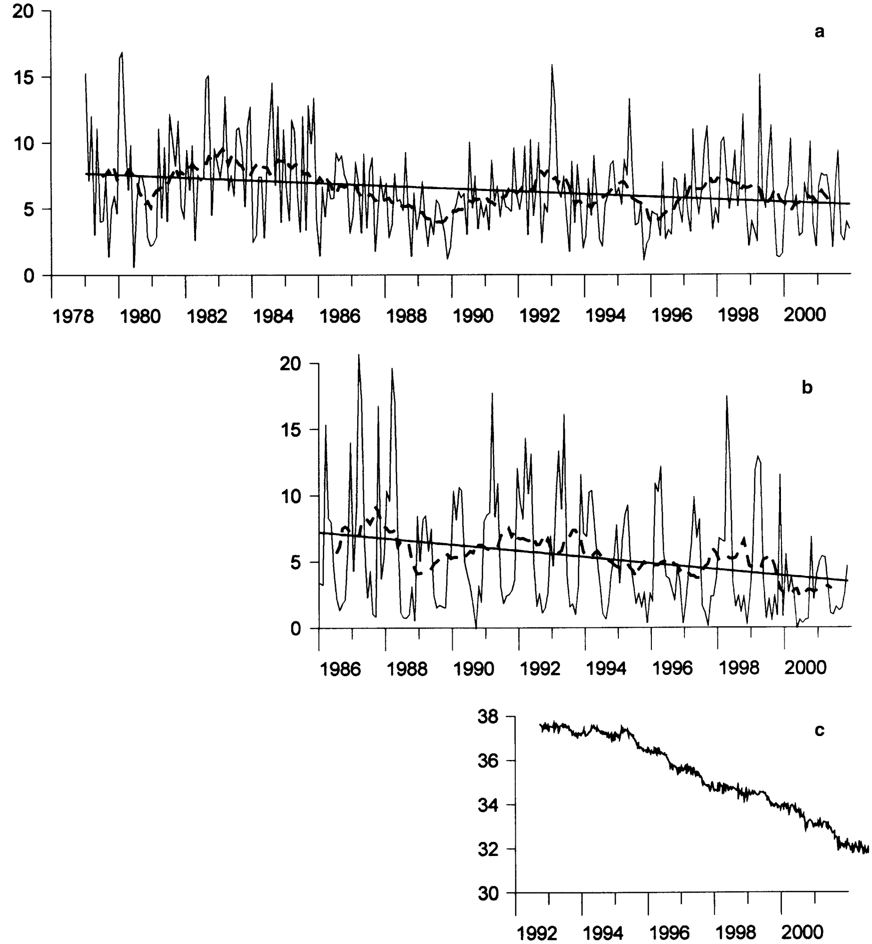


Fig. 14 Interannual variations of the discharge of Amudarya derived from precipitation integrated over its catchment area. (**a**) Satellite-measured (GPCP) precipitation (km^3/month); (**b**) gauge-measured (GPCC) precipitation (km^3/month); (**c**) satellite-measured (T/P) level of the Large Sea (m); *Dashed line* is moving average of about 1 year (13-point) period (after [34])

8 Normalized Difference Vegetation Index

Several vegetation indices have been developed to measure the state of terrestrial vegetation from orbital platforms based on a combination of two or more spectral bands (see [35]). The most widely used vegetation index for agricultural and ecological applications is the normalized difference vegetation index (NDVI). It is based on the general idea that chlorophyll pigments in leaves absorb solar radiation in the visible part of the spectrum and strongly reflect and backscatter

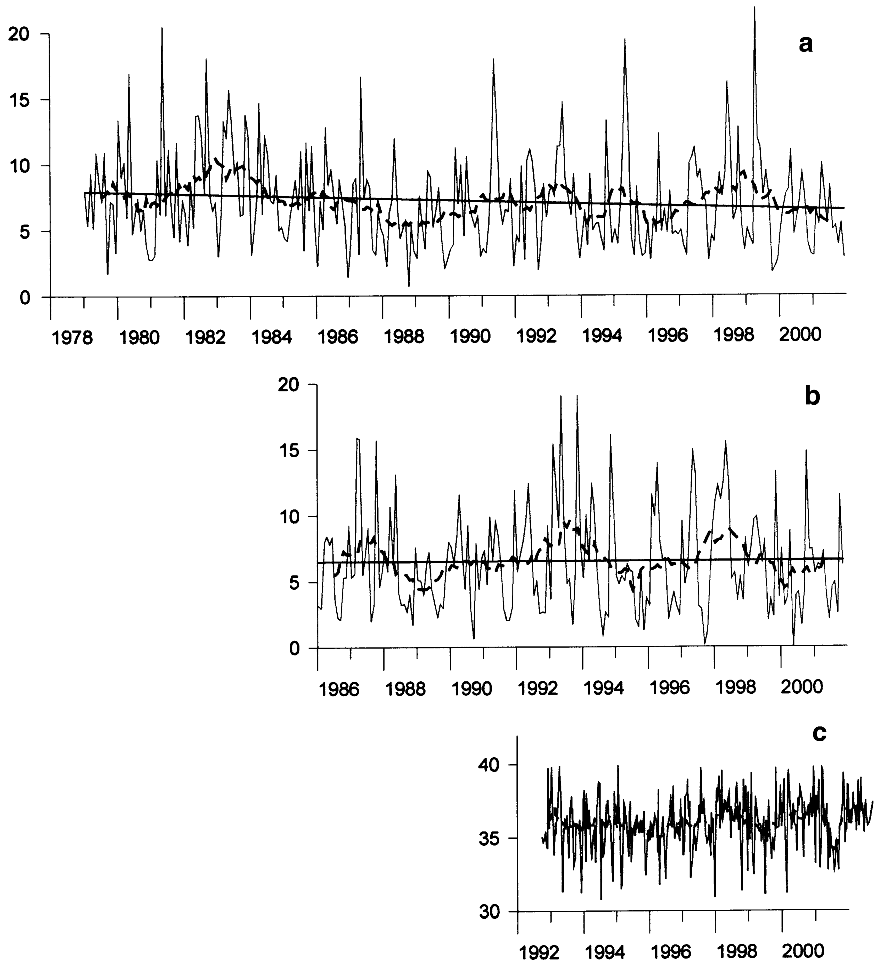


Fig. 15 Interannual variations of the discharge of Syrdarya derived from precipitation integrated over its catchment area. (**a**) Satellite-measured (GPCP) precipitation (km^3/month); (**b**) gauge-measured (GPCC) precipitation (km^3/month); (**c**) satellite-measured (T/P) level of the Small Sea (m); *Dashed line* is moving average of about 1 year (13-point) period (after [34])

radiation in the near-infrared band. Data from AVHRR radiometers onboard the NOAA satellites, which observe the earth in visible (VIS = 0.55–0.68 μm) and near-infrared (NIR = 0.73–1.10 μm) and embrace the period of observations exceeding two decades (since 1981), allows one to assess NDVI on a global scale. NDVI is defined as NDVI = (NIR-VIS)/(VIS+NIR). Analysis of seasonal and interannual variations of AVHRR NDVI (1981–2001) and their correlations with contemporary variations in atmospheric precipitation (GPCC data, 1986–2001) for the Aral Sea region is performed in [35].

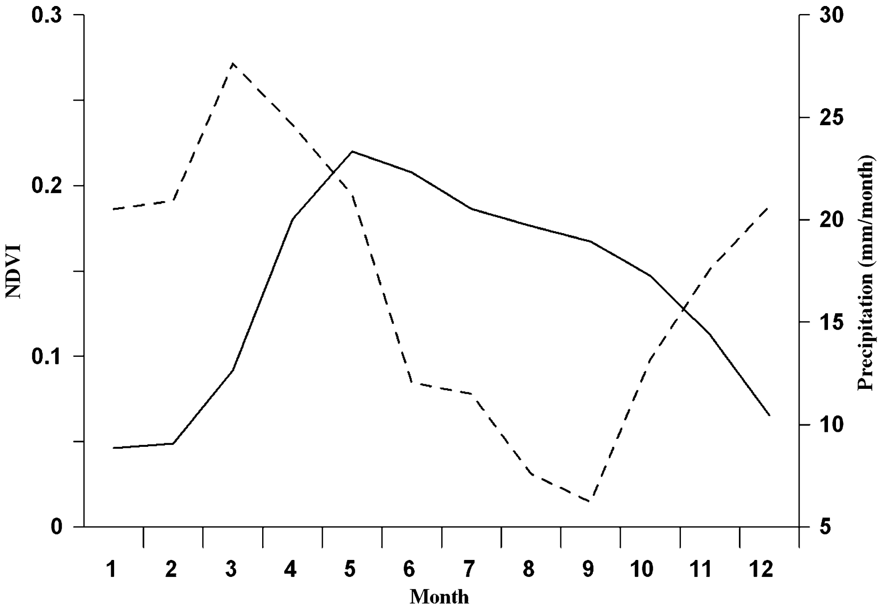


Fig. 16 Climatic seasonal variations of NDVI (*solid line*, *left Y*-axis) and precipitation (*dashed line*, *right Y*-axis) averaged over the entire study region (35°–50°N, 55°–75°E) (after [35])

It is shown that the zones of high NDVI values appear to correspond (in general) to high precipitation areas. However, some differences are evident. For example, the zone of rather high NDVI in the lower course of the Amudarya coincides with the zone of extremely low precipitation (the Amudarya seems to be an exclusive source of water for the plants growing there). Both GPCC and NDVI exhibit pronounced seasonal variation, with maximum precipitation in March and maximum NDVI in May–June (Fig. 16).

The regions of synchronous seasonal and interannual variability between NDVI and precipitation were distinguished using the empirical orthogonal functions (EOF) method and time-lagged correlations between the EOF modes [35]. It appeared that at a seasonal scale, precipitation and NDVI were correlated with a time lag from 1 to 6 months in different regions with peak plant growth following precipitation maxima. The absence of correlation between precipitation and NDVI in some regions around the Aral Sea indicates the lack of water for vegetation growth and the zones of desert.

9 Changes in Landscapes

Besides changes in morphometric, hydrological and other parameters, desiccation of the Aral Sea resulted in the formation of a large desert in place of the dried bottom. The area of this desert by now is about 5 million hectares [11].

Expeditionary investigations of soil-landscape changes on the dried bottom in combination with remote sensing observations are carried out by scientists from Uzbekistan and Kazakhstan [11]. Seasonal changes in the landscapes of a former sea bottom are investigated in the Department of Cartography and Geoinformatics of Moscow State University on the basis of satellite images. To this end the map of natural complexes of the Near-Aral region for 2002 was compiled [36], where terraces of three levels are characterized, having been formed 1–2 years back, 5–6 years, and 30–40 years back (Fig. 17).

Seasonal changes of landscapes were traced with satellite images taken in April, May, July, and September 2002, and a series of maps of seasonal changes of natural complexes has been firstly compiled (Fig. 18). These maps are representative of phenological changes of vegetation in the surrounding deserts, which are characterized by a green "wave" of vegetation in spring and early summer and the fading of vegetable cover during late summer and autumn. The maps also show temporal differences between phenological development of the deserts vegetation and reed thickets of deltas, which renew vegetation later (by summer) and complete it also later (in autumn).

The state of natural complexes varies with the drying of territory after humidification in winter-spring [37]. The mode of ground salinization is closely connected to the change of territory wetness. The wide zone (20–30 km) of low terraces of the 1-st and 2-nd level around the sea is moistened in spring. The salt crust is formed at the edge of these terraces owing to evaporation. This crust borders the moist surface of terraces by a continuous strip from 2 to 10 km in width.

As far as drying of territory, the crust dries up. Being eroded by wind, it becomes a source of salt storms and is gradually destroyed. In 2–3 months it breaks up to separate fragments, and the surrounding territories become covered by salts. By the end of summer, the remains of this salt crust completely disappears. In parallel with destruction of the first salt crust (formed in spring, the thickest one) with drying of the low terraces, at the edge of a narrowed wet strip, new salt crusts are forming, moist in the beginning and subsequently drying out and then destroyed by deflationary processes. Some time there are simultaneously two or even three strips of salt crust, each of which is at a different stage in a cycle of formation on the edge of the wet terrace, drying and then being destroyed by deflation (Fig. 19).

Thus, the basic processes of seasonal dynamics of the territory of a former sea bottom are connected to a regime of moistening and salinization, drying of the ground and formation and then destruction of salt crusts on the edge of the narrowed humidified strips.

10 Conclusions

Satellite information (images of visible and infrared ranges, time series from active and passive sensors onboard satellite platforms) is a necessary (in the absence of regular in situ measurements) and very effective means for monitoring the Aral Sea.

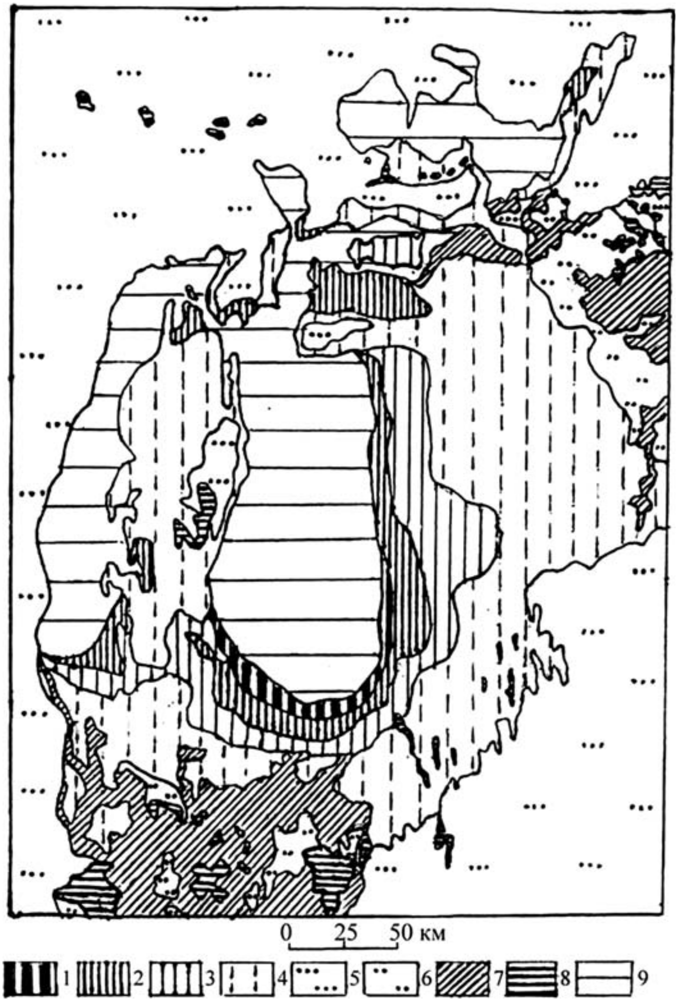


Fig. 17 The map of natural complexes of the Near-Aral Region. 1 – Marsches (alternations of sites of water and dried bottom). A former sea bottom getting free of water at different times: 2 – 1–2 years back – 1-st level terraces (silt waste lands without vegetation cover that are covered by salt crust when drying); 3 – up to 5–6 years back – 2-nd level terraces (loamy-silty waste lands with solonchak semi-shrubby vegetation, with salt crusts at the edge of strips of wetting, which are subjected to deflation processes and formation of eolian relief in initial stage); 4 – up to 30–40 years back – 3-rd level terraces (sand/salt deserts with parts of psammophytic-shrubby vegetation alternating with solonchak and blown sands, with developed processes of deflation and formation of eolian relief. 5 – Clayey and sandy deserts of bedrock land with psammophytic-shrubby and saxaul vegetation. 6 – Delta plains with desertified grassy and shrubby vegetation. 7 – Reed vegetation in river deltas and along sea shores. 8 – Solonchaks, lakes, temporary reservoirs. 9 – Sea area

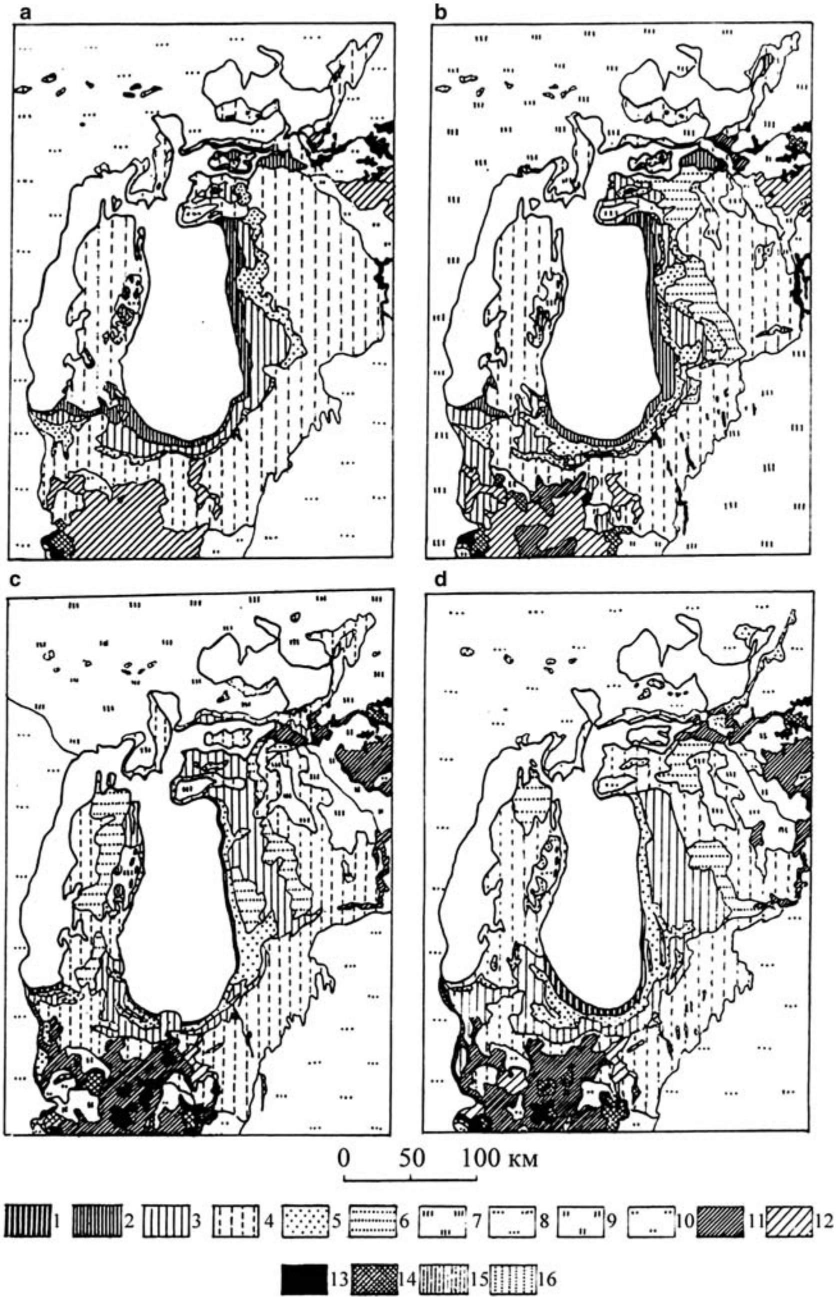


Fig. 18 Series of maps of seasonal changes of natural complexes in 2002: (**a**) 16 April; (**b**) 18 May; (**c**) 10 July; (**d**) 19 September. 1 – Marsches (alternations of sites of water and dried bottom). Loamy-silty waste lands and sand/salt deserts on a former sea bottom: 2 – strong wet; 3 – wet; 4 – dry. 5 – Salt crusts at the edge of wet strips of a former sea bottom. 6 – Deposits of deflated salts

Mapping of the changing shoreline of the sea with satellite images has shown that from 1961 to 2008 the total area of the Aral decreased from 66,400 to 10,400 km^2, which is a reduction of 84%; in this case, areas of the Large and Small Aral seas shrank by about 88 and 44%, respectively. The areas of the relatively deep western part of the Large Sea and its shallow eastern part decreased during 1989–2008 by 57 and 89%, respectively, and in 2008, the eastern Large Sea area (3,200 km^2) became for the first time less than the area of the western Large Sea (4,000 km^2) (see Table 1).

Judging by satellite altimetry, from 1992 to 2006, the Large Sea level dropped by about 8.8 m. Since 2003, a considerable slowing of sea level drop has been observed: during three years (2003–2006) the sea level dropped by about 0.5 m which was likely related to unusually high river discharge in 2002–2004 (see [15]). In the same period (1992–2006), the Small Sea level was not changed unidirectionally. Its changes within about 2 m were mainly associated with dam destruction and recovery between the Small and Large Aral seas. By 2007, the Small Sea level even exceeded that in 1992 by about 1 m.

By 2000, considerable changes in the temperature regime of the Aral Sea had taken place in comparison with the conventionally natural period. Coincidence of tendencies of these changes (a shift of the spring and autumn temperature phases by a month and a half month, respectively, in the Large Sea toward their earlier onset, higher summer SST maximum of the shallow eastern Large Sea relative to that of the "deep" western region, an increase of seasonal range of SST) with prognostic estimates of 1950–1980 suggests that the revealed changes in the temperature regime of the sea were determined mainly by decreasing depth and heat storage. However, large-scale changes in air temperature throughout Central Asia as well as physical processes associated with the shallowing of the sea (e.g., changing conditions of vertical mixing in the water column) can influence the rate of SST changes.

Dates of ice start/end and ice season duration in the Small Aral did not exhibit a marked trend during 1992–2006, whereas winter duration and date of ice disappearance in the shallow Large Aral had a distinct negative trend in 1996–2002 and a positive one in 2002–2006. The latter positive trend, which occurred under practically unchanged Large Sea level (and salinity, temperature of freezing), is an argument in favor of the supposition by Kouraev et al. [26] and Zavialov [10] that changes in the dates of the start and end of the ice season as well as in ice extent are related to climatic trends rather than to salinization effects. This supposition is supported by the similar character of interannual variability of the ice regime in 1992–2001 in the neighboring Caspian Sea, where no changes in heat capacity and water salinity are observed [26]. This is justified also by the character of changing

Fig. 18 (continued) and salt efflorescences on the dried sites of a former sea bottom. Desert-like vegetation on sites of bedrock land: 7 – vegetative (ephemeral); 8 – dried. Desertified vegetation of delta plains: 9 – vegetative; 10 – dried. Reed vegetation in river deltas and along sea shores: 11 – vegetative; 12 – dried. Reservoirs: 13 – with open water surface; 14 – reedy. Solonchaks: 15 – wet; 16 – dried, with salt crust

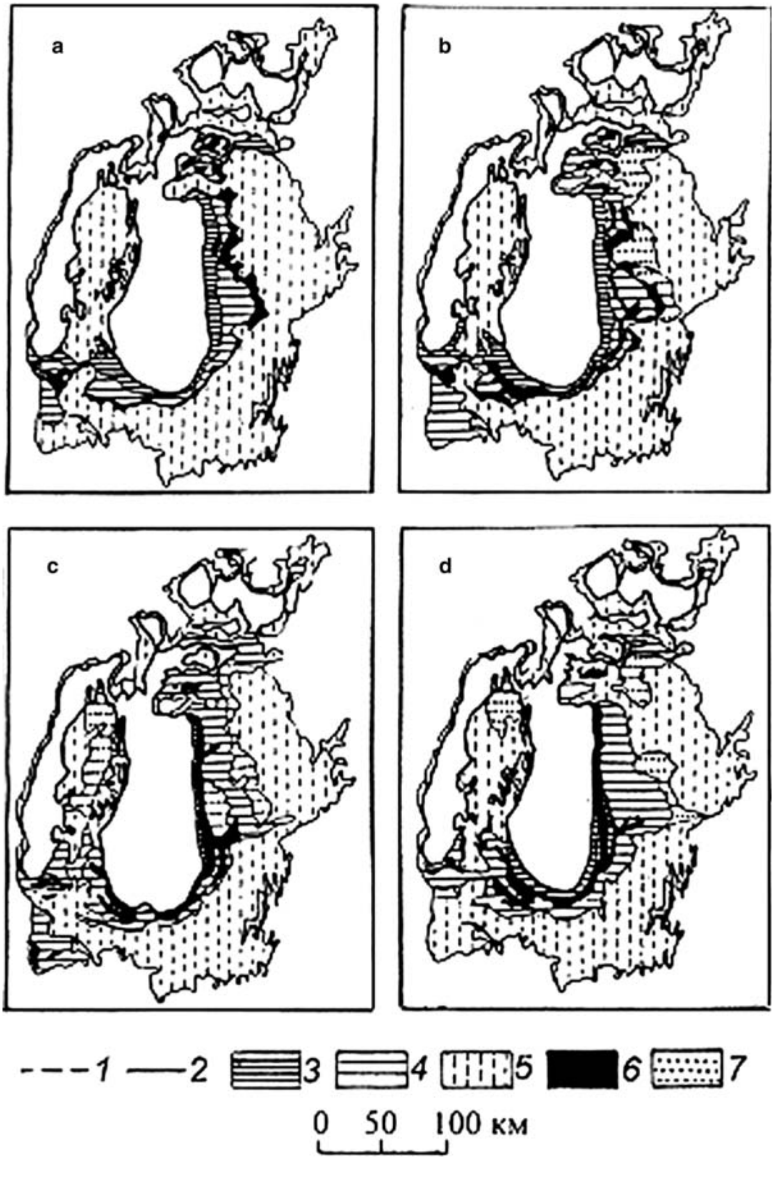


Fig. 19 Seasonal changes in humidity and salinization of a former sea bottom in 2002. Shoreline: 1 – in 1961, 2 – in 2002. Parts of former sea bottom: 3 – strong wet, 4 – moderate wet, 5 – dry. 6 – salt crusts. 7 – plots with salt accumulation after salt crust erosion by wind

winter (and mean annual) SST in the Black Sea in 1993–2006: its increase in 1993–2001 and a tendency to decrease in 2001–2006 [38].

A comparison of interannual variability of the atmospheric precipitation over the Amudarya and Syrdarya catchment areas with levels of the Large and Small Aral seas, respectively, allows one to conclude as well that not only the anthropogenic impact but also natural trends in regional climate changes (changes of the amount of total rain and snow precipitation) determine the level of the Large and Small seas [34]. In the future, analysis of changes in Aral Sea level, water temperature, and ice regime should be carried out with consideration of atmospheric processes (air temperature, total precipitation, wind speed and direction, etc.).

Acknowledgments This work was partially supported by the program of Leading Scientific Schools № NSh-171.2008.5, Russian Foundation for Basic Research Grant № 07-05-00187, and Presidium of Russian Academy of Sciences Project № 17.

References

1. Sigalov VM (1986) Geod kartogr 4:39 in Russian
2. A map of Aral Sea dynamics from 1957 to 1989 with prediction to 2000 (1990) GUGK SSSR, Moscow (in Russian)
3. Kravtsova VI, Lourie IK, Markov DV (2001) Geod kartogr 4:32 in Russian
4. Kravtsova VI, Lourie IK, Mudrya TM (2002) Geod kartogr 10:46 in Russian
5. Ressl R, Micklin P (2004) Morphological changes in the Aral Sea: Satellite imagery and water balance model. In: JCJ Nihoul, PO Zavialov, and PP Micklin (eds.) Dying and dead seas. NATO science series. IV. Earth and environmental sciences. The Netherlands, Kluwer Academic Publishers, 36, p 77
6. Bortnik VN, Chistyaeva SP (Eds.) (1990) Hydrometeorology and hydrochemistry of seas of the USSR. Project “Seas of the USSR”: Vol. VII. The Aral Sea. Gidrometeoizdat, Leningrad (in Russian)
7. Kouraev AV, Kostianoy AG, Lebedev SA (2009) J Mar Syst 76:272
8. Chub VE (2000) Climate change and its impact on the natural resources potential of the Republic of Uzbekistan, SANIGMI, Tashkent (in Russian)
9. Mikhailov VN, Kravtsova VI, Gurov FN, Markov DV, Greguar M (2001) Vestn Mosk Univ ser. 5 Geogr 6:14 in Russian
10. Zavialov P (2005) Physical oceanography of the dying Aral Sea. Springer- Praxis Publishing, Chichester, UK
11. Dukhovny VA, Navratil P, Ruziev I, Stulina G, Roshenko E (Eds.) (2008) Integrated remote sensing and ground investigations of the dried Aral Sea bottom. Scientific-information center of intergovernment coordination water commission, Tashkent (in Russian)
12. Zavialov PO, Kostianoy AG, Emelianov SV, Ni AA, Ishniyazov D, Khan VM, Kudyshkin TV (2003) Geophys Res Lett 30(13):2–1. doi:10.1029/2003GL017427
13. Zavialov PO, Kostianoy AG, Sapozhnikov PhV, Scheglov MA, Khan VM, Ni AA, Kudyshkin TV, Pinkhasov BI, Ishniyazov DP, Petrov MA, Kurbaniyazov AK, Abdullaev UR (2003) Oceanology 43(2):299 English Translation
14. Zavialov PO, Ginzburg AI, Sapozhnikov PhV, Abdullaev UR, Ambrosimov AK, Andreev IN, Validzhanov R, Ishniyazov DP, Koldaev AA, Kudyshkin TV, Kurbaniyazov AK, Ni AA, Petrov MA, Stroganov OYu, Tomashevskaya IG, Khan VM (2004) Oceanology 44(4):595 English Translation
15. Zavialov PO (2009). Physical oceanography of the Large Aral Sea. The handb environ chem. doi: 10.1007/698_2009_4
16. Kostianoy AG, Zavialov PO, Lebedev SA (2004) What do we know about dead, dying and endangered lakes and seas? In: JCJ Nihoul, PO Zavialov, PP Micklin (eds.) Dying and dead

seas. Climatic versus anthropic causes. NATO science series. IV. Earth and environmental sciences. Vol. 36. Kluwer Academic Publishers. Dordrecht/Boston/London, p 1
17. Peneva EL, Stanev EV, Stanychni SV, Salokhiddinov A, Stulina G (2004) J Mar Syst 47 (1–4):11
18. Stanev EV, Peneva EL, Mercier F (2004) Geophys Res Lett 31:L15505. doi:10.1029/2004GL020478
19. Aladin N, Crétaux J-F, Plotnikov IS, Kouraev AV, Smurov AO, Cazenave A, Egorov AN, Papa F (2005) Environmetrics 16(4):375. doi:10.1002/env.709
20. Crétaux J-F, Kouraev AV, Papa F, Bergé-Nguyen V, Cazenave A, Aladin N, Plotnikov IS (2005) J Great Lakes Res 31(4):520
21. Medvedev PP, Lebedev SA, Tyupkin YS (1997) An integrated data base of altimetric satellite for fundamental geosciences research. In: Proc. First East-European Symp. Advances in data bases and information systems (ADBIS'97), vol. 2., St.-Petersburg University, St.-Petersburg, Russia, p 95, September 2–5 1997
22. Medvedev PP, Tyupkin YS (2005) IST4Balt News J 1:39
23. Small EE, Giorgi F, Sloan LC, Hostetler S (2001) J Clim 14:300
24. Ginzburg AI, Kostianoy AG, Sheremet NA (2003) J Mar Syst 43:19
25. Stanichny S, Djenidi S, Stanichnaya R, Soloviev D. (2005) Geophysicl Research Abstracts. Vol. 7. SRef-ID:1607-7962/gra/EGU05-A-01163s
26. Kouraev AV, Papa F, Mognard NM, Buharizin PI, Cazenave A, Cretaux J-F, Dozortseva J, Remy F (2004) J Mar Syst 47:89
27. Kouraev AV, Papa F, Buharizin PI, Cazenave A, Cretaux J-F, Dozortseva J, Remy F (2003) Polar Res 22(1):43
28. Kouraev AV, Papa F, Mognard NM, Buharizin PI, Cazenave A, Cretaux J-F, Dozortseva J, Remy F (2004) IEEE Trans Geosci Remote Sens 42(10):2170
29. Kosarev AN (1975) Hydrology of the Caspian and Aral Seas. Moscow University, Moscow in Russian
30. Sklyarov VE (2008) Upwelling in the Aral Sea. In: Proc. concluding conference "Fundamental problems in oceanology: Physics, geology, biology, ecology", P.P. Shirshov Institute of Oceanology, Moscow, Russia, p 165, 27–28 November 2008. Abstracts (in Russian)
31. Fedorov KN, Ginsburg AI (1992) The Near-surface layer of the ocean. VSP, Utrecht, The Netherlands
32. Micklin PP (2004) The Aral Sea crisis. In: JCJ Nihoul, PO Zavialov, PP Micklin (eds.) Dying and dead seas. Climatic versus anthropic causes. NATO science series. IV. Earth and environmental sciences. Vol. 36. Kluwer Academic Publishers. Dordrecht/Boston/London, p 99
33. Grigoriev AA, Lipatov VB (1982) Izv AN SSSR, Geogr Ser 5:93 in Russian
34. Nezlin NP, Kostianoy AG, Lebedev SA (2004) J Mar Syst 47:67
35. Nezlin NP, Kostianoy AG, Li B-L (2005) J Arid Environ 62:677
36. Kravtsova VI, Mudrya TM (2004) Vest Mosk Univ, Geogr Ser 5:46
37. Kravtsova VI (2006) Degradation of the Aral Sea and surrounding territories: specific phenomena observed with satellite images. In: "Extreme hydrological events in Aral and Caspian Sea region". The Proceedings of international scientific conference, Moscow, p 331, 19–20 October 2006.
38. Ginzburg AI, Kostianoy AG, Sheremet NA, Lebedev CA (2008) Interannual variability of sea surface temperature and sea level of the Black, Marmara and Agean Seas (by satellite data). In: Proc. concluding conference "Fundamental problems in oceanology: Physics, geology, biology, ecology", P.P. Shirshov Institute of Oceanology, Moscow, Russia, p 139, 27–28 November 2008. Abstracts (in Russian)

Aral Sea Level Variability

Jean-François Crétaux, René Letolle, and Alexei Kouraev

Abstract The Aral Sea has drastically shrunk over the past 50 years, largely due to water withdrawal from the Amudarya and Syrdarya rivers for land irrigation. If one were to look back over the Holocene,[1] the paleolimnology of the Aral Sea is however already marked by the occurrence of several phases of regression and transgression. They resulted partly from climate change, for tectonic reasons, and over the last 2,000 years anthropogenic actions also played a role. After a short review of the paleohistory of the Aral Sea, we will focus on a description of the causes and magnitude of episodes of historical (last 100 years) Aral Sea level variability. The Aral Sea has been marked since the middle of the last century by a process of desiccation due to increase of water intake from the Amudarya and Syrdarya rivers for agricultural purposes. This led to the separation of the Aral Sea into two (in 1986–1987) and then four (in 2009) water bodies. Measurements of Aral Sea water level and surface and water balance were carried out by both in situ gauges and remote-sensing satellite data. This allows for a better understanding of the seasonal, interannual, and decadal trend in Aral Sea water storage variations.

Keywords Aral Sea, Irrigation, Satellite altimetry, Water balance, Water level

J.-F. Crétaux (✉)
CNES/Legos, 14 Av Edouard Belin, 31400, Toulouse, France
e-mail: jean-francois.cretaux@cnes.fr

R. Letolle
Dept de géologie appliquée, Lodyce, University PM Curie, Paris, France

A. Kouraev
Universite de Toulouse UPS (OMP-PCA), LEGOS, 14 av. Edouard Belin, 31400, Toulouse, France

State Oceanography Institute St. Petersburg branch, Vasilyevskiy ostrov, 23 liniya, 2a, St. Petersburg, Russia

[1]Holocene is the latest period of geological history, and it began at about 11,000 years BP.

A.G. Kostianoy and A.N. Kosarev (eds.), *The Aral Sea Environment*,
Hdb Env Chem (2010) 7: 181–193, DOI 10.1007/698_2009_37,

Contents

1 Introduction

The limnological and geomorphological history of the Aral Sea before the twentieth century, largely based on Russian literature, is poorly documented in current references with respect to the dozens of articles relating to the latest Aral Sea desiccation which started in 1960. It is, however, worth noting that the current Aral Sea regression, also called by several authors "the Aral Sea disaster," is far from the first time over the past 10,000 years that this shallow water body has desiccated to such an extent [1].

Establishing the history of Aral Sea level variability from geological time to the present-day through historical time is a challenging issue. Pluridisciplinary effort may help to reconstruct some part of the past of the Aral Sea, and several sources of information have been used: analyses of core and terrace sediment, paleoclimatological indicators (like tree-rings, or pollen), archaeological settlement distributions [2], historical archives, geomorphology patterns of shorelines, and measurements on crustal vertical deformations. It has been demonstrated that over the Holocene period, the Aral Sea has been affected by several episodes of regression and transgression, ranging from a few decades to centuries [1, 3]. The extent of the Aral Sea, particularly during a transgression phase is also a current issue which still divides researchers. Some authors think that except for the last 50 years, the paleolimnology of the Aral Sea has been almost fully governed by climate change with only a small contribution from human action, while others are more convinced by the contrary. This debate has reopened recently with articles that have tried to show that the first assumption is a good one, but which also showed that this fact which seemed to be well accepted by the scientific community for the last 100 years could still be an open question. A full description of the chronology of Aral Sea paleolimnology can be found in several articles: [1–10].

At the beginning of the nineteenth century the Aral Sea was declining by around 2–3 m to an absolute level of around 50 m above world sea level, followed by a succession of increasing and decreasing levels of around 2–3 m until 1905 when it reached 53 m [11]. Up to the 1960s, river discharge had provided 56 $km^3\ yr^{-1}$ [11] of fresh water to the Aral Sea on average, which was sufficient to maintain the lake level at +53 m above sea level [12]. Around 50–60 $km^3\ yr^{-1}$ was also lost by evaporation, loss through underground infiltration and irrigation along the 3,000 km length of the rivers. In the following we describe contemporary Aral Sea level variability.

2 Present-Day Aral Sea Level Variability and Water Balance

2.1 Modern Aral Sea Crisis

Irrigation in Central Asia has existed for centuries, and for example in the mid-nineteenth century, in the Amudarya delta, the Karakalpaks maintained sustainable systems of channels for agriculture that insured prosperity for the inhabitants of the delta [13]. However, in 1962, the Aral Sea started to drastically shrink due to growth of water intake for irrigation and construction of water reservoirs along both the Syrdarya and Amudarya rivers [11, 14]. In such an arid zone, irrigation provided the means to reach planned Soviet Union agricultural objectives. Large-scale development of ground infrastructure (irrigation channels, reservoirs) began and the extent of the irrigated area increased from 5.5 billion hectares in 1950 to 9 billion in 1985 [15]. For example, the Karakum channel was built between Amudarya and Turkmenistan's oasis, with runoff of 600 $m^3\ s^{-1}$, and other networks of channels along the Syrdarya River were also developed. For an arid water body like the Aral Sea, the water balance which determines the equilibrium level of water is strongly forced by the surface inflow from river discharge. Small changes in this component of the water balance will thus affect significantly the level of water since evaporation remains constant for a given climate condition and precipitation is generally very low and cannot compensate for the evaporation.

During the years 1961–1970 one of the first consequences of reduced river runoff (Fig. 1), particularly along the Amudarya, was to decrease the Aral Sea level by about 20 cm yr^{-1} [11]. The following decade (the 1970s) was characterized by enormous amplification of water intake, with only 17 $km^3\ yr^{-1}$ reaching the Aral Sea, instead of 56 km^3 before 1960 (Fig. 1). During the decade between 1975 and 1985 the release from the Syrdarya River into the Aral Sea was even close to zero (Fig. 1). Consequently, the rate of water level decrease was about 58 cm yr^{-1}. It is considered in [11] that during this period, climate change, as deduced from changes in precipitation and evaporation would have provoked a decline of the sea by 2.3 m in 20 years. In fact, a much higher decline of 8 m has been observed. During the

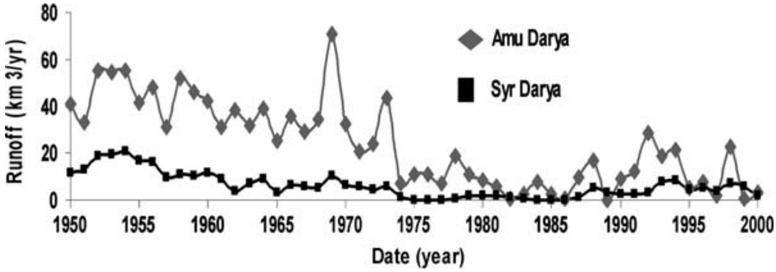


Fig. 1 Annual variation in river runoff for the Syrdarya and Amudarya, and of the two rivers together into the Aral Sea

1980s, it was for the first time that during some dry years the Amudarya could not reach the Aral Sea. The average water discharge during this period was about 4 km^3 yr^{-1} ([11], and Fig. 1). As a consequence, in the years 1986–1987 the Aral Sea was separated into two distinct water bodies, the North Aral (or Small Aral) and the South Aral (or Large Aral). The Small Aral is fed by the Syrdarya River, while the Large Aral is fed by Amudarya River. At the time of separation the level of the Aral Sea was about 40 m above sea level ([16], and Fig. 2).

Since that time they have both evolved in a different way. At the beginning of the 1990s, the Amudarya still supplied around 15 km^3 of water per year to the Large Aral Sea and delta [17] due to several years of precipitation in the Pamir mountains (Fig. 3). In the mid-1990s water runoff decreased again, and the level of the Large Aral in 2002 was 7 m lower than the Small Aral. The Large Aral has continued to shrink at an average rate of 80 cm yr^{-1}. Because the Small Aral received run-off

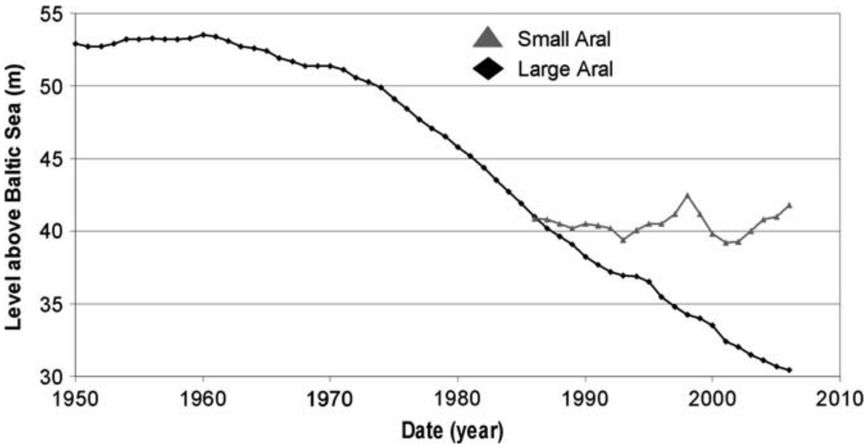


Fig. 2 Aral Sea level annual variations from 1950 to 2006. From 1950 to 1986 the level is plotted for the former Aral Sea, then it represents the level variations of the Large Aral (*black*) and Small Aral (*grey*)

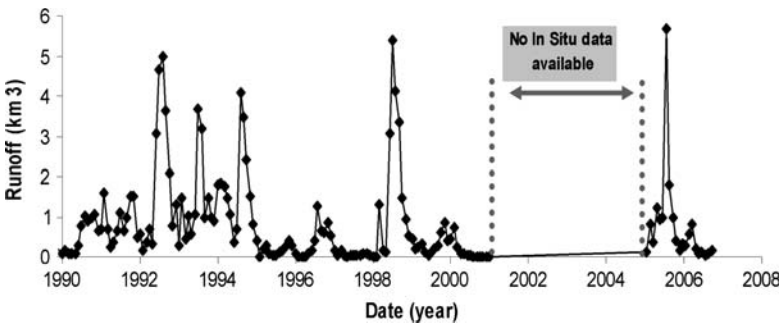


Fig. 3 Monthly variation of Amudarya runoff from 1990 to 2006

from the Syrdarya and because of the smaller surface of this lake, the evaporation was relatively balanced by precipitation and river runoff. The level of the Small Aral has hence become more or less stabilized to an average value of 40–42 m above sea level, with however large fluctuations due to seasonal and interannual climate changes, and because of the construction of a dam in the Berg Strait (Fig. 2). This dam was destroyed (and rebuilt) three times during the last 15 years. It has been demonstrated in [16] that during the period 1993–1999 the existence of the dam allowed some restoration of the Small Aral Sea. They calculated from the water balance that during periods of the dam's absence, only 20% of the river runoff entering the delta (in Kazalinsk) reached the sea. The rest was lost to evaporation in the delta and in the desert, as well as to underground infiltration and probably some inflow to the Large Aral Sea through the Berg Strait. They also showed that when the dam was in place, it allowed water retention of 80% of the river runoff that enters via the Syrdarya delta. This computation determined a correlation between the amount of water entering into the Syrdarya delta and the level of Small Aral Sea [16].

The differences in the hydrological regimes of the two lakes have thus led to stabilization of the Small Aral Sea level and continued desiccation and salinization of the Large Aral Sea. All the above has been widely documented in several articles: [11, 14, 16, 18–24], and Fig. 5 of [19].

At the beginning of the twentieth century the first systematic measurements of the Aral Sea level started and in 1940 there were already six to ten ground gauge stations [11]. In the mid-1990s there were no stations in operation. Then the level of the Aral Sea was calculated from satellite measurements, through radar altimeter instruments, or via optical satellite imagery of the sea surface [19]. The evolution of the Aral Sea level for the last 15 years based on radar altimetry data has been described in a few articles ([23–26] for the Large Aral and in [16, 24, 26] for the Small Aral). With T/P, Jason-1, and Jason-2 altimeters which overpass both new distinct seas (see Fig. 4 of [19]), it has been possible to measure precisely the level variations from 1992 until now. The elevation of the Large Aral reached a low of +29 m in 2008 [25]. In those articles the authors have tried to calculate the water balance of both water bodies in order to deduce some unknown parameters like ground water discharge. A description of the main water balance parameters is given in the following section.

2.2 Present-Day Water Balance of the Aral Sea

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 [27]. The assessment of lake water balance could hence provide improved knowledge of regional and global climate change and a quantification of the human stress on water resources across all continents.

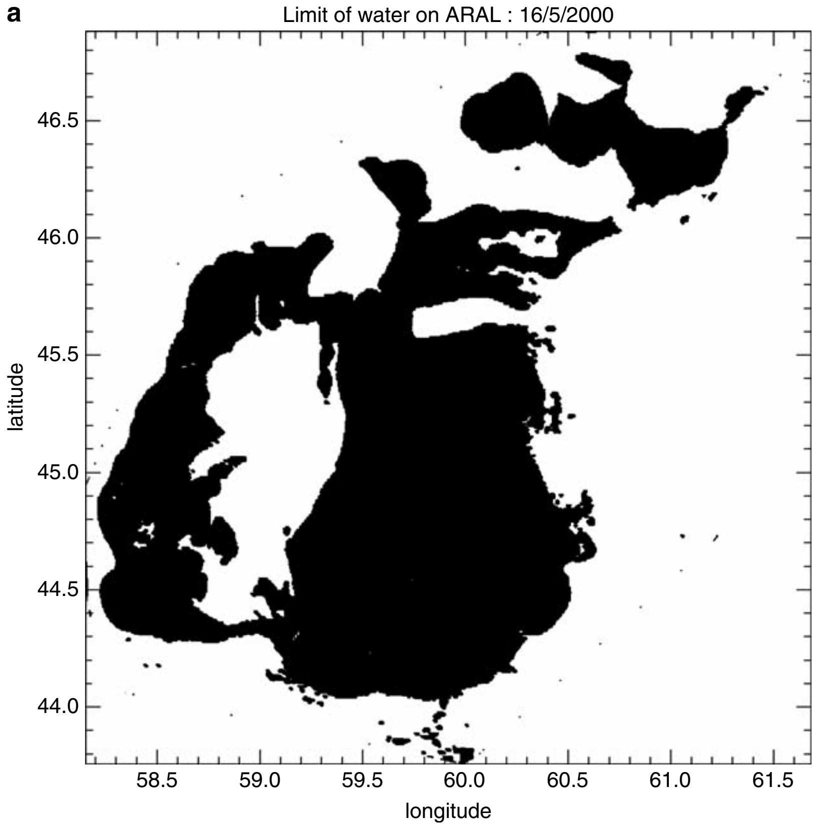


Fig. 4 (continued)

The precipitation rate in the Aral Sea region is rather low (less than 200 mm yr^{-1}) compared to the evaporation rate that ranges from 1,000 to 1,200 mm yr^{-1} [21, 28, 29]. Evaporation minus precipitation for the Large Aral Sea represented an average loss of 25–30 km^3 yr^{-1} during the last decade, while river discharge from the Amudarya varied from 0 to 15 km^3 yr^{-1} in the 1990s (Fig. 3). Thus, in the last decade of the twentieth century the water supply deficit reached 10–15 km^3 yr^{-1} depending on the year, and the Large Aral has continued to shrink as the equilibrium level has not yet been reached. The current level of the Large Aral (September 2009) has been measured by satellite altimetry and is now around 26.5 m above Baltic Sea level. Figure 4a, b, c also show the total area of the Aral Sea in spring 2000, 2004 and 2009 from Modis images (see [25] for more detail on Modis data image analysis). Desiccation of the Large Aral Sea was marked during this period, while the Small Aral kept a relatively stable surface with, however, an increase after August 2005 due to the new dam in the Berg Strait. Figure 4d shows

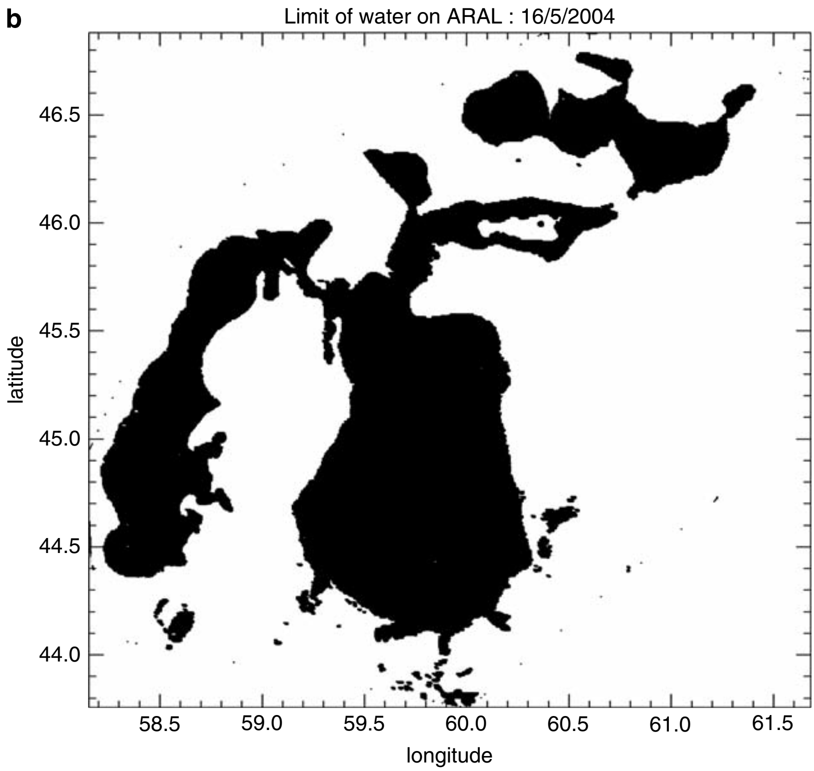


Fig. 4 (continued)

the Aral Sea in September 2009 (also from the Modis image), and clearly indicates an acceleration of the process of desiccation of the Large Aral, principally in the Eastern Basin during the summer of 2009. It is thus no longer valid to talk about the Small and Large Aral, as the Large Aral is now divided into three different basins (Fig. 4d).

After the separation from the Large Aral at the end of the 1980s, the water level in the Small Aral began to rise due to a positive water balance, and as a result, parts of its waters began to flow southward into the Large Aral. This outflow took place in the central part of the Berg Strait which had earlier been dredged (in 1980) in order to facilitate navigation between the northern and southern basins. This southward current was slow at first but increased as the level of the Large Aral continued to decrease. When the Large Aral level fell to +37 m the difference in level between the two water bodies reached 3 m and the flow reached 100 $m^3\ s^{-1}$ [18]. This canal was dammed in the summer of 1992 and the flow stopped. Over the next few years the dam in the Berg Strait was partly destroyed by floods and was restored several times (for details see [23]). In April 1999 the dam was completely destroyed and the

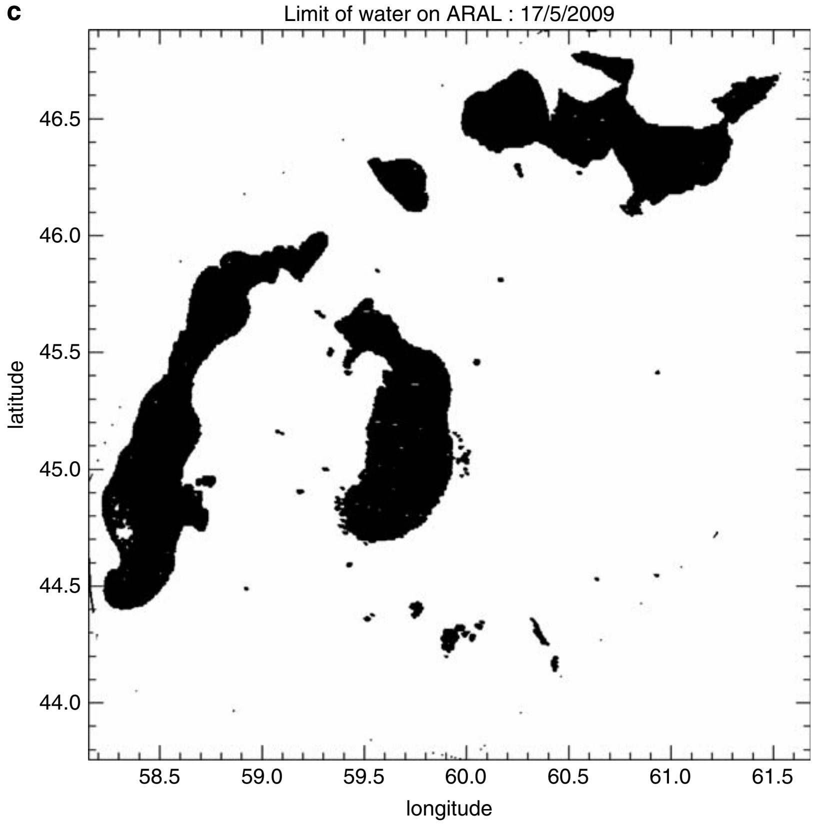


Fig. 4 (continued)

water of the Small Aral again flowed southward. But, as the length of the channel between the Large and Small Aral increased, water flowing from the Small Aral was retained in the sands and salt marshes north of the former Barsakelmes Island and did not reach the Large Aral. In 2005, a new dam was built with the support of the World Bank and Kazakhstan government which is still operating and has allowed an increase in the level of the Small Aral to about 2 m, with control of the level through seasonal release (in Spring) to the Berg Strait (see Fig. 5 of [19]).

Several publications have reported on studies of the water balance of the Aral Sea. Water balance estimation for the Aral Sea is rather difficult because of several sources of uncertainties in the parameters entering the water balance equation.

The problem with most of the water balance studies of the Aral Sea is that for several decades there were no continuous observations of the sea level, and the few data that do exist are fragmentary or unavailable. Because the historical sea volume cannot be determined accurately, there are large uncertainties in the water

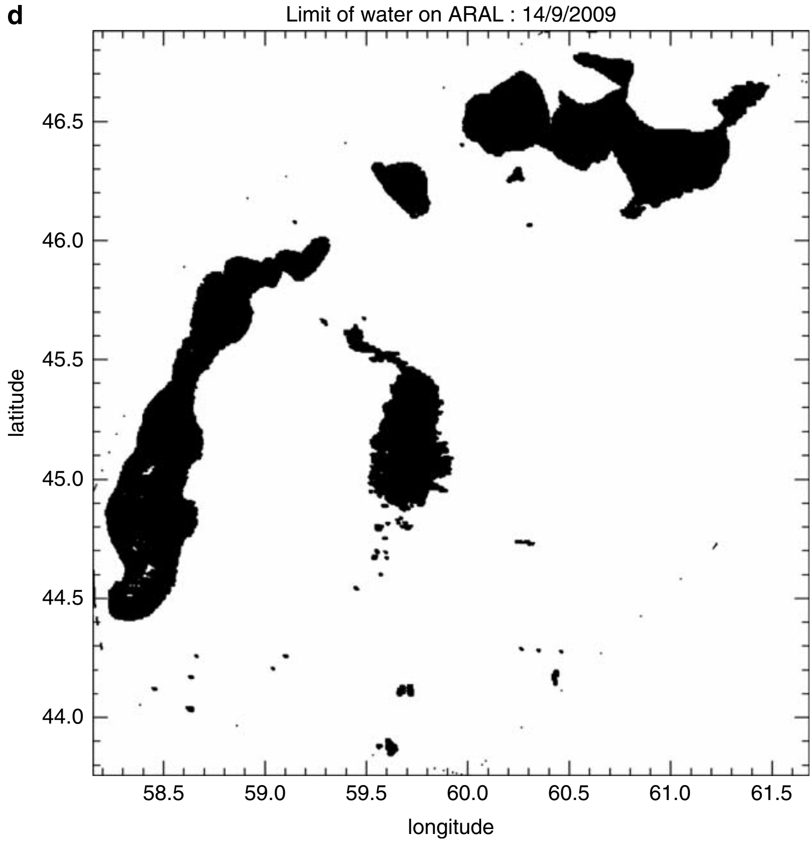


Fig. 4 Aral Sea as seen by the MODIS instrument on the Terra satellite. *Black* represents free water on the Sea on May 16 2000 (**a**), on May 16, 2004 (**b**), on May 17, 2009 (**c**), and on September 14, 2009 (**d**)

balance equations and the reliability of the results has suffered. By using satellite altimetry, it is now possible to observe level variations of large continental water bodies ([26, 30, 31]) with high precision (ranging from 2–3 cm for large lakes like Lake Victoria or the North American lakes, down to a few decimeters for very small lakes).

Satellite remote sensing also allowed the estimating of several physical and hydrological parameters of the Aral Sea and its watershed basin [19]. For example, the volume variations of the Aral Sea have been calculated by combination of optical satellite imagery and in situ water level [32]. More recently [16, 23] have estimated the volume variation of the Large and Small Aral by combination of a precise digital bathymetry map (DBM) of the basin, with level variation deduced from satellite radar altimetry, for the period 1993–2004.

Another problem concerns the measurements of river runoff into the Aral Sea. The first problem is their availability. It is almost impossible to use current data on river runoff of both the Syrdarya and Amudarya with regular updates, as they are either non-existent or not public due to national data policies. Figure 3 for example shows runoff measurements for the Amudarya on a monthly basis, from 1990 to 2006 with a lack of data in the period 2001–2004 and no data after 2006. The situation is the same for the Syrdarya. One can obtain some measurements on certain websites (http://water.freenet.uz/ or www.cawater-info.net/index_e.htm). The second main difficulty concerns the reliability of the measurements for the study of water balance of the Aral Sea. The in situ gauges are usually located several tens of kilometers upstream of the mouth of the deltas. These measurements are made far upstream from the Large and Small Aral, and it is very difficult to estimate how much water actually reaches the Aral Sea, as noted by [21] and [28]. Part of the water runoff measured at the gauge point may be lost between the observation point and the sea (due to evaporation and infiltration), or may eventually reach the sea as underground water but with a significant time lag. This uncertainty increases the error in water balance estimations. The component of water release from the Syrdarya to the Large Aral from the Berg Strait is also hard to measure.

Another parameter which is difficult to measure or to model is evaporation from the sea. Small et al. [28] attempted to resolve the water balance equation by using a regional lake model and they obtained values of evaporation minus precipitation (accounting for seasonal but not interannual variability) from 1960 up to 1990. Small et al. [21] also estimated the change of lake surface temperature and E-P term of the water balance and they have separated the feedback effect of Aral Sea desiccation on regional climate change from global climate change.

They calculated that between 1960 and the mid-1990s the net effect of desiccation was to decrease (on average) the P-E by 40 mm yr^{-1}, while the net effect of global warming was to decrease it by 100 mm yr^{-1}. The absolute value they have used for evaporation in the different model and configuration that they have tested are between 960 and 1,210 mm yr^{-1}. They also estimated SST (sea surface temperature) variation due to global warming, and they concluded that it increased by a few degrees with an obvious impact on evaporation, therefore on the water balance of the Aral Sea.

A more sophisticated model of evaporation for the Large Aral based on a modified Penman model has been developed in order to take into account the effect of wind and salinity increases of the Aral Sea on the evaporation rate ([29] and [33]). The main result obtained was that evaporation was about 1,140 mm yr^{-1} at the end of the 1990s on average, with a slight decrease due to higher salinity. The authors did not investigate possible interannual variability.

Aladin et al. [16] and Crétaux et al. [23, 25] attempted to improve the water balance calculation for the Large and Small Aral based on considerations on the uncertainties of each parameter of the water balance equation and new information now available from satellite remote sensing data.

They showed that the reduction of the Large Aral Sea volume as measured by T/P, GFO, and Jason is smaller than that deduced from examination of the hydrological budget, which may allow one to better estimate the quality of each parameter entering the water balance of the Aral Sea. For the Small Aral, [16] estimated the quantity of water which may be lost in the delta of the Syrdarya both during a period when the dam closed the Berg Strait, and a period with opening of the strait to the south towards the Large Aral Sea.

3 Conclusions

The understanding of Aral Sea water level and storage variability over the last 60 years since the beginning of the so-called “Aral Sea disaster” is a key issue within the framework of interaction between global and regional climate change and anthropogenic action. In a more regional context, the Aral Sea is today a case study of high interest as it evolved very rapidly from 1960 when it was the fourth largest lake in the world to September 2009 at which point the Aral Sea no longer existed as one unique water body, but as four small separate lakes of different size.

However, today the main limitations in such study lie in the fact that more and more in situ gauges have disappeared or that for political reasons very valuable data is no longer accessible. The transboundary water management issue which occurred after the collapse of the Soviet Union has enhanced this problem. One solution may be the use of remote sensing data that has already for many years provided very accurate data on Aral Sea level and surface variations. The future evolution of the former Aral Sea is hard to predict. It is however clear that the Small Aral, located in Kazakhstan, will certainly remain at its actual size and level, as it is fully controlled by the dam in its southern part. This dam allows the water of the Syrdarya River to compensate for evaporation, which is the main driving component of the water balance in an arid zone with very low precipitation.

The Southern part of the former Aral Sea is now divided into three water bodies of different size and morphometric conditions. They are all within a continuous desiccation process as there is almost no inflow from surface water. Those three water bodies are thus evaporating very quickly. It is not actually possible to predict precisely when they will totally disappear, but in 2009, the very shallow part in the East of the former Large Aral has already almost totally dried out. The western part which is deeper will probably remain for a few years but without a restoration plan for this basin, as was setup for the Small Aral in 2005, it will also desiccate totally sooner or later.

References

1. Boomer I, Wünnermann B, Mackay AW, Austin P, Sorrel P, Reinhardt C, Kayser D, Guichard F, Fontugne M (2009) Advances in understanding the late Holocene history of the Aral Sea region. Quat Int 194:79–90

2. Boroffka N, Oberhänsli H, Sorrel P, Demory F, Reinhardt C, Wünnermann B, Alimov K, Baratov S, Rakhimov K, Saparov N, Shirinov T, Krivonogov K, Röhl U (2006) Archaeology and climate: settlement and lake-level changes at the Aral Sea. Geoarchaeology 21(7): 721–734
3. Létolle R, Mainguet M (1997) Histoire de la mer d'Aral (Asie Centrale) depuis le dernier maximum glaciaire. Bull Soc Geol France 168(3):387–398
4. Létolle R (2008) La mer d'Aral, l'Harnattan Publ. Paris. p 315
5. Klige RK, Hong L, Selivanov AO (1996) Regime of the Aral Sea during historic time. Water Res 23:375–380 (in Russian)
6. Maev EG, Maeva SA, Karpitshev YA (1991) Aral Sea in the Holocene. In: Andrionov et al (eds) Aralskii Krisis, Inst. Ethnol. Anthrop. Ak. Nauk SSSR, Moscow, pp 76–86 (in Russian)
7. Reinhardt C, Wünnermann B, Krivonogov SK (2008) Geomorphological evidence for the Late Holocene evolution and the Holocene lake level maximum of the Aral Sea. Geomorphology 93:302–315
8. Sorrel P, Popescu S-M, Klotz S, Suc J-P, Oberhänsli H (2007) Climate variability in the Aral Sea basin (Central Asia) during the late Holocene based on vegetation changes. Quat Res 67:357–370
9. Sorrel P, Popescu S-M, Head MJ, Suc J-P, Klotz S, Oberhänsli H (2006) Hydrographic development of the Aral Sea during the last 2000 years based on a quantitative analysis of dinoflagellate cysts. Palaeogeogr Palaeoclimatol Palaeoecol 234:304–327
10. Svitoch AA (2009) Paleogeography history of the Aral Sea. In: Kostianoy AG, Kosarev AN (eds) The Aral Sea environment. The handbook of environmental chemistry, Springer, Berlin
11. Bortnik VN (1999) Alteration of water level and salinity of the Aral Sea. Creeping environmental problems and sustainable development in the Aral Sea basin. Cambridge University Press, Cambridge, pp 47–65
12. Zenkevich LA (1963) Biology of the seas of the USSR. Izd. AN SSSR, Moscow (in Russian)
13. Sarybaev K, Akimova A (2002) L'agriculture irriguée dans le delta de l'Amou Darya à la fin du XIX^{e} et au début du XX^{e} siècle, Cahier d'Asie Centrale, N° 10, Karakalpaks et autres gens de l'Aral, entre rivages et déserts
14. Micklin PP (1988) Desiccation of the Aral sea, a water management disaster in the Soviet Union. Science 241:1170–1176
15. Thorez J, Thorez P (2004) Le partage des eaux dans le Caucase oriental et les républiques d'Asie centrale, une manifestation des tensions post-soviétiques, Cahier d'Asie Centrale, N° 13/14, Gestion de l'indépendance et legs soviétique en Asie centrale. pp 245–260
16. Aladin NV, Crétaux J-F, Plotnikov IS, Kouraev AV, Smurov AO, Cazenave A, Egorov AN, Papa F (2005) Modern hydro-biological state of the Small Aral Sea. Environmetric 6(4): 375–392
17. Zholdasova I (1999) Fish population as an ecosystem component and economic object in the Aral sea basin. Creeping environmental problems and sustainable development in the Aral sea basin. Cambridge University Press, Cambridge, pp 204–224
18. Aladin NV, Plotnikov IS, Potts WTW (1995) The Aral Sea desiccation and possible ways of rehabilitating and conserving its Northern part. Environmetrics 6:17–29
19. Ginzburg AI, Kostianoy AG, Sheremet NA, Kravtsova VI (2009) Satellite monitoring of the Aral Sea region. In: Kostianoy AG, Kosarev AN (eds) The Aral Sea Environment. The handbook of environmental chemistry. Springer, Berlin
20. Letolle R, Chesterikoff A (1999) Salinity of surface waters in the Aral sea region. Int J Salt Lake Res 8:293–306
21. Small EE, Giorgi F, Sloan LC, Hostetler S (2001) The effects of desiccation and climate change on the hydrology of the Aral Sea. J Clim 14:300–322
22. Kostianoy AG, Zavialov PO, Lebedev SA (2004) What do we know about dead, dying and endangered lakes and seas? In: Nihoul JCJ, Zavialov PO, Micklin PhP (eds) Dying and dead seas. Climatic versus anthropic causes, NATO ARW/ASI Series. Kluwer Academic Publishers, Dordrecht, pp 1–48

23. Crétaux J-F, Kouraev AK, Papa F, Bergé-Nguyen M, Cazenave A, Aladin NV, Plotnikov IS (2005) Water balance of the Big Aral Sea from satellite remote sensing and in situ observations. J Great Lakes Res 31:4
24. Kouraev AV, Kostianoy AG, Lebedev SA (2009) Recent changes of sea level and ice cover in the Aral Sea derived from satellite data (1992–2006). J Mar Syst 76(3):272–286. doi:10.1016/j.jmarsys.2008.03.016
25. Cretaux J-F, Letolle R, Calmant S (2009) Investigations on Aral Sea regressions from Mirabilite deposits and remote sensing. Aquat Geochem. doi:10.1007/s10498-008-9051-2
26. Crétaux J-F, Birkett C (2006) Lake studies from satellite radar altimetry. C R Geosciences 338:1098–1112
27. Mason IM, Guzkowska MAJ, Rapley CG, Street-Perrot FA (1994) The response of lake levels and areas to climate change. Clim Change 27:161–197
28. Small EE, Sloan LC, Hostetler S, Giorgi F (1999) Simulating the water balance of the Aral sea with a coupled regional climate-lake model. J Geophys Res 104(D6):6583–6602
29. Benduhn F, Renard P (2004) A dynamic model of the Aral Sea water and salt balance. J Mar Syst 1 47:35–50
30. Birkett S (1995) Contribution of TOPEX/POSEIDON to the global monitoring of climatically sensitive lakes. J Geophys Res 100(C12):25,179–25,204
31. Cazenave A, Bonnefond P, Dominh K (1997) Caspian Sea level from Topex/Poseidon altimetry: level now falling. Geophys Res Lett 24:881–884
32. Kravtsova VI, Lourie IK, Markov DV (2001) Geodezija i kartographija 4:32 (in Russian)
33. Calder IR, Neal C (1984) Evaporation from saline lakes: a combination equation approach. J Hydrolog Sci 29:89–97 (in French)

Ice Conditions from Historical and Satellite Observations

Alexei V. Kouraev and Jean-François Crétaux

Abstract We address spatial and temporal variability of ice conditions in the Aral Sea from historical observations and recent satellite microwave observations. A short description of the historical evolution of the Aral Sea since the mid-twentieth century is given, as well as recent activities related to the dam in the Berg strait. An overview of historical observations of the ice regime at the coastal stations and using aerial surveys is provided. The lack of reliable in situ measurements and time series for ice cover parameters since the mid-1980s may be successfully overcome by using active and passive microwave satellite observations, which provide reliable, regular, frequent, and weather-independent data. An ice discrimination methodology, based on the synergy of active and passive data from radar altimeters TOPEX/Poseidon, Jason-1, ENVISAT and Geosat Follow-On (GFO) satellites, as well as the SMMR and SSM/I radiometers is presented. This methodology has been applied to the entire satellite dataset to define specific dates of ice events (first appearance of ice, formation of stable ice cover, appearance of open water and the complete disappearance of ice) for both the Small Aral and Eastern Large Aral. The resulting time series of ice cover parameters are analysed in the context of available in situ observations. First we complement historical observations by satellite imagery in the visible range to illustrate spatial patterns in ice formation, development and decay prior to the late 1980s and in recent time. Then we address interannual variability of timing of ice events and severity of ice conditions since the earliest coastal observations (1940s) until now

A.V. Kouraev (✉)
Université de Toulouse, UPS (OMP-PCA), LEGOS, 14 Av. Edouard Belin, 31400, Toulouse, France
State Oceanography Institute, St. Petersburg Branch, St. Petersburg, Russia
e-mail: kouraev@legos.obs-mip.fr

J.-F. Crétaux
Université de Toulouse, UPS (OMP-PCA), LEGOS, 14 Av. Edouard Belin, 31400, Toulouse, France
CNES, LEGOS, 31400, Toulouse, France

A.G. Kostianoy and A.N. Kosarev (eds.), *The Aral Sea Environment*, Hdb Env Chem (2010) 7: 195–218, DOI 10.1007/698_2009_9,

(2006/2007). Finally, we discuss temporal variability of ice regime parameters in the context of air temperature, bottom morphology and salinity changes.

Keywords Aral Sea, Ice cover, Spatial and temporal variability, Radar altimetry, Radiometry, Air temperature, Salinity

Contents

1 Introduction

The Aral Sea is located on the northern limit of the continental subtropical climate [1], with air temperature reaching more than +30°C in the summer and going down to −20°C in the southern and to −30°C in its northern parts in the winter. As a result, the Aral Sea is ice-covered for several months every winter. The presence of ice dramatically affects energy exchange between the water and atmosphere, and formation of hydrophysical and hydrochemical fields. It also affects navigation, fisheries and other human activities. Data on ice variability may also serve as an early indicator of regional and large-scale climate changes.

Ice processes in the Aral Sea have significant temporal and spatial variability, influenced by meteorological conditions (mainly by the thermal regime), but also by wind and currents, bottom topography, salinity, and – especially in the case of the Aral Sea – changing sea level. Changes in sea level greatly influence ice conditions through changes in the heat storage amount, water exchange and circulation [1–3].

As a result of continuing decrease of the sea level since the 1960s, the Aral Sea has been divided into two parts – the Small (Northern) and Large (Southern) Aral (Fig. 1, see also [4]). The water level and hydrological regime of the Small Aral is inherently linked to the Kokaral dam in the Berg Strait [3,5,6]. In the 1980s the decreasing level forced authorities to dredge the strait in order to continue navigation. Later, in the beginning of the 1990s, at the level of 37 m (with reference to the Baltic Sea level system) the difference between the Small and Large Aral was about 3 m and water started to flow south at a rate of about 100 $m^3 s^{-1}$ [5].

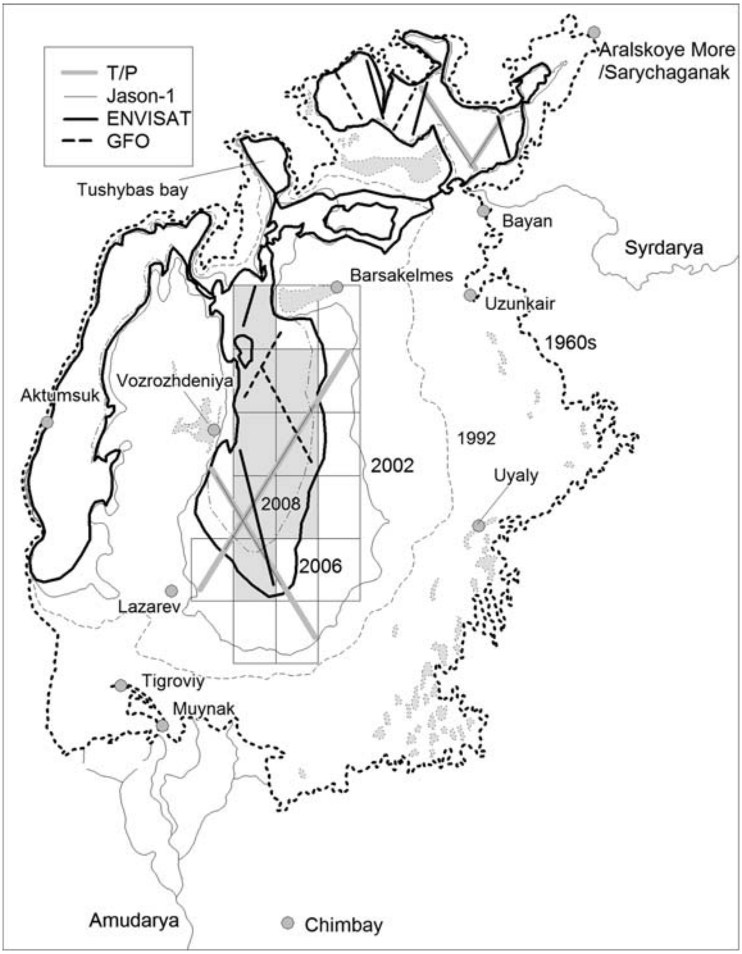


Fig. 1 Overview map of the Aral Sea. Coastline position in: 1960s (*dotted line*, islands are shown in *grey*), 1992 (*dashed line*), 2002 (*continuous line*), 26 October 2006 (*thick black line*, after Landsat TM image from Global Visualiser website, http://glovis.usgs.gov) and 01 April 2008 (*dash-dotted line*, after MODIS image from MODIS Rapid Response System (http://rapidfire.sci.gsfc.nasa.gov/gallery/), shown are only new coastline positions for the eastern Large Aral and for the eastern coast of the western part of the Large Aral). *Grey circles* – hydrometeorological stations. Selected radar altimetry tracks: T/P – *thick grey line*, Jason-1 – *thin black line* over T/P tracks (selected only within sea coastline of 2006), ENVISAT – *thick black line*, GFO – *thick dashed line*. Selected EASE-grid pixels of SMMR-SSM/I observations: *black rectangles* – area used for calculation up to 2002, *grey rectangles* – area used for calculation up to 2006

After the separation of the Small and Large Aral in 1989, efforts have continuously been put into constructing a dam in the Berg Strait to stabilise the level of the Small Aral [3]. Construction of the dam dramatically affected the sea level and thus the ice conditions in the Small Aral.

The first dam was constructed in July 1992 (1 m high, made of sand) but soon collapsed under the pressure of water. A second dam 2 m in height was immediately constructed in late July–early August 1992 and survived for 9 months until April 1993. After 3 years without a dam a third one was constructed and operated for more than 1 year (April 1996–May 1997). However, these three dams were made of sand and were not able to resist water pressure for a long time.

In October 1997 a fourth dam, this time made of sand and concrete, was constructed. This was a 14-km long and 30-m wide dam [7] that remained until 22nd April 1999. On that date a strong storm raced through Kazakhstan and the combined efforts of waves and winter ice led once more to the dam's break-up. Before the dam's collapse water level was about 42.8 m and by September 1999 the sea level decreased by 2.5 m. In 2003–2005 a fifth dam was built by a Russian company called Zarubezhvodstroy with the financial support of the World Bank. This dam has been in operation since August 2005 and we have observed a steady increase of sea level since that time [3,6].

The level of the Large Aral continues to decrease, and since 1998 this water body has consisted of two distinct basins. The western one is a deep depression, while the eastern basin is a constantly diminishing and very shallow water body. With the coastline position in April 2008 (see Fig. 1) corresponding to the Digital Bathymetry Model [6] mark of +25 m depth (or the 28 m mark above the Baltic Sea level), one can estimate the maximal depth of 44 m in the western and only about 3 m in the eastern part. These two basins are connected through a narrow (more than 3 km in 1998 and several hundreds of metres in 2007) channel with depths up to 7 m in 2006 and 5–6 m in 2007 [7,8, P. Zavialov, personal communication 2008]. Rather intense water exchange processes take place between the western and eastern basins, with strong currents (20–50 cm s^{-1}) [9] that erode the silty bottom of the strait and thus maintain the link between these two parts of the Large Aral.

2 Historical Observations of Ice Regime

Regular observations of ice conditions, as well as the sea level, meteorological and oceanographic parameters in the Aral Sea have been performed at ten coastal hydrometeorological stations (see Fig. 1). The first observations of the ice regime started in the winter 1940/1941 at stations Aralskoye more (observing both the Port Aralsk bay and Sarychaganak bay), Uzunkair, and Vozrozhdeniya (Table 1). One year later they started at Uyaly and Muynak, in 1942/1943 – at Tigroviy and in 1947/1948 – at Aktumsuk. In 1960/1961 two more stations – Bayan and Lazareva island – were put into operation. At some stations observations have been made separately for two regions – for the bay and the open sea.

With the continuously receding coastline many coastal stations have been closed down – Vozrozhdeniya and Muynak at the end of the 1940s to the beginning of the 1950s, the bay in Aralsk port at the end of the 1950s, and Uzunkair and Aktumsuk in 1962 and 1964, respectively. By the end of the 1970s to the beginning of the

Table 1 Historical observations of ice regime at the hydrometeorological stations (based on data from [1,10])

Station name	Height, m	Visibility, km	Visibility sector	Observation start	Observation end	Time series duration, winters
Port Aralsk, bay (Aralskoye More)	2.5	1.5	W-N-NE	1940/1941	1959/1960	20
Sarychaganak bay (Aralskoy More)	10	12	E-S-W	1940/1941	1982/1983	43
Bayan	3	6.5	SSW-W-NW	1960/1961	1982/1983	23
Uzunkair, bay	1.5	3	NE-E-SE	1940/1941	1961/1962	22
Uzunkair, sea	8	11	SW-N-NE	1941/1942	1961/1962	21
Aktumsuk	11	12	N-E-S	1947/1948	1963/1964	17
Vozrozhdeniya, bay	2.5	6	NW-S-NE	1940/1941	1948/1949	9
Barsakelmes	26	19.5	NNE-E-S-SW	1949/1950	n.i.	
Uyaly, bay	3	6.5	SSW-S-SE	1941/1942	1982/1983	42
Uyaly, sea	3	6.5	W-N-NE	1941/1942	1982/1983	42
Tigroviy, bay	10.5	12.5	E-S-W	1942/1943	1978/1979	37
Tigroviy, sea	10.5	12.5	W-N-NE	1942/1943	1978/1979	37
Muynak bay	2.5	6	S-W-N	1941/1942	1950/1951	10
Lazareva island	12.4	13.5	360°	1960/1961	n.i.	

1980s station observations stopped at Sarychaganak bay, Bayan, Uyaly and Tigroviy. By the end of the 1980s only two stations – Barsakelmes and Lazareva provided observations [1].

Starting from the 1950s, coastal observations have been complemented by regular aerial surveys, which provided information on ice conditions at the sea-wide scale. By 1985 a total of 241 aerial surveys had been carried out [1]. Starting from the late 1970s, the frequency and amount of aerial surveys sharply decreased due to their high cost. The lack of aerial surveys has been compensated by the use of satellite remote sensing data, mostly in the visible range, from low-resolution Soviet weather satellites such as “Meteor”. However, these observations depend on the availability of solar light and are affected by the presence of cloud cover.

As a result, published continuous time series of various ice cover parameters are present only up to the mid 1980s. These observations on ice conditions from coastal hydrometeorological stations and aerial surveys have been extensively analysed in various publications. The Atlas of Aral Sea ice [10] presented maps of ice type and distribution for typical months in mild, average and severe winters, as well as under various wind fields. It also presented tables of timing of ice events and ice thickness as observed at the hydrometeorological stations, as well as derivative statistical tables. A brief overview of Aral Sea ice conditions was presented by Kosarev [11] but the most comprehensive assessment was within the monograph [1] which presented the state of the art of the studies of Aral Sea environmental conditions available at that time. Most of the publications on historical variability of ice conditions of the Aral Sea are in Russian and thus remain inaccessible for many western readers.

The present limits of the Large Aral Sea make it physically difficult to access for oceanographic and meteorological measurements. However, between 2002 and 2006 researchers from the P.P. Shirshov Institute of Oceanology, Moscow, Russia, in cooperation with Uzbek and Kazakh institutions, performed six field expeditions on the western and eastern parts of the Large Aral [8,9,12,13]. During these expeditions various hydrographic, meteorological and oceanographic observations were made, but for obvious practical reasons all expeditions were undertaken during the ice-free period.

If some observations of ice conditions have been made recently at some coastal stations, they reside in local archives and are generally not available for public use. The meteorological station at Aktumsuk in the western Large Aral is now again in operation (Zavialov, personal communication). The Small Aral is actually experiencing a "renaissance" in conditions due to the sea level rise (see also [14]), and one could expect observations to be restarted. However, no new in situ information on ice conditions of the Small and Large Aral is available.

3 Microwave Satellite Observations of the Ice Regime

To fill the gap in information on the ice regime of the Aral Sea since the mid 1980s an obvious solution is the use of microwave satellite observations, which provide reliable, regular and weather-independent data on ice cover. For the last 30 years the scientific community has extensively used passive microwave data from the SMMR (Scanning Multichannel Microwave Radiometer, 1978–1987) and the SSM/I (Special Sensor Microwave Imager, since 1987) instruments to estimate ice cover extent and type (first-year and multi-year ice) both in the Arctic and in the Antarctic. Passive microwave data have been complemented with various optical, infrared and radar data, from sensors having different spatial resolution and incidence angle. A promising source of information is presented by radar altimeter satellites, which provide continuous and long time series of both active (radar altimeter) and passive (radiometer used to correct altimetric observations) simultaneous observations, from the same platform and with the same incidence angle (nadir-looking).

An ice discrimination methodology that uses simultaneous active and passive data from several radar altimeters [TOPEX/Poseidon (T/P), Jason-1, ENVISAT and Geosat Follow-On (GFO)] complemented by passive microwave observations (SMMR and SSM/I) collected over a 15-year period has been developed. This methodology was initially tested and applied in the Caspian and Aral Seas. In [15] data from the two T/P tracks over the Caspian and Large Aral Sea for 1992–2002 was used to estimate (a) dates of ice formation and break-up, (b) ice period duration and (c) percentage of ice presence in the altimetric data. In [16,17] the T/P data was complemented by the SSM/I observations with a dedicated ice/water discrimination approach, and time series of ice formation and break-up and ice period duration were obtained. Ice presence was also calculated – as a percentage of ice presence in the altimetric data (same as in [17]) and also as total and maximal numbers of ice-classed pixels for various sub-regions of the Caspian and Large Aral Sea.

Later, this approach was extended to (a) complement the T/P observations by Jason-1, GFO and ENVISAT data, and (b) provide better spatial and temporal resolution using an improved ice discrimination approach, which combines all altimetric and SSM/I data. This approach was implemented for the Lake Baikal [18] and Large and Small Aral Seas [3]. Using this approach, new improved time series of ice events (ice formation, break-up and duration) for the longest possible period (since 1991/1992) for various regions of Lake Baikal and Aral Sea have been obtained. On the basis of these time series for Lake Baikal and air temperature data, an analysis of how the ice regime is influenced by air temperature and dynamic (wind field, currents) and other (bathymetry, precipitation, etc.) factors has been carried out [19].

A comprehensive description of the existing state of the art of this methodology, with discussion of drawbacks and benefits of each type of sensor, influence of sensor footprint size, ice roughness and snow cover on satellite measures, and validation is given in [20]. Therein the particularities of the application of the methodology have been demonstrated for the two salt water (Caspian and Aral Seas) and three freshwater (lakes Baikal, Onega and Ladoga) water bodies. In the next sections we present a brief overview of the data used (Sect. 3.1), ice discrimination methodology (Sect. 3.2) and the resulting time series of ice cover parameters (Sect. 4) in the context of available in situ observations.

3.1 Satellite Data Used

3.1.1 Satellite Altimetry

Data from four radar altimetry missions have been used (Fig. 1). The earliest data are available from the T/P satellite, which has operated since 1992. From February 2002 T/P was followed by Jason-1 (on the same orbit). In August 2002, T/P was manoeuvred onto a new orbit, flying halfway between its previous tracks, and provided data until the end of its mission in October 2005. We used T/P data for September 1992–August 2002, T/P tracks on the new orbit do not cover the regions of interest. In June 2008 a successor to Jason-1 – Jason-2 was launched on the same orbit. We have complemented T/P and Jason-1 data by observations from radar altimeters onboard the GFO (since January 2000) and ENVISAT (since November 2002) satellites. All four altimeters have two main nadir-looking instruments – a radar altimeter and a passive microwave radiometer. The repeat period is 10 days for T/P and Jason-1, 17 days for GFO and 35 days for ENVISAT. For T/P, Jason-1 and GFO backscatter and brightness temperature (TB) values are provided for every 1 Hz data, thus giving an along-track ground resolution of about 6 km.

For ENVISAT we use 18 Hz backscatter values from the Ice2 retracker (450 m resolution along the ground track).

3.1.2 SSM/I Data

The passive microwave SMMR and SSM/I radiometers with an incidence angle ranging from 50.2 to 52.8° provide measurements of TB at different frequencies and at different (vertical or horizontal) polarisation. We used SMMR data from October 1978 to August 1987 and SSM/I data from July 1987 to September 2007. The National Snow and Ice Data Centre (NSIDC) provide the SSMI data mapped onto an Equal-Area Scalable Earth Grid (EASE-Grid) projection with 628.4 km^2 pixel size [21]. The initial data were averaged to obtain pentad (5-day) mean values to provide continuous spatial coverage. In our previous works [3,15–17] in order to minimise the effects of ice and snow melting, we have used only night TBs (thus affecting the choice of ascending or descending passes). This resulted in gaps of observations for some years, especially for SMMR. This time, when night temperatures were not available, we have used day temperatures. This allowed us to obtain more homogeneous time series of ice cover parameters. Both altimetry and radiometry data were obtained from the Centre for Topographic Studies of the Oceans and Hydrosphere (CTOH) at the LEGOS laboratory.

3.1.3 Geographical Selection

To minimise the potential contamination of the altimetric and radiometric signal by land reflections, a geographical selection of the data needs to be carried out. For the Aral Sea with a rapidly shifting coastline, we have used several masks to select the altimetry data. In order to account for the lowest possible sea level for each time span of satellite operations, for T/P we have selected data using coastline position for 2002 (Fig. 1), and for Jason-1, GFO and ENVISAT - for the end of 2006. For the Small Aral all EASE-Grid pixels were subject to land contamination, so we used only altimetry data for this part. For the western part of the Large Aral there were not enough data to perform reliable ice/open water discrimination. For the eastern part of the Large Aral, two datasets were used for SMMR and SSM/I data: a larger area up to winter 2001/2002, and a smaller one up to winter 2005/2006.

3.2 Ice Discrimination Methodology

3.2.1 Altimetry Data

For the altimetric data the methodology is based on the analysis of time and space evolution of observations in the space of two parameters: (a) backscatter coefficient at the Ku band from the radar altimeter, and (b) the average value of the TB (K) values from the radiometer at two frequencies. Open water has a low backscatter coefficient and low TB values, while ice cover is characterised by a high backscatter coefficient and elevated TBs. Observations from various satellite altimetry missions in the space of the two parameters form two well-defined clusters, thus making it possible to distinguish between open water and ice (using a set of linear thresholds) with a high degree of reliability. These two clusters are typical for many seasonally ice-covered seas and lakes [20].

3.2.2 Passive Microwave Data

Among the most commonly used algorithms for estimation of ice concentration from passive microwave data (such as SMMR and SSM/I) are the NASA Team and Bootstrap algorithms [22–24]. These algorithms use various combinations of TB data from various polarisations (H or V) and various frequencies (19 or 37), such as the polarisation (PR) and spectral (GR) gradient ratios. For Arctic and Antarctic tie points for open water, first-year and multi-year ice has been identified and based on them estimation of both ice concentration and type are possible [24,25].

However, there are two main difficulties for the use of PR and GR values for the Aral Sea. First, no in situ data on radiometric properties of various types of surface (open water, ice and snow etc.) is available to select the tie points. A second and more important difficulty is that we seldom observe the open water cluster. Only for SMMR which operated when the sea level was relatively high and thus the surface much larger, did we observe two distinct clusters – open water and ice (not shown). For SSM/I open water values have a much lower PR ratio and are much closer to the ice cluster. This could be attributed to a land-to-water spillover effect (land contamination) [26]. In fact, most SSM/I measurements are to some degree affected by land influence and it is often difficult even to distinguish with a high degree of confidence between ice and water. We apply threshold values of PR to distinguish between ice and open water and, in general, we consider that altimetry-derived ice cover parameters are of better quality.

3.2.3 Combination of Altimetric and SSM/I Data

For the common period of altimetric and SSM/I observations (since 1992) each observation was classed as ice or open water, according to the methodology [20], and graphically presented as a series of maps for each pentad. Examples of the maps and detailed descriptions of their analysis are given in [18] using Lake Baikal as an example.

Through analysis of these classification maps for each pentad it is possible to define specific dates of ice events for the water body or its sub-regions. In some cases the definition of ice event dates could be uncertain due to: (a) data gaps, (b) ambiguous ice detection related to land contamination of the microwave signal, and

(c) consecutive freezing and melting events. In order to account for this uncertainty, for each event we estimate a time span of earliest and latest possible dates, as has been done for Lake Baikal and Aral Sea [3,18]. In most cases using pentad maps it is possible to define ice event dates with an uncertainty of ± 2.5 days.

When the ice cover is well developed both SSM/I and altimetric approaches provide a robust discrimination between water and ice. However, for detecting young and rotten/broken ice, altimetric simultaneous active/passive data are more sensitive than the SSM/I passive data. By combining these two types of observations we can combine their specific advantages – wide spatial coverage and good temporal resolution for SMMR-SSM/I and high radiometric sensitivity and along-track spatial resolution for altimetry and this assures high reliability of estimates of ice event dates.

4 Ice Regime from Historical and Satellite Observations

Here we address spatial and temporal variability of ice conditions in the Aral Sea from historical and satellite data. In Sect.4.1 we complement historical observations with satellite imagery in the visible range to illustrate spatial patterns in ice formation, development and decay prior to the late 1980s and in recent time. Section 4.2 addresses interannual variability of timing of ice events and severity of ice conditions since the earliest coastal observations (1940s) to the present (2006/2007). In Sect. 5 we discuss temporal variability of ice regime parameters in the context of air temperature, bottom morphology and salinity changes. In order to avoid ambiguities, we use the terms "Northern Aral" and "Southern Aral" when speaking about various parts of the Aral Sea prior to the separation, or when referring to the coasts of the Aral Sea for the period of historical observations. On the other hand, we use the terms "Small Aral" and "Large Aral" (eastern and western parts) for the more recent period covered by satellite data.

4.1 Spatial Patterns of Ice Formation, Development and Decay

According to historical observations made up to the mid-1980s [1], the most severe ice conditions have been observed in the Northern Aral, characterised by a colder climate, and shallow eastern part of the Southern Aral. In general, the number of days with ice was minimal for the deepwater western part of the sea (70–80 days), in the eastern Southern Aral it was 100–110 days, and in the Northern Aral – 120–140 days. Ice formation usually began in the shallow northern and north-eastern coastal regions in mid-November. By the end of December ice was forming in the open sea (actual eastern part of the Large Aral), and only at the beginning of January did ice form in the western coastal zone of the Southern Aral.

In moderate winters by mid-December a 20–30 km wide band of fast ice was formed along the northern and north-eastern coasts. In January ice covered the

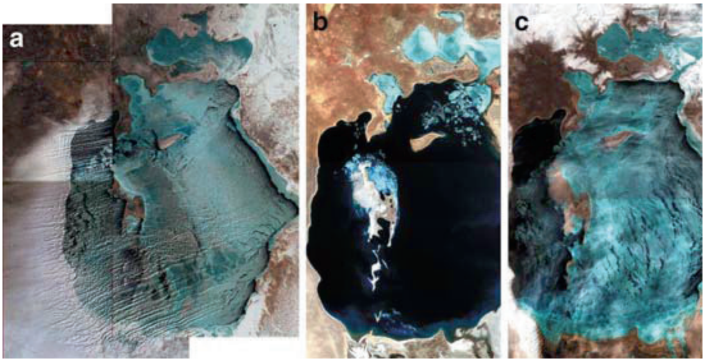


Fig. 2 Ice conditions from Landsat mosaic for 24–25 December 1976 (**a**), and images for 23 January 1984 (**b**), and 10 April 1986 (**c**). Landsat imagery is from USGS Global Visualisation Viewer (http://glovis.usgs.gov, accessed 09 July 2008)

whole Northern Aral and regions along the eastern and southern coasts, and formed 4–6 km wide bands on the western coasts. The maximal development of ice cover was in February, and in severe winters ice could cover the whole sea. The highest ice thickness was observed in February–March, reaching 65–70 cm in the northern and 35–45 cm in the southern parts.

The distribution of drifting ice in the open Aral Sea is strongly influenced by the wind field conditions, and the north-easterly and easterly winds often lead to rapid increases in ice concentration in the southern part of the sea. This is well illustrated on the visible imagery from Landsat for December 1976 and January 1984 (Fig. 2a, b). On both images the Northern Aral and Tushybas bay are completely ice-covered, and bands of fast ice are seen along the eastern coast. The north-easterly wind can be deduced from the lines of well-developed cloud streets over the central and southern parts of the sea (Fig. 2a) or in the south-western part (Fig. 2b). The wind is pushing drifting ice, forming well-developed polynyas (seen as a black line of open water on both images) along the eastern coast, compacting ice in the regions of Vozrozhdeniya, Lazareva and Barsakelmes islands, and increasing ice concentration in the southern and western parts of the sea.

Ice decay began at the end of February–beginning of March. Usually the southern and south-eastern parts become ice-free at the end of March and the northern part – in mid-April, and 1 month later the whole Aral Sea was ice-free. On Fig. 2c, we see that in April 1986 (winter 1985/1986 was average by severity) the western and central parts of the sea are ice-free, except for some broken ice that is still observed near Amudarya delta, Vozrozhdeniya island, and a region near the Berg Strait. In Tushybas bay the ice cover has just started to break-up and the Northern Aral is still completely ice-covered. In severe winters, however, ice could reside until the end of April or even the beginning of May.

Under the currect conditions, the general spatial pattern did not change much, as illustrated by a sequence of Landsat images for winter 2002/2003 (Fig. 3). By the end of December 2002 the Small Aral and the region north of the former

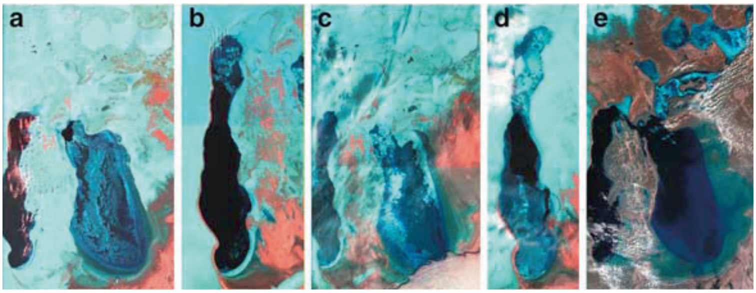


Fig. 3 Ice cover evolution during winter 2002/2003. Landsat images for 26 December 2002 (**a**), 18 January 2003 (**b**), 27 January 2003 (**c**), 07 March 2003 (**d**) and 01 April 2003 (**e**). Landsat imagery is from USGS Global Visualisation Viewer (http://glovis.usgs.gov, accessed 09 July 2008)

Barsakelmes island are ice-covered (Fig. 3a). Stable ice is also observed in the region of the strait between the western and eastern part of the Large Aral, as well as in the northern tip of the western part. A band of coastal fast ice started to form along the eastern coasts of the Large Aral and southern part of the western Large Aral. An open part of the eastern Large Aral is covered by young drifting ice. By 18 January thin young ice started to form near the fast ice in the western Large Aral (Fig. 3b). By the end of January 2003 (Fig. 3c) young ice is extending in the western Large Aral, and the eastern Large Aral is almost fully covered either by older, snow-covered (white) ice along its north-eastern and north-western boundaries, or by young (dark) ice in other places. In the beginning of March 2003 (Fig. 3d) only the central part of the western Large Aral remained ice-free. One month later, by the 1st April 2003, the Large Aral was ice-free except for a small bay in the western Large Aral near the strait and shallow region north of the former Barsakelmes island. The Small Aral was still fully ice-covered by that date. However, the winter of 2002/2003 was severe (the coldest winter of the period 1998/1999–2004/2005, see Fig. 10 in Sect. 5.1) and the fact that the western Large Aral was not frozen even by March indicates some significant changes in its hydrological regime (see more discussion in Sect. 5).

4.2 *Interannual Variability of Ice Events and Severity of Ice Conditions*

The whole altimetric and SMMR-SSM/I dataset has been processed using the ice discrimination methodology described in Sect. 2. Compared to our previous work we have now filled many gaps due to the absence of SMMR or SSM/I data and have extended the dataset up to winter 2006/2007. Using these data we have defined the dates of four specific ice events: (a) first appearance of ice, (b) first formation of stable ice cover (100% ice), (c) first appearance of open water and (d) the complete disappearance of ice (100% open water) for both the Small Aral and for the eastern

Large Aral. For the Small Aral these dates are obtained for 1992/1993–2006/2007 using only passive and active altimetric data. For the eastern Large Aral they are based on SMMR-SSM/I data for 1978/1979–1991/1992 and on SSM/I and altimetric data afterwards. In cases when, after the formation of stable ice cover some consequent melting and refreezing was observed, we give the earliest possible date for 100% ice and latest possible date for appearance of open water. This melting and refreezing has been observed only in the eastern Large Aral (winters 1988/1989–1990/1991, 1994/1995, 1996/1997 and 1998/1999). Dates of all ice events are defined as days since 31st December.

In order to place these satellite-derived estimates in the context of changes of ice regime in the twentieth century, we have used two more sources of historical in situ data. The first one [10] gives us the timing of various ice events (we have used dates of observations of first ice, stable 100% ice cover, last opening of stable 100% ice cover, and final clearing up of floating ice) for several coastal stations starting from winter 1940/1941 (see Sect. 2). We have selected three stations that have the longest available time series and reflect ice conditions for various parts of the sea – Sarychaganak (Aralskoye more) for the Northern part of the Aral Sea, Barsakelmes for the region south of the Berg Strait, and Uyaly (sea) for the eastern coastal part. The second source [1] does not provide estimation of ice event timing for each winter, but provides a table of ice concentration (in %) for each decade (10 days) for winters 1950/1951–1984/1985 based on in situ data and aerial observations. From this table we have estimated the four dates of timing of ice events (after the names of the authors of the second source – Bortnik and Chistyaeva – we call them BCh series) with an uncertainty of about ± 5 days.

Cross-comparison of the three sources is not straightforward. Comparing to observations at the coastal station, for the table in [1] the calculation has been done for the whole sea and authors have evidently put a threshold on very small values of ice concentrations. As a result, the BCh dates of both first ice appearance and of full open water could be later than those observed at in situ coastal stations, where small patches of ice will nevertheless be reported. When comparing satellite estimates and historical observations at the coastal stations it is necessary to bear in mind (a) the difference in methodology of definition of specific ice dates at the coastal stations, and (b) the difference between the size of the region observed from the coast and the much larger lake area observed by satellites [18, 19].

As a result, we have three sources of time series that have an overlap of 18 winters (1950/1951–1967/1968) for coastal stations and BCh series, and seven winters (1978/1979–1984/1985) for BCh and satellite-derived estimates. This overlapping gives us the possibility to estimate the interannual variability in timing of ice events for 67 winters (1940/1941–2006/2007).

4.2.1 First Ice Appearance

First ice is observed earlier at Uyaly and Sarychaganak (Fig. 4), which corresponds to the general pattern of ice development. The BCh series are closer to the

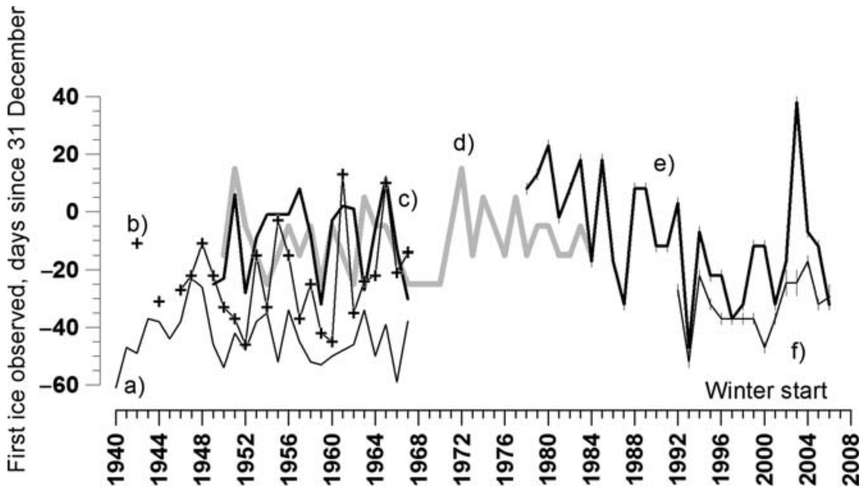


Fig. 4 Date (in days since 31 December) of first ice observed. Hydrometeorological station data (after Atlas of Aral Sea ice, 1970): (**a**) Sarychaganak, *thin black line*, (**b**) Uyaly (sea), *thin black line with crosses*, (**c**) Barsakelmes, *thick black line*. Average dates for the whole Aral Sea (after [1]),(**d**) *thick grey line*. Satellite-derived data for eastern part of the Large Aral (**e**), *thick black line* and Small Aral (**f**), *thin black line* and associated error bars. Winter start – year of the beginning of winter (e.g. 1984–winter 1974/1985)

Barsakelmes series, which, as noted earlier, can be related to coarser time resolution and a minimal ice concentration threshold for the BCh series. For the Northern Aral (Sarychaganak) interannual variability is small (38 days) as compared to Barsakelmes and Uyaly (44 and 59 days, respectively). Timing from satellite observations is in phase with the BCh series, though the radiometer sees first ice later than BCh due to its lower radiometric resolution [18]. There are no discernible interannual trends in the historical time series, except some tendency for ice to form earlier in the Northern Aral (Sarychaganak) for 1948–1967. Satellite time series for the eastern Large Aral indicate a cooling trend between 1978/1979 (10–20 days) and an extremely early ice formation in winter 1992/1993 (−47 days, i.e. mid-November). Since then, there is a tendency for ice to form later with a peak in winter 2003/2004 (38 days i.e. beginning of February). This warming trend is also visible for satellite-derived time series for the Northern Aral, though in winter 2003/2004 ice was not forming extremely late, as in the eastern Large Aral.

4.2.2 Formation of Stable Ice Cover

100% ice cover (the whole sea is ice-covered) has not been observed every winter (Fig. 5), except for the Northern Aral (Sarychaganak historical data and Small Aral satellite-derived time series). BCh time series also illustrate that at the scale of the whole Aral Sea this was not always the case. Variability in timing of 100% ice cover is much higher than for first ice appearance – 60 days for Sarychaganak, and

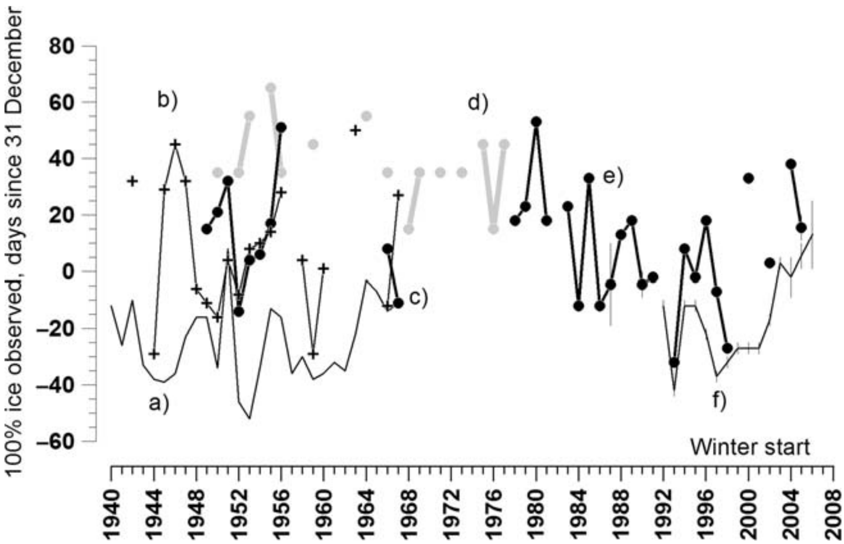


Fig. 5 Same as Fig. 4 but dates for 100% ice observed. For (**c**), (**d**), and (**e**) points are added to lines in order to show single year on a *discontinued line*.

65 and 79 days for Barsakelmes and Uyaly, respectively. BCh time series show smaller variability – about 50 days. There are no winters where BCh time series have 100% ice cover that overlap directly with satellite radiometric time series for the eastern Large Aral, though for 1970–1980 both time series are in the same range of 15 to 53 days (mid-January–end of February). Historical observations do not show some significant trends; but satellite observations, as for the first ice observed, show first the tendency for earlier dates since 1980/1981 (53 days i.e. end of February) up to 1993/1994 or 1997/1998 (−32 and −27 days, respectively, i.e. end of November – beginning of December) and then the warming tendency for later dates up to the mid 2000s. This warming trend is also seen for Northern Aral satellite-derived time series.

4.2.3 First Open Water Observed

In winters when 100% ice cover was not observed, there are no dates of first water appearance, so all time series have gaps, except for the Northern Aral (Fig. 6). For coastal stations interannual variability is low in the Northern Aral (38 days) and higher for Barsakelmes and Uyaly (44 and 96 days, respectively). BCh time series are comparable with that of Barsakelmes; they oscillate between 45 and 95 days (i.e. end of February–beginning of May). For Sarychaganak dates are later and they vary between 77 and 115 (mid-March–end of April). As for 100% ice, no direct comparison can be made between BCh and satellite estimates for the eastern Large Aral, but absolute values for the mid-1970s–beginning of 1980s are similar

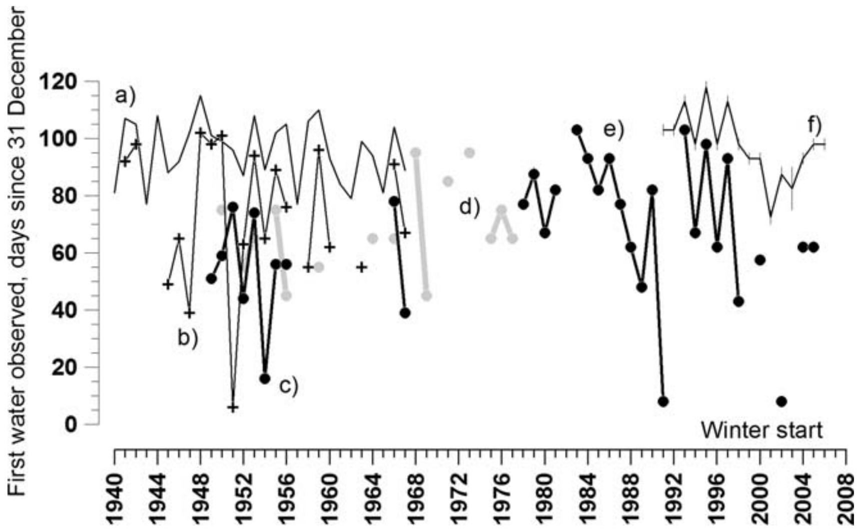


Fig. 6 Same as Fig. 5 but dates for first open water observed

(65–95 days). There was a warming tendency to observe first water earlier for the Sarychaganak series, but for other historical time series there are no significant trends. For satellite observations the variability is high (8–103 days, comparable to Uyaly) and we observe several periods with different trends. For 1983/1984–1991/1992 there was a sharp tendency for earlier timing (dates changed from 103 to 8, i.e. from mid-April to the beginning of January), after the winter 1992/1993 (gap in observations) the dates came back to the 103 days mark, and for 1993/1994–2002/2003 there was another period with a sharp decreasing trend with the same range of interannual variability. Since 2002/2003 values increased again up to 62 days in 2003/2004 and 2004/2005. For the Small Aral there is a similar tendency first in earlier open water observation, and since 2001/2002 for a later one, however absolute values changed less than for the large Aral.

4.2.4 100% Open Water

For this parameter historical data are in very good accordance with each other (Fig. 7). Earliest dates are observed for the most southern station – Uyaly, data for Barsakelmes, Sarychaganak and the BCh time series are almost identical. Interannual variability is 68 days for Uyaly and 45 days for other historical time series. Satellite estimates for the eastern Large Aral are in the same phase and almost in the same amplitude as BCh data. For historical time series no significant tendencies could be observed, short-term (2–3 years) oscillations dominate. Very early ice disappearance has been observed in 1982/1983. For the eastern Large Aral satellite data show some weak tendency for later ice disappearance between 1978/1979 and

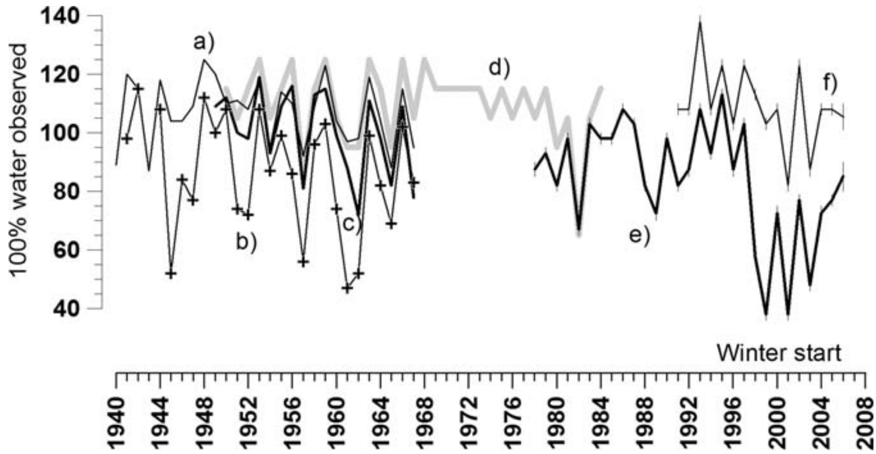


Fig. 7 Same as Fig. 4 but dates for 100% open water observed

1997/1998 (up to 113 days i.e. end of April in 1995/1996), and then a sharp drop of 75 days during the two winters 1998/1999 and 1999/2000 down to the very early 38 days (beginning of February) in 1999/2000 and 2001/2002 and, again, a recent tendency for later 100% open water dates. For the Small Aral the phase is similar, but absolute changes are not as dramatic, the decrease was observed, but was just 40 days between 1997/1998 (123 days) and 2001/2002 (82 days).

4.2.5 Winter Duration

This parameter is defined as time between the first ice observed and 100% open water observed, i.e. the duration of the ice event. For historical data values of winter duration are almost identical for Uyaly and Barsakelmes; BCh time series are also very close to them (Fig. 8). Winter duration varies between 34 and 147 days for coastal stations in Southern Aral. Sarychaganak values are higher and variability is smaller (52 days, from 124 to 176 days). BCh time series show a slight tendency for shorter winters since 1968/1969 up to the mid-1980s. Satellite observations correspond well to BCh both by phase and by amplitude, and show that this tendency has been followed by a cooling trend between the early 1980s and mid-1990s. Since 1993/1994 for both the eastern Large Aral and Small Aral we observe a tendency for shorter winters, related with later ice formation in autumn and earlier ice break-up in spring.

4.2.6 Severity of Ice Conditions

In order to assess the severity of ice conditions for each winter, one can use several parameters, and two of them are related to ice extent. The first parameter is the

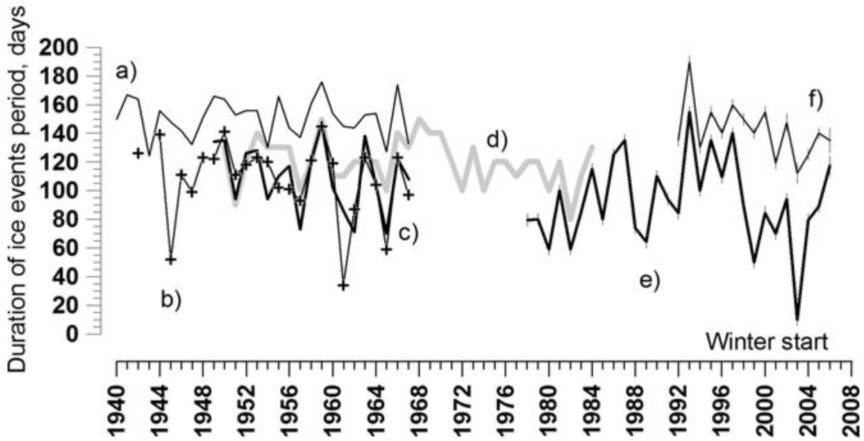


Fig. 8 Same as Fig. 4 but duration of ice events period, days

maximal area of ice development, which is often used. However, in the case of water bodies that almost every winter are completely covered, as is the case with the Aral Sea, this parameter is not very informative (maximum extent is limited by the relatively small sea surface). Another parameter is the cumulative ice surface of all observations made during the winter, in the case of passive microwave observations from SMMR and SSM/I this is expressed as the total number of pixels classed as ice. In fact, this parameter is the same as the average winter ice concentration over a given area for a fixed period of time. This second parameter is more robust in estimating the degree of severity of winter, as it avoids ambiguity in cases when one short and one long winter, both having the same area of maximal ice development, are considered equally severe (if using only maximal area).

Using the SMMR and SSM/I data we have calculated for each pentad the number of EASE-grid pixels classed as ice (Fig. 9). For pentads where data is missing we have filled the gaps using linear interpolation. From these data the total number of ice pixels for each winter has been calculated for two regions of the eastern Large Aral: a larger one as delimited by the coastline of 2002, and a smaller one – by that of 2006 (see Fig. 1). This has been done in order to obtain two homogeneous series for different lengths of observation. The comparison shows that they are closely related (for 24 years of common observations $R = 0.996$). Therefore, we are using here time series for the smaller region, which gives us estimations for 29 winters (1978/1979–2006/2007).

We have also used historical data from [1]. The data was initially provided as % of sea surface, but we recalculated them into km^2 using the mean annual values of sea surface for each year. In order to be able to compare the satellite-derived time series and historical data expressed in various units, a relation has been established for the overlap period 1978/1979–1984/1985. This relation is $y = (x + 19.53)/0.005$ ($R = 0.72$) where y is the average surface in km^2 and x is number of pixels. In spite of the fact that historical data refer to the whole Aral Sea and satellite data to the

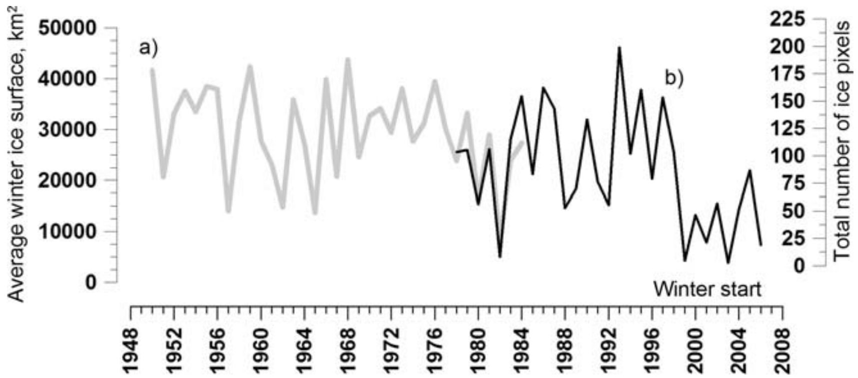


Fig. 9 Severity of ice conditions expressed as (**a**) average ice cover surface in km^2 (recalculated from [1]) and (**b**) total number of EASE-Grid pixels classed as ice for each winter. Size and position of the Y-axis of (**b**) have been adjusted using the relation established between the two time series

eastern Large Aral, they both agree very well. They show high interannual "seesaw-like" variability of ice conditions, when milder and severe winter conditions alternate with 2–3 years interval. This variability is often superimposed on alternating warming or cooling trends. However, as observed for the first and 100% open water, the last cooling trend between 1982/1983 and 1993/1994 (up to 225 pixels) has been followed by an unusually sharp decrease between the same two winters 1998/1999 and 1999/2000 down to just 3 pixels in 1999/2000. Since then the values have been slightly growing (up to 97 pixels in 2005/2006), but they still have not regained the earlier typical values.

5 Ice Regime Parameters and Their Relation to Various Factors

Satellite observations show several recent tendencies. For first ice and 100% ice first we observe a cooling tendency that started since the end of the 1970s and lasted until the exceptionally cold winter 1992/1993. Since then an opposite – warming – tendency for ice to form later is observed for both the Small and eastern Large Aral. For the eastern Large Aral we also observed extremely late ice formation in 2003/2004. Appearance of first open water and complete ice disappearance did not change much for the Small Aral, but for the eastern Large Aral we observe first a tendency for earlier open water appearance between the early and late 1990s, with a sharp change that has been observed between winters 1997/1998 and 1999/2000. Since then dates of open water have been observed later. As a result, for the total winter duration we observe a steady trend for colder winters for the eastern Large Aral between 1978/1979 and 1993/1994, and then a warming trend seen for both the Small Aral (weak trend) and eastern Large Aral (strong trend).

The recent increasing difference in ice regime between the Small Aral and eastern Large Aral is striking. For 1992–1997 the difference between the two water bodies was on average 18 days for 100% open water and 23 days for first open water. Then the mean difference more than doubled: 55 days in 1998/1999, with maximal value of 65 days (1999/2000) for 100% open water and 80 days (2002/2003) for first open water. This rapid change is also evident on the winter duration – while for the Small Aral the winter duration was in the range of 140 days, for the eastern Large Aral this value decreased from 112 days in 1992–1997 to 69 days for 1998–2006.

All these changes could be attributed to several factors that are discussed further. The main driving mechanism for ice regime is air temperature. However, other parameters, such as water salinity, changes in sea depth, currents and water exchange, could significantly affect thermal influence.

5.1 Air Temperature

In order to assess variability of air temperature, we have selected two series of daily air temperature observations at meteorological stations Aralskoye more in the north and Chimbay in the south (see Fig. 1). We also used ERA-40 reanalysis data (grid size 2.5 × 2.5°) for 1957–2002. Six-hourly reanalysis data on air temperature have been processed in order to produce daily surface air temperature indexes, referred to central parts of the Small Aral and eastern Large Aral. From this data we calculated sums of all negative (below 0°C) daily mean air temperature values (SNT, expressed in degree-days) for each winter (Fig. 10). Though variability of interannual changes

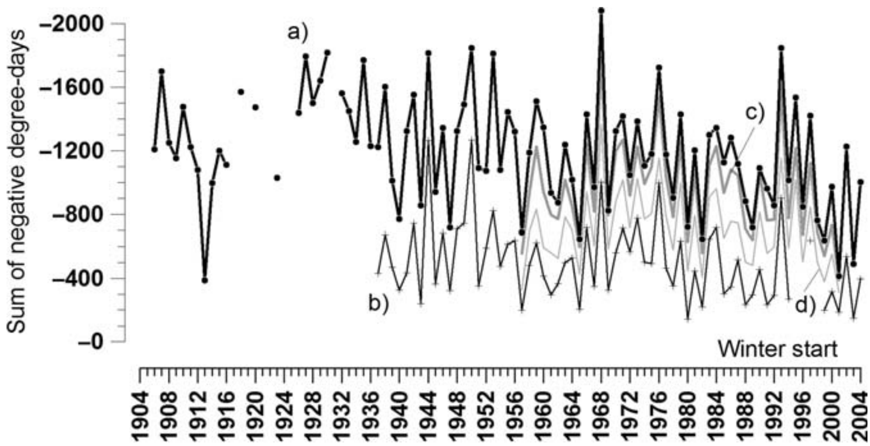


Fig. 10 Sum of negative daily air temperatures (SNT) for each winter from in situ data (in some winter data are missing). SNT at the hydrometeorological stations Aralskoye more (**a**), *thick black line with dots* and Chimbay (**b**), *thin black line with crosses*, and ERA-40 temperature indexes for Small Aral (**c**), *thick grey line* and eastern Large Aral (**d**), *thin grey line*. Y-axis is in reverse order

is larger for the Small/Northern Aral, where climate is more severe, all four series are very similar, reflecting the fact that there is no significant difference between various parts of the Aral Sea. At the beginning of the twentieth century there was a significant warming trend observed at Aralskoye More station, SNT reached the lowest value for all periods of observation (−387 in 1913/1914). In the 1920s winter became colder, and since that time we observe for all four series a general trend for a warmer winter, highly modulated by short (2–3 years) and longer (10 years and more) variability. For Aralskoye More data one may note two series of rapid warming. One started in 1973/1974 (−1384 degree-days) and lasted until the very warm winter 1982/1983 (−647 degree-days, this winter was marked by very early 100% water observed, see Sect. 3.2). Another, more recent warming trend started in 1993/1994 (−1846 degree-days) and continued until 2001/2002 (−412 degree-days, this is the second warmest winter for all periods of observation). This second trend explains the warming signal that we observe in the satellite-derived dates of first and 100% open water, as well as in winter duration and severity (number of ice pixels).

However, variations in air temperature alone cannot explain the difference in ice regime between the Small and eastern Large Aral, observed in the 1990–2000s. To do this we need to consider two more factors – salinity and sea depth.

5.2 Salinity and Sea Depth

The influence of air temperature on ice regime is significantly affected by water salinity, which changes freezing temperature. Until the 1960s mean salinity was about 10 ppt [27], since then it has been growing (Fig. 11a) with the decrease of sea depth and the shrinking of the sea surface. Before the separation of the Small and Large Aral in 1989 the salinity was 28–30 ppt. Since then, salinity in the Small Aral was relatively stable and river discharge together with the effect of dams brought the salinity back to about 20 ppt [5]. For the Large Aral, however, things were only getting worse. Salinity was growing almost exponentially and it reached 58 ppt in 1998, 108–112 ppt in 2001 and 155–160 ppt in 2002 [27]. For the same period, the salinity of the western Large Aral, almost isolated from the eastern Large Aral save for the narrow strait, rose only up to 69–74 ppt in 2002. Recent in situ measures [9] show an increase of salinity in the western Large Aral up to 99 ppt and decrease of salinity in the eastern Large Aral (100 ppt in the region of the strait in 2004 and 132 ppt in the eastern Large Aral in October 2005]. This could be associated with the increased water exchange between fresher western and saltier eastern parts of the Large Aral, which is confirmed by intense currents in the strait and its depth of up to 7 m [9].

All of these changes should have resulted in the dampening of air temperature's influence on the ice regime in the eastern Aral. We have calculated the corrected SNT for Aralskoye More as a sum of negative daily air temperatures below the freezing point specific for each year. For salinity below 50 ppt we have used Zubov's (1945) formula $T_{fr} = -0.054{*}S$ where T_{fr} is the freezing temperature

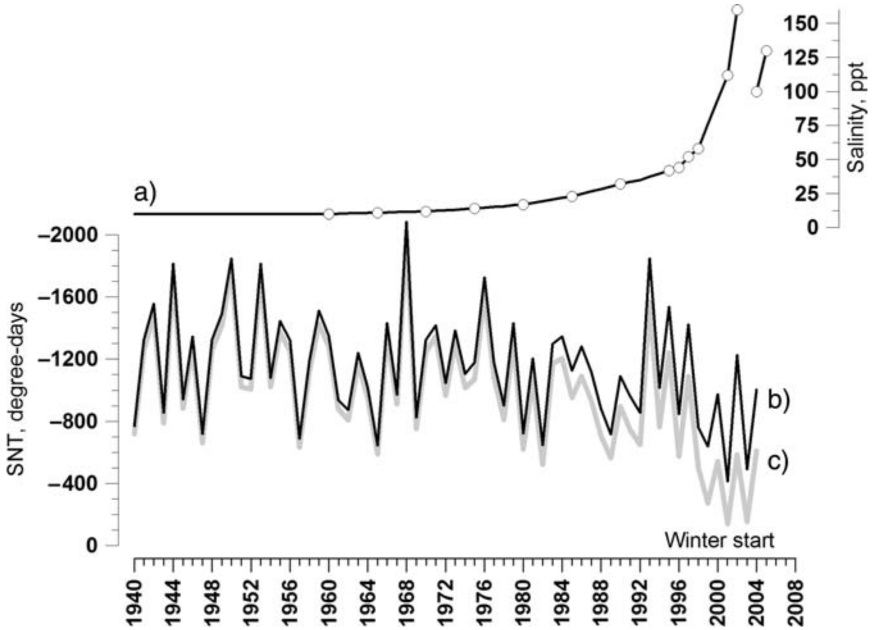


Fig. 11 (**a**) Salinity of eastern Large Aral, after [27] up to 2002 and after [9] for 2004–2005. Sum of negative daily air temperatures for the meteorological station Aralskoye more: (**b**) uncorrected (same as Fig. 10a) and (**c**) corrected using freezing temperature

and S – the salinity in ppt. This formula takes no account of particularities of salt composition of the Aral Sea. A second formula $T_{fr} = 0.44–0.048*S$ [8] has been calculated specifically for the Aral Sea for salinity between 50 and 100 ppt, but we have also applied it for salinity higher than 100 ppt. The increase of salinity in the eastern Large Aral from 30 to 160 ppt shifts the freezing temperature from −1.3 to −7.24°C. With rising salinity the difference between uncorrected and corrected SNTs goes up to 300–400 degree-days and the highest value 641 degree-day in 2002. This difference can represent up to 60–70% of the value of the uncorrected SNT. As a result, the same air temperature would have a much milder effect on the eastern Large Aral than on the Small Aral (Fig. 11b, c). High salinity leads to the development of thinner ice cover, and in spring this ice is more easily melted. This explains the noted differences in the timing of open water (both first and 100%) appearance and winter duration between the Small and eastern Large Aral. The decrease of salinity since 2004 has resulted in the time series for the two water bodies being closer to each other, which is well seen in Figs. 7 and 8.

A salinity increase also lowers the temperature of maximal density, which even at 40–50 ppt becomes less than the freezing temperature [2]. Thus, during the autumnal cooling the sea is strongly stratified and the cold surface layer does not sink downward. This could well reflect the fact that we do not observe a significant difference in the timing of ice formation between the brackish Small Aral and highly saline eastern Large Aral.

The variability of sea level results in changes of its surface and volume, and thus of heat storage capacity. While for the Small Aral the sea level has been stabilised, for the Large Aral Sea level decrease is continuing [5,6]. Using the dedicated Digital Bathimetry Model (DBM) of the Aral Sea [6] and altimetric series of the sea level we have estimated changes in the mean depth (defined as the ratio of sea volume to sea surface) for the eastern part of the Large Aral and for the Small Aral. While for 1992–2006 for the Small Aral this value was relatively constant – between 7.1 and 8 m, for the eastern Large Aral mean depth has gradually decreased almost three times: from 5.1 to 1.9 m. One of the potential consequences of the decrease of heat storage capacity would be an earlier start of ice formation in autumn. This is not a feature that we observe for the eastern Large Aral – apparently the influence of changes in salinity is much stronger. Another consequence would be an earlier ice break-up and melting in the spring. This is exactly what we observe not only for the eastern Large Aral, but also for the Small Aral, suggesting that the main driving factor for this is variability of air temperature.

Acknowledgements We are grateful to the Centre for Topographic Studies of the Oceans and Hydrosphere (CTOH) at LEGOS, Toulouse, France for provision of the altimetric and radiometric data. ECMWF ERA-40 data have been obtained from the ECMWF data server. We thank Peter Zavialov (Institute of Oceanology, Moscow, Russia) for his valuable comments. The research has been partly supported by the AICSEX (Arctic Ice Cover Simulation Experiment) Project of the 5th EU Framework program, NATO CLG Grant "Physical and Chemical Fluxes in Dying Aral Sea," and by the two INTAS Projects: 00-1053 and "ALTICORE" (Contract Nr 05-1000008-7927).

References

1. Bortnik VN, Chistyayeva SP (eds) (1990) Gidrometeorologiya i gidrohimiya morey (Hydrometeorology and hydrochemistry of seas), vol 7 Aral Sea. Gidrometeoizdat, Leningrad (in Russian)
2. Ginzburg AI, Kostianoy AG, Sheremet NA (2003) Thermal regime of the Aral Sea in the modern period (1982–2000) as revealed by satellite data. J Mar Syst 43:19–30
3. Kouraev AV, Kostianoy AG, Lebedev SA (2008) Recent changes of sea level and ice cover in the Aral Sea derived from satellite data (1992–2006). J Mar Syst. doi:10.1016/j.jmarsys.2008.03.016 Available online 12 August 2008
4. Zavialov PO (2009) Physical oceanography of the Large Aral Sea. The Handbook of Environmental Chemistry. doi: 10.1007/698_2009_4
5. Aladin N, Crétaux J-F, Plotnikov IS, Kouraev AV, Smurov AO, Cazenave A, Egorov AN, Papa F (2005) Modern hydro-biological state of the Small Aral Sea. Environmetrics 16(4): 375–392. doi:10.1002/env.709
6. Crétaux J-F, Kouraev AV, Papa F, Bergé-Nguyen M, Cazenave A, Aladin N, Plotnikov IS (2005) Water balance of the Big Aral Sea from satellite remote sensing and in situ observations. J Great Lakes Res 31(4):520–534
7. Létolle R, Chesterikoff A (1999) Salinity of surface waters in the Aral Sea region. Int J Salt Lake Res 8(4):293–306. doi:10.1007/BF02442116
8. Zavialov PO (2005) Physical oceanography of the dying Aral Sea, Springer praxis books. Springer, Berlin, p 146
9. Zavialov PO, Ni AA, Kudyshkin TV, Kurbaniyazov AK, Dikarev SN (2008) Five years of field hydrographic research in the Large Aral Sea (2002–2006). J Mar Syst. doi:10.1016/j.jmarsys.2008.03.016 Available online 12 August 2008

10. Atlas of the Aral Sea Ice (Atlas l'dov Aralskogo morya), Main Hydrometeorological service of the Soviet of Ministers of USSR, Hydrometeorological service of Uzbekistan SSR, Aralskaya Hydrometeorological Observatory, Tashkent (1970), 64 pp
11. Kosarev AN (1975) Gidrologiya Kaspiyskogo i Aralskogo morey (Hydrology of the Caspian and Aral Seas). Moscow University Publishing, Moscow, p 271 in Russian
12. Zavialov PO, Kostianoy AG, Emelianov SV, Ni AA, Ishniyazov D, Khan VM, Kudyshkin TV (2003) Hydrographic survey in the dying Aral Sea. Geophys Res Lett 30:1659–1662. doi:10.1029/2003GL017427
13. Zavialov PO, Kostianoy AG, Sapozhnikov PhV, Scheglov MA, Khan VM, Ni AA, Kudyshkin TV, Pinkhasov BI, Ishniyazov DP, Petrov MA, Kurbaniyazov AK, Abdullaev UR (2003) Modern hydrophysical and hydrobiological state of the western Aral Sea. Okeanologiya 43(2):316–319 in Russian
14. Crétaux et al (2009) The Handbook of Environmental Chemistry. This volume
15. Kouraev AV, Papa F (2003) Buharizin P.I, Cazenave A, Crétaux J-F, Dozortseva J, and Remy F., "Ice cover variability in the Caspian and Aral Seas from active and passive satellite microwave data". Polar Res 22(1):43–50
16. Kouraev AV, Papa F, Mognard NM, Buharizin PI, Cazenave A, Crétaux J-F, Dozortseva J, Remy F (2004) Synergy of active and passive satellite microwave data for the study of first-year sea ice in the Caspian and Aral Seas. IEEE Trans Geosci Remote Sens 42(10):2170–2176
17. Kouraev AV, Papa F, Mognard NM, Buharizin PI, Cazenave A, Crétaux J-F, Dozortseva J, Remy F (2004) Sea ice cover in the Caspian and Aral Seas from historical and satellite data. J fsMar Syst 47:89–100
18. Kouraev AV, Semovski SV, Shimaraev MN, Mognard NM, Legresy B, Remy F (2007) Observations of lake Baikal ice from satellite altimetry and radiometry. Remote Sens Environ 108(3):240–253
19. Kouraev AV, Semovski SV, Shimaraev MN, Mognard NM, Legresy B, Remy F (2007) Ice regime of lake Baikal from historical and satellite data: Influence of thermal and dynamic factors. Limnol Oceanogr 52(3):1268–1286
20. Kouraev AV, Shimaraev MN, Buharizin PI, Naumenko MA, Crétaux J-F, Mognard NM, Legrésy B, Rémy F (2008) Ice and snow cover of continental water bodies from simultaneous radar altimetry and radiometry observations. Survey in Geophysics – Thematic issue "Hydrology from space". doi: 10.1007/s10712-008-9042-2
21. Armstrong RL, Knowles KW, Brodzik MJ, Hardman MA (2003) DMSP SSM/I Pathfinder daily EASE-Grid brightness temperatures. National Snow and Ice Data Center. Digital media and CD-ROM, Boulder, CO
22. Swift CT, Cavalieri DJ (1985) Passive microwave remote sensing for sea ice research. EOS 66 (49):1210–1212
23. Comiso JC (1986) Characteristics of Arctic winter sea ice from satellite multispectral microwave observations. J Geophys Res 91:975–994
24. Steffen K, Key J, Cavalieri DJ, Comiso J, Gloersen P, StGermain K, Rubinstein I (1992) The estimation of geophysical parameters using passive microwave algorithms. In: Carsey FD (ed) Microwave remote sensing of Sea Ice. AGU, Washington, DC Geophysical Monograph 68
25. Ulaby FT, Moore RK, Fung AK (1986) Microwave remote sensing, active and passive, vol 3, From theory to applications. Artech house, Inc, Norwood, MA
26. Cavalieri DJ, Parkinson CL, Gloersen P, Comiso JC, Zwally HJ (1999) Deriving long-term time series of sea ice cover from satellite passive-microwave multisensor data sets. J Geophys Res 104(C7):15803–15814
27. Mirabdullayev IM, Joldasova IM, Mustafaeva ZA, Kazakhbaev S, Lyubimova SA, Tashmukhamedov BA (2004) Succession of the ecosystems of the Aral Sea during its transition from oligohaline to polyhaline water body. J Mar Syst 47:101–107

Chemistry of the Large Aral Sea

Peter O. Zavialov and Anatoliy A. Ni

Abstract The objective herein is to describe the present hydrochemical state of the Large Aral Sea and quantify the ongoing changes accompanying the contemporary desiccation. Compared with the predesiccation period before 1960, the sulfate-to-chloride mass ratio decreased by about 40%, whilst the relative content of calcium decreased by a factor of nine in the western basin and a factor of 40 in the eastern basin. However, the reduction of the sulfate-to-chloride ratio in the eastern basin is smaller than that for the western basin. Because the eastern basin water, penetrating into the western trench through the connecting channel, sinks to the bottom layer and forms there a water mass partly retaining the properties of the eastern basin, the relative concentration of calcium in the western basin, generally, decreases downwards, while the sulfate-to-chloride ratio increases.

The ongoing desiccation has also resulted in significant changes in the distributions of dissolved gases in the residual water body. The once fully oxygenized sea developed anoxic conditions and intermittent hydrogen sulfide contamination in the bottom layers. However, H_2S is a variable rather than a permanent feature of the present Aral Sea.

Keywords: Dissolved gases, Ionic composition, Large Aral Sea

P.O. Zavialov (✉)
P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, 36 Nakhimovsky Pr.,117997, Moscow, Russia
e-mail: peter@ocean.ru

A.A. Ni
Institute of Geology and Geophysics, 49 Khadjibaeva Street, Tashkent, 700041, Uzbekistan

A.G. Kostianoy and A.N. Kosarev (eds.), *The Aral Sea Environment*,
Hdb Env Chem (2010) 7: 219–233, DOI 10.1007/698_2009_3,

Contents

1 Introduction

The objective herein is to describe the present hydrochemical state of the Large Aral Sea and quantify the ongoing changes accompanying the contemporary desiccation. Much of the content of this study has been published in the form of a journal article [1]. Some of the data were also reported earlier in the book [2]. Herein, we have added the most recent, previously unpublished data of 2008, and significantly expanded the discussion.

To begin with, we recall that, even before the onset of desiccation, Aral Sea water already had a rather peculiar salt composition, which was quite different from that of the ocean water, as well as many other saline seas. Historically, the first piece of scientific information on the salt composition of the Aral Sea was obtained in 1872 from a water sample collected by Sharngorst, a Staff-Captain of the Russian Army traveling from St. Petersburg to Bukhara. Later he described his sampling procedure as follows: "While men were changing the horses at the Ak-Dzhulpas station, I got into the sea up to my knees and filled two Champagne bottles with the water" (cited after [3], translated from the Russian). The subsequent analysis of the sample revealed the unusually high content of the sulfate ion in the Aral Sea water.

Before the contemporary desiccation, the salt composition was spatially uniform over the sea, and nearly stable in time. The average salinity spanned around 10 g kg^{-1} and the total mass of dissolved salts in the Aral Sea exceeded 10^{10} metric tons. The content of major anions and cations in the Aral Sea water for the 1950s as reported by [3] is shown in Table 1. The relative contents of the principal salts in the water were estimated by this author as follows: NaCl – 56.07%; KCl – 2.05%; $MgCl_2$ – 0.82%; $MgSO_4$ – 25.87%; $CaSO_4$ – 14.98%; $CaCO_3$ – 0.21%. The sulfate/chloride molar concentration ratio SO_4/Cl was 0.68, compared with 0.10 for the ocean and 1.00 for continental discharges [4], and the corresponding mass ratio was about 0.9. Thus, according to the classification used by [3], the Aral Sea waters belonged to the so-called modified sulfate–sodium chemical type, intermediate

Table 1 Absolute mass content of principal ions in the Aral Sea water in the predesiccation period, after [3]

Ion	Cl^-	SO_4^{2-}	HCO_3^-	Na^+	Mg^+	K^+	Ca^{2+}
Content (g kg^{-1})	3.55	3.20	0.15	2.26	0.54	0.12	0.48

between the chloride–sodium-type ocean water and bicarbonate–calcium-type continental waters.

The contemporary desiccation has led to significant additional alteration of the chemical composition. During the desiccation, the salt composition of the Aral Sea has been subject to continuous changes because of chemical precipitation accompanying the salinity build-up [4]. As the salinity increased initially, the first precipitated compound was calcium carbonate:

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \downarrow . \tag{1}$$

For higher salinities, magnesium carbonate ($MgCO_3$) was also precipitated in a similar reaction. The subsequent salinization led to the precipitation of gypsum:

$$Ca^{2+} + SO_4{}^{2-} + 2H_2O \rightarrow CaSO_4{\cdot}2H_2O \downarrow . \tag{2}$$

According to [4], this major process started when the salinity exceeded 26–28 g kg^{-1}, i.e., in the late 1980s. Massive deposits of gypsum precipitated during the recent and ancient regressions of the Sea can be seen on the former bottom. Processes expected at higher salinities include the precipitation of mirabilite $Na_2SO_4{\cdot}10H_2O$, halite NaCl, glauberite $CaSO_4{\cdot}Na_2SO_4$, and epsomite $MgSO_4{\cdot}7H_2O$ [5]. Obviously, the large-scale precipitation of the salts must have led to significant changes in the salt composition of the remaining water mass of the sea, so that today's figures differ considerably from those known for the predesiccation period.

Prior to the onset of desiccation in 1960, the deep convection in the cold season was typically responsible for complete mixing and ventilation of the water column. Therefore, the entire column contained oxygen at high concentrations. No hydrogen sulfide content in the water was ever reported for the predesiccation period [except, maybe, rare and unconfirmed occurrences in limited deltaic areas with enhanced buoyancy-controlled stratification (Friedrich, personal communication)], although traces of H_2S in Aral bottom sediments have long been known. This situation also persisted through the initial decades of the desiccation in 1961–1991, but significantly changed sometime between 1991 and 2002. By the early 2000s, enhanced density stratification had arisen, largely impeding vertical mixing and ventilation. As a consequence, the bottom portion of the column turned anoxic and contained hydrogen sulfide.

Details of the changes of Aral's hydrochemical regime since the early 1990s, including the salt composition and dissolved gases, had been essentially unknown until recently, when several water sampling campaigns were conducted. Herein, we present and discuss some of the data obtained from these field surveys.

2 Data and Methods

The data presented in this paper are based on analyses of water samples collected in the Large Aral Sea from inflatable motor boats during the nine field surveys of 2002–2008. The sampling areas are depicted in Fig. 1. Sampling was carried out in the western basin sampling area repeatedly every year, while the northeastern area

Fig. 1 Satellite image of the Aral Sea (2005) and sampling areas where the data discussed in this study were collected (*white boxes*)

was only sampled in 2004 and 2005, and the eastern one in 2008. The water samples were obtained from the surface and (where applicable) standard depth levels (5, 10, 15, 20, 25, 30, 35, 40 m) by Niskin and Molchanov bottles. The sampling campaigns were always accompanied by CTD (conductivity–temperature–depth) profiling. For further details of the field surveys, see also Zavialov [6].

Most of the samples were analyzed in the chemical laboratory of the Institute of Geology and Geophysics, Academy of Sciences of Uzbekistan. The concentrations of Ca^{2+} and Mg^{2+} were determined by the atomic absorption method; those of Na^+ and K^+ were obtained through the flame photometry method; those for SO_4^{2-} by weighting; those for Cl^- by the volume argentometric titration method; those for HCO_3^- by the titration method.

All vertical profiles of the dissolved gases were obtained at the deepest site of the western basin, at the point with coordinates 45°06′N, 58°23′E ("Station A2"). The samples were taken with Molchanov bottles from the standard depth levels. The dissolved oxygen content was obtained through the Winkler method, and the content of hydrogen sulfide through titration.

3 Results and Discussion

3.1 Ionic Composition: Changes Compared with the Predesiccation Period

To provide a quick summary of the "old" and the "new" ion compositions of the Aral Sea water, we selected here a typical sample (western basin sampling area, surface, 2008) and depicted the concentrations of the principal anions and cations

Table 2 Relative contents of the principal ions in the Aral Sea water in 1952 and 2008

Ion	Cl^-	SO_4^{2-}	HCO_3^-	Na^+	Mg^{2+}	K^+	Ca^{2+}
Content (%) 1952	34.5	31.1	1.5	21.9	5.2	1.2	4.6
Content (%) 2008	43.3	22.6	0.6	24.8	6.7	1.5	0.5

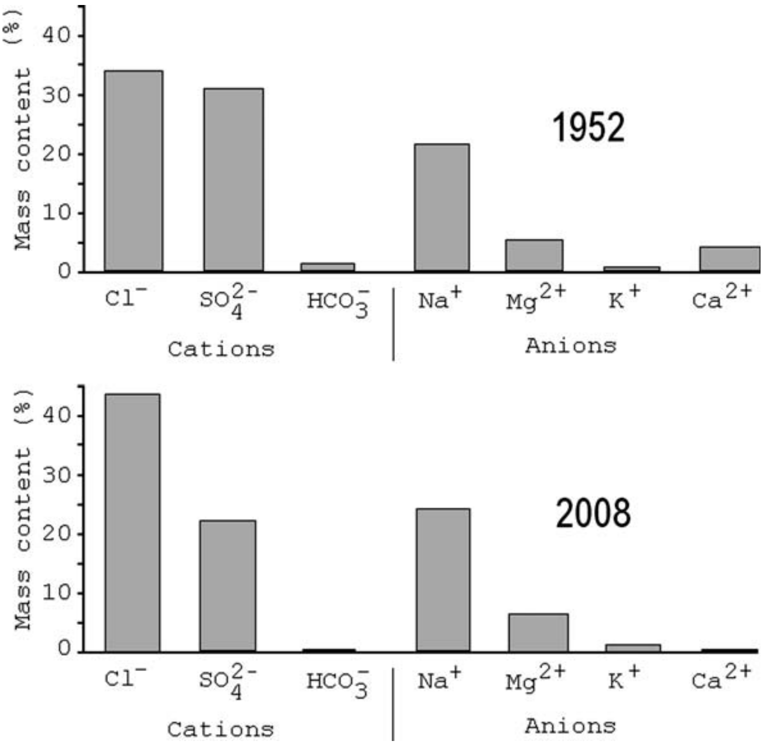


Fig. 2 Schematic illustrating relative mass contents of principal ions in the Aral Sea water before desiccation of the sea (*upper panel*, after [3]), and at the date of this writing (*lower panel*)

together with similar data for 1952 extracted from [3]. It should be noted that this particular sample was chosen as a mere example, but the main points of the discussion below are confirmed by the other nearly 60 samples we collected and analyzed. Because the "old" and the "new" salt contents differ by an order of magnitude, comparing the absolute concentrations is not particularly instructive. Instead, we calculated the relative concentrations, i.e., the massive percentages of each ion with respect to the total mass of dissolved salts. These relative concentrations are shown in Table 2 and are graphically illustrated by Fig. 2.

It is evident that the relative contents of the ions changed significantly during the desiccation. The most pronounced changes occurred with Ca^{2+} whose relative concentration decreased nine-fold, from 4.6 to only 0.5%. Of course, this must have been expected, because the precipitation of both calcium carbonate and gypsum consumes calcium. We can affirm that, in a sense, about 8/9 of the total calcium (in relative units) was already precipitated, and, therefore, further precipitation of gypsum might be limited by depletion of Ca. The sulfate ion, also consumed in gypsum precipitation, decreased in relative content as well, from 31.1 to 22.6%. In contrast, the relative content of Cl^- grew from 34.5 to 43.3%. In consequence, the mass ratio SO_4^{2-}/Cl^- decreased from 0.90 to 0.52, i.e., by 42%. Hence, because of the desiccation, the sulfate-type profile of Aral Sea water became less pronounced, and its waters moved somewhat closer to the chloride type, i.e., ocean waters. Also strongly reduced by about a factor of 2.5 is the content of the bicarbonate ion HCO_3^- which was consumed by the formation and precipitation of calcium and magnesium carbonates, see (1). The relative content of sodium increased from 21.9 to 24.8%. This increase is likely to have been a mere reflection of the precipitation-related reduction of relative contents of the other ions mentioned above.

3.2 Ionic Composition: Interannual Changes During 2002–2008

The succession of the chemical changes during the period 2002 through 2008 is depicted in Table 3. In the western basin samples of 2002, the relative content of calcium was above 1.1% (cf. with 4.6% in 1952). Then it further decreased to about 0.8% in 2003, 0.7% in 2004, below 0.6% in 2005 and 2006, and attained the lowest value of 0.54% in 2008. We, therefore, have witnessed the continuing drop of calcium, presumably, due to continuing precipitation of gypsum, detectable even over the relatively short 7-year period of recent observations. At the same time, the western basin sulfate-to-chloride mass ratio exhibited no obvious trends during the study period, spanning between 0.52 and 0.74 (0.65 on the average, rms deviation 0.06). This ratio must be less sensitive to the precipitation of salts, because in the present conditions, only a relatively small fraction of the available Cl^- is involved in these processes – unlike Ca^{2+} and HCO_3^-, much of which has been precipitated. Nevertheless, all SO_4^{2-}/Cl^- values are significantly smaller than those reported for the predesiccation state, so a decrease is well evident at the interdecadal temporal scales.

The samples collected from the eastern basin (no. 7 and 10 in Table 3) and the strait connecting the two basins (no. 6 in Table 3) are of particular interest. In the eastern basin, water is the saltiest, and the alteration of the ionic composition must therefore be most pronounced. Indeed, on the one hand, the eastern basin and the strait samples yield the smallest content of calcium (between 0.11 and 0.41%, compared with the average of 0.71% for the western basin). The value 0.11% obtained in 2008 for the eastern sampling area is the lowest on record to the date of this writing, constituting a decrease by a factor of 42(!) with respect to the predesiccation period. On the other hand, somewhat surprisingly, the eastern basin waters are also characterized by the highest SO_4^{2-}/Cl^- ratio (0.82–0.88, compared

Table 3 Ionic composition of the Aral Sea water in different years (2002–2006) and parts of the sea. For each sample and ion, the following numbers are given: absolute mass content; relative mass content with respect to the total mass of dissolved salts; and the ratio of the ion content to the content of Cl^-

No	Units	Date	Cl^-	SO_4^{2-}	HCO_3^-	Na^+	K^+	Ca^{2+}	Mg^{2+}	Total dissolved salts ($g\ kg^{-1}$)
1	$mg\ kg^{-1}$	05.07.02	27,155	20,160	494	18,964	175	802	4,378	72.1
	%	West basin	37.67	27.95	0.67	26.29	0.25	1.10	6.07	
	Ion/Cl		1.00	0.742	0.018	0.698	0.006	0.029	0.161	
2	$mg\ kg^{-1}$	25.10.03	38,010	22,100	458	8,634	1,000	700	13,220	84.1
	%	West basin	35.97	25.74	0.53	20.38	1.16	0.81	15.4	
	Ion/Cl		1.00	0.581	0.012	0.227	0.026	0.18	0.348	
3	$mg\ kg^{-1}$	08.04.04	33,175	22,938	442	21,137	1,133	600	5,400	84.9
	%	West basin	39.09	27.01	0.54	24.92	1.35	0.73	6.36	
	Ion/Cl		1.00	0.691	0.013	0.637	0.034	0.018	0.163	
4	$mg\ kg^{-1}$	10.08.04	34,790	23,823	366	22,313	1,214	580	5,412	88.5
	%	West basin	39.31	26.92	0.41	25.21	1.37	0.66	6.12	
	Ion/Cl		1.00	0.685	0.011	0.641	0.035	0.017	0.156	
5	$mg\ kg^{-1}$	30.09.05	37,577	25,056	152.5	24,095	1,209	540	5,760	94.5
	%	West basin	39.81	26.55	0.16	25.23	1.28	0.57	6.1	
	Ion/Cl		1.00	0.667	0.004	0.641	0.032	0.014	0.153	
6	$mg\ kg^{-1}$	03.10.05	39,562.2	34,660	183	27,382.5	1,080	456	7,164	110.5
	%	Strait	35.81	31.37	0.17	24.78	0.98	0.41	6.48	
	Ion/Cl		1.00	0.876	0.005	0.700	0.027	0.012	0.181	
7	$mg\ kg^{-1}$	10.10.05	44,667	36,660	183	30,953.4	1,180	416	7,524	121.6
	%	East basin	36.74	30.15	0.15	25.46	0.97	0.34	6.19	
	Ion/Cl		1.00	0.821	0.004	0.693	0.026	0.009	0.168	
8	$mg\ kg^{-1}$	25.09.06	38,924	25,996	564	23,920	1,184	568	6,544	97.7
	%	West basin	39.84	26.61	0.58	24.48	1.21	0.58	6.70	
	Ion/Cl		1.00	0.668	0.014	0.614	0.030	0.014	0.168	
9	$mg\ l^{-1}$	01.06.08	44,357	23,145	579	25,346	1,550	550	6,870	102.4
	%	West basin	43.32	22.60	0.57	24.75	1.51	0.54	6.71	
	Ion/Cl		1.00	0.522	0.013	0.571	0.035	0.012	0.155	

(continued)

Table 3 (continued)

No	Units	Date	Cl^-	SO_4^{2-}	HCO_3^-	Na^+	K^+	Ca^{2+}	Mg^{2+}	Total dissolved salts (g kg^{-1})
10	mg l^{-1}	08.06.08	78,975	67,775	945	57,316	2,500	250	12,330	220.1
	%	East basin	35.88	30.79	0.43	26.04	1.14	0.11	5.60	
	Ion/Cl		1.00	0.858	0.012	0.726	0.031	0.003	0.156	

with the average of 0.65 for the western basin), which is opposite to what may have been expected for waters affected by the precipitation of salts to a larger degree. One hypothetical explanation might be precipitation of halite in the eastern basin, resulting in consumption of Cl^-. Of course, such a process would also consume Na^+, which is apparently not supported by the data. The reduction of sodium would be less readily reflected in the mass content changes, given that the molar weight of Cl is much bigger than that of Na.

Before finishing this subsection, we take the opportunity to additionally present here for the first time a small piece of data on concentrations of some nutrients in the water of today's Aral Sea. The only data of the kind since the early 1990s were obtained from the samples collected from the surface layer at Station A2 (the deepest site of the western basin) in September, 2006. The analyses made at the Shirshov Institute of Oceanology by Makkaveev and his coworkers yielded the following contents: for Si – 10.5 μg l^{-1}, for P (general) – 1.31 μg l^{-1}, for N (general) – 3.11 μg l^{-1}.

3.3 Ionic Composition: Vertical Structure

The vertical structure of the ion composition in the relatively deep western basin is demonstrated by a typical example given in Table 4. The samples were collected in the deepest spot of the western basin (station A2) in October, 2005. Table 4 depicts a depth profile of the absolute and relative contents of the major ions. Perhaps, the most notable features of the profile are the continuous decrease of the relative content of Ca^{2+} from 0.57% at the surface to 0.48% at the bottom, accompanied by an increase of the SO_4^{2-}/Cl^- mass ratio from 0.67 to 0.82. The corresponding vertical distributions are graphically illustrated by Fig. 3 (also shown in the figure is the salinity profile as revealed from CTD measurements). We note that similar vertical patterns are also evident in the profiles for other years (not shown here). For instance, in September of 2006, the relative mass content of Ca^{2+} was 0.65% at the surface and 0.55% at the bottom, while the SO_4^{2-}/Cl^- mass ratio was 0.67 at the surface and 0.88 at the bottom.

To explain the observed peculiarities of the vertical structure of the ionic content, we recall that, as we substantiated in our previous publications, the water in the bottom part of the western trench usually contains a significant admixture of the water originating from the shallow eastern basin [2, 9, 10]. Saltier, denser, and chemically altered to a larger extent, this eastern water penetrates into the western basin under favorable wind conditions and then sinks into the near-bottom layer, while gradually mixing with the ambient waters. In fact, this mechanism is likely to be the principal controller of the western basin stratification. As shown in [2], typically, 10–20% of the water mass in the western basin is associated with recent intrusions from the eastern basin. Because the advected "eastern water" transports negative buoyancy, its core must be located in the bottom layer and little or none of it is manifested at the surface. The deeper a sample is taken, the larger is the content of the eastern water in it.

Table 4 Ionic composition of the Aral Sea water at different depth levels (October, 2005). For each sample and ion, the following numbers are given: absolute mass content (mg kg^{-1}); relative mass content with respect to the total mass of dissolved salts (%); and the ratio of the ion content to the content of Cl^-

No	Unit	Depth level (m)	Cl^-	SO_4^{2-}	HCO_3^-	Na^+	K^+	Ca^{2+}	Mg^{2+}	Total dissolved salts (g kg^{-1})
1	mg kg^{-1}	0 (surface)	37,577	25,056	152	24,095	1,209	540	5,724	94.3
	%		39.8	26.6	0.16	25.6	1.28	0.57	6.10	
	Ion/Cl		1.00	0.67	0.004	0.64	0.03	0.014	0.152	
2	mg kg^{-1}	10	38,640	25,640	152	25,856	1,289	524	5,688	97.7
	%		39.5	26.2	0.16	26.5	1.32	0.56	5.82	
	Ion/Cl		1.00	0.66	0.004	0.67	0.03	0.014	0.148	
3	mg kg^{-1}	20	36,655	27,160	183	24,886	1,289	488	5,508	96.2
	%		38.1	28.2	0.19	25.9	1.33	0.51	5.73	
	Ion/Cl		1.00	0.74	0.005	0.68	0.04	0.013	0.150	
4	mg kg^{-1}	30	34,847	28,740	183	24,472	1,195	476	5,580	95.5
	%		36.5	30.1	0.19	25.6	1.25	0.50	5.84	
	Ion/Cl		1.00	0.82	0.005	0.70	0.03	0.014	0.160	
5	mg kg^{-1}	39 (bottom)	34,847	28,740	183	24,490	1,200	456	5,580	95.5
	%		36.5	30.1	0.19	25.6	1.26	0.48	5.84	
	Ion/Cl		1.00	0.82	0.005	0.70	0.03	0.013	0.160	

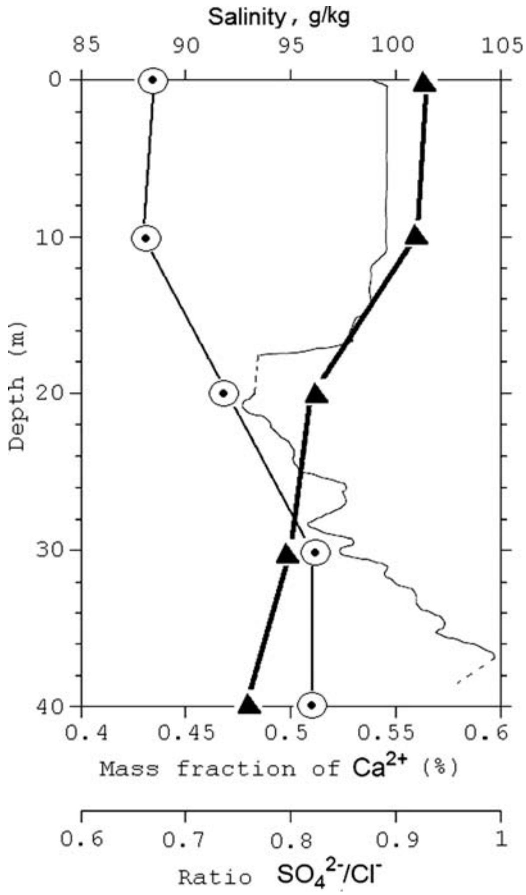


Fig. 3 Vertical distributions of salinity (g kg^{-1}, as obtained from CTD measurements – *solid curve*); SO_4^{2-}/Cl^-ratio (*circles with dots, thin line*); and relative mass content of Ca^{2+} (*triangles, bold line*). Western basin, October 2005. Dashed parts of the salinity profile (*solid line*) indicate layers where no reliable data were collected

The ionic content data presented above seem to be consistent with this concept. Indeed, on the one hand, the admixture of the eastern basin water increases with the depth. On the other hand, it was demonstrated above that the eastern basin water is characterized by a relatively low Ca^{2+} and relatively high SO_4^{2-}/Cl^- ratio. If so, then the corresponding increase of the sulfate-to-chloride ratio from the surface to the bottom, as well as the decrease of calcium content, should be expected in the western basin.

3.4 *Dissolved Oxygen and Hydrogen Sulfide*

Before the onset of desiccation, the Aral Sea was, typically, rather uniform vertically and not stratified (except maybe the limited deltaic areas adjacent to the river mouths). Therefore, nothing impeded sea–atmosphere exchanges and top-to-bottom vertical mixing of the water column, which was also subject to yearly convective overturns in winter [11]. As a result, the column was always fully ventilated and oxygenized. Typically, the maximum O_2 concentration was observed in the bottom layer [4]. This situation has changed in the course of the desiccation. In the new state of the Aral Sea, the water column is, typically, strongly stratified, with the vertical density gradients sometimes exceeding 1 kg m^{-4} [2]. As is well-known, the higher the vertical gradient of density, the more difficult it is to mix the water column. Accordingly, the present-day hydrological regime of the Aral Sea often results in stagnation of the bottom part of the water column, which lacks connection with the atmosphere and thus develops anoxic conditions.

Despite the elevated salinity, there is a considerable biomass of zooplankton and other biota in the western Aral Sea [12, 13]. The reduction of the organic matter in the absence of oxygen results in H_2S production. Hydrogen sulfide in the Aral Sea water was first discovered in 2002, almost simultaneously by a German–Russian–Kazakh expedition in the Chernyshev Bay (the northernmost tip of the western basin) [14] and a Russian–Uzbek expedition in the open western basin [9]. Of course, this does not mean that H_2S was not there before 2002, given that there had been virtually no soundings or sampling of the bottom layer since the early 1990s. Therefore, we can only affirm that hydrogen sulfide first appeared sometime between 1992 and 2002.

Typical vertical profiles of dissolved H_2S and O_2, as measured in October, 2003, are exhibited in Fig. 4. In the same plot, we show the long-term average vertical distribution of oxygen for 1960–1985, i.e., the predesiccation period and the initial stage of the desiccation, according to [4]. In the composite profile of the past, the O_2 concentration is high at 9–11 mg l^{-1} throughout the column. The oxygen content is distributed rather uniformly, with a moderate maximum attained in the lowermost layer. In the present-day profile, the maximum concentration is about 6 mg l^{-1}, and O_2 is restricted to the upper 15–20 m of the column, i.e., the upper mixed layer, and disappears completely below it. Immediately below the depth where oxygen vanishes, hydrogen sulfide appears, and its concentration generally increases towards the bottom. In the case shown in the figure, the maximum concentration was as high as 80 mg l^{-1}. To give the reader a scale, we note that such a H_2S concentration is roughly ten times higher than that typical for the Black Sea [15].

The horizontal extent of the H_2S-containing zone is determined by the local bathymetry and the depth of the upper boundary of the hydrogen sulfide layer. The zone tends to be confined to the deepest portion of the western basin. We know that, at least sometimes, there exists also a separate pool of H_2S in the relatively deep Chernyshev Bay [14], disconnected from the main western basin by a sill, but this location is undersampled.

A summary of H_2S observations over the period from 2002 to 2007 is given in Table 5. It can be seen that the H_2S concentration is highly variable at the interannual scale, spanning from zero or nearly zero to at least 80 mg l^{-1}. Equally variable is the depth of the sulfide layer, which was as deep as 35 m in October, 2006, but as shallow as 15 m in September, 2005. In 2004, following deep convection during the winter 2003–2004 [2], there were no H_2S present at all.

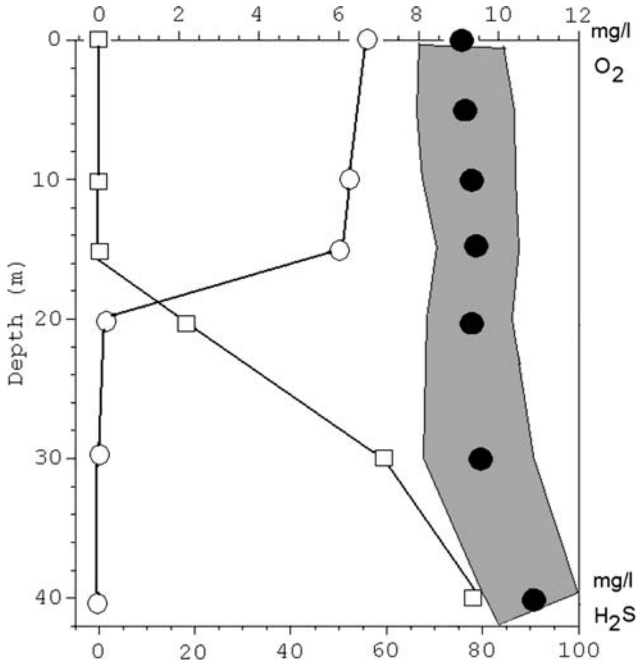


Fig. 4 Vertical distributions of dissolved gases in the deepest site of the western basin of the Aral Sea. O_2 concentration, average over the period 1960–1985, after [4] – *black bullets and grey shading* indicating the rms variability range; O_2 concentration in October, 2003, our data – *white bullets*; H_2S concentration in October, 2003, our data – *white boxes*

Table 5 Summary of available data on H_2S in the Aral Sea for the period from 2002 to 2008

Date	H_2S	Maximum concentration (mg l^{-1})	Depth of H_2S-containing layer (m)
November 2002	Yes	Not measured	25
October 2003	Yes	80	20
April 2004	No	–	–
August 2004	No	–	–
October 2005	Yes	5	35
September 2006	Yes	30	15
November 2007	Yes	Not measured	30
June 2008	Yes	Not measured	30

4 Conclusions

Shrinkage and salinization of the Aral Sea has been accompanied by not only changes of the physical regime but also profound alteration of the sea's chemical state. In turn, the ongoing changes in the ionic composition of the Aral Sea water must have led to corresponding alterations in the basic physical properties and dependencies, such as those of density on salinity and temperature (i.e., the equation of state); freezing temperature on salinity; evaporation rate on the sea surface temperature, etc. There exist, therefore, strong mutual feedbacks between the chemical and physical regimes of the sea. The Aral Sea can be thought of as a natural model for investigating these complex processes, which may also occur in other desiccating or endangered saline basins.

The ongoing desiccation of the Aral Sea has resulted in significant changes in the distributions of dissolved gases in the residual water body. In particular, the once fully oxygenized sea developed anoxic conditions and intermittent hydrogen sulfide contamination in the bottom layers. The sulfide content depends on the density stratification and is mainly controlled by the physical regime of the sea. However, H_2S is a variable rather than a permanent feature of the present Aral Sea. The biogeochemical and physical mechanisms behind such rapid formation of hydrogen sulfide and its removal are one important topic for future research.

Precipitation of calcium and magnesium carbonates, gypsum, and, possibly, mirabilite and halite successively occurred as the salinity increased by an order of magnitude. Accordingly, compared with the predesiccation period before 1960, the sulfate-to-chloride mass ratio decreased by about 40% (western basin of the sea), whilst the relative content of calcium decreased by a factor of nine in the western basin and a factor of 40 in the eastern basin. We hypothesize that, presently, calcium depletion may limit further precipitation of gypsum. The progressive alterations of the ionic composition are also evident at the interannual scale over the period of the recent observational campaigns (2002–2008). The tendencies are characteristic for both basins of the Large Aral Sea. The shallow eastern basin, where the most intense evaporation occurs and the salinity is generally higher, is expected to exhibit a larger extent of the chemical alteration, and, indeed, the reduction of calcium content is more pronounced in this part of the sea. However, somewhat paradoxically, the reduction of the sulfate-to-chloride ratio in the eastern basin is smaller than that for the western basin. Hypothetically, this could be explained through precipitation of halite already taking place in the eastern basin, but not yet in the western basin.

Because the eastern basin water, penetrating into the western trench through the connecting channel, sinks to the bottom layer and forms there a water mass partly retaining the properties of the eastern basin, the relative concentration of calcium in the western basin, generally, decreases downwards, while the sulfate-to-chloride ratio increases. These parameters, therefore, can be thought of as the natural "tracers" of the eastern basin water intrusions into the bulk of the western basin.

Acknowledgments The field research in the Aral Sea was supported by the Russian Academy of Sciences, Russian Foundation for Basic Research, NATO Science program, and the US National Geographic Society. The authors wish to thank D. Mukhamedzhanova, T. Kudyshkin, and other colleagues who participated in collecting and analyzing the samples used in this study.

References

1. Zavialov PO, Ni AA, Ishniyazov DP, Kudyshkin TV, Kurbaniyazov AK, Mukhamedzhanova D (2008) Ongoing changes in salt composition and dissolved gases in the Aral Sea. Aquat Geochem. doi: 10.1007/s10498–008–905–79
2. Zavialov PO (2005) Physical oceanography of the dying Aral Sea. Springer Praxis, Chichester, UK, p 146
3. Blinov LK (1956) Hydrochemistry of the Aral Sea. Gidrometeoizdat, Leningrad, 152 pp (in Russian)
4. Bortnik VN, Chistyaeva SP (eds) (1990) Hydrometeorology and hydrochemistry of the seas of the USSR. The Aral Sea, vol 7. Gidrometeoizdat, Leningrad, 194 pp (in Russian)
5. Rubanov IV, Ishniyazov DP, Baskakova MA, Chistyakov PA (1987) Geology of the Aral Sea. FAN, Tashkent, 246 pp (in Russian)
6 Zavialov PO (2009) Physical oceanography of the Large Aral Sea. Handbook Environ Chem. doi:10.1007/698_2009_4
7. Morachevskiy YuV, Petrova EM (eds) (1960) Analytical methods for brines and salts. Khimiya, Moscow, Leningrad, 104 pp (in Russian)
8. Rubanov IV, Timokhina NI (1982) Conditions for formation of mirabilite (Aral Sea as an example). Zapiski Uzbekistanskogo Otdeleniya VMO 35:57–60 (in Russian)
9. Zavialov PO, Kostianoy AG, Emelianov SV, Ni AA, Ishniyazov D (2003) Hydrographic survey in the dying Aral Sea. Geophys Res Lett 30(21):1–4
10. Zavialov PO, Ginzburg AI, Sapozhnikov FV, Abdullaev UR, Ambrosimov AK, Andreev IN, et al (2004) Interdisciplinary field survey of western Aral Sea in October 2003. Oceanology 44(4):667–670 (in Russian)
11. Kosarev AN (1975) Hydrology of Caspian Sea and Aral Sea. Moscow State University, Moscow, 272 pp (in Russian)
12. Mirabdullaev IM, Zholdasova IM, Mustafaeva ZA, Kazakhbaev S, Lyubimova SA, Tashmukhamedov BA (2004) Succession of the ecosystems of the Aral Sea during its transition from oligohaline to polyhaline water body. J Mar Syst 47(1–4):101–108
13. Arashkevich EG, Sapozhnikov FV, Soloviev KA, Kudyshkin TV, Zavialov PO (2008) *Artemia parthenogenetica* (Branchiopoda: Anostraca) from the Large Aral Sea: Abundance, distribution, population structure, and cyst production. J Mar Syst. doi:10.1016/j.jmarsys.2008.03.015
14. Friedrich J, Oberhansli H (2004) Hydrochemical properties of the Aral Sea water in summer 2002. J Mar Syst 47: 77–88
15. Yakushev EV, Lukashev YuF, Chasovnikov VK, Chzhu VP (2002). Modern notion of redox zone and vertical hydrochemical structure in the Black Sea. In: Flint MV, Zatsepin AG (eds) Multidisciplinary investigations of the Northeast part of the Black Sea. Nauka, Moscow, pp 119–133 (in Russian)

Biodiversity

Philipp V. Sapozhnikov, Elena G. Arashkevich, and Polina S. Ivanishcheva

Abstract During the last five decades the Aral Sea has been undergoing dramatic changes. Because of river runoff cessation and subsequent decrease in water body volume, mineralisation in the western Large Aral increased from 10 ppt in 1960 to 116 ppt in 2008. Concurrently, crucial changes have been occurring in the Aral ecosystem manifested by the disappearance of most native species and a significant decline in biodiversity. The objective of this chapter is to consider the main results on species composition and distribution of benthic and pelagic organisms obtained between 2002 and 2008 along with the historical data on biodiversity of the Aral Sea.

Keywords Aral Sea, Artemia, Hypersalinisation, Phytobenthos, Phytoplankton, Zoobenthos, Zooplankton

Contents

P.V. Sapozhnikov (✉), E.G. Arashkevich, and P.S. Ivanishcheva
P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, 36 Nakhimovsky Pr., Moscow, 117997 Russia
e-mail: katarsysalva@gmail.com

A.G. Kostianoy and A.N. Kosarev (eds.), *The Aral Sea Environment*,
Hdb Env Chem (2010) 7: 235–282, DOI 10.1007/698_2009_36,

1 Introduction

In the first half of the twentieth century the flora and fauna of the Aral Sea existed in quasistationary, brackish conditions [1–6]. The average salinity of waters of the high sea was 10–12 ppt. Insignificant fluctuations of level and salinity had a character of seasonal and interannual fluctuations.

The open part of the Aral Sea had a fresh-water fauna which included certain Caspian species [5–8]. In gulfs with higher salinity lived euryhaline species of sea origin and drimophiluses from continental waters. During that epoch in the Aral lived 33 species of fishes, 61 of bottom invertebrates (zoobenthos), 49 species of zooplankton, 306 species of phytoplankton (including bento-planktonic microalgae) and 37 species of macrophytes [5].

The Aral Sea accounted for 7% of the total fishery for internal waters of the USSR. The main trade species were roach (*Rutilus rutilus aralensis*), sazan (*Cyprinus carpio aralensis*) and bream (*Abramis brama orientalis*).

In the 1960s, salinity levels in the Aral Sea began to increase progressively. Along with this increase in water salinity all ecosystem communities changed. The majority of the hydrobionts inhabiting the Aral Sea before salinisation disappeared from the basin. Communities of fish, benthic invertebrates (macrozoobenthos), zooplankton and macroalgae suffered to the utmost. To a lesser degree these changes concerned communities of bottom microalgae (microphytobenthos) and phytoplankton.

In the 1960–1980s, new species adapted to the new conditions were introduced into the Aral. At first these were brackish water organisms, then marine, and later hyperhalobs. Most of them later also disappeared from the Sea when mineralisation reached a critical (lethal) concentration. For both autochthonous species and invaders this lethal concentration had individual, species-specific character in relation to salt compositions [9, 10]. Thus, in spite of the invasion of new species, the biodiversity of the Aral communities steadily decreased.

Before salinisation several tens of fish species and more than 100 species of free-living invertebrates lived in the Aral [11]. The changes in environmental conditions became a problem for the national economy as euryhaline species adapted to the increased salinity levels had to be introduced.

During the period from the 1960s to the end of the 1980s, many species of invertebrates and fish were artificially settled into the Aral. At the beginning of the

1960s the Azov Sea species, polychaeta *Hediste diversicolor* and bivalva *Syndosmya segmentum* were introduced and established successfully. In the 1960s and 1970s, attempts at installation of planktonic euryhaline copepods for strengthening of the fish forage reserve were made; this led to the successful acclimatisation of the copepod *Calanipeda aquaedulcis* in the sea. From the beginning of the 1970s, these copepods were observed in quantity all over the Aral [12, 13]. During this acclimatisation larvae of the crab *Rhitropanopeus harrisii tridentata* were accidentally brought into the Aral. In 1976 it extended into the southern area of the Aral [14].

The positive role of the invaders became apparent since the middle of the 1970s when mineralisation increased up to 12–14 ppt, and mass extinction of freshwater species began. At the initial salinity of 8–10 ppt, all freshwater fish and invertebrates living in the Sea were at the limit of their salinity tolerance. Even a slight increase in salinity caused the disappearance of these species [6, 15–17]. During the first decade of salinisation more than 70% of the species of fish and invertebrates vanished. After the successful introduction of euryhaline crustaceans, gloss flounder was introduced from the Azov Sea at the end of the 1970s. By that time, from 20 species of native fish only euryhaline tittlebat from the Azov Sea lived in the Aral. The introduction of flounder allowed maintenance of the fishery during this period of salinisation of the basin.

By the beginning of the 1980s, alongside gloss flounders and tittlebats only three species of gobies, silverside, and Baltic herring survived in the new environment.

At the end of the 1980s, the period of anthropogenic acclimatisation was finished. All new species were introduced to the Aral by the natural course. In 1989, after the separation of the Small Aral, only seven species of fish, ten species of zooplankton, 11 species of macrozoobenthos, and 52 species of phytoplankton inhabited the Large Aral Sea [11, 18]. *Artemia parthenogenetica* was first found in the Large Aral Sea in 1998 [19]. Since 2002, the hypersaline species, *A. parthenogenetica*, has absolutely dominated the zooplankton community making up 99% of the total biomass [20, 21].

In autumn 1994, macrophytes included five species (*Zostera noltei*, *Ruppia cirrhosa*, *Chaetomorpha linum*, *Cladophora glomerata* and *Cladophora fracta*) [22]. Macrozoobenthos included four species, polychaete worm *H. diversicolor,* bivalves *S. segmentum* and *Cerastoderma isthmicum,* and gastropod *Caspiohydrobia* sp. [23]. Two fish species, *Latichtis flesus luscus* and *Atherina bueri*, were found in the sea [24]. Phytoplankton included 50 species, mainly diatoms and cyanobacteria [25].

In 2002, the research group under the direction of P. Zavialov began an investigation of the Large Aral Sea. At that time we found rare small groups of dying *Ruppia cirrosa*. Gloss flounder was represented only by adults while the silverside population included both adult and young specimens. In a year only silversides were observed, in 2004 when mineralisation reached 90 ppt, no fish were found in the Large Aral. During 2002–2008, studies of species composition and distribution of benthic and pelagic organisms were performed along with measurements of the main hydrophysical and chemical parameters.

The objective of this chapter is to consider the main results obtained in the period 2002–2008 along with historical data on biodiversity of the Aral Sea.

2 Phytoplankton

Species composition and biodiversity of the Aral phytoplankton have changed dramatically since the early 1970s [2, 26 and citations therein]. Before this period, the list of species numbered 375 with the domination of Bacillariophyta and Chlorophyta species [27]. The most abundant species in the central parts of the sea was *Actinocyclus ehrenbergii* var. *crassa* [28]. In the 1970–1980s, not only did most brackish water species disappear from the Aral Sea, but also some marine species. In this period, the biodiversity of the phytoplankton community decreased from 306 to 250 species with the predominance of Bacillariophyta, Cyanophyta, and Chlorophyta [18, 29]. In 1999–2002, the number of species dropped to 159 with the absolute dominance of Bacillariophyta (115 species) [26].

In June 2008, only 42 species were identified from the pelagic zone of the Western basin of the Aral Sea, Bacillariophyta – 27 species, Chlorophyta – seven species, Cryptophyta, Dinophyta, and Cyanophyta – two species of each division, and one species of Prasinophyta and Flagellate [30]. The average concentration of phytoplankton in terms of number was 2.3×10^6 cells l^{-1}, in terms of biomass 231 μg C l^{-1}. Bacillariophyta was dominated by two species namely *Nitzschia pellucida* and *Nitzschia fonticola* (71 and 27% of total number, respectively). Cryptophyta was represented by two species, *Rhodomonas* sp. (*salina*?) and *Chroomonas* sp., and Dinophyta by *Phytodinium* cf. *simplex*. About 90% of the total numbers of Chlorophyta were comprised of *Chlamidomonas* sp. Cyanophyta was dominated by *Synechococcus elongatus*.

In the Eastern basin, 14 species of Bacillariophyta were found; the dominant species were *Amphora normanii*, *N. fonticola*, *Navicula* spp., and *Nitzschia communis* (32, 18, 22, and 10% of total alga number, respectively). Chlorophyta was represented by only unidentified species. The total number of phytoplankton was 0.9×10^6 cells l^{-1}, and the biomass was 93 μg C l^{-1}.

In June 2008, the composition of the phytoplankton community changed depending on site and depth (Fig. 1). In the Eastern basin, where mineralisation reached 211 ppt, the community was dominated by diatoms and green algae (Fig. 1a) while in the Western basin, with mineralisation of 119 ppt, all groups of algae were represented (Fig. 1b). Phytoplankton composition showed significant changes in relation to the depth. At the surface, more than 50% of the total number of phytoplankton was comprised of cyanophytes while the share of Bacillariophyta, Dinophyta and Cryptophyta was very small (Fig. 1c). At the depth of 5–10 m, the community was dominated by flagellates and cyanophytes (Fig. 1d), and deeper the phytoplankton was comprised mainly of Bacillariophyta and Chlorophyta (Fig. 1e, f).

In the Western basin in June 2008, the vertical distribution of phytoplankton reflected the light and temperature preferences of the different groups (Fig. 2). Bacillariophyta, Chlorophyta and Cryptophyta peaked at 20 m depth with a temperature of about 2°C (Zavialov, this issue) and low irradiation (Fig. 2a–c), while warm-water and light-requiring Cyanophyta inhabited mainly the upper 5-m layer (Fig. 2d).

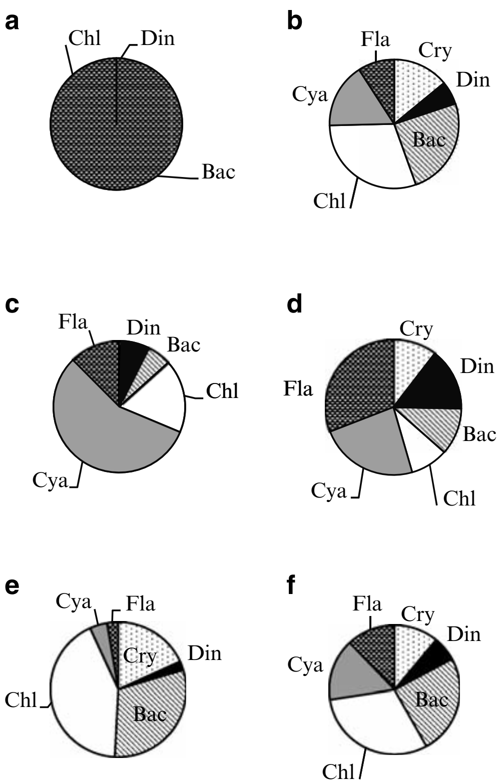


Fig. 1 The share of different divisions in the total number of phytoplankton at different sites of the Large Aral Sea in June 2008. *Cry* Cryptophyta; *Din* Dinophyta; *Bac* Bacillariophyta; *Chl* Chlorophyta; *Cya* Cyanophyta; *Fla* Flagellate. (**a**) Eastern basin, surface; (**b**) Western basin, mean for the water column; (**c**) Western basin, surface; (**d**) Western basin, 5–10 m depth; (**e**) Western basin, 20 m depth; (**f**) Western basin, 20 m depth

3 Zooplankton

During the last five decades, zooplankton of the Aral Sea have been undergoing dramatic changes. Mineralisation in the western Large Aral increased from 10 ppt in 1960 to 98 ppt in 2005 [31], and reached 119 ppt in 2008 (Zavialov, this issue). Concurrently crucial changes have been occurring in the zooplankton community [2, 5, 19, 26, 32, 33] manifested by the disappearance of most native species and a significant decline in biodiversity. The number of zooplankton species decreased from 42 species in 1971 to four species in 2002 [26].

A. parthenogenetica, Barigozzi 1974, Bowen and Sterling 1978, a typical resident of hypersaline basins, was first found in the Large Aral Sea in 1998 [19]. Since 2000, this species absolutely dominated the zooplankton community making up 99% of the total biomass [21, 34].

3.1 Propagation of A. parthenogenetica in the Large Aral Sea

The globally widespread brine shrimp *Artemia* is intensively studied in view of both fundamental scientific objectives (ecological, genetic, evolutional, paleontological)

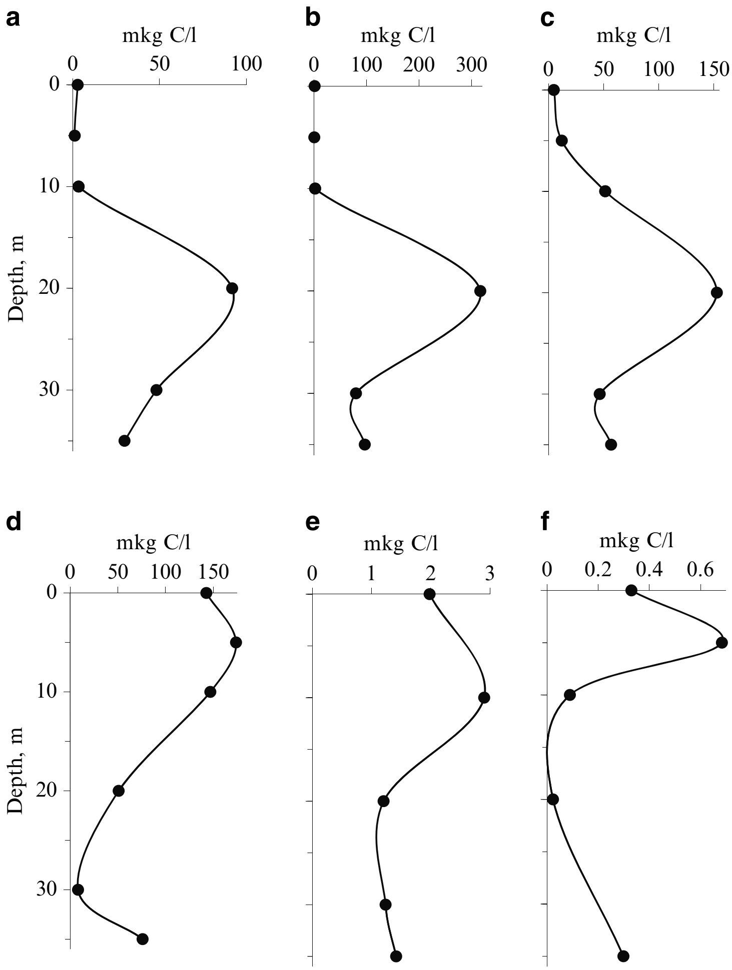


Fig. 2 Vertical distribution of phytoplankton biomass (μg C l^{-1}) in the deep part of the Western basin of the Aral Sea. (**a**) Bacillariophyta, (**b**) Chlorophyta, (**c**) Cryptophyta, (**d**) Dinophyta, (**e**) Flagellate, (**f**) Cyanophyta

and for commercial aims as *Artemia* eggs are of great commercial value and used in the aquaculture industry.

In the Large Aral Sea the *Artemia* population appeared in noticeable numbers only in 2000 but earlier a few individuals were reported in the shallow lagoons and from separated salt ponds near the sea [19, 20, 32]. The appearance of *Artemia* in the Aral coincided with the increase in salinity up to 63 ppt. At a salinity of less than about 70 ppt, an *Artemia* population usually does not develop because of fish predation [35]. Most likely *Artemia* cysts were introduced into the sea by wind or migratory waterfowl [36].

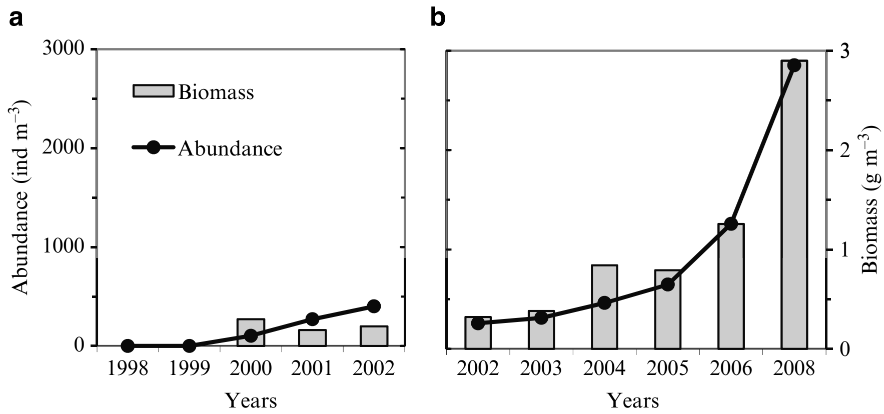


Fig. 3 Interannual changes in *Artemia* abundance and biomass in the Western basin of the Large Aral Sea in (**a**) 1998–2002 (redrawn from [34]) and (**b**) 2002–2008 (after [21] with addition)

In 2000–2002, in the western Aral basin, the abundance of *Artemia* increased by a factor of four while the biomass varied from 0.2 to 0.3 g m^{-3} (Fig. 3a). From 2002–2006, the population density grew progressively, in terms of number from 250 to 1260 ind. m^{-3} and in terms of biomass from 0.3 to 1.3 g m^{-3}. In summer 2008, the biomass reached 2.9 g m^{-3} (Fig. 3b).

According to some authors [37, 38], in the Eastern basin in summer the average density of the *Artemia* population was 5–10-fold higher than that in the Western basin, 20–30 ind. l^{-1} and 2–6 ind. l^{-1}, respectively. However, these data were obtained only for the shallows of the Western basin. Taking into consideration the whole population inhabiting the entire water body volume of the Western basin, the difference in population abundance and biomass between the two basins was not significant. In October 2005, *Artemia* abundances in the eastern and Western basins were 0.95 ± 0.65 ind. l^{-1} and 0.65 ± 0.27 ind. l^{-1}, respectively. Average biomasses were similar in the eastern and western parts – 0.65 ± 0.36 and 0.79 ± 0.32 g m^{-3}, respectively [21].

In June 2008, the biomass of *Artemia* was higher in the Eastern basin compared to the western part, 4.7 g m^{-3} and 2.9 g m^{-3}, respectively.

Since the volume of the Western basin is greater by a factor of five than that of the Eastern basin (Zavialov, this issue), the total stock of *Artemia* in the Western basin exceeded that in the eastern basin.

3.2 *Spatial Distribution of Artemia*

The spatial distribution of *Artemia* is usually very patchy [39–41]. However, this seems to be true only for the shallow basins. High variability in the population density was observed in the shallow (2–3-m depth) Eastern basin and in the shallows of the Western basin. In contrast, the horizontal distribution of the *Artemia* population was rather uniform in the deep central part of the Western basin. At these locations, variability in abundance and biomass was in the usual range known for normal zooplankton distribution. In both basins a noticeable increase in *Artemia* abundance was observed near the eastern shores. This finding suggests the strong influence of wind forcing on the distribution of the upper-dwelling part of the population. The deeper-dwelling *Artemia* were not affected by wind forcing and were distributed evenly [21].

3.3 Vertical Distribution of Artemia

Vertical distributions of the *Artemia* population at the deep station off Aktumsuk in the Western basin in summer 2008 and autumn 2005 are shown in Fig. 4. The depth habitat of *Artemia* was restricted to the upper 15-m layer in both seasons. The majority of the population, 93% in summer and 89% in autumn, inhabited this layer. Roughly, it was in accordance with profiles of hydrophysical and chemical parameters. Oxygen depletion and the formation of an anoxic layer containing hydrogen sulphide prevented distribution of *Artemia* in deeper waters. At depths below 20 m, few or no *Artemia* were found. The proportion of older stages usually increased with depth while the sum portion of nauplii and metanauplii was higher in the upper layer [21]. There was no confirmation of strong positive phototaxis in *Artemia* [40] from the pattern of their vertical distribution. The concentration of both the youngest stages (nauplii and metanauplii) and the oldest ones (postlarvae and adults) was lower in the upper 5 m layer. Only a slight trend of increasing ratio of younger stages/total number of the population was noticed for this layer.

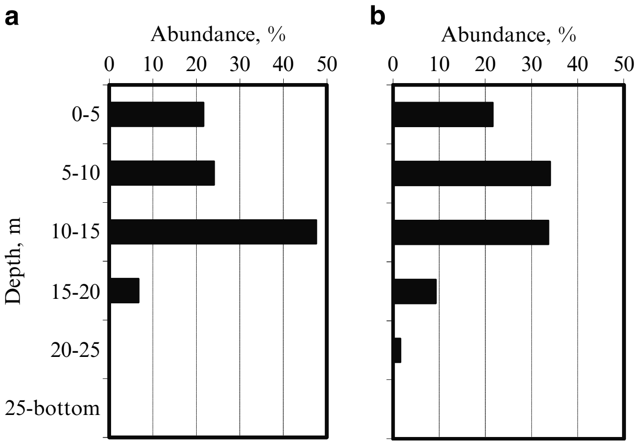


Fig. 4 The depth distribution of *Artemia parthenogenetica* in the western Large Aral Sea (45°05′N, 58°23′E) in (**a**) June 2008 and (**b**) October 2005

3.4 Feeding Habits of Artemia

Artemia is a typical filter feeder consuming small particles from the water at a high rate. While a large number of feeding experiments were carried out under laboratory conditions, [see 42] most of them were performed at the "normal" salinity of 30–35 ppt using algae culture as food. At present there are little data on the feeding habits of *Artemia* under hypersaline conditions. In the experiments we performed in June 2008, natural sea water with a salinity equal to approx. 119 ppt and reside phytoplankton assembly was used (for the method see [30]). The experiments revealed the cessation of *Artemia* feeding at a temperature below 3°C. The maximal feeding rate was observed at 20°C, a noticeable decrease in feeding activity occurred at $T \geq 26$°C. The relationship between clearance rate and body size of *Artemia* is shown in Fig. 5. The clearance rate increased with increase of the body weight of *Artemia* from 100 ml ind.$^{-1}$ day^{-1} in small larva to 600–800 ml ind.$^{-1}$ day^{-1} in adult females (Fig. 5a). The specific clearance rate was five-times higher in young artemia compared to the adults (Fig. 5b). On the basis of these data we estimated that the grazing impact of the *Artemia* population on phytoplankton reached 30% of alga biomass per day.

3.5 Reproductive Characteristics

Artemia have two modes of reproduction: ovoviviparous (producing free-swimming nauplii released from egg sacs when conditions are stable) and oviparous (producing dormant cysts in diapause when conditions are unfavourable). All strains of *Artemia* possess both reproduction modes and can switch from one mode to the other in a response to changing environmental conditions [35]. In early summer, all the Aral *Artemia* females produce ovoviviparously. In mid-summer,

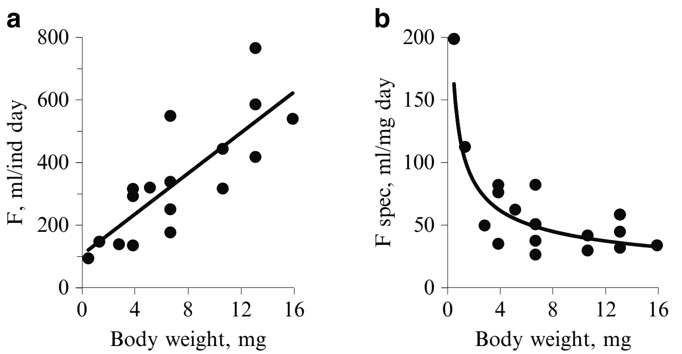


Fig. 5 *Artemia parthenogenetica*. Clearance rate (**a**) and specific clearance rate (**b**) in relation to the body weight of animals in June 2008

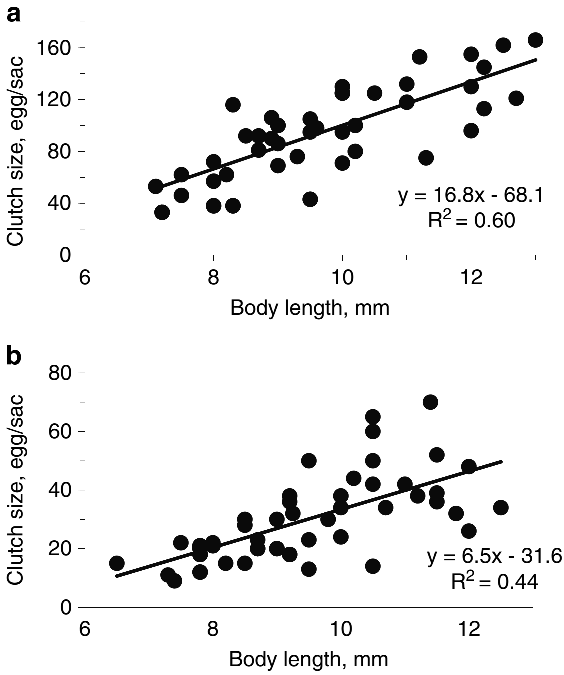


Fig. 6 Brood size versus *Artemia* female length in the Large Aral Sea in (**a**) June 2008 and (**b**) in October 2005

they switch to oviparous reproduction, and by August, only a small proportion of reproducing females (<2%) produces nauplii. In autumn, all females produce only dormant cysts.

There was a positive correlation between clutch size and body length of the Aral *Artemia* female for both reproduction modes (Fig. 6). In ovoviviparous reproduction, the number of offspring is much higher (109 ± 22 naupl. per female) than in oviparous reproduction (33 ± 13 cysts per female). These figures are in agreement with values reported for *Artemia* species inhabiting other hypersaline basins [41, 43].

It has been shown that both the temperature and salinity strongly affect the reproduction potential in Artemia [44–48]. The optimal salinity regime ranges between 80 and 150 ppt, while the preferred temperature was found to be 22°C. In summer 2008, in the Eastern basin where mineralisation exceeded 200 ppt, the brood size ranged from 5 to 20 eggs clutch^{-1} and only 50% of females carried brood sacs. In the Western basin with a salinity of 119 ppt, approx. 90% of females carried brood sacs containing 109 eggs on average (Fig. 6a).

3.6 Artemia Cysts

Usually *Artemia* females carry cysts in the brood sacs for four to five days, then they are released into the water. The average diameter of cysts produced by the Aral *Artemia* was 262 ± 13 m.

In autumn 2005, in the Western basin the concentration of cysts in a square metre of the surface ranged in the 2×10^5–2×10^8 interval. In the Eastern basin their concentration was much lower ranging from 0.8×10^4 to 2×10^4cysts m^{-2} [21]. Because of their positive buoyancy the cysts float on the surface and are gathered in clouds by currents and wind. However, at a salinity below 150 ppt, a proportion can be suspended in the water column [41]. In the Aral Sea they were found in huge concentrations (7×10^5 cysts m^{-2}) at the bottom. Cysts could have appeared there in previous years when the salinity was lower. The deposition of cysts in the sediments can serve as a tracer of basin salinity level for paleontological studies [49].

3.7 Life Cycle of the Aral Artemia

In early spring, the first offspring appears from the overwintered cysts. Adults of the first generation consist of ovoviviparous females and small numbers (less than 1%) of males. Males exist only for a very short period and then disappear. As the temperature rises and food conditions worsen, females switch reproduction mode from ovoviviparity to oviparity. In autumn all females reproduce only cysts. In winter time, Artemia disappear from the sea.

4 Bacterioplankton

In 1965, during the first stage of an increase in mineralisation of the Aral Sea the mean number of bacteria was 0.166×10^6 cells ml^{-1}, and biomass –0.033 mg wet weight l^{-1} [50]. Coccoid forms dominated the bacterial community and were more abundant in the coastal areas. As estimated from the relationship between biomass and number of bacteria, they were large cells with mean volume of about 0.2 μm^3.

When mineralisation reached 36 ppt, the number of bacteria increased. According to Sulalina and Smurov [51] in the small Aral Sea and Butakov Bay the number of bacteria varied from 0.7 to 2.4×10^6 cells ml^{-1} with a tendency of increasing to the bottom. At that time bacterioplankton were mainly represented by rod-like, coccoid, filamentous and spiral forms.

In June 2008, bacterioplankton in the Large Aral were dominated by small coccoid forms with a mean volume of 0.014 μm^3. Rod-like forms made up no more than 5% of the total number. In the Western basin, the number of bacteria in the upper layer averaged 0.353 10^6 cells ml^{-1}. In the coastal areas the abundance of bacterioplankton was higher as compared with the central parts of the basin, 0.402×10^6 cells ml^{-1} and 0.271×10^6 cells ml^{-1}, respectively. The mean biomass in terms of wet weight was 0.005 mg l^{-1}, in terms of carbon – 0.728 μg C l^{-1}. Maximum abundance was observed at a depth of 20 m and coincided with the phytoplankton maximum (see Fig. 2). In the shallow Eastern basin the number of bacteria was similar to that in the Western basin, about 0.380×10^6 cells ml^{-1} [30]. Thus, the increase in mineralisation from 12 to 119 ppt (Western basin) and 211 ppt (Eastern basin) did not affect significantly the number of bacterioplankton but caused the replacement of large cells with small ones which resulted in the decrease of bacteria biomass by an order of magnitude. No difference between bacterioplankton in the western and eastern parts was found.

5 Changes in Benthic Communities of the Large Aral Sea During a Period of Hypersalinisation (2002–2008)

From the beginning of the 1960s the salinity of the Aral sea steadily increased, and its water area and depths decreased. This was reflected in the character of the surface of the bottom and in ground structure. Considerable changes in abiota have influenced the bottom‘s ecosystem, initially adapted for low salinity and other grounds.

The publication [20], published recently and devoted to the biota of the Large Aral Sea, includes data about benthic communities. On the basis of data from 22 expeditions (from 1990 till 2002), the authors observed considerable changes in diversity over the last few decades in the Western and Eastern basins. In the late 1980s to the beginning of the 1990s the majority of not only local species of macrozoo- and macrophytobenthos, but also invaders had become extinct. The authors showed that since 2000 the zoobenthos consisted of only two species (one bivalva and larvae of diptera *Baeotendipes* gr. *noctivaga*). The most resistant was peryphyton: according to data from the review 1990 to 2002, and the most diversified were Bacillariophyta (159 species). However, our data shows that since then communities have already again considerably changed.

Our studies [52] have shown a progressive salinity increase from 2002 till 2008. The NaCl concentration has considerably increased relative to $MgSO_4$ content. Probably, the chemical compounds of the salts have specific impacts on the structure and composition of communities of various habitats.

Over eight expeditions, we collected biological specimens from different water depths and measured hydrological conditions (Table 1) in the Western and Eastern basins. Macrozoo-, macrophyto-, microphytobenthos and microepiphyton samples of the ultra-shallow zone (0–0.2-0.3 m) we collected in the area of Cape Kiim-Chijak (Western basin, 2002–2008), in the channel to the north (2004, 2005) and in a few points of the Eastern basin (2004, 2005, 2008). We sampled at different points along the coastline of the Western basin near Cape Kiim-Chijak, to a distance of about 3 km to the north and south of an exit point of a road of descent from the plateau Ustyurt to the sea (45°05′37" N and 58°20′17" E).

We studied species composition, assemblage structure, and provided information on spatial distribution. We concentrate on observations of the benthic algal coenoses. These communities remain the most diversified in the modern Aral Sea.

Table 1 Station list of hydrobiological expeditions in the Large Aral Sea from 2002 to 2008. The station numbers of the hydro-biological survey relate to the hydrological and hydrochemical station numbers (expeditions organised by Peter Zavialov, Shirshov Institute, Moscow)

Stations	Sampling date	Latitude	Longitude	Water depth (m)	Salinity (ppt)	Temperature (°C)
D1	11.11.2002	45°05′36"N	58°25′49"E	25	89.88	9.15
D2		45°05′07"N	58°29′55"E	40	91.15	3.47
11-1	20.10.2003	44°52′34"N	58°13′58"E	6	88.76	13.78
11-2		44°50′32"N	58°13′55"E	10	88.88	13.55
11-3		44°50′29"N	58°13′53"E	15	89.73	13.65
9	24.10.2003	45°34′19"N	58°40′56"E	24.6	91.98	13.72
1	07.08.2004	45°45′26"N	59°11′28"E	7	99.04	23.44
2		45°45′30"N	59°11′05"E	1	98.3	23.21
3		45°45′40"N	59°11′29"E	6	99.03	23.52
4		45°41′29"N	59°01′13"E	1	98.3	23.21
5	08.08.2004	45°39′27"N	59°15′59"E	0.15	102.28	21.65
6		45°38′20"N	59°21′08"E	0.75	109	23.23
7	10.08.2004	45°05′34"N	58°20′42"E	6.6	91.77	24.86
8		45°05′33"N	58°20′34"E	10.3	91.9	24.81
9		45°05′29"N	58°20′41"E	14.9	91.73	24.53
10		45°05′25"N	58°20′57"E	20.7	88.03	4.97
12		45°05′23"N	58°22′11"E	30.3	87.85	2.41
15		45°04′31"N	58°28′17"E	38.8	87.89	1.62
AO-9	03.10.2005	45°05′33"N	58°20′34"E	8	99.84	18.09
AO-2		45°05′30"N	58°20′43"E	13	99.96	18.05
AO-3		45°04′59"N	58°23′09"E	38	101.59	9.09
SO-BENTH1	07.10.2005	45°41′02"N	59°14′06"E	0.1	130.89	20.23
SO-BENTH2		45°40′42"N	59°16′00"E	0.2	130.89	20.23
SO-2		45°46′59"N	59°11′25"E	5	130.89	15.56
EO-3	10.10.2005	45°36′59"N	59°31′29"E	3	134.06	15.89
P-4	25.09.2006	45°05′31"N	58°20′34"E	5.4	109.40	18.27
P-3		45°05′24"N	58°20′52"E	17	106.01	9.70
Lit-1-06	27.09.2006	45°05′39"N	58°20′21"E	0.3	109.37	18.55
B-5 (B-6)		45°05′36"N	58°20′26"E	2.5	109.39	18.32
B-4 (B-5)		45°05′27"N	58°20′43"E	10	109.40	18.23
B-3		45°05′34"N	58°21′15"E	20.4	104.49	5.60
B-2		45°05′21"N	58°22′17"E	30	104.52	2.70
Al-6	29.09.2006	45°17′32"N	58°29′00"E	38	105.56	2.75
Lit-1-07	15.11.2007	45°05′39"N	58°20′23"E	0.2	116.66	9.88
A-1		45°05′38"N	58°20′53"E	13	117.35	10.05
A-2		45°04′53"N	58°23′16"E	38	126.45	11.44
A-08-04	02.06.2008	45°01′42"N	58°31′00"E	25	116.96	0.95
A-08-06	03.06.2008	45°02′47"N	58°32′42"E	11	118.87	9.01
A-08-07		45°01′54"N	58°35′48"E	2.5	114.11	22.07
E-08-01	06.06.2008	45°05′51"N	59°30′27"E	0.2	211	26
Lit-1-08	08.06.2008	45°05′38"N	58°20′25"E	0.3	114.13	23.13
A-08-10		45°05′21"N	58°20′77"E	17	115.80	1.89
A-08-13		44°55′59"N	58°26′00"E	22	116.58	1.10
A-08-14		44°58′03"N	58°22′00"E	34	117.92	1.76

Benthic algal assemblages at different depths were observed in connection with different salinity and temperature conditions, oxygen saturation of benthonic waters, and also seasonal occurrence of sulphide in deep-water layers of the Western basin. We also consider the influence of characteristics of the surface of bottom sediments on assemblage composition.

Unfortunately studies were very limited of microphytobenthos of the Large Aral grounds during the period of salinisation up to 2002. Therefore, we have nothing to compare our data with. However, the received results show essential reorganisations of microalgae coenoses in an interval of salinity change from 35 ppt and more.

5.1 Macrozoobenthos

Our researches in 2002–2008 have shown that in the modern Aral Sea macrozoobenthos still exist. Hypersalinisation and super-low temperatures of water during the winter periods have introduced notable corrective amendments in structure and species composition of benthic fauna. Nevertheless, despite severe conditions, life at the bottom of this basin continues to remain diversified.

Already during the period of our observations, i.e., since November 2002, the Aral ecosystem has undergone certain regressive changes. In particular, during autumn expeditions in 2002 and 2003, in benthic communities occurred the bivalve mollusc *S. segmentum*. Adult individuals – with complete absence of young individuals – were found out in the Western basin, around cape Kiim-Chijak, at depths of 6–18 m. In November 2002, the salinity in this layer changed from 87 ppt (on the surface) to 91 ppt (at the bottom), and in October of 2003 – from 89 to 92 ppt. Nevertheless, despite the salinity increase, the abundance of *S. segmentum* increased with depth. For example, in 2003 the number of molluscs changed from 10 to 12 ind. m^{-2} at depths of 7–10 m, to 280–290 ind. m^{-2} at a depth of about 18 m. *S. segmentum* biomass also increased with depth from 1–1.5 g m^{-2} to 47–50 g m^{-2}. The linear sizes of the molluscs did not exceed on the greatest axis 1 cm, and the majority of individuals were small-sized. During both expeditions at depths below 20 m there was a layer of hydrosulphuric infection interfering with the ability of the molluscs to live. We assume that the absence of *S. segmentum* individuals below 20 m water depth was caused by the cumulative action of this limiting factor and the salinity increase in the benthonic water layer (over 90 ppt).

In August 2004 when salinity at the surface of the Western basin around cape Kiim-Chijak reached 91.8 ppt, living *S. segmentum* individuals in the benthos were absent. Thus, we ascertain that extinction of this mollusc in the Aral Sea occurs at a salinity of over 90 ppt.

The second species of macrozoobenthos, noted by us in the Aral Sea in 2002–2008, was Chironomidae *Baeotendipes* gr. *noctivaga*. This species is the latest invader, it arrived in the Aral Sea when it was already at a stage of deep hypersalinisation. As our work has shown, larvae of this diptera insect occupy the surface of the Aral bottom in large quantities at the end of summer and in the autumn. In the samples taken at the beginning of April 2004 and in June 2008, the larvae were absent, so we assume they colonise the bottom not earlier than July.

The habitat of this species in the modern Aral covered depths from 0 to 25–30 m in the Western basin, down to 6.2 m in the channel and down to 3–4 m – in the north of the Eastern basin (2002–2005).

For the first time the change in density of the *B.* gr. *noctivaga* population with depth was investigated in October 2003 in the Western basin (the material was processed by N.I. Andreev). The number of larvae gradually increased from the water boundary to depths of about 10 m, where it reached almost 13,000 ind. m^{-2}, and at depths greater than this the abundance began to recede. In samples from 23 m water depth the density averaged 30 ind. m^{-2}, and at 25 m water depth they were completely absent.

In August 2004 (the material was processed by G.A. Koljuchkina, P.P. Shirshov Institute of Oceanology, Moscow) the zone of the maximum number of larvae was again fixed at depths of about 10 m (on the average – 13,100 ind. m^{-2}). At a depth of 15 m we observed insignificant reduction of density (to 12,200 ind. m^{-2}). With further increase in depth the larvae population decreased and at a depth mark of 31 m averaged only 50 ind. m^{-2}.

The expansion in Chironomidae in August 2004 below the 30-metre mark – this is essentially deeper than described for October 2003 – we relate to the absence of hydrosulphuric infection at these depths at the end of summer. Apparently, the limiting factor on depth of the *B.* gr. *noctivaga* habitat in October 2003 was hydrogen sulphide.

In October 2005, the number and biomass of larvae were studied in the Western basin, northern part of the Eastern basin and in the channel (Samples were processed by E.S. Bocharova, Russian Institute for Fishery and Oceanography, Moscow).

In the Western basin the maximum values of abundance corresponded to depths of about 8 m (11,360 ind. m^{-2}, 32 g m^{-2}). At 13 m water depth *B.* gr. *noctivaga* number and biomass were essentially lower (1,950 ind. m^{-2}, 5.1 g m^{-2}). At a depth of 38 m, under conditions of weak hydrosulphuric infection, larvae were absent.

The density of the larvae population significantly increased in the channel over an interval of depth from 0 to 0.5 m, reaching, on average, 20,580 ind. m^{-2} (at a biomass nearby of 57 g m^{-2}). Then, with further increase in depth of habitat, we observed decline in species abundance – at a mark of 6.2 m the density of larvae population reached only 2,500 ind. m^{-2} (at a biomass of 8 g m^{-2}).

In the northern part of the Eastern basin, at a depth of 3 m, larvae occupied the bottom surface also rather densely: on average 9,150 ind. m^{-2} (at a biomass of 27 g m^{-2}).

In September 2006 and in November 2007 *B.* gr. *noctivaga* larvae also occupied the surface of a bottom in the Western basin.

Considering, that in recent years the salinity of Aral waters has steadily grown, and in October 2005 *B.* gr. *noctivaga* larvae developed in a top layer of the bottom surface at a salinity of up to 134 ppt in the northern part of the Eastern basin, it is possible to speak about their high resistance to this factor. Also we noted that in the lagoon cut off from the sea on the east coast of the Vozrozhdenija peninsula where in October 2005 the salinity reached 163 ppt, larvae of *B*. gr. *noctivaga* have not been found. In other words, the limit of tolerance for the species is below this concentration.

At the present time (2008) the macrozoobenthos of the Large Aral is represented by only this one species and its presence has a seasonal nature.

5.2 Macrophytobenthos and Microphytobenthos, Microepiphyton

Before we describe the spatial distribution of the benthic algae and tackle the coenoses structure and their ecological stability, we briefly define the biological collective terms used in this study. Macrophytobenthos includes multicellular green algae (*Cladophora* spp., *Vaucheria* cf. *dichotoma*) and diatom *Navicula ramosissima* macrocolonies as shown in Fig. 7. These structures contain many cells, and their thickets cover areas ranging from a few mm up to dozens of square metres (*Cladophora*). Microphytes are monocellular algae. Microepiphytes are an ecological group of monocellular algae that inhabit macrophyte surfaces. In this study, macrophytes are called basiphytes. Microepiphytes include attached and mobile forms. A list of species we observed in the Large Aral Sea during the 2002–2008 surveys is provided in Table 2.

5.2.1 Structure of Coenosis in Coastal and Shallow Water (<2 m Water Depth)

Macrophytes

In the shallow areas of the Western basin, macroalgae (Chlorophyta, Xanthophyta, and Bacillariophyta) occurred at all coastal stations at the surface of the bottom in

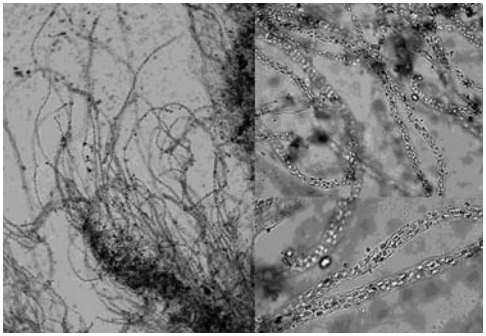


Fig. 7 An image of diatom algae *Navicula ramosissima* macrocolonies – tube-dwelling diatom. Cells are located inside mucilage tubes of their own making. Western basin, November 2002

Table 2 The total list of benthic microalgae, observed in different parts of the Large Aral in 2002–2005

Family	Species	02 WB	03 WB	04 S	04 EB	04 WB	05 S	05 EB	05 WB	06 WB	07 WB	08 WB	08 EB
Kingdom Plantae													
Division Bacillariophyta													
Achnanthaceae	*Achnanthes* sp. 1	–	+	–	–	–	–	–	+	+	+	–	–
	Achnanthes sp. 2	–	+	–	–	–	+	–	–	+	+	+	–
Bacillariaceae	*Cylindrotheca closterium* (Ehremberg) lewin	+	+	–	–	+	–	–	–	–	–	–	–
	C. gracilis (Brebisson) Grunow	+	+	–	–	–	–	–	–	–	–	–	–
	Nitzschia amphibia Grunow	–	–	+	+	+	+	–	+	+	+	+	+
	N. amphibioides Hustedt	–	–	+	–	–	+	–	+	+	+	–	–
	N. clausii Hantzsch	–	–	–	–	–	–	+	+	+	+	+	–
	N. communis Rabenhorst	–	–	–	–	–	+	–	+	+	+	+	+
	N. dissipata (Kützing) Grunow	+	+	+	+	+	+	–	+	+	+	+	+
	N. fonticola Grunow	+	+	+	+	+	+	–	+	+	+	+	–
	N. frustulum (Kützing) Grunow	+	–	+	+	+	+	–	+	–	–	–	–
	N. fruticosa Hustedt	+	–	–	–	–	–	–	–	–	–	–	–
	N. graciliformis Lange-Bertalot et Simonsen	–	–	+	+	+	+	–	+	+	–	+	–
	N. incognita Legler & Krasske	–	+	+	–	+	+	–	+	+	+	+	–
	N. inconspicua Grunow	–	+	+	+	+	+	–	+	+	–	+	–
	N. liebetruthii Rabenhorst	–	–	+	–	+	–	–	+	+	+	–	–
	N. liebetruthii var. *major Grunow*	–	–	–	–	–	+	–	+	+	+	+	–
	N. longissima (Brebisson) Ralfs	+	–	–	–	–	+	–	–	–	–	–	–
	N. pellucida Grunow	–	+	–	–	+	+	–	+	+	+	+	+
	N. scalpelliformis Grunow	–	–	–	–	–	–	+	–	–	–	–	–
	N. sigma (Kützing) W. Smith	+	+	+	+	+	+	+	+	+	–	–	+
	N. sigmaformis Hustedt	–	+	–	–	+	+	+	+	+	+	+	+
	N. tenuirostris (Kützing) W. Smith	–	–	–	–	–	+	–	+	+	+	+	–
	Psammodictyon panduriforme (Greg.) D.G. Mann var. *continua* Grunow	+	–	–	–	–	–	–	–	–	–	–	–
	P. panduriforme (Gregory) D.G. Mann	+	+	–	–	–	–	–	–	–	–	–	–
	Tryblionella acuminata (W. Smith) Grunow	+	+	–	–	–	–	–	–	–	–	–	–

(*continued*)

Table 2 (continued)

Family	Species	02 WB	03 WB	04 S	04 EB	04 WB	05 S	05 EB	05 WB	06 WB	07 WB	08 WB	08 EB
	T. compressa var. *balatonis* (Grunow) H. Lange-Bertalot	–	–	+	+	+	+	–	–	–	–	–	–
	T. constricta Gregory	+	+	–	–	+	–	–	+	–	–	–	–
	T. gracilis W. Smith	+	–	–	–	–	–	–	–	–	–	–	–
	T. levidensis W. Smith var. *salinarum* Grunow	–	+	–	–	–	–	–	–	–	–	–	–
	T. punctata W. Smith	+	+	–	–	–	+	+	+	–	–	–	–
Brachysiraceae	*Brachysira gomphonemoides* H. Lange-Bertalot & G. Moser	–	–	–	–	+	–	–	–	+	+	+	–
	B. styriaca (Grunow in Van Heurck) R. Ross in B. Hartley	–	–	–	–	–	–	–	+	+	+	+	–
Catenulaceae	*Amphora acutiuscula* Kutzing	+	+	+	+	–	–	–	+	+	+	+	–
	A. cingula Cleve	–	–	–	–	–	+	–	–	–	–	–	–
	A. coffeaeformis (Agardh) Kützing	+	+	+	+	+	+	+	+	+	+	+	+
	A. copulata (Kutzing) Schoemann	+	+	–	–	–	–	–	–	–	–	–	–
	A. cymbifera Gregory	–	+	+	+	+	+	+	+	+	+	+	+
	A. dusenii Brun	–	–	+	+	–	+	–	+	+	+	+	–
	A. exiqua Gregory	+	–	–	–	–	–	–	+	–	–	–	–
	A. holsaticoides Nagumo & Kobayasi	–	–	+	–	–	+	+	+	–	+	+	+
	A. littoralis Donkin	–	+	–	–	–	–	–	–	–	–	–	–
	A. normanii Rabenhorst	–	+	+	+	+	+	+	+	+	+	+	+
	A. ostrearia Brébisson ex Kützing	+	–	–	–	–	–	–	–	–	–	–	–
	A. pediculus (Kützing) Grunow	–	+	–	–	–	–	–	–	–	–	–	–
	A. proteus Gregory	–	+	+	+	+	+	+	+	+	+	+	+
	A. pseudoholsatica Nagumo & Kobayasi	+	+	–	–	–	+	–	+	+	+	+	–
	Amphora sp.1	–	+	+	+	–	+	–	+	–	–	–	–
	A. subholsatica Krammer	+	+	+	+	+	+	+	+	+	+	+	+
	A. terroris Ehrenberg	+	+	–	–	–	–	–	–	–	–	–	–
Cocconeidaceae	*Cocconeis placenthula* Ehrenberg	–	–	+	+	+	+	–	–	+	+	+	–
	C. placenthula Ehrenberg var. *euglypta* Ehrenberg	+	+	+	–	–	+	–	+	+	+	+	–
	C. scutellum Ehrenberg	+	+	–	–	–	–	–	–	–	–	–	–
Diploneidaceae	*Diploneis dydima* Ehrenberg	+	–	–	–	–	+	–	–	–	–	–	–
	D. interrupta (Kützing) Cleve	–	+	–	–	–	–	–	–	–	–	–	–
	D. litoralis (Donkin) Cleve var. *clathrata* (Östrup) Cleve	–	+	–	–	–	–	–	–	–	–	–	–

	D. oblongella (Nägeli) R. Ross	+	+	–	–	–	+	–	+	+	–	–	–
	D. ovalis (Hilse) Cleve	+	+	–	–	–	–	–	–	–	–	–	–
	D. parma Cleve	+	–	–	–	–	–	–	–	–	–	–	–
Entomoneidaceae	*Entomoneis punctulata* (Grunow) Osada & Kobayasi	–	–	–	–	–	+	–	–	+	–	+	–
Fragilariaceae	*Asterionella formosa* Hassall	–	–	–	–	–	–	–	–	–	–	+	–
	Tabularia fasciculata (Agardh) Williams et Round	+	+	+	+	+	–	–	–	–	–	–	–
Hemidiscaceae	*Actinocyclus octonarius* Ehrenberg	+	+	+	–	+	+	–	+	–	–	–	–
Lyrellaceae	*Petroneis humerosa* (Brebisson) Stickle & D.G. Mann	–	+	–	–	–	–	–	–	–	–	–	–
Mastogloiaceae	*Mastogloia balaiensis* Voigt	+	–	+	+	–	+	–	+	+	+	–	–
	M. exigua Lewis	–	–	–	–	–	–	–	+	–	–	–	–
	M. fimbriata (Ehrenberg) Cleve	–	–	–	–	–	–	–	–	–	–	+	–
	M. pumila (Cleve et Möller) Cleve	+	+	–	–	–	–	–	–	–	+	–	–
	M. pusilla (Grunow) Cleve	–	–	+	–	+	+	–	–	–	–	–	–
	M. smithii Thwaites	+	–	+	–	+	+	–	+	+	+	+	–
Naviculaceae	*Navicula capitoradiata* Germain	+	+	–	–	–	–	–	–	–	–	–	–
	N. crucifera Grunow ex A. Schmidt	+	–	–	–	–	–	–	–	–	–	–	–
	N. cryptocephala Kützing	+	–	–	–	–	–	–	–	–	–	–	–
	N. cryptotenella H. Lange-Bertalot	+	+	+	+	+	+	–	+	+	+	+	+
	N. digitoradiata (Gregory) Ralfs	+	+	–	–	–	–	–	–	–	–	–	–
	N. graciloides A. Mayer	+	–	–	–	–	–	–	–	–	–	–	–
	N. menisculus Schumann	+	+	–	–	–	–	–	–	–	–	–	–
	N. menisculus Schumann var. *upsaliensis* Grunow in Cleve & Grunow	+	+	–	–	–	–	–	–	–	–	–	–
	N. molesta Krasske	–	–	–	–	–	–	–	–	+	–	+	–
	N. phyllepta Kützing	+	+	+	+	+	+	+	+	+	+	+	–
	N. radiosa Kützing	+	+	–	+	–	+	–	+	–	–	–	–
	N. radiosafallax H. Lange-Bertalot	+	+	+	–	–	+	–	–	+	+	+	+
	N. rhamosissima Mollis	+	+	+	–	+	+	–	+	–	+	+	–
	N. rhynchocephala Kützing	+	–	–	–	–	–	–	–	–	–	–	–
	N. scolipleura A. Schmidt	+	–	–	–	–	–	–	–	–	–	–	–
Neidiaceae	*Neidium affine* (Ehrenberg) Pfitzer var. *longiceps* (Gregory) Cleve	+	–	–	–	–	–	–	–	–	–	–	–

(*continued*)

Table 2 (continued)

Family	Species	02 WB	03 WB	04 S	04 EB	04 WB	05 S	05 EB	05 WB	06 WB	07 WB	08 WB	08 EB
Pinnulariaceae	*Caloneis* sp. 1	–	–	+	–	+	+	–	+	–	–	–	–
	Caloneis alpestris (Grunow) Cleve	+	+	–		–	+	-	–	–	–	–	–
Plagiotropidaceae	*Plagiotropis gibberula* Grunow	+	+	–	–	–	–	–	–	–	–	–	–
Pleurosigmataceae	*Gyrosigma distortum* (Smith) Griffith and Henfrey	+	–	–	–	–	–	–	–	–	–	–	–
	G. fenestratum Meister	+	+	–	–	+	–	–	+	+	+	–	–
	G. scalproides (Rabenhorst) Cleve var. *eximia* (Thwaites) Cleve	+	+	–	–	–	–	–	–	–	–	–	–
	Gyrosigma sp. 1	+	–	–	–	–	–	–	–	–	–	–	–
	Pleurosigma affine Grunow	+	–	–	–	–	–	–	–	–	–	–	–
	P. hippocampus (Ehrenberg) W. Smith	+	+	–	–	–	–	–	+	+	+	–	–
Pposchkiniaceae	*Proschkinia complanata* (Grunow) D.G. Mann	+	–	–	–	–	–	–	–	+	+	+	–
Rhoicospheniaceae	*Rhoicosphenia curvata* (Kützing) Grunow	–	+	–	–	–	+	–	–	–	–	–	–
Rhopalodiaceae	*Epithemia sorex* Kützing var. *gracilis* Hustedt	–	–	–	–	+	–	–	–	–	+	–	–
	Rhopalodia constricta (W. Smith) Krammer	+	–	–	–	–	+	–	+	–	+	–	–
Scoliotropidaceae	*Biremis ambigua* (Cleve) D.G. Mann	–	–	–	–	+	–	–	–	–	–	–	–
Sellaforaceae	*Fallacia forcipata* (Greville) A.J.Strickle et D.G.Mann var. *densestriata* (Schmidt) Sickle et Mann	+	–	–	–	–	–	–	–	–	–	–	–
	Fallacia sp. 1	–	–	+	–	+	–	–	+	–	–	–	–
Stephanodiscaceae	*Cyclotella meneghiniana* Kutzing	+	–	–	–	–	–	+	+	+	+	+	+
Surirellaceae	*Surirella fastuosa* Ehrenberg	+	+	+	–	+	+	+	+	+	+	–	–
	S. variabilis A. Cleve-Euler	–	–	+	–	–	+	+	+	–	–	–	–
Division Chlorophyta													
Chlorococcaceae	*Chlorella* sp. 1	–	+	–	–	–	–	–	+	+	+	+	+
Dunalieelaceae	*Dunaliella salina* Powder & Oil	–	–	–	–	–	–	–	+	+	+	+	–
Oocystacea	*Oocystis submarina* Lagerh	–	–	+	+	+	–	+	+	+	+	+	+
	Westella botryoides De-Wildeman	–	–	–	–	–	–	–	+	–	–	+	+
Scenedesmaceae	*Desmodesmus opoliensis* (P. Richer) E. Hegewald (Sp. 48)	–	–	+	–	+	–	–	+	–	–	+	–
	Scenedesmus arcuatus Lemmermann	–	–	–	–	–	–	–	–	–	–	+	–
	Scenedesmus circumfusus Hortobagyi	–	–	–	–	–	–	–	–	–	–	+	–

Division Cryptophycophyta													
Cryptomonadaceae	*Cryptomonas* sp. 1	–	–	–	–	–	–	–	–	+	–	+	–
Division Euglenophycota													
Euglenaceae	*Euglena* cf. *pasheri* Swirenko	–	–	+	+	–	+	–	–	+	–	–	–
	E. texta (Dujardin) Hübner var. *salina* (Fritsch) Popowa	–	–	+	+	–	+	–	+	–	–	–	–
Sphenomonaceae	*Anisonema* sp. 1	+	+	–	–	+	–	–	+	–	+	+	+
	Petalomonas sp. 1	–	–	–	–	–	–	–	+	+	+	+	–
	Petalomonas raiula (Lackey) Lee and Patterson	–	–	–	–	–	–	–	+	–	–	+	–
	Metanema cf. *strenuum* (Skuja) Larsen	–	–	–	–	–	–	–	–	–	–	+	–
Division Pyrrophycophyta													
Gymnodiniaceae	*Gymnodinium* sp. 1	–	+	–	–	–	–	–	+	+	+	+	–
Phytodiniaceae	*Phytodinium* cf. *simplex* Klebs	–	+	+	–	+	+	+	+	+	+	+	+
Phytodiniaceae (?)	*Dinophyta* sp.	–	–	–	–	+	–	–	–	–	–	–	–
Division Chrysophyta													
Chrysococcaceae	*Chrysococcus* sp. 1	–	+	–	–	–	–	–	–	–	+	–	–
	Kephyrion sp. 1	–	–	+	+	+	–	+	+	–	+	+	–
Kingdom Monera													
Phylum Cyanophycota													
Chroococcaceae	*Gloeocapsa turgida* (Kützing) Hollerbah	–	–	+	+	–	+	–	–	–	–	–	–
	Microcystis aeruginosa (Kutzing) Kutzing	–	–	+	+	+	–	+	–	–	–	–	–
	Synechocystis aeruginosa	–	–	–	–	–	+	+	–	–	–	–	+
Merismopediaceae	*Coelomoron pusillum* (Van Goor) Komárek	–	–	+	+	+	–	–	–	–	–	–	–
	Gomphosphaeria lacustris Chodat	–	–	+	+	+	–	+	+	–	–	–	–
	Merismopedia glauca (Ehrenberg) Nägeli	–	–	–	–	–	+	–	–	–	–	–	–
Nostocaceae	*Anabaena* sp. 1	–	–	–	–	–	–	–	–	–	+	+	+
	Anabaena sp. 2	–	–	–	–	–	–	–	+	–	–	+	–
Oscillatoriaceae	*Lyngbya nordgaardii* Wille	+	+	+	+	+	+	+	+	+	+	–	–
	Lyngbya sp. 1	–	–	–	–	–	–	–	+	–	–	–	–
	Oscillatoria sp. 1	–	–	–	–	–	–	–	–	–	–	–	+

WB the Western basin; *EB* the Eastern basin; *S* the Channel. 02 – 2002; 03 – 2003; 04 – 2004; 05 – 2005; 06 – 2006; 07 – 2007; 08 – 2008. The algae classification is in accordance with ITIS [67] the late summers and autumns of 2002–2005. The only Xanthophyta species disappeared by 2006. By 2008 only green macrophytes (Chlorophyta) had survived. In spring 2004 (April), however, macrophyte vegetation was absent in the coastal zone. Probably it forms later in the year.

In November 2002, the macroalgae assemblage dominated by *C. fracta* (Chlorophyta) locally occurred on sediment surfaces most abundantly at depths of 1–1.5 m. They were attached to dead mollusc shells (*Cerastoderma* spp. and *Syndosmya* spp.) and their thallus sizes reached a height of 10–15 cm. When accumulation was maximal, *C. fracta* covered up to 80% of the sediment surface.

V. cf. *dichotoma* (Xanthophyta) lived only at minimal depths (0–0.3 m). We observed a species resembling *V. dichotoma*, which was reported in the Aral Sea only in the 1980s and 1990s [1, 3, 4]. However, despite the fact that it was now observed in a more saline environment (85 ppt) and showed typical, though slightly different morphological features in the dark-brown coloured thallus (with only few generative cells), we conclude that it is most likely a *V.* cf. *dichotoma*. During a later survey (spring 2004), the only evidence for macrophytes in the Western basin came from thallus fragments that were washed onto the shore. The detachment of the algae possibly occurred in the surface layer during the winter period when the water temperature reached −3 to −3.5°C [52]. Given that such extreme temperature situations are rare, we only once observed reworked macroalgae. The growth of macrophyte thickets at coastal sites of the Western basin is probably restricted to the warm period of the year.

The habitat of this alga was rather unique, as along the coast they inhabited sediment beds with solid sulphide-bearing clays, which are gradually washed away by rolling waves. They were most common near Cape Kiim-Chijak, where the sulphide-bearing layers were up to 3–4 cm thick. The top of the clay layers, constantly agitated by water, was covered with a fringe of black thalli (up to 3–5 cm long) originating from *V.* cf. *dichotoma*. As a result of erosion by sea water at the edges of the clay layers, these layers were exposed like open book pages. The edges of the top layers were covered with black thalli of Xanthophyta while the surface of this clay layer was covered with thickets formed by scrubs (up to 1–1.5 cm thick) of *C. fracta*, and two other stable morphotypes of *V.* cf. *dichotoma*. The first *Vaucheria* morphotype formed an intensely brown, curly scrub (2–2.5 cm height), and the second morphotype consisted of papillar rosettes of non-branched shoots (up 1 sm height).

Along the coast, we observed over 3 km of both stable morphotypes of macrophytes. Despite their dark brown, almost black “fringed” thalli, the *Vaucheria* sitting on top were alive.

A third macrophyte type was represented by macrocolonies of the diatom *N. ramosissima* (Bacillariophyta) (Fig. 7). The macrocolonies used the surface of *C. fracta* and *V.* cf. *dichotoma* as habitat, where the microalgae formed branched polymeric tubes (“curly scrub” effect). Polymeric tubes of *N. ramosissima* were made of mucilage excreted by the diatoms [53]. As a result, we observed on top of the clay layer, a “brown fur” habitus covering 100% of the washed clay surface. The same “brown fur” spots growing directly on sediment substratum were observed along the shoreline down to a water depth of 10–15 cm, where the fur was widespread.

By October 2003 solid layers of clay on shoals had been washed away by surf to softer layers. Therefore, in the coastal zone, only the "fringed" form of the macroalgae was present. The microepiphytic assemblages grazing on the surfaces of *C. fracta,* which formed very dense thickets of *N. ramosissima,* had not undergone changes. An intense green, abundantly branched thallus of *C. fracta* (up to 15–18 cm high) covered up to 90% of the sediment surface down to a water depth of 0.5 m. Along the shoreline, we observed a cohesive macrophyte festoon (up to 15 cm thick) thrown onto the shore by the surf. Sometimes *N. ramosissima* colonies were observed on rocks.

At the beginning of August 2004, we observed again abundant *C. fracta* in the coastal zone of the Western basin. This species, together with *C. glomerata*, was observed on the large shoals along the channel, whereas in the northern Eastern basin we observed only *C. glomerata*. Thus, we can infer that when salinity increased in the Aral Sea, by 2004 the second species only inhabited areas where salinity was above 100 ppt.

In October, 2005 we observed in the channel and in the northern part of the Eastern basin both *Cladophora* species. In the central part of the Western basin lived only *C. fracta*.

In autumn 2006 and 2007 we observed macrophyte thickets in the central part of the Western basin (*C. fracta* and *C. glomerata*).

In 2008 macrophytes were absent in the central part of the Eastern basin. On coastal rocks around Cape Kiim-Chijak (the Western basin) in the beginning of June we observed only rare medium-sized thickets of *C. glomerata*. We do not have information as to whether macrophytes have remained in the northern part of the Western basin and in the channel. Probably macrophyte thickets develop in the central part of the Western basin in later summertime.

Microphytes and Microepiphytes

Changes of Shoal Coenoses

November, 2002. On the macrophyte thalli, we observed that both trichomal surfaces of *C. fracta* and *V.* cf. *dichotoma* and polymeric tubes of *N. ramosissima* were settled by microepiphytic assemblages. The structures of microepiphytes developing on clay surfaces covered with "brown fur" were most complex. The papillar non-branched shoots of *V.* cf. *dichotoma* were completely covered with *Tabularia fasciculata*. These needle-shaped diatom cells formed palisade-like layers at the surface of the host. This "amalgamation" increased the volume of the epiphyte/basiphytic "complex" by 2–2.5-times when compared to the volume of the basiphyte alone. At some sites, the curly shoots of *V.* cf. *dichotoma* were covered with a layer of *Cocconeis placentula var. euglipta* cells.

Because of numerous branching, *N. ramosissima* colonies have a much greater surface than their basiphyte (*C. fracta*). Therefore, the greater number of non-colonial diatom microepiphytes was concentrated on the polymeric tubes of *N. ramosissima* macrocolonies. Frequently, branches of *N. ramosissima* colonies were inhabited by attached amalgamates of *T. fasciculata*. The microepiphytes at the surface of scrubby forms exhibited a great diversity of mobile diatoms. Most abundant were the following three species: *Navicula cryptotenella, Navicula complanata* and *Navicula radiosafallax*. Among the 28 other species and subspecies, we observed species like *Navicula radiosa, Navicula graciloides, Navicula phyllepta, Nitzschia clausii, N. pellucida, Nitzschia longissima, Nitzschia sigma, Cylindrotheca closterium, Cylindrotheca gracilis, Mastogloia balaiensis, Mastogloia pumila, Gyrosigma scalproides, G. scalproides var. eximia, Amphora coffeaeformis* and *Amphora subholsatica*. The *Mastogloia* cells were observed as (a) exometabolic polymeric capsules attached either to other diatoms or to surfaces of macrophyte colonies, or (b) as mobile, non-capsulated forms. At the same time, some *G. scalproides var. eximia* cells formed tube-dwelling colonies.

At the surface of large *C. fracta* scrubs, which inhabited sandy shoals, the microepiphytes had a different composition. *N. ramosissima* colonies were less abundant. But most common was *T. fasciculate,* which was typically attached directly to the *Cladophora* branches. In agglomerates, *Nitzschia fruticosa* colonies developed abundantly. This diatom lived solitarily on the short, branched, thin polymeric filaments. The filaments were produced by *N. fruticosa* with the support of exometabolites; during binary fission (asexual reproduction) the filaments ramified. Thus, *N. fruticosa* occurred as branched colonies, the first time this was observed in the Aral Sea. Rarely, we observed cyanobacterial conglomerates of *Gloeocapsa turgida* in the diatom cell agglomerates. Furthermore, we observed three cyanobacteria species (*Lyngbya nordgaardii* and two species that could not be classified) with trichom thallus structures inhabiting the *Cladophora* surface.

At sandy bars where currents were strong, four diatom species (*N. cryptotenella, N. complanata, Nitzschia bacillum,* and *N. longissima)* lived freely on the *C. fracta* surface. We observed abundant *Nitzschia frustulum, C. gracilis, N. radiosa, N. graciloides, N. phyllepta, Navicula crucifera, A. coffeaeformis,* and *A. subholsatica* in the assemblages. Also, *Cocconeis placentula var. euglipta* was present as attached but individual cells on terminal basiphyte shoots. Mature *Cladophora* branches were inhabited rather densely by *C. placentula* var. *euglipta* and *T. fasciculata*.

Microepiphyton from *N. ramosissima* macrocolonies, growing directly on sediment substratum, exhibited a peculiarity. On *C. fracta* thallus *N. fruticosa* colonies and numerous *T. fasciculata* cells lived on the common mucous substrate, secreted by *T. fasciculata*.

Mixed assemblages occurred only occasionally. On polymeric tubes of *N. ramosissima* these two species lived separately from each other and mixed assemblages occurred only occasionally.

This might be controlled by the chemical and/or biochemical surface parameters of the basiphyte. The mobile "background" components (29 species) consisted mainly of *N. cryptotenella*, *N. radiosafallax,* and *N. radiosa*. Frequently, we also observed the following species: *N. complanata, N. graciloides, N. clausii, N. sigma,* and *N. bacillum,* while *C. placentula var. euglipta, A. subholsatica, Entomoneis paludosa* var. *punctulata,* and *N. fonticola* occurred only occasionally. A thin silt lamina covering pebbles at minimal water depths was inhabited by mobile diatoms, such as *Nitzschia compressa*, *N. frustulum*, *N. sigma*, *N. cryptotenella*, *G. scalproides var. eximia*, *Gyrosigma distortum*, *Pleurosigma affine* and *A. subholsatica*.

October, 2003. The microepiphytic assemblages on the surfaces of *C. fracta,* which formed very dense thickets, and microepiphytic assemblages on the surface of *N. ramosissima,* had not undergone changes.

August 2004. By that time the salinity in the central part of the Western basin reached almost 92 ppt from 0 to a 1 m water depth. On the basis of previous observations, we concluded that *T. fasciculata*, *N. fruticosa* and *L. nordgaardii* attached to *C. fracta* microepiphytes can tolerate a salinity range from 85 ppt (November 2002) up to 92 ppt (August 2004). Hence, we called this assemblage the "western" epiphytic type. The salinity in the shallow water of the channel was definitely higher. It reached about 102 ppt, while in the Eastern basin we measured as much as 130 ppt. Accordingly, we observed the following four microepiphyte species attached to *Cladophora* species in the channel sites: *T. fasciculata*, *C. placentula* var. *lineata*, *C. placentula* var. *euglipta,* and *L. nordgaardii*. In the Eastern basin, only the microepiphyte *C. placentula* var. *lineata* and *L. nordgaardii* were observed.

October, 2005. We noted that in the Western basin of the Large Aral Sea only two microepiphytes, *C. placentula* var. *lineata* and *L. nordgaardii,* were attached to *C. fracta*, which clearly can be taken as evidence for rising salinity in the deep Western basin.

By *November 2007* this epiphytic complex was replaced by *C. placentula* var. *euglipta* + *L. nordgaardii*. And in *June 2008* we observed on young *C. glomerata* thickets only rare cells of *C. placentula* var. *euglipta*. Probably, cyanobacteria *L. nordgaardii* has disappeared from the Large Aral Sea, or its development begins later in the summer.

At ultra-shoal sediment surfaces of the Western basin, we observed microphytobenthos in 2002–2003. During surveys in 2004–2005, microphytobenthos were absent (down to 0.3 m).

In September 2006, at depths of 0–0.3 m, 22 species of mobile microphytes (Table 3) were again present. *In November 2007* (0–0.2 m water depths) there were only 13 species (Table 4). In the beginning of June 2008 microphytobenthos of ultra-shoals (0–0.3) consisted of two species on soft clay ground (*Nitzschia tenuirostris* and *N. radiosafallax*) and of 14 species – on rocky ground (Table 5).

5.2.2 Changes of Coenoses Below 2 m Water Depth (Microphytobenthos of the Bottom Surface)

In *November 2002*, we found a large number of living microalgae species on silty sediment surfaces covering the lake bottom to depths of more than 20 m, independent of dissolved hydrogen sulphide concentration at the sediment–water

Table 3 The structure of microalgal coenoses from stations at different depths in the central part of the Western basin (September, 2006)

Station numbers; depth, m; salinity; temperature, °C	Dominant and abundant species	Often observed species	Comments
St. Lit-1-06; 0.3 m; 109.37 ppt; 18.55°C	*Nitzschia sigmaformis, Nitzschia acicularis*	*Amphora coffeaeformis, Amphora dusenii, Amphora veneta, Nitzschia liebetruthii* var. *major, Navicula complanata*	On bars of clay which were intensively washed by a rolling wave, diatoms formed films of mobile cells up to 1 mm thick
St. B-6; 2.5 m; 109.39 ppt; 18.32°C	*Amphora veneta, Amphora dusenii, Amphora proteus*	*Amphora coffeaeformis*	Sandy substratum
St. P-4; 5.4 m; 109.4 ppt; 18.27°C	*Amphora proteus, Phytodinium* cf. *simplex*	*Amphora dusenii*	Silted sand substratum
St. B-4 (B-5); 10 m; 109.40 ppt; 18.23°C	*Phytodinium* cf. *simplex*	*Amphora cymbifera*	Silted sand substratum
St. P-3; 17 m; 106.01 ppt; 9.7°C	*Navicula cryptotenella*	Other species were minor	Besides a main dominant, coenosis on a silty substratum included only three species: *Navicula phyllepta*, *Nitzschia fonticola* and *Oocystis submarina*
St. B-3; 20.4 m; 104.49 ppt; 5.6°C	*Navicula phyllepta, Nitzschia fonticola*	*Nitzschia liebetruthii*	At this station and deeper the ground was represented by white friable crystalline pulp ("an amorphous bottom"). Its top layer was occupied by algae
St. B-2; 30 m; 104.52 ppt; 2.7°C	*Oocystis submarina, Nitzschia fonticola*	*Phytodinium* cf. *simplex*	"Amorphous bottom"
St. Al-6; 38 m; 105.56 ppt; 2.75°C	*Nitzschia fonticola, Phytodinium* cf. *simplex*	*Amphora normanii*	"Amorphous bottom"

interface [52]. At a depth of 25 m, we observed eight diatom species, while at a depth of 40.3 m, the deepest point in the Western basin, 19 diatom species and subspecies were recorded (Table 6).

In *October 2003* we managed for the first time to investigate structure and species composition of microphytobenthos at different depths and, accordingly. The temperature and salinity in the bottom layer changed slightly at different

Table 4 The structure of microalgal coenoses from stations at different depths in the central part of the Western basin (November, 2007)

Station numbers; depth, m; salinity; temperature, °C	Dominant and abundant species	Often observed species	Comments
St. Lit-1-07; 0.2 m; 116.66 ppt; 9.88°C	*Navicula radiosafallax, Amphora proteus, Navicula cryptotenella*	Other species were minor	Clay ground with sand alluviums
St. A-1a; 13 m; 117.35 ppt; 10.05°C	*Phytodinium* cf. *simplex, Amphora proteus*	*Nitzschia sigmaformis, Gyrosigma fenestratum*	At this station there were different sites of a sediment surface: silted sand and silted sand with crystals of salt. In this case the coenosis of the first habitat is considered
St. A-1b; 13 m; 117.35 ppt; 10.05°C	*Gyrosigma fenestratum, Rhopalodia constricta*	*Mastogloia pumila, Nitzschia sigmaformis*	The coenosis of the second habitat is considered
St. A-2; 38 m; 126.45 ppt; 11.4°C	*Phytodinium* cf. *simplex*	*Amphora cymbifera, Nitzschia fonticola, Nitzschia sigmaformis, Oocystis submarina*	"Amorphous bottom"

stations (Table 1). The biodiversity of microalgae at all studied water depths was 42. Thirty-eight species were diatoms (90.5%), three species were dinophytes, and one species belonged to the non-chromatic flagellates (Euglenophycota, Sphenomonaceae, *Anisonema* sp.).

In a southern part of the Western basin the diversity of microalgae was low and decreased a little with depth (11 species at 6 m, ten species at 10 m, and seven species at 15 m). The domination structure in communities also changed with increasing of depth and salinity (Table 7). In Fig. 8a, the Margalef index (Dmg) [54–56] and Shannon–Weaver index (H') for the microphytobenthos are shown to decrease with depth.

In the northern part of the Western basin, at 24.6 m water depth, the salinity was 92 ppt and the temperature 13.7°C. The centric diatom *Actinocyclus octonarius* dominated the assemblage. In total, we observed at that location 33 diatom algae species. The diversity was high (Dmg = 4.8, PIE = 0.73, H′ = 2). Dinophytes and euglenids were absent.

In August 2004 we studied microphytobenthos in the central part of the Western basin, and also – for the first time – in the Channel and in the north of the Eastern basin. Results of the researches revealed essential differences in these areas.

The total microphyte assemblage of the Western basin, the channel, and the Eastern basin consisted of 66 species, of which 52 were diatom species, four were

Table 5 The structure of microalgal coenoses from stations at different depths in the central part of the Western and Eastern basin (June 2008). At St.A-08-06 on some sites of a surface of a friable crystalline pulp there were fragments of a salt crust up to 2–3 mm thick

Station numbers; depth, m; salinity; temperature, °C	Dominant and abundant species	Often observed species	Comments
St. Lit-1-08; 0.3 m; 114.13 ppt; 23.13°C	*Nitzschia acicularis, Nitzschia pellucida, Navicula radiosafallax*	*Nitzschia sigmaformis*	Rocky ground with thin layer of silt
St. Lit-1-08; 0.3 m; 114.13 ppt; 23.13°C	*Nitzschia acicularis*	*Navicula radiosafallax*	Clay ground with a thin layer of silt
St. A-08-07; 2.5 m; 114.11 ppt; 22.07°C	*Amphora normanii*	Other species were minor	Well granulated washed out ground: sand and shells, all acquired by salt
St. A-08-06; 11 m; 118.87 ppt; 9.01°C	*Nitzschia pellucida, Phytodinium* cf. *simplex*	*Nitzschia fonticola, Dunaliella salina*	"Amorphous bottom" with fragments of salt crust. During sampling in 2008 such pulp began hardly deeper than 10 m
St. A-08-10; 17 m; 115.80 ppt; 1.89°C	*Nitzschia pellucida, Phytodinium* cf. *simplex*	*Nitzschia fonticola, Navicula cryptotenella, Amphora cymbifera*	"Amorphous bottom"
St. A-08-13; 22 m; 116.58 ppt; 1.10°C	*Nitzschia fonticola, Nitzschia pellucida, Phytodinium* cf. *simplex*	Other species were minor	"Amorphous bottom"
St. A-08-04; 25 m; 116.96 ppt; 0.95°C	*Nitzschia fonticola, Nitzschia pellucida*	Other species were minor	"Amorphous bottom"
St. A-08-14; 34 m; 117.92 ppt; 1.76°C	*Nitzschia fonticola, Nitzschia pellucida*	Other species were minor	"Amorphous bottom"
St. E-08-01; 0.2 m;	*Amphora normanii, Nitzschia communis, Amphora subholsatica*	*Amphora coffeaeformis, Navicula cryptotenella*	Crystalline salt crust

green algae species, three were euglenids, five were cyanobacteria species, and one was a dinophyte (*Ph.* cf. *simplex*). One organism with differentiated chloroplasts in the cells, typical of autotrophic microalgae, and with stable bicellular structure at different stages of development could not be identified (Table 8; Fig. 9); possibly it belongs to the group Pyrrophycophyta (*Dinophyta* sp.).

Table 6 Diatom algae, found in the middle of November 2002 on an oozy ground below 20 m depth

No	Taxon	Noted at a depth: 25 m	40 m	Com.	Hab.
1	*Actinocyclus octonarius* Ehr.	+	+	mass	M
2	*Amphora subholsatica* Hust.		+		M
3	*Caloneis alpestris* (Grun.) Cleve	+			F
4	*Cyclotella meneghiniana* Kütz.	+	+	mass	FB
5	*Diploneis didyma* (Ehr.) Cleve		+		M
6	*Diploneis ovalis* (Hilse) Cleve	+	+	mass	F
7	*Diploneis parma* Cleve		+		FB
8	*Gyrosigma* sp.		+		?
9	*Lyrella forcipata* Greville var. *densistriata* A. Schmidt		+		M
10	*Mastogloia smithii* Thwaites ex W. Smith	+			F
11	*Navicula capitoradiata* Germain	+	+		FB
12	*Navicula digitoradiata* (Greg.) Ralfs		+	mass	BM
13	*Navicula menisculus* Schum.		+	mass	B
14	*Navicula menisculus* Schum. var. *upsaliensis* Grun.		+		B
15	*Navicula phyllepta* Kütz.	+	+	mass	F
16	*Neidium affine* (Ehr.) Pfitzer. var. *longiceps* (Greg.) Cleve		+		F
17	*Nitzschia dissipata* (Kütz.) Grun.		+		F
18	*Nitzschia sigma* (Kütz.) W.Smith		+		BM
19	*Surirella fastuosa* Ehr.		+		M
20	*Tryblionella gracilis* W. Smith	+	+		F

In the column "Com." we furnish comments on the abundance of a species at a depth of 40 m. In the column "Hab." – data about its preferences to the salinity, known from the literature [68–70]. *F* freshwater; *B* brackish; *M* marine; *E* eurihalob

Table 7 The structure of microalgae domination against depth increase in the southern part of the Western basin. October, 2003

Depth, m	Dominants and background group of species (% of the total number)		Often observed species (%)
6	*Phytodinium* cf. *simplex* *Navicula phyllepta*	51.6 20.9	*Nitzschia fonticola* (6.4), *Surirella fastuosa* (4.8), *Nitzschia dissipata* (4.8)
10	*Surirella fastuosa* *Phytodinium* cf. *simplex*	50.7 30.1	*Navicula phyllepta* (8.8), *Amphora subholsatica* (3.7), *Anisonema* sp. (2.9)
15	*Phytodinium* cf. *simplex* *Surirella fastuosa*	50.9 30.9	*Anisonema* sp. (7.2), *Actinocyclus octonarius* (3.6), *Navicula phyllepta* (3.6)

Assemblages of the Channel and Eastern basin considerably differed (see Table 9). The diversity of the microalgae in the Channel was 33 taxa, in the northern part of the Eastern basin – 27 and in the Western basin- 34 taxa. The proportion of diatoms in the total number of species was, respectively, 78.8, 77.8 and 82.3%, i.e., in the Aral microphytobenthos diatoms were still represented by the greatest number of species.

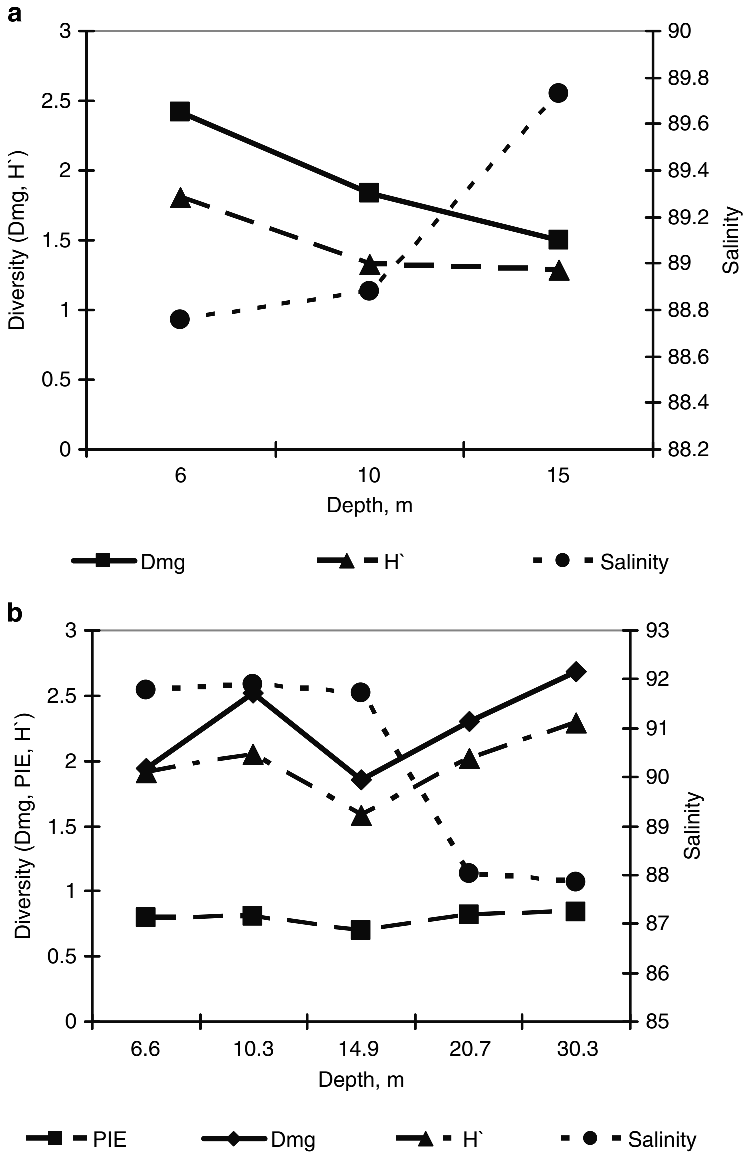


Fig. 8 Changes of microalgae alpha-diversity indices along a vertical transect in the southern part of the Western basin, (**a**) Station 11.3, October 2003; (**b**) Station 12, August 2004: Margalef's diversity index (Dmg) and Shannon–Weaver index (H′)

In the Western basin the changes in number of species and diversity with depth were ambiguous (Fig. 8b). The highest biodiversity parameters were observed at depths of 10.3 m (Dmg = 2.52, PIE = 0.81, H′ = 2.05) and 30.3 m (Dmg = 2.68,

Table 8 The structure of microalgae domination against depth increase in the central part of the Western basin. August, 2004

Depth, m	Dominants and background group of species (% of the total number)		Often observed species (%)	Comments
6.6	*Oocystis submarina*	31.2	*Tryblionella constricta* (9), *Nitzschia frustulum* (5), *Navicula phyllepta* (3.5), *Amphora veneta* (1.5), *Surirella fastuosa* (1.5), *Amphora subholsatica*, *A. proteus, Cocconeis scutellum* var. *euglipta* (by 1)	–
	Phytodinium cf. *simplex*	27.1		
	Nitzschia liebetruthii	13.6		
10.3	*Phytodinium* cf. *simplex*	29.2	*Tryblionella constricta* (10.3), *Nitzschia frustulum* (7.2), *Nitzschia fonticola* (4), *Navicula phyllepta* (2.8), *Nitzschia inconspicua* (2.8), *Nitzschia liebetruthii* (1.9), *Amphora subholsatica* (1.2), *Lyrella forcipata* var. *densistriata* (1.2)	The relative abundance of *Amphora normanii* (we shall talk about it in connection with microphytobenthos of more salty areas) accounted only for 0.9% of total
	Oocystis submarina	29.2		
14.9	*Oocystis submarina*	46	*Tryblionella constricta* and *Nitzschia liebetruthii* (by 5.2), *Nitzschia frustulum* (4.1), *Navicula phyllepta* and *Lyrella forcipata* var. *densistriata* (by 2)	For the first time was observed Dynophyta sp. (1.5%) *Navicula cryptotenella, Surirella fastuosa* and *Epithemia sorex var. gracilis* parts accounted only for 1% of total abundance
	Phytodinium cf. *simplex*	29.3		
20.7	*Nitzschia inconspicua*	29.3	*Phytodinium* cf. *simplex* (9.2), *Nitzschia liebetruthii* (8.9), *Nitzschia fonticola* (4.4), *Nitzschia frustulum* (3.8)	The main part of the assemblage was represented by small mobile *Nitzschia* species
	Oocystis submarina	25.4		
	Nitzschia bacillum	10.8		
30.3	*Oocystis submarina*	34.3	*Nitzschia bacillum* (7.6), Dinophyta sp. (7.3), *Nitzschia frustulum* (6), *Nitzschia liebetruthii* (5.7), *Navicula phyllepta* (3.5), *Phytodinium* cf. *simplex* (2.8), *Navicula cryptotenella*, *Actinocyclus octonarius, Cocconeis placenthula* var. *euglipta*, *Nitzschia fonticola* (by 1.9)	*Amphora normanii* and *Amphora cymbifera* numbers accounted for 0.3% of total
	Nitzschia inconspicua	10.4		
38.8	Dinophyta sp.	99.3	–	–

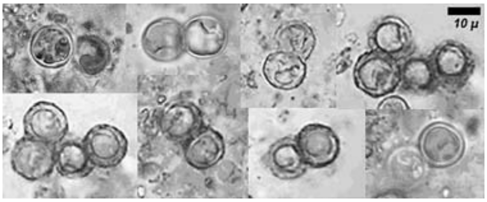


Fig. 9 Bicellular microorganism of the division Pyrrophycophyta, a typical representative of the Aral Sea microphytobenthos (38 m, August 2004). Cells reach a size of 11–13 μm

PIE = 0.84, H′ = 2.29). In both cases it was connected with an abundance of often observed species against not too big a share of dominants. Changes of microphytobenthos structure along with depth in the central part of the Western basin are presented in Table 8.

In October 2005, assemblages in the Western basin near Cape Kiim-Chijak (Table 10) differed compared to the previous year. At the maximum depth (40 m), the water temperature was only 3–4°C and salinity reached 102 ppt. The top 20 cm of the surface sediment consisted of a friable crystalline pulp with discrete salt crystals ("an amorphous bottom"), which formed due to low temperatures (A. Ni, pers. comm., 2006). We observed 12 living microalgae species and their abundance was rather high (more than one million specimens per m^2). *Ph.* cf. *simplex*, *N. pellucida*, *N. inconspicua*, *Oocystis submarina* and *Dunaliella salina* were most frequent. Under these conditions, the morphology of *N. pellucida* was modified, and was quite different from the widespread morphotypes living in the supralitoral salt crystals at higher temperatures.

The further changes of coenoses, noted by us at different depths in 2006, 2007 and 2008, are presented in Tables 3, 4 and 5.

5.2.3 Influence of Salinity in the Shallow and Deep Areas on Flora of Crystal Crusts

In 2003, the sandy sediments at the transect stations in the Western basin were covered with a 1–2 mm thick salt crust. All microalgae that we observed between water depths of 6 and 15 m rested on top of the salt crust covering the sediment. Therefore, these communities can be considered epilithic. With increasing depth, the assemblage changed. As a result, the previously dominant species *Ph.* cf. *simplex* [57] remained common and, together with *Surirella fastuosa,* they were the most dominant species, whereas the previously dominant *N. phyllepta* became a minor component of the assemblage (Table 11).

In October 2005, the salinity in the channel was above 130 ppt for the first time. We observed two species of euglenids (*Euglena texta var. salina* and *Euglena* cf. *pasheri* [58]) in the extended shallow water areas covered with chloride salt crust. *E. texta var. salina* occurred (2.3% of the total abundance) down to 1 m depth, with the highest abundance at 0.2 m. The abundance of *E.* cf. *pasheri* was highest at

Table 9 The part of Amphora species in the Strait's and in the Western basin's assemblages. August, 2004

Depth, m	Dominants and background group of species (% of the total number)		Often observed species (%)	Comments
0.15–0.20 (the Channel)	*Amphora normanii*	≤ 57	*Euglena texta* var. *salina* (9.8), *Amphora proteus* (5.4), *Nitzschia inconspicua* (5), *Oocystis submarina* (4.7), *Amphora cymbifera* (3.6), *Amphora veneta* (3.3), *Nitzschia bacillum* (1.9), *Amphora aponina* (1.7).	The part of *Navicula phyllepta* was extremely low (0.9%)
0.75 (the northern part of the Eastern Basin)	*Amphora normanii* *Oocystis submarina*	42.4 40.3	*Navicula phyllepta* (3.8), *Cocconeis placenthula* var. *euglipta* (2.9), *Amphora subholsatica* and *Nitzschia inconspicua* (by 1.7), *Nitzschia frustulum* (1.3)	*Euglena texta var. salina* at this depth was not mass (0.8%)
1 (the Channel)	*Amphora normanii* *Nitzschia inconspicua* *Nitzschia bacillum*	35.8 31.8 12.4	*Amphora dusenii* (2.8), *Amphora aponina* (2.6), *Navicula phyllepta* and *Cocconeis placenthula* var. *euglipta* (for 2.5), *Navicula cryptotenella* and *Nitzschia frustulum* (by 1.5), *Amphora veneta* and *Oocystis submarina* (by 1.3)	–
7 (the maximum depth of the Channel in August, 2004)	*Oocystis submarina*	33.5	*Amphora subholsatica* (5.8), *Nitzschia inconspicua* (3.5), *Navicula phyllepta*, *Gloeocapsa turgida* and *Phytodinium* cf. *simplex* (by 2.9)	–

0.1 m (1.7%), and below 0.2 m, it became extremely rare (0.03%). The total microphyte assemblage consisted of 27 species and 31 species at a depth of 0.1 and 0.2 m, respectively. We observed for the first time the cyanobacteria *Synechocystis* sp. (7.9%) in the shallowest zone (0.1 m).

The *Amphora* genera were most abundant, contributing 60% (at 0.1 m) and even 74% (at 0.2 m) to the total assemblage (Table 12).

At 5 m water depth, the deepest in the Channel, the algal coenosis was dominated by *A. normanii* (19.1%), *S. fastuosa* (10.8%) and *Tryblionella punctata* (7.6%) (Table 13). The total contribution of *Amphora* species was reduced to half of its abundance in shallow water (31.8%) (Table 13). The assemblage exhibited a

Table 10 The features of the Western basin's algocoenosis structure at a depth of 8 m. October, 2005

Dominants and background group of species (% of the total number)		Often observed species (%)
Nitzschia frustulum	15.4	*Phytodinium* cf. *simplex* (8.3),
Nitzschia fonticola	12	*Amphora normanii* (6.6),
Oocystis submarina	10.8%	*Amphora proteus* (6.6)

Table 11 Depth stratification of *Phytodinium* cf. *simplex*, *Surirella fastuosa* and *Navicula phyllepta* with salinity and temperature changes in the Western basin in October 2003 and in August 2004 (Pi: species fraction to the total assemblage)

Seasons	Factors			Species, Pi		
	Depth, m	Salinity, ppt	Temperature, °C	*Navicula phyllepta*	*Phytodinium* cf. *simplex*	*Surirella fastuosa*
October, 2003	6	88.76	13.78	0.1625	0.3250	0.0375
	10	88.88	13.55	0.0694	0.2370	0.3988
	15	89.73	13.65	0.0217	0.3043	0.1848
September, 2004	6.6	91.77	24.86	0.0352	0.2714	0.0151
	10.3	91.9	24.81	0.0282	0.2915	0.0001
	14.9	91.73	24.53	0.0209	0.2932	0.0105
	20.7	88.03	4.97	0.0254	0.0922	0.0016
	30.3	87.85	2.41	0.0348	0.0285	0.0001
	38.8	87.89	1.62	0.0001	0.0001	0.0001

higher equability in their species structure (in shallow water: Pielu index (E) [59] 0.67–0.74; at 5 m: 0.88 with 25 taxa).

In the northern Eastern basin, where salinity was slightly above 134 ppt, diatom species diversity was still at 17 at a water depth of 3 m. *O. submarina* (19.5%) and *A. normanii* (12.5%) and the mobile diatom *N. sigma* (11.2%), which we earlier observed only in the Western basin, were major representatives of the assemblage. For the first time, we also noted abundant *S. fastuosa* (5%). Moreover, Cyanobacteria *Chroococcum* sp. contributed a significant portion to the total abundance (28.6%).

In June 2008 we managed for the first time to study algal flora of the central part of the Eastern basin. The depth was 0.2 m, the bottom was covered with a salt crust, and the salinity reached 211 ppt. At that time 18 species of microphytes (Table 2) lived there. Seventeen of them were observed at the same time in the Western basin. The eighteenth – *N. sigma* –disappeared from its coenoses in 2006.

5.3 General Changes of Microalgae Flora

During our researches of the Large Aral Sea (2002–2008) we found 135 species and subspecies of microalgae (including 11 cyanobacteria species). This value includes

Table 12 Depth stratification of species *Amphora normanii*, *A. proteus*, *Phytodinium* cf. *simplex*, *Surirella fastuosa* and *Navicula phyllepta* in the Channel in August 2004 and in October 2005 (Pi: species fraction to the total assemblage)

Seasons	Factors			Species, Pi				
	Depth, m	Salinity, ppt	Temperature, °C	*Amphora normanii*	*Amphora proteus*	*Navicula phyllepta*	*Phytodinium* cf. *simplex*	*Surirella fastuosa*
August, 2004	0.15	102.28	21.65	0.5703	0.0537	0.0095	0.0001	0.0001
	1	98.3	23.21	0.3578	0.0017	0.0248	0.0029	0.0001
	7	99.04	23.44	0.1965	0.0173	0.0289	0.0289	0.0058
October, 2005	0.1	130.89	20.23	0.3735	0.0907	0.0847	0.0045	0.0004
	0.2	130.89	20.23	0.4236	0.0280	0.0210	0.0088	0.0005
	5	130.89	15.56	0.1911	0.0255	0.0001	0.0637	0.1083

Table 13 Depth stratification of species *Amphora normanii* and *A. proteus* with salinity and temperature changes in the Western basin, August 2004 (Pi: species fraction to the total assemblage)

Stations	Factors			Species, Pi	
	Depth, m	Salinity, ppt	Temperature, °C	*Amphora normanii*	*Amphora proteus*
St. 7	6.6	91.77	24.86	0.0050	0.0101
St. 8	10.3	91.9	24.81	0.0094	0.0031
St. 9	14.9	91.73	24.53	0.0001	0.0001
St. 10	20.7	88.03	4.97	0.0001	0.0032
St. 12	30.3	87.85	2.41	0.0032	0.0001
St. 15	38.8	87.89	1.62	0.0001	0.0001

all species that lived at the bottom of the sea in different seasons of different years. These are microalgae, which were capable of living at the bottom of the Aral during different stages of late salinisation (85(87)–135(211) ppt). Annually some species disappeared from floras of basins. Others adapted to the salinity increase. Thus, there was a partial integration between basins. The third installed into the Aral.

Three areas of the present-day Large Aral – Western and Eastern basins and the narrow Channel connecting them – differ considerably for a set of conditions (depth, character of sediments, salinity intervals etc.). For geographical reasons, these areas were studied by us to different degrees. We had the possibility annually to study only the Western basin. Therefore, in Table 14 we present data on the dynamics of microalgae flora only for this area.

In the column "total number of species" is noted number of taxa, found during the different periods from November 2002 till June 2008; "Lived constantly" means, that species have been noted on surveys of all seasons; "Are noted incidentally" – species appeared, lived in a certain interval of conditions, and then disappeared (are noted in samples of one or several seasons, except 2002 and 2008). Microphytobenthos researches of the Large Aral were rare till 2002. Therefore, in our work on species detection in the samples of 2002 we mean "lived in the Aral at the beginning of researches".

By June 2008 sediment surface distribution in the Western basin had strongly changed. The friable crystalline pulp covering the bottom in a layer tens of centimetres thick ("an amorphous bottom") was observed for the first time by us in August 2004, at a depth of 38 m. In June 2008, the top of this layer began already hardly deeper than 10 m. As a result conditions of habitation for microalgae at depths of 13–15 m had been changed irreversibly. Some species disappeared or their number decreased to a level where they are not representative. The latter statement is fair for taxa, specified in the column "disappeared".

Lastly, the concept "appeared" means successful invasion from the outside (from other Aral areas or from other basins). The species which have lived till June 2008, are placed into this category.

From year to year the total number of species of flora of the Western basin (Fig. 10) gradually decreased. From November 2002 (63 taxa) till June 2008 (54 taxa) it has decreased approximately twice. The number of diatom species as the

Table 14 Structural changes of microalgae flora in the Western basin of the Aral Sea in 2002–2008

Area	Total number of species	Lived constantly	Are noted incidentally	Disappeared	Installed
Western basin	135	15	28	48	39

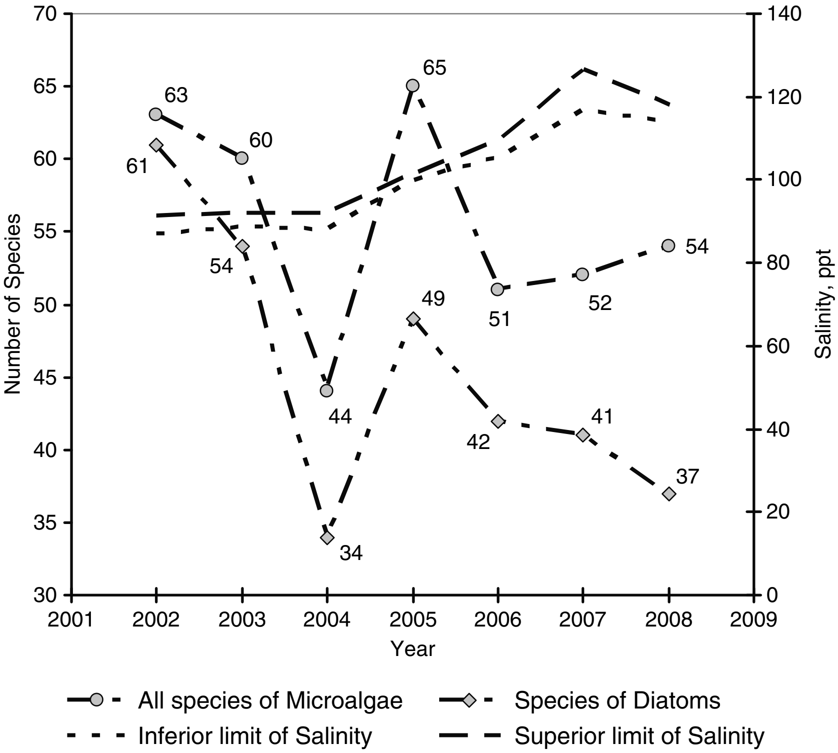


Fig. 10 Changes in number of species of microphytes according to salinity increase, 2002–2008

most widely represented group, also proportionally decreased from 61 to 37 (Fig. 10, Table 2).

Over the period 2002–2008 microalgae flora of the Large Aral Sea has essentially become poor. However, since 2004, we observed a decrease in the rates of falling numbers in the Western basin. And from September 2006 till June 2008 – occurred a period of relative stabilisation of the total number of species. Thus, the diatom component which is diversified and consequently significant continues to grow slowly, but steadily.

For the entire period of observations in the Western basin 48 initially found species have disappeared. This is almost two times more than installed species that have lived through the salinity increase (totally, Table 14). Invaders and extra-eurybionts could not compensate for flora pauperisations.

5.4 Adaptation of Benthic Microalgae to Environment Changes

The ecologic change resulted in a drastic decrease in floral and faunal diversity (see also [21, 60]). Today, eukaryotic algae are the most important in the Aral Sea. Both autotrophic (Chlorophyta) and mixotrophic (Bacillariophyta, Pyrrophycophyta) organisms are common in the entire body of water and form characteristic assemblages. Surprisingly, species, which have never been described as tolerant to hypersalinisation before, spread during the studied time interval across the Aral Sea. Furthermore, we observed that some organisms survived through high salinity conditions though initially they had been classified as freshwater or brackish water inhabitants (Table 6). Considering the specific hydrochemical features that developed during the gradual salinisation process [52], these organisms must have developed adaptive strategies to deal with changing osmotic pressure.

We will now discuss the depth stratification of selected species, their salinity tolerance, and their adaptation to oxygen-depleted and/or sulphuric bottom water conditions. With increasing salinity, the species composition and quantitative structure of algal coenosis changes. Therefore, in order to obtain an objective picture of the adaptations to changing hydrologic and hydrochemical conditions [52, 61–64], we considered all components of the algal coenosis. Accordingly, we comment on observed changes in algal coenosis including data from past and present studies.

5.4.1 Specific Adaptation to Depth and Salinity Stratification Across the Basins and in the Channel

In the Western basin, *Ph.* cf. *simplex*, *N. phyllepta* and *S. fastuosa* were the most important algal marker species. Their abundances in assemblages were quite variable, but we observed them at most stations during our survey. *In October 2003* (Table 11), they lived in shallow water on a solid crystalline crust covered with a thin layer of silt. *Ph.* cf. *simplex* was the most abundant. At 10 m water depth (Station 11.2), the large mobile diatom *S. fastuosa* living on the crust (almost bare of silt) dominated the assemblage and with increasing depth and silt contents its abundance decreased. Similarly, the abundance of the small mobile diatom *N. phyllepta* gradually decreased with depth. Since the temperature and salinity changes of this profile were minimal, we are inclined to explain vertical abundance changes by differences in sediment quality and light intensity. Increasing amounts of silt may have favoured the small mobile *Nitzschia* species, which became more abundant with depth.

From salinity and temperature profiles in the channel, we inferred water stratification with less dense surface waters from the Western basin overriding denser water from the Eastern basin [52]. Along the channel bottom, we observed intense currents eroding silt from the salt crust. These hydrographic changes were observed for the first time in *August 2004* and they are mirrored in the assemblages. Both salinity and temperature may have influenced the abundance patterns of *Ph.* cf. *simplex* and *S. fastuosa* (Tables 11 and 12). In general, we observed fewer *Ph.* cf. *simplex*, *S. fastuosa* and *N. phyllepta* (Table 12) than in the Western basin. At a depth of 7 m, where salinity was slightly higher, both species contributed 2.9% to the total assemblage while the abundance of *S. fastuosa* increased to the maximal water depth, where salt crusts were exposed. This should be taken as a clear indication that the three species have definitely adapted to higher salinity than in the Western basin. In the Eastern basin, where salinity was at a maximum (>130 ppt), only *N. phyllepta* was recorded.

The relative abundances of *Amphora proteus* and *A. normanii* at different depths did not exceed 1% (*2004*) in the Western basin. Moreover, their contribution to the assemblage decreased gradually with depth (Table 13). In the channel, *A. normanii* occurred at most stations and was most abundant at shallow depth (0.1–0.2 m), but its abundance decreased with depth (in three steps) (Fig. 11). Sites with *Amphora* species in the different shallow areas, namely in the channel and at the outlet to the Eastern basin, exhibited the highest salinity in the bottom water layer. On the basis of these observations, we consider *A. normanii* and *A. proteus* as marker species of the channel-specific environment. As *A. proteus* was almost absent in the Eastern basin at this time (0.01%), we believe that *A. normanii* has adapted to the higher salinity. It occurs more abundantly in the Eastern basin, and is therefore considered as a marker of the high salinity conditions in the Eastern basin of the Large Aral Sea (Table 12).

In 2005, when salinity in the channel reached 130.9 ppt, the relative abundances of *Ph.* cf. *simplex* and *S. fastuosa* increased at the maximal water depth (approx. 5 m) to 6.4 and 10.8%, respectively (Table 12). Also *N. phyllepta,* a marker of the Western basin, became abundant in the silts of channel shoals (8.5%) but was absent on bare salt crusts deposited at greater depth. In the northern part of the Eastern basin (salinity 134.06 ppt), at the maximal depth of 3 m, the assemblage consisted of rare *N. phyllepta* (0.8%) and *Ph.* cf. *simplex* (2.5%) cells, and mass *S. fastuosa* (4.9%). We take this as an indication that these species could adapt to the salinity gradient from the Western basin to the Eastern basin. Moreover, by that time, we observed increasing abundances of the species *A. normanii* and *A. proteus* in the Western basin (Fig. 11a), species, which previously were more common in the saline waters of the channel and the Eastern basin. In 2004, the abundance was still low (1%), but increased in 2005 to 6.6% at a depth of 8 m.

In October 2005, we observed 33 microalgae taxa with a dominance of mobile nitzschioides and *Ph.* cf. *simplex* at a depth of 8 m in the Western basin. In 2004, a similarly structured assemblage was described at a depth of 20.7 m. This may indicate that the Western basin started to fill gradually with higher salinity water

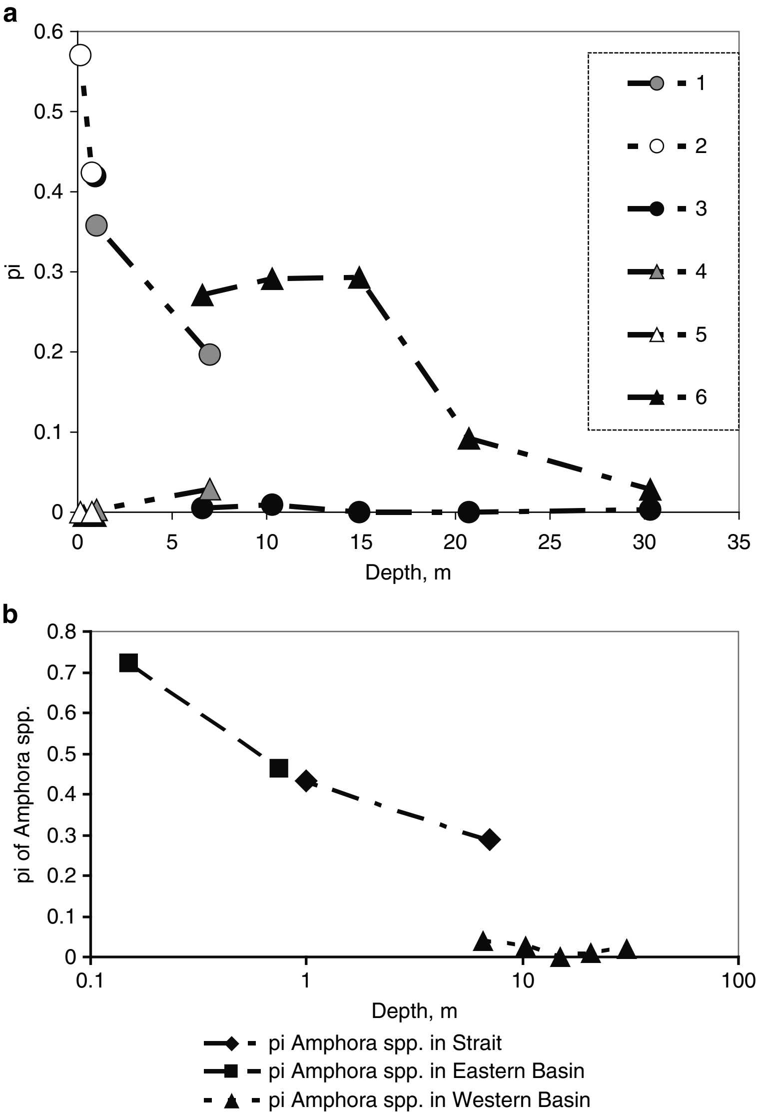


Fig. 11 Abundance of *Phytodinium* cf. *simplex* and *Amphora normanii* at different water depth and stations. Pi: (**a**) species fraction to the total assemblage (1 – *Amphora normanii*, the Channel, 2 – *A. normanii*, Eastern basin, 3 – *A. normanii,* Western basin, 4 – *Ph.* cf. *simplex*, the Strait, 5 – *Ph.* cf. *simplex*, Eastern basin, 6 – *Ph.* cf. *simplex*, Western basin); (**b**) total contribution of *Amphora* spp., representatives of the "eastern" hyperhaline assemblage, at different depths and different sites, August 2004

delivered across the channel. This is corroborated by observations from the channel where, at a depth of 5 m, the most typical representative of the "eastern" assemblage (*A. normanii*) (Fig. 12) was mixed with a typical representative of the

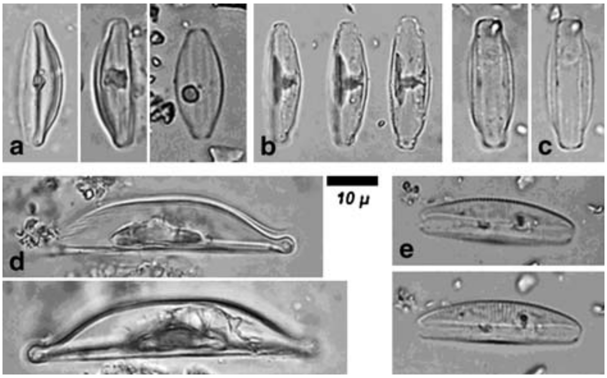


Fig. 12 "Eastern" species, observed in August 2004: (**a**) *Amphora normanii*, (**b**) *Amphora dusenii*, (**c**) *Amphora veneta*, (**d**) *Amphora cymbifera*, (**e**) *Amphora proteus*

"western" assemblage (*S. fastuosa*), indicating that the latter is gradually adapting to hypersaline conditions.

The salinity of the Western basin steadily grows. The top of the crystalline pulp layer covering the bottom ("an amorphous bottom") rises. Set against these phenomena there are reorganisations of algocoenoses at different depths. In particular, together with the rise in the top of the crystalline pulp layer more close to shoal coenoses with *N. fonticola* and *N. pellucida* domination. In 2005 such coenoses were observed only at the maximum depths (38 m), and in 2008 we observed them on "an amorphous bottom" at 10–11 m. Thus, the share of *Ph.* cf. *simplex* gradually decreases with depth of habitat. In June 2008 this species was the second dominant in the coenoses hierarchy only to 17 m water depth. At 22 m it was already the third dominant, and deeper it was observed only occasionally.

In September 2006 we discovered for the first time in the Western basin the mobile diatom *Nitzschia sigmaformis*. The species was represented down to a depth of 10 m (solitary cells at 38 m), and it was the main dominant in ultra-shallow coenoses of the surf zone. The general part of the diatom films on the surface of clay layers had been formed by it ("moving diatom coat"). In November 2007 this species was also observed at all depths. In June 2008 it was observed on ultra-shoals as mass (on rocks), and at depths – solitary cells at 17 m in the Western basin and at 0.2 m in the Eastern basin (we didn't sample at greater depths). The species "is superseded" on shoals by the crystalline pulp rising from the bottom to the coast. Probably, the non-physical structure of the "amorphous bottom" oppresses its development. In November 2007 the species was mass at 13–37 m. Presumably, the superseding factor for *N. sigmaformis* are changes in chemical environment on the surface of "an amorphous bottom", and temperature lower than 9°C.

The species *A. normanii* and *A. proteus*, extended from the Eastern basin into the Western basin in 2004–2005 and occupied small depths, settling during the past 3 years to the maximum depths (34–36 m).

5.4.2 Oxygen-Deficient and Hydrogen-Sulphide Conditions

At Stations 9 (2003) and 10 (2004), the salinity (92 ppt and 88 ppt, respectively) and temperature of the bottom water (13.7°C and 5°C, respectively) were quite different despite comparable water depths (24.6 and 20.7 m, respectively). The coenoses structures clearly reflected different living strategies adapted to oxic (Station 10) and hydro-sulphuric (Station 9) conditions. Most striking was the high diversity at Station 9 (33 microalgae taxa) compared with Station 10 (19 species). Only nine species were common to both stations (Table 2). *A. octonarius* was dominant (49.4%) in the anoxic environment (Station 9), but was absent at Station 10 (2004). Instead, we observed *Nitzschia inconspicua* (29.2%) and juvenile cells of *O. submarina* (20%) at Station 10. In general, the assemblage structure was more homogeneous in the oxic than in the anoxic environments (Fig. 13). But in neither of the two facies did we observe morphological variability of the species. As revealed by optical measurements in the Western basin, light was not a limiting factor for photosynthetic reactions of benthic diatom algae [61]. We propose that under suboxic-anoxic conditions, the trophic activities were mediated by microaerofilic processes using the oxygen stored in the mucilage (exopolysaccharides), as discussed by [65].

The centric diatom *A. octonarius* was dominant in autumn 2003 at a depth of 24.6 m and abundant in the upper 15 m layer. It occurred as solitary cells in periphytes, but in plankton it was absent (A.A. Moruchkov, pers. comm. 2003). The relative abundance of the microalgae increased with depth. It is possible that, since the species is sessile, it can adapt after settling on the bottom with the help of photosynthesis in microaerofilic conditions.

The presence of hydrogen sulphide is another limiting condition for the community settling in the Western basin at depths more than 20 m [63]. We propose that the absence of *Ph.* cf. *simplex* and *Anisonema* sp. was related to this factor, which is corroborated by our survey data from the following years. The aforementioned algae therefore lived under oxic hypersaline conditions down to the deepest part of the Western basin.

As for bathymetric preferences, we observed abundance and diversity changes with depth in the central part of the Western basin in August 2004. Species such as *Ph.* cf. *simplex* and *Tryblionella constricta* were replaced by the small mobile species *Nitzschia*. The widespread species *O. submarina* contributed to the planktonic assemblages everywhere. Therefore, its high relative abundance can be explained by the redistribution of cells from pelagic assemblages. However, up to 99% of the cells originated from germinated autospores, i.e., cells which continued to reproduce intensively at the bottom. Since *O. submarina* contributed to the reproduction of bottom assemblages, it should not be considered as an "artifact", but rather as a true "member" of the microphytobenthos.

The development of abundant and various microphytobenthos in an ultra-shallow zone of the Western basin (0–0.3 m) occurs only during periods of exposure of firm clay layers (2002, 2006, 2007). These surfaces are slowly washed away by rolling waves. The top layer of such clay under the thin layer of silt is anoxic. Under

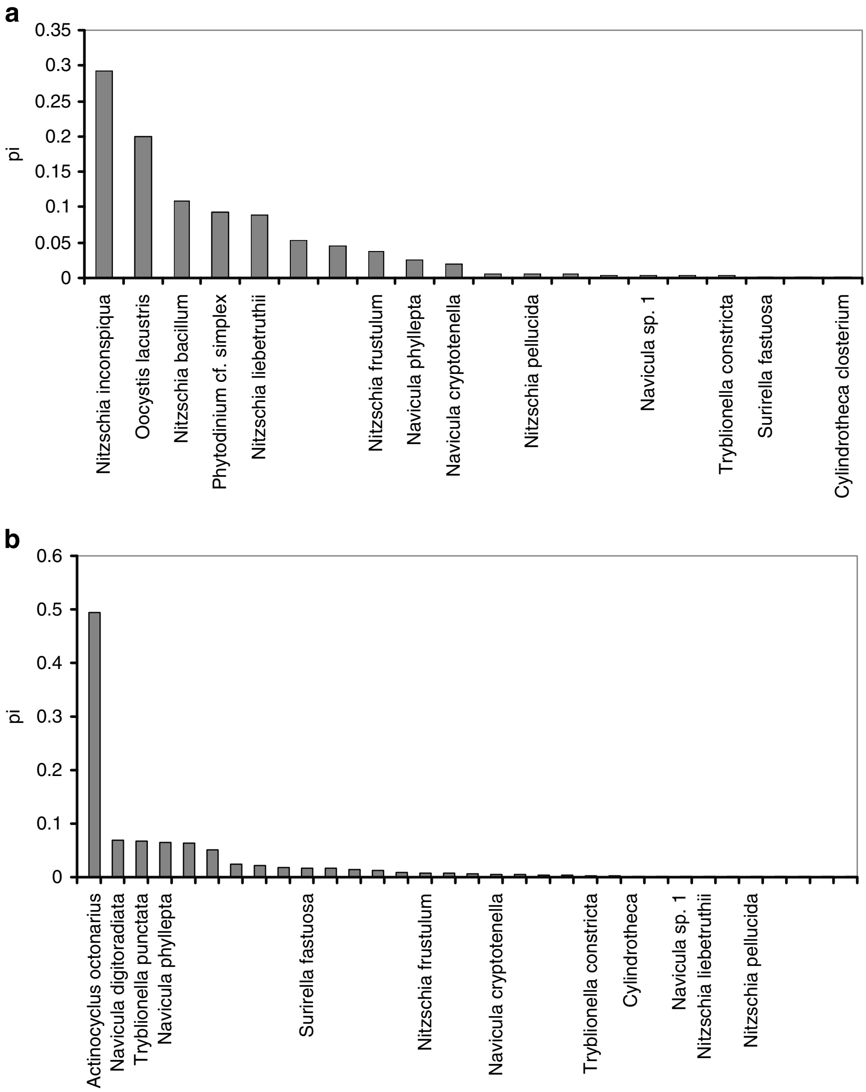


Fig. 13 Abundance of species (pi: species fraction to the total assemblage) living in: (**a**) Station 9, anoxic sulphide-rich conditions; (**b**) Station 10, oxic conditions

the influence of rolling waves it is enriched by oxygen. Many species of microalgae occupy its surface. If the clays are soft (2004, 2005, 2008), their washout occurs quickly and the top layer does not have time to be adequately oxidised and microphytes cannot live on it. Therefore, they were either not represented (2004, 2005), or they were few and their variety was low (2008: *Nitzschia acicularis* and *N. radiosafallax*). Only *C. fracta* thickets attached to coarser mineral particles and covered with microepiphytes could develop in the shallow water because they float above the sediment surface.

5.5 Short Results

We reviewed the assemblage changes due to slowly, but steadily increasing salinity of the Western basin. Algal coenoses with complex organisation still exist.

We observed a redistribution of many species previously living only in the Eastern basin at salinities of 100 ppt or more. Migrating through the channel, they began to establish themselves in the Western basin. By August 2004, a few species had reached the channel (salinity about 100 ppt) and by October 2005, *A. normanii* had reached the area of Cape Ciim-Chijak where salinity at the surface was 97 ppt and up to 100 ppt on the bottom (39 m water depth). Other species like *Diploneis ovalis* and *Navicula capitoradiata,* formerly abundant in the Western basin, became rare in autumn 2005 and later disappeared. However, the majority of algal flora representative of the modern Aral Sea adapted to the salinity increase. *S. fastuosa*, *Epithemia zorex* var. *gracilis*, *N. sigma*, *Gyrosigma fenestratum*, *Gyrosigma hippocampus*, *N. phyllepta*, *Ph.* cf. *simplex*, *O. submarina, C. fracta,* and others in 2005 were still abundant in the Western basin and even settled in the channel [66].

By June 2008 microalgal flora of the central area of the Eastern basin already at 87% consisted of species that were observed at the same time in the Western basin (and ≈1/2 of the Western basin flora lived in the Eastern basin; Tables 5 and 2). The large mobile diatom *N. sigma* disappeared from the central part of the Western basin in 2006. It has successfully adapted to the super-high salinity of the Eastern basin. Probably, a primary factor in *N. sigma* adaptation is distinctions in concentrations of different salts of waters of these areas.

Unfortunately, we cannot determine the further association of flora of basins, because already by the end of September 2008 the area of the Eastern basin was essentially reduced. Probably, by the beginning of the summer of 2009 this basin will be split into parts and almost absolutely dry up, having turned into a small northeast gulf of the Western basin. In this case it is possible that further reduction of its algal flora, and its preservation by adaptation are both possible.

6 Conclusions

Since the 1950s the ecosystem of the Aral Sea has undergone essential changes. During the period of quasistationary conditions in the reservoir, when salinity in the open water was 10–12 ppt, the flora and fauna had a mainly fresh-water character. This included euryhaline species of sea origin and drimophiluses that lived in shallow gulfs at higher salinity. The main sources of primary organic substance were bottom macrophytes and microphytobenthos, the role of phytoplankton was insignificant.

The first essential changes to the ecosystem occurred in the 1950s. This was promoted by the installation of some new species of fish and invertebrates. The structure of communities and trophic networks was disturbed.

After regulation of river flow at the beginning of the 1960s, the surface area of the sea began to reduce and salinity began to increase. Further changes in the ecosystem occurred against the background of salinisation, reorganisation of ionic balance and increase in the concentration of biogenes in water, and also against changes in bottom geomorphology, coastal contours and current structure. A huge role was played by changes in competitive and trophic relations between hydrobionts. The majority of primary organic substance began to be produced in the pelagic region.

From 1960 till 2008 the fauna of the Aral Sea evolved from mainly fresh-water to hyperhalinic. The fish fauna of the sea had disappeared: at first autochthonous, and then introduced species. Almost all macrozoobenthos species, native and invaders, had gradually died out. In 2008 there remained only invader-euryhalob *Baeotendipes noctivaga*, the larvae of which develop in the top layer of the bottom ground in the summer–autumn period. In meiozoobenthos there were a few species of Nematoda, Harpacticoida, Ostracoda (*Cyprides torosa*) and Turbellaria (*Mecynostomum agile*). By that time zooplankton were represented by only one hypersaline species, *A. parthenogenetica*, installed into the Aral Sea in 1996.

The macrophyte flora had reduced in the period 1960 till 2008 from 37 to three species. At a salinity of up to 116 ppt in the Aral Sea we observed *C. fracta*, *C. glomerata* and *V.* cf. *dichotoma*. At 134 ppt *Vaucheria* was absent.

By 2008 phytoplankton and microphytobenthos coenoses remained the most diversified. Despite the general impoverishment of taxonomic structure, they still included tens of species. Investigating the Aral throughout 2002–2008, we observed regular installation of one species of microalgae and extinction of others. Only five species lived there constantly.

Since 2001 the Large Aral Sea exists in the form of two reservoirs (Western and Eastern basins), connected by a narrow channel in the north. Abiotic conditions in these basins are essentially different (Zavialov, this issue). The flora and fauna of the shallow Eastern basin can be considered as a later stage of salinisation of similar depth sites of the Western basin.

Despite considerable impoverishment of flora and fauna, the Aral is still a foraging reserve for many species of birds of passage. During autumn flights they eat *A. parthenogenetica* and *Baeotendipes noctivaga*, which develop in mass by this time.

References

1. Aladin NV (1995) Ecological state of the fauna of the Aral Sea during the last 30 years. GeoJournal 35(1):29–32
2. Aladin NV, Kotov SV (1989) Estestvennoe sostoyanie ecosystemy Aralskogo morya i eye izmenenie pri antropogennom vozdeystvii. Proc Zool Inst USSR Acad Sci 199:4–24 (in Russian)

3. Aladin NV, Potts WTW (1992) Changes of the Aral Sea ecosystems during the period 1960–1990. Hydrobiologia 237(2):67–79
4. Aladin NV, Plotnikov IS, Orlova MI et al (1996) Changes in the form and biota of the Aral Sea over time. In: Micklin PhP, Williams WD (eds) The Aral Sea Basin. Springer in co-operation with NATO Scientific Affairs Division, Heidelberg, pp 33–55
5. Andreev NI (1989) Zooplankton Aralskogo morya v nachalnyi period ego osoloneniya. Proc Zool Inst USSR Acad Sci 199:26–51 (in Russian)
6. Andreeva SI (1989) Makrozoobenthos Aralskogo morya v nachalnyi period ego osoloneniya. Proc Zool Inst USSR Acad Sci 199:52–82 (in Russian)
7. Nikolskij GV (1940) The fishes of the Aral Sea. Moscow (in Russian)
8. Zenkevich MA (1947) Fauna I biologicheskaja produktivnost moria. V. 2: Moria SSSR, ih fauna I flora. Sovietskaja nauka, Moscow (in Russian)
9. Aladin NV (1986) Features of hemolympha regulation of Ostracods and Branchiopodas from sea and continental brackish waters. Proc Zool Inst Acad Sci USSR 141:75–97 (in Russian)
10. Aladin NV (1988) The concept of relativity and plurality of barrier salinity zones. J Gen Biol 49(49):825–833 (in Russian)
11. Alimov AF, Bogutskaya NG (eds) (2004) Biological invasions in aquatic and terrestrial ecosystems. KMK Scientific Press Ltd, Moscow-Saint Petersburg (In Russian)
12. Andreev NI (1978) Results of *Calanipeda aquaedulcis* Kritschagin acclimatization in the Aral Sea. In: Biological bases of a fishery in reservoirs of central Asia and Kazakhstan. Materials of Conference. Ilim, Frunze, pp 6–9 (in Russian)
13. Kazahbaev SK (1974) Calanipeda in southern part of the Aral Sea. Hydrobiol J 10(1):89–91 (in Russian)
14. Andreev NI, Andreeva SI (1988) Crab *Rhithropanopeus harrisii tridentatus* (Decapoda, Xanthidae) in the Aral Sea. Zoological Journal 67(1):135–136 (in Russian)
15. Aladin NV, Kotov SV (1989) Natural condition of the Aral Sea ecosystem and its change under anthropogenous influence. Proc Zool Inst Acad Sci USSR 199:4–25 (in Russian)
16. Karpevich AF (1975) The theory and practice of acclimatization of water organisms. Nauka, Moscow (In Russian)
17. Plotnikov IS, Aladin NV, Filippov AA (1991) The past and the present of fauna of the Aral Sea. Zoolog J 70(4):5–15 (in Russian)
18. Dobrynin EG, Koroliova NG, Burkova TM (1990) Estimation of the ecological conditions of the Aral Sea in the area around Barsakelmes island. Proc Zool Inst Acad Sci USSR 223:31–36 (in Russian)
19. Joldasova IM, Pavlovskaya LP, Elbayeva MK (1999) Kardinalnye izmeneniya v sostave bioty Aralskogo morya. Uzbek Biol J 5:68–70 (in Russian)
20. Mirabdullayev IM (2004) Succession of the ecosystems of the Aral Sea during its transition from oligohaline to polyhaline water body. In: The dying Aral Sea, selected papers from the 35th international liege colloquium on ocean dynamics. J Mar Syst 47(1–4):101–107
21. Arashkevich EG, Sapozhnikov PV, Soloviov KA (2008) Artemia parthenogenetica (Branchiopoda: Anostraca) from the Large Aral Sea: abundance, distribution, population structure and cyst production. J Mar Syst. doi:10.1016/j.jmarsys.2008.03.015
22. Zhakova LV (1995) Notes on the structure, distribution and biomass of the higher water plants and confervoid green seaweed of the Big Sary-Chaganak gulf of the Aral Sea. Proc Zool Inst RAS 262:231–236 (in Russian)
23. Orlova MI, Komendantov AJ (1995) The ecology of the dominant macrozoobenthos species of the Aral Sea. Proc Zool Inst RAS 262:174–188 (in Russian)
24. Alimov AF, Panov VE, Krylov PI, Telesh IV, Bychenkov DE, Zimin VL, Maximov AA, Filatova LA (1998) The problem of anthropogenic introductions of non-indigenous organisms in the Gulf of Finland basin. In: Frolov AK (ed) Ecological situation in St. Petersburg and Leningrad region in 1997. Analytic review. St. Petersburg, pp 243–248 (in Russian)
25. Orlova MI, Rusakova OM (1995) Structurally functional characteristics of the phytoplanktonic community in a district of cape Tastubek (the Norther Aral) in September, 1993. Proc Zool Inst RAS 262:208–230 (in Russian)

26. Mirabdullayev IM, Joldasova IM, Mustafaeva ZA et al (2004) Succession of the ecosystems of the Aral Sea during its transition from oligohaline to polyhaline waterbody. J Mar Syst 47:101–107
27. Kiseliov IA (1927) New data on algae of the Aral Sea. Depart Appl Ichtiol Sci Res. GIOA 5(2):1–64 (in Russian)
28. Zenkevich LA (1963) Biology of the Seas of the USSR. Nauka, Moscow (in Russian)
29. Pichkily LO (1981) Phytoplankton of the Aral Sea under the anthropogenic influence (1957–1980). Naukova Dumka, Kiev (in Russian)
30. Arashkevich EG, Nikishina AB, Sergeeva VM et al (2009) Modern state of the pelagic community in the Large Aral. Oceanology (in press)
31. Zavialov PO, Ni AA, Kudyshkin TV (2008) Five years of field hydrographic research in the Large Aral Sea (2002–2006). J Mar Syst. doi: 10.1016/j.jmarsys.2008.03.013
32. Aladin NV, Filippov AA, Plotnikov IS et al (1998) Changes in the structure and function of biological communities in the Aral Sea, with particular reference to the northern part (Small Aral Sea), 1985–1994: a review. Int J Salt Lake Res 7:301–343
33. Mirabdullayev IM, Joldasova IM, Kazakhbaev S et al (2001) Modern state of the ecosystem of the western part of the Aral Sea. In: Mirabdullaev II (ed) Problemy sohraneniya i ratsional'-nogo ispol'zovaniya biologicheskih resursov vodoemov Uzbekistana. Tashkent, Uzbekistan, pp 74–78 (in Russian)
34. Mirabdullaev IM (2004) Development of *Artemia* population in the Aral Sea. *Artemia* biodiversity in the newly independent states: current global recourses and their sustainable exploitation. FGUP "State research center of fishery (Gosrybtsentr)", Tyumen, Russia, pp 51–55 (in Russian)
35. Van Stappen G (1997) *Artemia*. Introduction, biology and ecology of *Artemia*. In: Manual on the production and use of live food for aquaculture. FAO Fisheries Technical Paper No. 361. FAO, Rome, pp 79–106
36. Green AJ, Sanchez ML, Amat F (2005) Dispersal of invasive and native brine shrimps *Artemia* (Anostraca) via waterbirds. Limn Ocean 50:737–742
37. Mirabdullayev IM, Musaev A, Zhumaniesova NI (2006) New data on zooplankton of the Aral Sea. Proceedings on problem of fishery of Uzbekistan, Tashkent, Uzbekistan, pp 110–115
38. Musaev A, Khankuliev K, Marden B et al (2007) Dynamics of Artemia population in the Aral Sea. In: Biodiversity of Uzbekistan – monitoring and management. Tashkent, Uzbekistan, pp 177–179
39. Conte F, Conte P (1988) Abundance and spatial distribution of *Artemia salina* in lake Abert, Oregon. Hydrobiologia 158:167–172
40. Lenz PH (1987) Ecological studies on *Artemia*: a review. In: Sorgeloos P, Bengtson DA, Decleir W, Jaspers E (eds) *Artemia* research and its applications, 3. Ecology, Culturing, Use in Aquaculture. University Press, Wetteren, Belgium, pp 5–18
41. Van Stappen G, Fayazi G, Sorgeloos P (2001) International study on *Artemia* LXIII. Field study of the *Artemia urmiana* (Günther, 1890) population in lake Urmiah, Iran. Hydrobiologia 466:133–143
42. Sushchenya LM (1975) Quantitative characteristics of feeding of crustaceans. Nauka and Tekhnika, Minsk (in Russian)
43. Wutsbaugh WA, Gliwicz ZM (2001) Limnological control of brine shrimp population dynamics and cyst production in the Great Salt Lake, Utah. Hydrobiologia 466:119–132
44. Abatzopoulos TJ, El-Bermawi N, Vaskedis C (2003) Effects of salinity and temperature on reproductive and life span characteristics of clonal Artemia. (International Study on Artemia. LXVI). Hydrobiologia 492:191–199
45. Browne RA, Wanigasekera G (2000) Combined effects of salinity and temperature on survival and reproduction of five species of *Artemia*. J Exp Mar Biol Ecol 244:29–44
46. Litvinenko LI, Kozlov AV, Kovalenko AI, Bauer DS (2007) Salinity of water as a factor to determine the development of the brine shrimp *Artemia* populations in Siberian lakes. Hydrobiologia 576:95–101

47. Torrentera L, Dodson SI (2004) Ecology of the brine shrimp *Artemia* in the Yucatan, Mexico, Salterns. J Plankton Res 26:617–624
48. Triantaphyllidis GV, Poulopoulou K, Abatzopoulos TJ et al (1995) International study on *Artemia* XLIX Salinity effects on survival, maturity, growth, biometrics, reproductive and lifespan characteristics of a bisexual and a parthenogenetica population of *Artemia*. Hydrobiologia 302:115–227
49. Clegg JS, Jackson SA (1997) Significance of cyst fragments of Artemia sp. recovered from a 27, 000 year old core taken under the Great Salt Lake, Utah, USA. Int J Salt Lake Res 6:207–216
50. Novozhilova MN (1973) The microbiology of the Aral Sea. Alma-Ata (in Russian)
51. Sulalina AV, Smurov OA (1993) State of bacterioplankton of the Aral Sea in 1992. Proc Zool Inst Russian Acad Sci 250:108–113 (in Russian)
52. Zavialov PO (2005) Physical oceanography of the dying Aral Sea. Springer, Praxis
53. Lobban CS (1989) Environmental factors, plant responses and colony growth in relation to tube-dwelling diatom blooms in the Bay of Fundy, Canada, with a review of the biology of tube-dwelling diatoms. Diatom Res 4:89–109
54. Margalef R (1974) Ecologia. Osmega, Barcelona (in Spanish)
55. Margalef R (1991) Teoría de los sistemas ecológicos, 1991. Thesis Universitat de Barcelona, Barcelona (in Spanish)
56. Megarran E (1992) An ecological variety and methods of its measurement. Mir, Moscow (in Russian)
57. Kiseliov IA (1950) Dinoflagellates of the seas and fresh waters of the USSR. Izdatelstvo Akademii Nauk SSSR, Moscow (In Russian)
58. Vasiljeva II (1987) Euglenophyta and Xanthophyta of Yakutya. Nauka, Leningrad (In Russian)
59. Pielou EC (1966) Shannon's formula as a measure of species diversity: its use and misuse. Amer Nature 100:463–465
60. Mokievsky VO (2008) Seasonal distribution of the meiobenthos in the Large Aral Sea in 2003 and 2004. J Mar Syst. doi:10.1016/j.jmarsys.2008.03.014
61. Zavialov PO, Kostianoy AG, Sapozhnikov FV et al (2003) Current hydrophysical and hydrochemical conditions of the environment in the western part of the Aral Sea. Oceanology 43:299–302
62. Zavialov PO, Kostianoy AG, Sapozhnikov FV (2003) Following the fading sea. Science&Life 4:27–29 (In Russian)
63. Zavialov PO, Ginzburg AI, Sapozhnikov FV et al (2004) Multidisciplinary expeditionary studies in the western part of the Aral Sea in October 2003. Oceanology 44:595–598
64. Zavialov PO, Ni , Sapozhnikov FV (2004) The faded away sea. National Geographic Russia 5:32–40 (In Russian)
65. Kondratjeva EN, Maximova IV, Samuilov VD (1989) The phototrophic microorganisms. Izdatelstvo Moskovskogo Universiteta, Moscow (In Russian)
66. Sapozhnikov FV, Ivanishcheva PS, Simakova UV (2008) Modern assemblage changes of benthic algae as a result of hypersalinisation of the Aral Sea. J Mar Syst. doi:10.1016/j.jmarsys.2008.03.021
67. Thomas O. Integrated taxonomic information system (ITIS). The reduction of 07.06.2007. Internet page: http://www.itis.gov/access.html
68. Hartley B (1996) An Atlas of British Diatoms. Biopress Ltd., Bristol
69. Round FE, Krawford RM, Mann DG (1990) The Diatoms: Biology & Morphology of the Genera. Cambridge University Press, New York
70. Krammer K, Lange-Bertalot H (1986) Süßwasserflora von Mitteleuropa. Bacillariophyceae. VEB Gustav Fisher, Jena (in German)

Archaeology and Its Relevance to Climate and Water Level Changes: A Review

Nikolaus G.O. Boroffka

Abstract A brief review of archaeological data is given and their relevance to the reconstruction of climate and water level changes is discussed. Research since the nineteenth century has established a good database, especially for the southern Aral Sea region (ancient Khorezmia). Human occupation of the area first began during the Late Pleistocene, but was interrupted by the last glaciations. The Aral Basin was again settled by Neolithic populations after the 8.2 ky event and continued until now. A humid climate is indicated for the early period, as several large lakes in the Kyzylkum sustained Neolithic settlements, however, the water level of the Aral Sea may have been low, since the Amudarya drained to the Caspian Sea via the Uzboi at this time. Towards the end of the Third Millennium BC in the northern Aral region forest–steppe vegetation predominated, as indicated by a cultural and economic change in archaeological culture. Around 2000 BC the Amudarya stopped flowing to the Caspian Sea, changing its course to the Akchadarya channel which was now densely settled for the first time. The water level may have reached 40–45 m above sea level (a.s.l.). Climate change is indicated as causing the Scytho-Saka migration at the beginning of the First Millennium BC. Beginning from the sixth century BC irrigation activity may have influenced the water balance and possibly the Uzboi was active for part of this period. A major regression in the fourth century AD was probably caused by climate, but aggravated by extensive irrigation systems. In the tenth century water level was below 53 m a.s.l., although both Amudarya and Syrdarya drained to the Aral Sea. Extreme regressions in the early thirteenth century and at the end of the fourteenth century were caused by war, possibly also influenced by earthquakes. In both cases dams were destroyed and the Amudarya drained to the Sarykamysh depression and/or the Uzboi, withdrawing water

N.G.O. Boroffka
Eurasia Department, German Archaeological Institute, Im Dol 2-6, Haus II, 14195 Berlin, Germany
e-mail: nboroffka@t-online.de

A.G. Kostianoy and A.N. Kosarev (eds.), *The Aral Sea Environment*,
Hdb Env Chem (2010) 7: 283–303, DOI 10.1007/698_2009_1,

supply from the Aral Sea. A transgression sometime after the fourteenth century is documented by marine sediments overlying archaeological sites and may have existed as late as the nineteenth century.

Keywords Aral Sea, Archaeology, Climate, Historical written sources, Human settlement, Palaeogeography, Water levels

Contents

Abbreviations

AD	Anno Domini (after Christ), calibrated age
a.s.l.	Above sea level
BC	Before Christ, calibrated age
BP	Before present
ky	Kiloyears (1,000 years)

1 Research History

Interest in the archaeology of the Aral Sea region began around the mid-nineteenth century [1, 2], shortly after the area was first scientifically documented geographically [3, 4]. By the beginning of the twentieth century the first monument lists were compiled [5, 6] in which caravan routes and traces of ancient irrigation were also taken into account. Parallel to this, questions of water balance and climate were already being discussed [7, 8], although only a sketchy scientific database existed.

Systematic archaeological research began in the late 1930s with the Khorezmian expeditions led by Tolstov [9, 10] and still continues. During the field campaigns there was early collaboration between archaeologists and geoscientists. The resulting maps of settlement distribution, traces of ancient irrigation systems and geomorphologic features [9, 11] are still useful today, especially since many of the features documented earlier have since been destroyed or eroded. Sites discovered by the Khorezmian expeditions, especially to the south and southeast of the Aral Sea, covered the period from the Neolithic (beginning around 6000 BC) to the Late Medieval period and thus give a reasonably complete image of the settlement history. The northern part of the Aral Sea was less well studied; some discoveries were connected to the construction of the Moscow–Tashkent railroad at the beginning of the twentieth century, others to field trips by Formozov in the 1940s and by Vinogradov in the 1950s [12].

Interest revived after the collapse of the Soviet Union and new expeditions took place in the late 1990s and early 2000s to the northern shores, aimed mainly at the Palaeolithic period [13, 14] and to both the northern and southern shores of the Aral Sea, concerned with environment and climate reconstruction [15–19].

The southern shores of the Aral Sea can thus be considered well researched archaeologically, while in the north, although the general development is known, there are still considerable gaps in detailed settlement history.

2 General Evolution of Human Settlement

2.1 Settlement from Archaeological Remains

Human settlement of the wider Aral Sea Basin began during the *Middle Palaeolithic period* (50000–35000 BP), when Central Eurasia was generally settled for the first time [20, 21]. However, settlements of this time near old shores of the Aral Sea (near Akespe and Tastubek), relevant to reconstructions of water levels, were discovered only recently [13, 14, 16] (Figs. 1–3). Their importance lies in their location at 55–60 m above sea level (a.s.l.) and their completely undisturbed preservation, thus definitely disproving a formerly proposed high water level at 72 m a.s.l. ([22], criticized already by [23]) for any time during the Upper Pleistocene and the entire Holocene.

No settlements are documented for the following periods, roughly until the beginning of the Atlantic period. This gap is not yet well understood, but may be connected to the cold periods of the late Pleistocene and pre-Boreal phases.

Roughly starting with the Atlantic, around 6000 BC, *Neolithic populations* of the Kel′teminar culture occupied large areas of the Aral Sea Basin [21, 24–26]. The settlements are distributed on the Ustiurt Plateau, along the northern shore of the Aral Sea, seldom on the ancient courses of the Kuvandarya and Zhanadarya, frequently around former lakes (e.g. Liavliakan) in the Kyzylkum desert continuing south down to the Zerafshan delta, in the Khorezmian Basin southeast of the Aral Sea and further west along former river courses leading towards the Sarykamysh depression and the Uzboi channel (Figs. 1, 2). These populations lived in light structures which have left few archaeological traces. Their toolkit (set of instruments) included ceramic vessels as well as stone tools, amongst which microlithic projectile points (Fig. 3) and bone harpoons are of special interest [21, 26].

They document the high importance of fishing and hunting of small animals and birds in the economy, although domesticated livestock have recently also been identified [24]. Both the placement of the settlements around former lakes and the

Fig. 1 General map of the Aral Basin showing major geographic features, modern cities and archaeological sites mentioned in the text

economy-determined toolkit indicate a wetter climate for the entire Aral Sea area during life of the Kel′teminar culture from 6000 to 3000 BC.

The *Eneolithic* or Copper Age (3000–2000 BC) follows the Neolithic period. Major change may be observed at this time for a part of the territory interesting us here. While in the south and in the Kyzylkum desert Kel′teminar populations continued life as before, in the north cultural orientation and the economy changed. During more recent research near Tastubek and Askespe (Fig. 1) it was observed that the toolkit now includes larger projectile points (Fig. 3) connected to hunting larger animals [16]. Besides, the pottery style along the northern Aral shores now

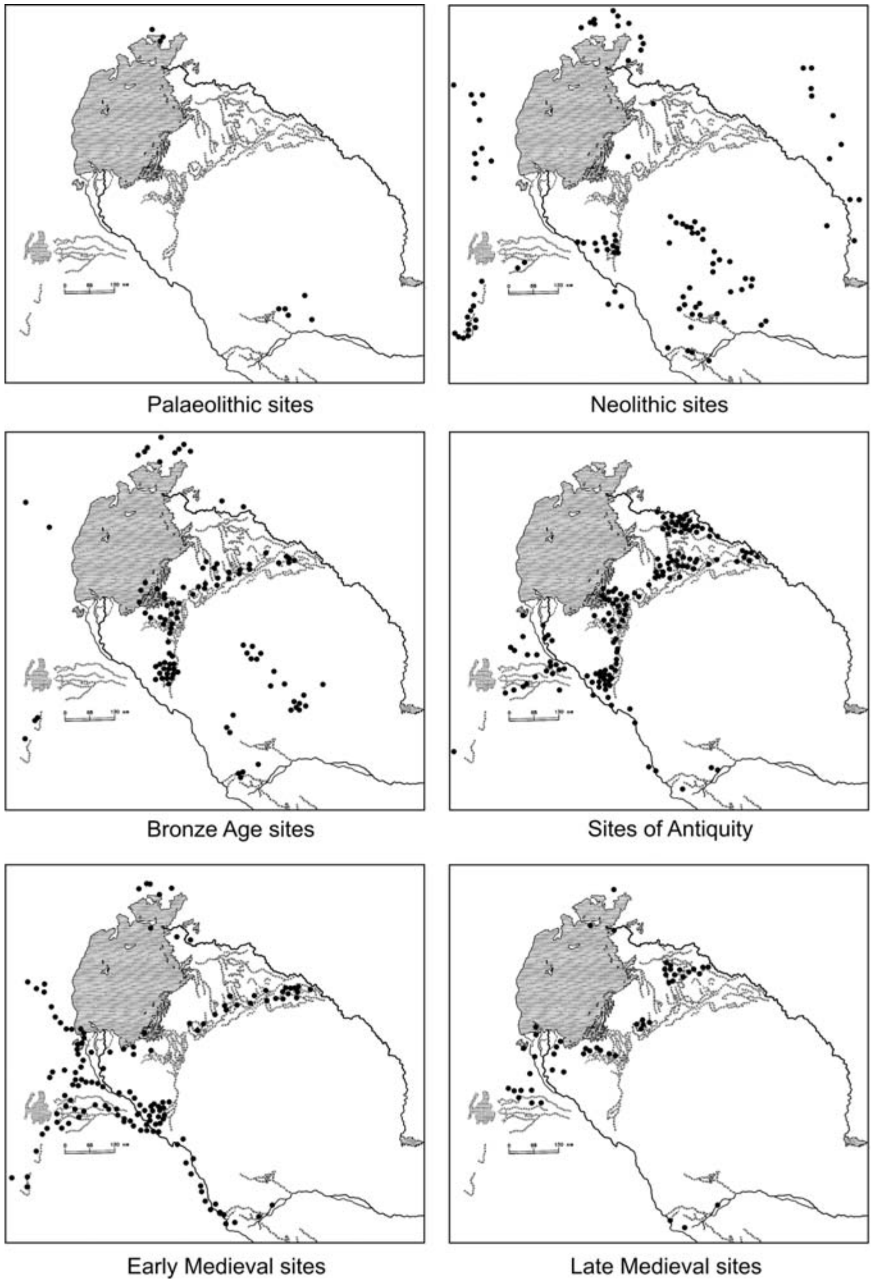


Fig. 2 Distribution pattern of archaeological sites in the Aral Basin at various periods. Changes in settlement structure are clearly visible

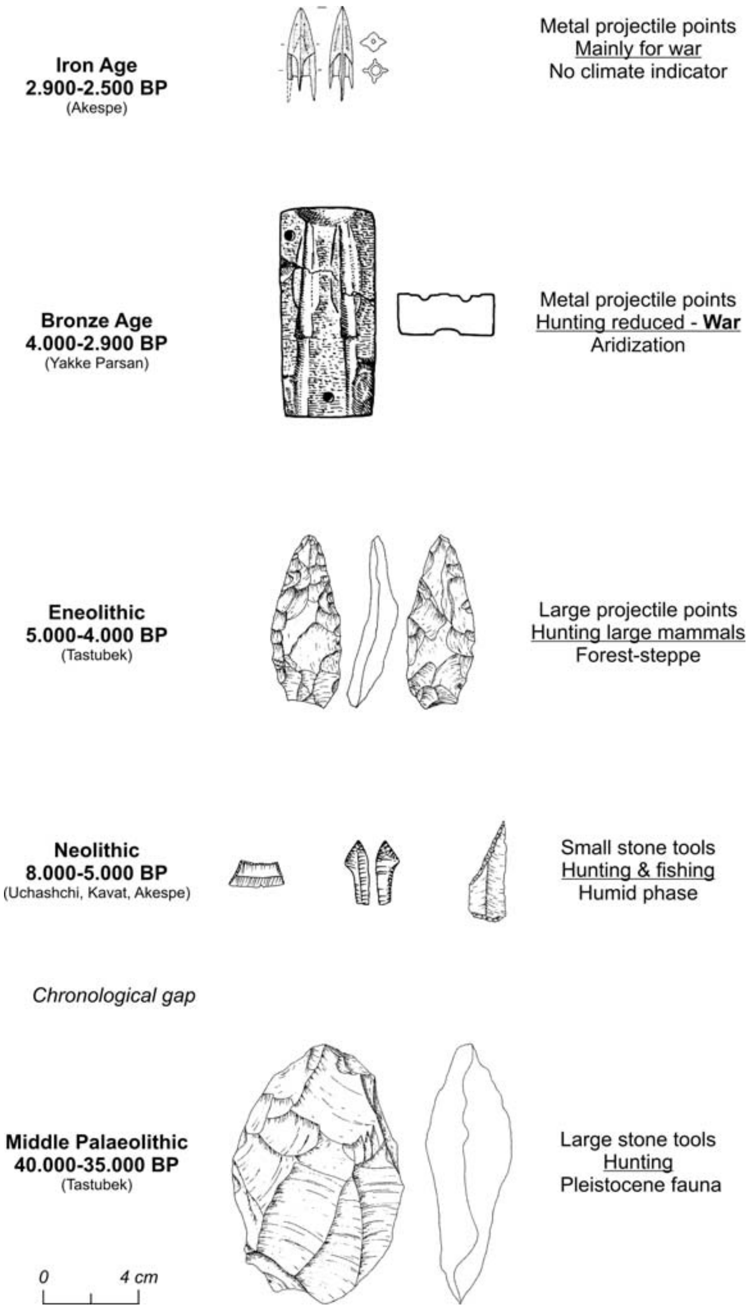


Fig. 3 Changes in archaeological tool-types from the Palaeolithic to the Iron Age. *Left legend* gives dates and (sites), *right legend* gives object type, use and climate data

shows similarities to that known from the forest–steppe zones of the Tobol–Ishim–Irtysh river system and the eastern Ural Mountains, allowing the reconstruction of a similar environment for the Aral Basin. In these areas to the north and west more extensive research has shown that mainly horses, an animal well adapted to forest–steppe environments, were hunted [27], so that the forest–steppe belt of Eurasia must have extended southwards at this time, indicating a climate more humid than now.

From the *Bronze* (Andronovo Culture: 2000–900 BC) and *Iron Ages* (Scytho-Saka Culture: 900–500 BC) onwards, man became more independent of the environment. Stockbreeding was a mainstay of alimentation and permitted the exploitation of almost all ecozones from forest to semi deserts or even deserts (Fig. 2). Hunting was less important and therefore the general economy ceases to give indications for reconstructions of the environment. It is also during this period that irrigation begins, for example at Kokcha [28] (Figs. 1, 4), although in the Bronze Age only at a very local scale and presumably with little effect on the water balance. For these periods it is only the location of archaeological sites in relation to topography (e.g. along the Akchadarya channel, now obviously carrying water) and old shorelines which may yield data on the water levels of the Aral Sea.

Under *Achaemenid* domination (from around 500 BC) large fortified town centres began to appear and irrigation was systematically organized and may already have influenced the water balance. However, since these early archaeological traces are still insufficiently studied and written sources are lacking discussions would be too speculative for this period.

Classical Antiquity (ca. 400 BC–400 AD) is better documented, both from archaeological monuments and from written sources. In the north we have few data on this period, since the settlements of the Scytho-Saka populations, known from written sources, were probably of short duration and left few visible traces, however, the south was very well researched during the Khorezmian expeditions led by Tolstov [9, 29, 30] and written sources for this area from Greek, Persian, Arab and Chinese authors were comprehensively collected by Bartold [31, 32]. Large, often fortified, settlements (Fig. 5) spread throughout the Khorezmian Basin, including the entire course of the Akchadarya channel, further north along the Zhanadarya and in the Dzhety Asar region along the Kuvandarya (south of the modern Syrdarya) and further west up to the Sarykamysh basin, while the Kyzylkum was no longer habitable (Fig. 2).

Intensive irrigation agriculture was practiced [28, 33], partly controlled by the Persian state [31, 32], indicating that rainfall was insufficient. The canals could reach widths of more than 20 m and cut the landscape for many kilometres. Altogether irrigation traces have been identified covering a surface 5–10 million ha [28] (Fig. 4). Herodot (Fifth century BC) stated that the Caspian Sea was not in contact with any other sea (Herodot I, 202), but later Greek and Roman sources (e.g. Erastosthenes, Strabon, Plinius [31, 32]), drawing on older documents not preserved, report that both Syrdarya (Jaxartes) and Amudarya (Oxos) reached the Caspian Sea and were actually navigable. This idea, possibly due to confusion of the Caspian and the Aral Sea, persevered among geographers of Antiquity until

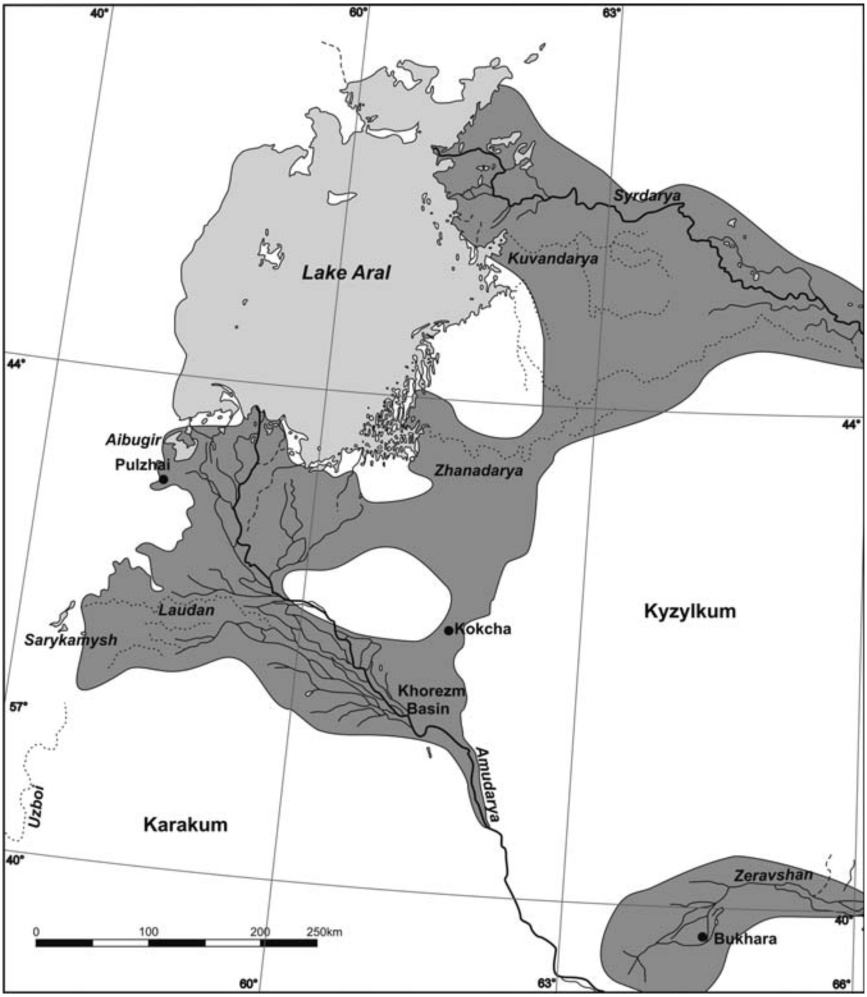


Fig. 4 Archaeological traces of ancient irrigation systems in the Aral basin (*shaded*) and location of Kokcha and Pulzhai

Ptolemaeus (second century AD) again sustained that the Caspian Sea was not connected to any other large body of water [31, 32]. Chinese travellers of later Antiquity heard about a country (Yen t'sai) on the shallow shores of a large lake far to the west (of China), which may be identified as the Aral Sea, but precise information is lacking [31, 32]. The end of Classical Antiquity is marked by the Migration period, bringing the decline of the large states (Sassanian Iran) and the expansion of steppe powers (Huns, Hephthalites).

Many of the settlements, however, continue to be occupied during the following *Medieval period*. Especially after Khorezmia became independent under the Khorezmshahs in the eleventh century AD, a shift of the major settlement concentration

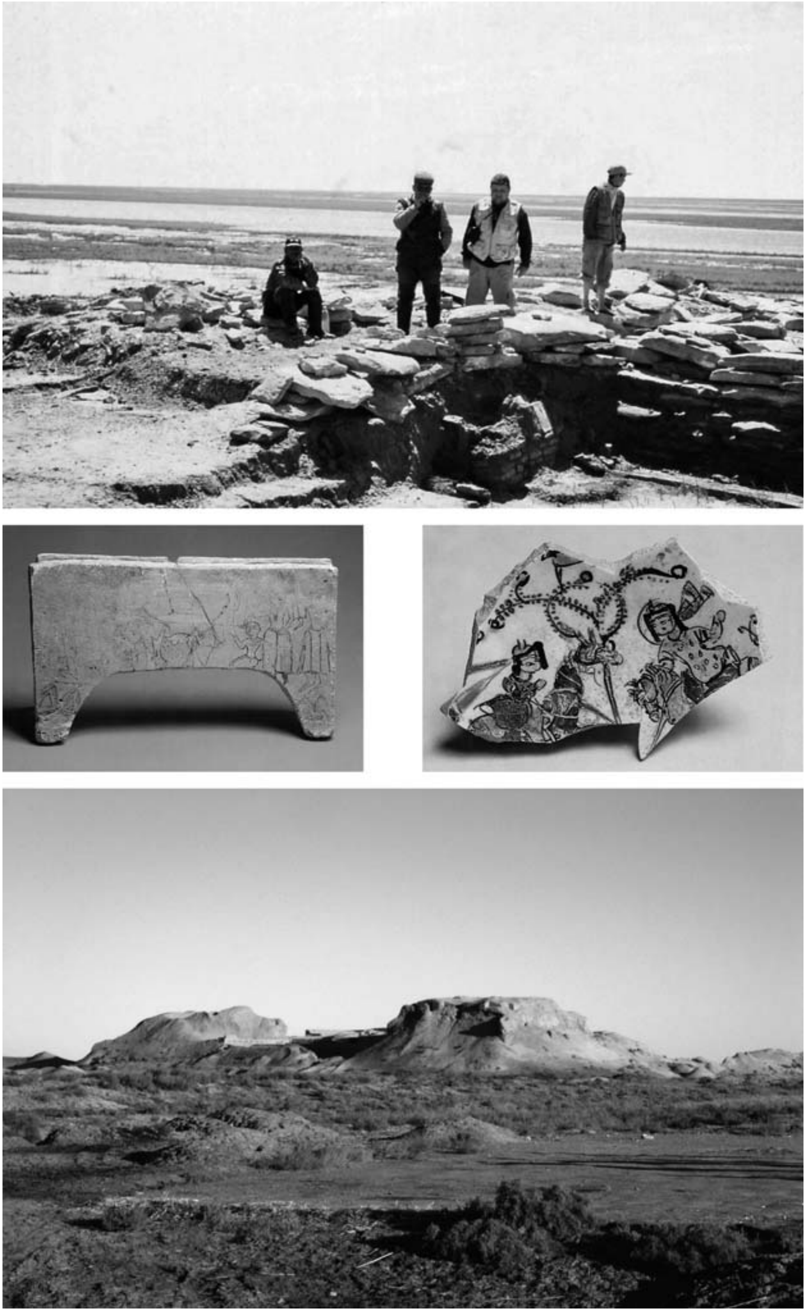


Fig. 5 Archaeological sites/finds from the Aral region: *below*: Toprak-Kala (Antiquity), *middle left*: ossuary from Tok-kala (Early Medieval), *middle right:* medieval pottery from Dzhanpyk-kala, *above*: view of mausoleum at Kerderi with submerged settlement in the background

from the Khorezmian Delta towards the Sarykamysh Basin may be observed (Fig. 2), following the change of the course of the Amudarya westwards and the formation of its modern delta. Further north mainly the course of the Zhanadarya was still occupied, while occupants of settlements in the Dzhety Asar region gradually left. In the later Medieval period (sixteenth/seventeenth century AD onwards) the Zhanadarya also gradually became dry, with only a few settlements surviving near the former Akchadarya delta. Some areas of the Dzhety Asar region, south of the Syrdarya, were again occupied by man, but much reduced in comparison to the intensity that had existed here in Antiquity (Fig. 2).

2.2 Historical Written Sources

It is here necessary to briefly review the ancient written information on the region which gives some data on the river courses and thus the water balance. In the tenth century AD the Amudarya clearly drained to the Aral Sea according to the detailed descriptions of Ibn-Ruste (written ca. 903–913) and Ibn-Haukal (around 976) [31, 32]. Ibn-Haukal also mentions the Syrdarya, the fact that the Aral Sea was salty, a dam a little downstream from Gurgandj (today Kunya Urgench), which blocked shipping, and many irrigation channels. Towards the end of the tenth century al-Makdisî also mentions the dry bed of the Uzboi. The dam near Kunya Urgench needed annual repairs and functioned until the early thirteenth century (report by Jakut [31, 32]). According to Ibn-al-Athîr it was destroyed by the Mongols in 1221, the Amudarya flooding Kunya Urgench and flowing west towards the Sarykamysh. Hamdallah Kazwînî, describing the route from Persia to Khorezmia in 1339, mentions the Amudarya flowing via the Uzboi to the Khazarian (Caspian) Sea, which rose to flood formerly dry islands or peninsulas. This rise of the Caspian Sea is also mentioned by several other authors, among them the Venetian Marino Sanuto the Elder, of Torcello (ca. 1260–1338), who attributed it to the effects of an earthquake closing a (mythical) drainage opening [31, 32]. The geographer Schihâb-ad-dîn Ibn-Fadlallah al-′Omari, who died in 1348, obtained information from the merchant Bedr-ad-dîn-Hasan ar-Rûmi, according to which the Djeihûn (Amudarya) reached a large salt lake (Khowârizm = Aral Sea) into which the Syrdarya also drained. Especially the Zafar-nameh by Scheref-ad-dîn Jezdî, describing the campaigns of Timur against Khorezm between 1372 and 1388, although not mentioning the Uzboi, gives further information on the destruction of irrigation installations. The report on the journey in 1392 of the Sejjids, rulers of Mazanderan, by Zahîr-ad-dîn al Mar′aschî describes the trip as taking place by ship up the Uzboi, with an interruption around the Uzboi rapids over land. Hafîz Abrû, geographer at the court of Shah Rokh in 1417, obviously knowing the older reports, wrote that "...now the "Sea of Khowarîzm" (Aral Sea) no longer exists; the waters of the Djeihûn (Amudarya) have found a (new) route and flow to the Khazar Sea (Caspian Sea) ..." [31, 32]. He also states that the Syrdarya "unites with the Djeihûn in the steppe of Khowarîzm and flows to the Khazar Sea". While this latter comment was a little unclear to Barthold [31, 32], it can now easily be understood if by the Syrdarya in fact its southern branch, the Zhanadarya was meant, which flowed to the southwest and joined the former Akchadarya in one delta at the south-eastern corner of the Aral Sea – clearly a connection to the Amudarya would have been possible here via the Kuvan Djerma channel (Fig. 1). This could also explain the temporary "disappearance" of the Syrdarya [34]. Khan Abulghazi (1603–1663) in the history of his family describes the journey from Urgench to Balkhân as formerly going from Aul to Aul along the Amudarya, passing fields, vineyards and woods, but during his lifetime the Uzboi was already dry. He mentions that the change in river course towards the Aral Sea, which withdrew water from Urgench (and the Sarykamysh), took place some 30 years before his birth, i.e. in 1573. Somewhat earlier, in 1558 Anthony Jenkinson had seen a large bay of what he considered the Caspian Sea (most probably in fact the Sarykamysh) into which the waters of the Amudarya (partially?) drained via the Daryalyk or the Daudan. Neither Jenkinson, nor Abulghazi actually give information on water flowing in the Uzboi during their time – in both cases the changes of river course concern Urgench and the Sarykamysh basin, but not the Uzboi. Although settlements were mostly given up along the Zhanadarya during the Late Medieval period, it must have still carried water to some extent, since it was completely shut off by a dam only in 1815/1816 [35]. Similarly the Kuvandarya, another southern branch of the Syrdarya was separated from the Aral Sea only in the nineteenth century [35]. On the lower Amudarya the Daudan, leading towards the Sarykamysh, was also closed as late as 1857 and several other major dams were erected to regulate branches of the Amudarya delta during the nineteenth century, sometimes also motivated politically, withdrawing water supply as punishment for marauding robbers [17].

3 Water Levels and Climate Based on Archaeological Data and Written Sources

Even recently a high water level for the Aral Sea of 72–73 m a.s.l. was still accepted by some scientists, sometimes in connection with a possible overflow towards the Sarykamysh Basin and the Uzboi channel [22, 36, 37]. This high water level had already been criticized by Létolle and Mainguet [23] and can now definitely be ruled out due to the undisturbed settlements from the Upper Pleistocene discovered at heights of 55–60 m a.s.l. near Tastubek (Figs. 1, 2) on the northern shores of the Aral Sea. What the actual water level was can not be determined from archaeological data at present, but it must have been below 55 m a.s.l.

The long break in human settlement, from around 35000 BP to 8000 BP, is most probably explained by the glacial period. The renewed occupation of the region by the Kel′teminar culture begins around 8000 BP and thus coincides with the end of the 8.2 ky event. A population migration from the Levant and Anatolia due to worsening (severe aridity) climatic conditions towards the west and northwest (Greece and the Balkans) has been proposed for this period [38] and, although not yet studied in detail, such a scenario can probably also be applied to the beginnings of agriculture in Central Asia. Here clearly a more humid situation existed from 6000 to 3000 BC, as shown by the former lakes in the Kyzylkum. The water level of the Aral Sea was presumably low (Fig. 7), since the Amudarya appears to have drained completely towards the Caspian Sea via Daudan and the Uzboi, as indicated by intensive settlement along these water courses and the complete lack of settlements on the Akchadarya river (Fig. 2), which did not carry water at this time. Older opinions [39] concerning a possible course of the Amudarya through the Unguz solonchaks in the Karakum far to the south have recently been ruled out [34, 40]. Near the Syrdarya delta and around the northern shores of the Aral Sea Neolithic settlements are known, so at least the northern Small Aral did exist, possibly also fed by a former river coming from the north, and now marked by dunes stretching north from Akespe in a narrow band. Such northern inflow is marked on early maps, beginning with Idrisi (1154) and as late as the eighteenth century [4].

Between 3000 and 2000 BC cultural change occurred, especially in the north. The Eneolithic toolkit, especially the projectile points, changes from one developed for fishing and hunting small mammals and birds to one adapted to the hunting of large mammals (Fig. 3). Judging from analogies further north, in the Tobol–Ishim–Irtysh river system these were mainly horses, an animal well adapted to steppe and forest–steppe landscapes. An extension of this vegetation belt towards the south (against today) is thus observed, although the earlier humid climate of the Neolithic may in fact mean that steppe and forest–steppe demonstrate a gradual aridization of the region.

Slightly later, around 2000 BC, the Amudarya evidently changed its course, now flowing towards the Aral Sea via the Akchadarya. This river and its delta were intensely settled beginning with the Bronze Age, while the Uzboi and the Sarykamysh region were largely given up [17, 28, 41] (Fig. 2). The Zhanadarya, a southern branch of the Syrdarya, also became active at this time, additionally alimenting the Aral Sea. The water level clearly rose, but did not exceed 48–49 m a.s.l., since archaeological traces of the Bronze and Iron Ages have recently been found at this level [17]. Irrigation was practiced at this time, although only on a small scale which could hardly affect the water balance. Thus, the changes in river courses and water level up to this time must have had natural causes. Possibly terrace V (43.7–44.5 m a.s.l.) or VI (40–41 m a.s.l.), previously dated to the pre-Boreal and Boreal Paskevich phase [22], could actually belong to this time. In this case archaeology may correct the dating of the terrace, but this should also be re-checked by geoscientists.

The Scytho-Saka culture of the Iron Age (tenth to fifth century BC) spread southwards, as indicated by sites such as Tagisken and Uigarak in the Zhanadarya region or Sakar-chaga and Tumek-Kichidzhik near the Daudan [41, 42]. They indicate that these rivers carried water at this time. On the basis of data from Siberia, the southward spread of the Scytho-Saka culture has recently been connected to a more humid climate, mainly on account of pollen records, beginning around 850 BC, which allowed new parts of the steppe to be exploited [43–45]. This may be in conflict with data from northern China, where on the contrary aridization, beginning around 1100 BC and documented globally, has been considered as a driving factor for the southward migration of nomadic populations [46]. The change in China, however, has also been linked to the south-easterly maritime and the north-westerly continental monsoon, which may not have played any significant role for the climate of the Aral region [19].

Khorezmia became part of the Persian Empire in the sixth century BC. One major consequence was the organization and extension of irrigation systems, which were to include millions of hectares during Antiquity, especially from the fourth century BC to the fourth century AD. The surface of 5–10 million ha [28, 47] (Fig. 4), which shows traces of ancient irrigation, is quite comparable to the extent reached during the Soviet period (6.5 million ha [22]), which is known to have affected the water level. Therefore a similar effect as the modern one, a major regression of the Aral Sea caused by man, may be presumed especially towards the end of Antiquity, when long-term results of intensive irrigation took effect. A significant reduction of settlement intensity in the Dzhety Asar region, the complete drying and leaving of the Akchadarya area and the shift of habitation from the Khorezmian Basin to the Pri-Sarykamysh region archaeologically confirm a major change in the hydrographic system in Late Antiquity (Fig. 2). Especially the shift from Khorezm to the Pri-Sarykamysh region, together with the irrigation canals, was clearly caused by man and additionally withdrew water supply from the Aral Sea [28, 41].

The dating of a marine layer in an outcrop near Pulzhai at the southern end of Aibugir Bay (Figs. 1, 6) shows a transgression in the second to third century AD [15, 17], but slightly later, a major regression has been observed by analysis of various proxies for the fourth century AD [22, 48–50]. This has been confirmed archaeologically, since the Pulzhai settlement of the fourth to fifth century AD situated at 54 m a.s.l. (the water level must have been significantly lower) is well dated by a silver coin [17], so there is an excellent correlation between archaeology and geosciences for this period. However, whether the fourth to fifth century regression was exclusively due to human activity may be contested since abrupt aridization has been observed for this period in other parts of the world as well [51–54].

Data for the Medieval period (fifth/sixth century AD and later) is somewhat more detailed (Fig. 2). Written sources inform us of irrigation systems and dams, that both Amudarya and Syrdarya fed a salty Aral Sea throughout the tenth century and that, although water reached the Sarykamysh, the Uzboi channel was dry [31, 32, 47]. The settlement of Pulzhai again flourished from the eleventh to the fourteenth century, showing that the area had a water supply, probably from the Kunyadarya branch of the modern Amudarya delta flowing west of Kungrad. Possibly parts of Aibugir Bay were flooded, however, since the open settlement immediately south-east of Pulzhai fortress and irrigation fields of the same period further to the northeast lie at absolute heights of 52–53 m a.s.l., the water level must still have been lower than in the 1960s (Fig. 7).

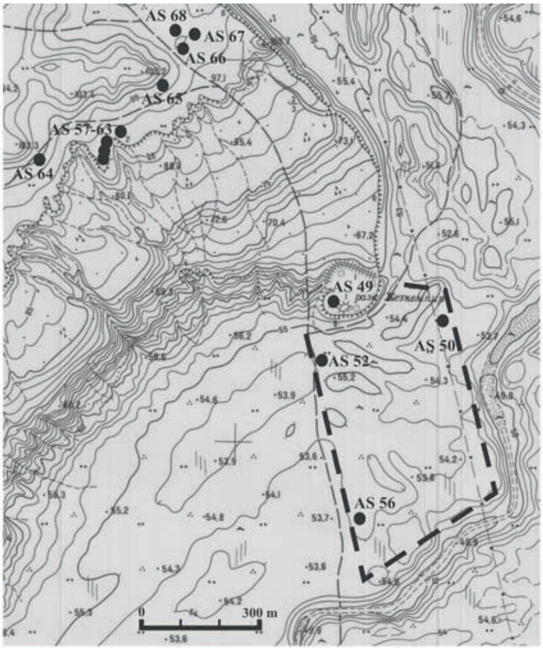


Fig. 6 Plan of the Pulzhai site and satellite image of irrigation traces to the north-east from Pulzhai

The situation dramatically changes at the time of the devastating invasion of the Mongols in 1221. Several reports confirm that the Amudarya, at least to a very large extent, changed its course towards the Sarykamysh Basin, flooded Kunya Urgench (written sources) and probably large areas to the west, as indicated by layers from the twelfth–thirteenth century at Saksaulsai (Fig. 1) overlain by sediments containing molluscs of the Aral fauna [55]. Water flowed down the Uzboi to the Caspian Sea, possibly leading to a rise in its water level, while the Aral suffered a major regression (Fig. 7). High strontium peaks in cores from the Aral Sea, dated to the early thirteenth century, confirm that the Syrdarya contributed a disproportionately large amount of water, since strontium is brought only by this river due to the rock composition in the watershed [28]. Most ancient reports clearly state that the cause of these changes was the Mongol invasion, so man can be considered responsible for the regression of this time. However, a major earthquake occurred in 1208/1209 (605 Hedshra) [56], which may also have contributed to the destruction of dams and the written sources could be politically biased by putting the blame on the Mongols. Additionally, climate may have become more humid [47].

The irrigation structures were rebuilt after the Mongol invasion, and for some time the Amudarya again fed the Aral Sea, allowing the water level to rise. However, part of the water was still diverted artificially towards the Sarykamysh, while the sites on the right bank of the Amudarya, especially in the northern parts of the former Akchadarya delta, did not recover and this region was not resettled (Fig. 2).

Another serious human intervention occurred during the campaigns of Timur against Khorezm between 1372 and 1388. Once more earthquakes, documented for 1389 and 1405 [56], may also have contributed. The dams were again destroyed and the Amudarya once more drained mostly towards the Sarykamysh, flooding a thirteenth century farmstead near Baimurad-Kala [47]. The Uzboi carried water again and was probably active until 1417, which is the date of the last direct report mentioning its flowing to the Caspian Sea (Hafîz Abrû), while the Amudarya appears to have continued flowing west until 1573, presumably only partly and only to the Sarykamysh Basin (Anthony Jenkinson, Khan Abulghazi). A regression to a water level below 31 m a.s.l. (Fig. 7) is also documented by the site of Kerderi north-east of the former island of Barsakelmes [16, 18, 57], which was built at this height in the fourteenth or fifteenth century. In fact, according to the geographer Hafîz Abrû, mentioned above, the Aral Sea disappeared completely. The south-western area, with settlements such as Pulzhai and Saksaulsai, was not resettled after the destruction by Timur. These sites were later covered by sediments containing typical Aral molluscs. This transgression, probably with a water level around 55 m a.s.l., occurred at some time after the sites were left at the end of the fourteenth century but can not be dated more precisely at present. It may actually have been quite late and could have lasted until 1848 (Fig. 7), as may be seen from the first precise maps of the Aral region, where the mentioned sites are located in what Butakoff describes as "Marshy Lake of Aybughir or Laudan" [3]. This high water level was perhaps induced by the closing of several branches of the Syrdarya

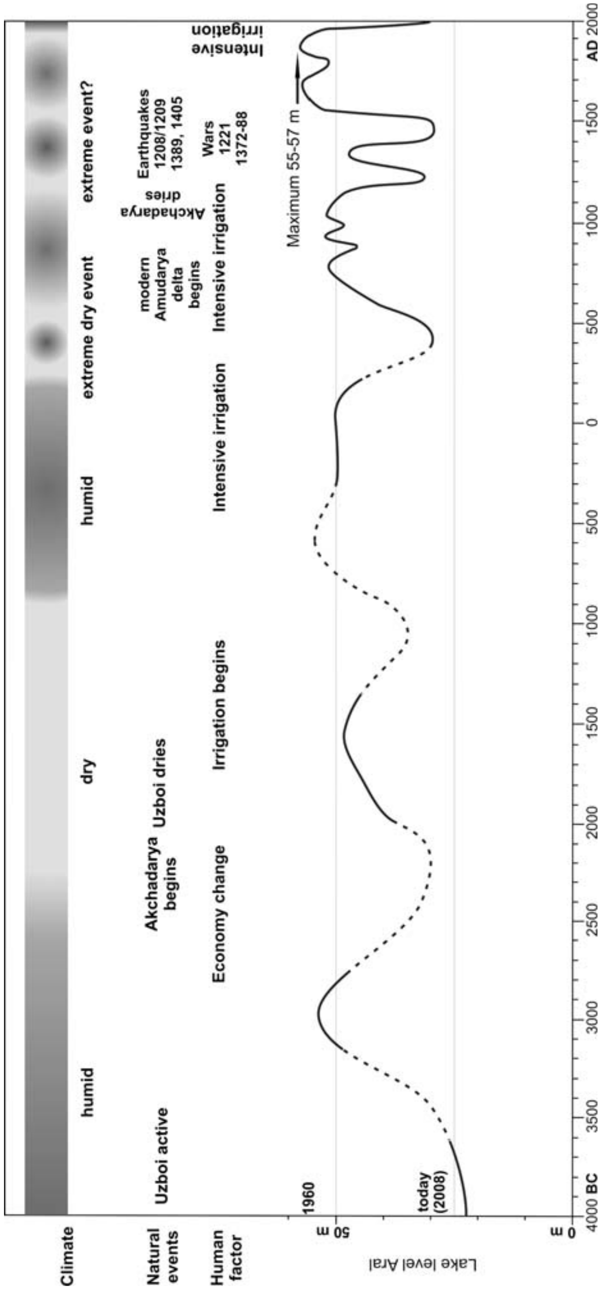


Fig. 7 Reconstruction of climate and water levels (*full line*: certain, *broken line*: conjectural) based on archaeological data

(Zhanadarya, Kuvandarya) and the Amudarya (Daudan) in the nineteenth century, concentrating the flow of water to the main river beds.

4 Conclusions

Collaboration between geosciences and archaeological–historical sciences can be fruitful for both disciplines. Geosciences provide data on environment and climate, while archaeology dates historical periods or specific events. When man was dependent on surroundings during early prehistory data on the environment can explain settlement patterns. Later, when humans began to take influence, information on these activities helps to understand changes in the environment. In the Aral Sea Basin this can be demonstrated very well by shifting habitation centres and analysis of irrigation history.

Previously assumed high water levels of the Aral Sea for the period of the Atlantic to sub-Boreal transition can definitely be ruled out by the presence of datable archaeological settlement traces at lower levels [16]. Alternative explanations for geomorphologic features, such as shorelines at high altitudes [22], must be sought (e.g. tectonic rising [23]). After first Pleistocene habitation, continuous human settlement of the region began as a consequence of global warming following the 8.2 ky event.

The change in the flow of the Amudarya from a course westwards via the Uzboi to the Caspian Sea, presumably due to natural causes not yet defined can be dated by archaeological settlement patterns. It must have occurred as late as ca. 2000 BC and not during the pre-Boreal as had been previously assumed. Terraces V and/or VI, previously dated to the Boreal may belong to this time. Accepting that the Amudarya probably did not discharge to the Aral Sea before this date, the question of the age, size and extent of the water body during the Pleistocene and early Holocene must be posed; however, it can not be answered by archaeology at the present stage of research.

While the regression of the fourth century AD has been connected to human influence (extensive irrigation), in fact this period is historically characterized by the decline of established states (Sassanian Iran) and the rise of steppe powers (Huns, Hephthalites). Abrupt aridization has been observed in various parts of the world and may have been a major driving factor both in population movements and in the drop in water level of the Aral Sea. Probably natural and human factors both contributed in this case.

The major regressions in the thirteenth and fourteenth centuries AD can definitely be connected to human influence (extensive irrigation, war and destruction), natural factors (earthquakes) possibly playing a minor additional role. The earthquake history of the wider region has hardly been studied so far and is known only roughly from few archaeological traces and written historical sources. For the medieval regressions of the thirteenth and fourteenth centuries the significance of strontium as an indicator of river discharge to the Aral Sea basin [28] was recognized only recently in collaboration between geosciences and archaeology. It has proved a useful proxy to differentiate Amudarya and Syrdarya inflow, a question highly relevant concerning the changes in the course of the Amudarya (westwards via the Uzboi to the Caspian Sea or north to north-westwards to the Aral Sea), which have long been discussed by historians. This is in turn clearly important for the reconstruction of water level history.

Although a complete study and mapping of archaeological remains is still lacking, the presently available research results already permit re-dating of some shorelines observed by the geosciences. Human influence on the water level of the Aral Sea, possible since the mid-first Millennium BC, can be evaluated and helps explaining regressions, especially those of the thirteenth and fourteenth centuries AD.

The medieval oscillations of the Aral water level were extreme and short-term. Although clear only in their general outlines at present, they could contribute to understanding the present regression and the planning of mitigating measures.

References

1. Stroganov S (1868) Doklad o deistviiakh Imperatorskoi Arkheologicheskoi Kommissii za 1867 god. In: Otchet Imp. Arkheol. Kom. za 1867 god. Imp. Arkheol. Kom., Sankt-Peterburg
2. Vereshchagin VV (1874) Ot Orenburga do Tashkenta 1867–1868 gg. Vsemirnyi puteshestvennik 5:1–118
3. Butakoff A (1853) Survey of the Aral Sea. J R Geogr Soc Lond 11(3):93–101
4. Berg L (1908) Aral´skoe More. Opyt fiziko-geograficheskoi monografii. Izv. Turkestanskago Otd. Imp. Rus. Geogr. Obshchestva 5. Nauchnye result. Aral´skoi eksped. snarjazhennoj Turkestanskago otd. Imp. Rus. Geogr. Obshchestva 9. M. M. Stasiulevich, Sankt-Peterburg
5. Kallaur VA (1901) Drevnie goroda, kreposti i kurgany na r. Syr-Dar´e, v vostochnoi chasti Perovskogo uezda. Protok Turkestanskogo kruzhka liubitelei arkheol 6:69–78
6. Kallaur VA (1903) Drevnie goroda i seleniia (razvaliny) v Perovskom uezde, v doline r. Syr-Dar´i i Iany-Dar´i. Protok Turkestanskogo kruzhka liubitelei arkheol 8:59–69
7. Murchison RI, Khanikoff MN (1844) On the desiccation of the Tanghi-Daria, a branch of the Jaxartes. J R Geogr Soc Lond 14:333–335
8. Kropotkin P (1904) The desiccation of Eurasia. Geogr J 23(6):722–734
9. Tolstov SP (1962) Po drevnim del´tam Oksa i Jaksarta. Vostochnaia literatura, Moskva
10. Levina LM 1998 K istorii issledovanii Khorezmskoi arkheologo-etnograficheskoi ekspeditsii v Vostochnom Priaral´e. In: Nerazik EE (ed) Priaral´e v drevnosti i srednevekov´e. K 60-letiiu Khorezmskoi arkheologo-etnograficheskoi ekspeditsii. Vostochnaia literatura, Moskva
11. Tolstov SP, Kes´ AS (eds) (1960) Nizov´ia Amu-Dar´i, Sarykamysh, Uzboi. Istoriia formirovaniia i zaseleniia. Mater. Khorezmskoi Eksped. 3. Akademiia Nauk SSSR, Moskva
12. Ageeva EI, Akishev KA et al (1960) Arkheologicheskaia karta Kazakhstana. Akademii nauk Kazakhskoi SSR, Alma-Ata
13. Artiukhova OA (2001) O paleolite Priaral´ia. Izv Natl Akad Nauk Resp Kazakhstan ser obshchestvennykh nauk 1 (230):32–38
14. Dervianko AP, Taimagambetov ZhK et al. (1999) Paleoliticheskie mestonakhozhdeniia severnogo poberezh´ia Aral´skogo moria. Probl Arkheol etnogr antropol Sibirii i sopredel´nykh territ. 5:46–49

15. Reinhardt C (2005) Untersuchungen zur holozänen Seespiegelentwicklung des Aralsees. Diplomarbeit am Interdisziplinären Zentrum für Ökosystemdynamik in Zentralasien der Freien Universität Berlin, April 2005. Freie Universität, Berlin http://www.geosigns.de/ Accessed September 2008
16. Boroffka NGO, Bajpakov KM et al (2005) Prospektionen am nördlichen Aral-See, Kazachstan. Archäol. Mitt. Iran Turan 35–36, 2003-2004:1–81
17. Boroffka NGO, Sorrel Ph. et al (2006a) Prospektionen am südlichen Aralsee, Uzbekistan. Archäol Mitt Iran Turan 37, 2005:247–306
18. Boroffka N, Oberhänsli H et al (2006b) Archaeology and climate: settlement and lake-level changes at the Aral Sea. Geoarchaeology 21(7):721–734
19. Sorrel Ph (2006) The Aral Sea: a palaeoclimate archive. PhD thesis, Universität Potsdam and Université Claude Bernard -Lyon 1, Potsdam, Lyon. http://opus.kobv.de/ubp/volltexte/2006/780/pdf/sorrel_diss.pdf. Accessed July 2008
20. Dolukhanov PM, Shukurov AM et al. (2002) Colonization of Northern Eurasia by modern humans: radiocarbon chronology and environment. J Archaeol Sci 29:593–606
21. Vinogradov AV (1981) Drevnie okhotniki i rybolovy sredneaziatskogo mezhdurech´ja. Trudy Khorezmskoi arkheologo-etnograficheskoi eksped. 13. Nauka, Moskva
22. Boomer I, Aladin N et al. (2000) The palaeolimnology of the Aral Sea: a review. Quart Sci Rev 19:1259–1278
23. Létolle R, Mainguet M (1996) Der Aralsee. Eine ökologische Katastrophe. Springer, Berlin
24. Szymczak K, Khudzhanazarov M (2006) Exploring the Neolithic of the Kyzyl-Kums. Ayakagytma 'The Site' and other collections. Światowit Suppl. Ser. P: Prehistory and Middle Ages 11. Central Asia – Prehist. Stud. 2. Institute of Archaeology, Warsaw
25. Vinogradov AV (1968) Neoliticheskie pamiatniki Khorezma. Mater. Khorezmskoi Eksped. 8. Nauka, Moskva
26. Vinogradov AV, Mamedov ED et al. (1977) Pervye radiouglerodnye daty dlia neolita Kyzylkumov. Sov. arkheol. No 4:267–269
27. Benecke N, von den Driesch A (2003) Horse exploitation in the Kazakh steppes during the Eneolithic and Bronze Age. In: Levine M, Renfrew C et al (eds) Prehistoric steppe adaptation and the horse. Oxbow Books, Cambridge
28. Oberhänsli H, Boroffka N et al. (2007) Climate variability during the past 2,000 years and past economic and irrigation activities in the Aral Sea basin. Irrig Drain Syst 21:167–183
29. Tolstov SP (1948a) Drevnii Khorezm. Opyt istoriko-archeologicheskogo issledovaniia. Moskovskii Gosudarstvenyi Universitet, Moskva
30. Tolstov SP (1948b) Po sledam drevnekhorezmiiskoi Tsivilizatsii. Akademiia Nauk SSSR, Moskva, Leningrad (translated to German as: S. P. Tolstow SP (1953) Auf den Spuren der altchoresmischen Kultur. Sowjetwissenschaft, Beiheft 14. Verlag Kultur und Fortschritt, Berlin; and to English as: Tolstov SP (2005) Following the tracks of Ancient Khorezmian civilization. UNESCO, Tashkent
31. Barthold V (1902) Svedeniia ob Aral´skom more i nizov´iakh Amu-dar´i se drevneishikh vremen do XVII veka. Izv. Turkestanskago Otd. Imp. Rus. Geogr. Obshchestva 4. Nauchnye result. Aral´skoi eksped. snariazhennoi Turkestanskago Otd. Imp. Rus. Geogr. Obshchestva 11. Turkestanskago Otd. Imp. Rus. Geogr. Obshchestva, Tashkent
32. Barthold W (1910) Nachrichten über den Aral-See und den unteren Lauf des Amu-darja von den ältesten Zeiten bis zum XVII. Jahrhundert. Deutsche Ausgabe mit Berichtigungen und Ergänzungen vom Verfasser. Quellen und Forsch. zur Erd- und Kulturkunde 2. Otto Wigand, Leipzig
33. Andrianov BV (1969) Drevnie orositel´nye sistemy Priaral´ia (v sviazi s istoriei vosniknoveniia i razvitiia oroshaemogo zemledeliia). Nauka, Moskva
34. Aladin N, Létolle R et al. (2005) Uzboy and the Aral regressions: an hydrological approach. Preprint from: International Conference on Rapid Sea Level Change- A Caspian Perspective, May 2–9, 2005 Rasht, Islamic Republic of Iran http://www.cig.ensmp.fr/~hydro/aral/Uzboy.pdf. Accessed August 2008

35. Wood H (1875) Notes on the Lower Amy-darya, Syr-darya and Lake Aral, in 1874. J R Geogr Soc Lond 45:367–413
36. Pinkhasov IR (2003) Paleografiia Aralo-Kaspiiskogo regiona v pozdnem kainozoe. Geol i Mineral Resur 4:7–12
37. Schutter J de, Dukhovny VA (eds.) South Prearalie-New perspectives. NATO Science Programme "Science for Peace", Taschkent
38. Weninger B, Alram-Stern E et al (2005) Die Neolithisierung von Südosteuropa als Folge des abrupten Klimawandels um 8200 Cal BP. In: Gronenborn D (ed.), Klimaveränderung und Kulturwandel in neolithischen Gesellschaften Mitteleuropas, 6700–2200 v. Chr./Climate variability and culture change in Neolithic Societies of Central Europe, 6700–2200 cal BC. Römisch-Germanisches Zentralmuseum, Mainz
39. Rawlinson HC (1879) The road to Merv. Proc R Geogr Soc Lond and Mon Rec Geogr New Mon Ser 1(3):161–191
40. Lyberis N, Mering C (2000) Evolution of the hydrographic network of the Karakum desert and environmental implications for the Aral Sea. ERS-Envisat Symposium, Göteborg, 16–20 October, A219. http://earth.esa.int/pub/ESA_DOC/gothenburg/219merin.pdf. Accessed July 2008
41. Vainberg BI (1991) Istoriia obvodneniia Prisarykamyshskoi delty Amudaryi v drevnosti v svete arkheologicheskikh rabot poslednii desiatiletii. In: Aral´skii Krizis (Istoriko-geograficheskaia retrospektiva. Akademiia Nauk SSSR, Moskva
42. Itina MA, Yablonskii LT (1997) Saki nizhnei Syrdar´I (po materialam mogil´nika Yuzhnii Tagisken). Rosspen, Moskva
43. Bokovenko NA (2004) Migrations of early nomads of the Eurasian steppe in a context of climatic changes. In: Scott EM, Alekseev AYu, Zaitseva G (eds) Impact of the environment on human migration in Eurasia. Proceedings of the NATO Advanced Research Workshop on Impact of the Environment on Human Migration in Eurasia, St. Petersburg, Russia, 15–18 November 2003. NATO Science Ser. IV: Earth and Environ. Sci. 42. Kluwer, Dordrecht
44. Dirksen VG, van Geel B (2004) Mid to Late Holocene climate change and its influence on cultural development in South Central Siberia. In: Scott EM, Alekseev AYu, Zaitseva G (eds.) Impact of the environment on human migration in Eurasia. Proceedings of the NATO Advanced Research Workshop on Impact of the Environment on Human Migration in Eurasia, St. Peteresburg, Russia, 15–18 November 2003. NATO Science Ser. IV: Earth and Environ. Sci. 42. Kluwer, Dordrecht
45. van Geel B, Bokovenko NA et al (2004) The sun, climate change and the expansion of the Scythian culture after 850 BC. In: Scott EM, Alekseev AYu, Zaitseva G (eds.) Impact of the environment on human migration in Eurasia. Proceedings of the NATO Advanced Research Workshop on Impact of the Environment on Human Migration in Eurasia, St. Petersburg, Russia, 15–18 November 2003. NATO Science Ser. IV: Earth and Environ. Sci. 42. Kluwer, Dordrecht
46. Huang ChCh, Pang J et al. (2002) Abruptly increased climatic aridity and its social impact on the Loess Plateau of China at 3100 a B.P. J Arid Environ 52:87–99
47. Tsvetinskaya EA, Vainberg BI et al. (2002) An integrated assessment of landscape evolution, long-term climate variability, and land-use in the Amudarya Prisarykamysh delta. J Arid Environ 51:363–381
48. Maev EG, Maeva SA (1991) Donnye otlozheniia Arala. In: Sevast´ianov DV, Mamedov ED, Rumiantsev VA (eds) Istoriia ozer Sevan, Issyk-Kul´, Balkhash, Zaisan i Aral. Istoriia ozer SSSR 5. Nauka, Leningrad
49. Nikolaev SD (1991) Razvitie Arala po izotopno-kislorodnym dannym. In: Sevast´ianov DV, Mamedov ED, Rumiantsev VA (eds) Istoriia ozer Sevan, Issyk-Kul´, Balkhash, Zaisan i Aral. Istoriia ozer SSSR 5. Nauka, Leningrad
50. Sorrel P, Popescu S-M et al (2006) Hydrographic development of the Aral Sea during the last 2000 years based on a quantitative analysis of dinoflagellate cysts. Palaeogeogr Palaeoclimatol Palaeoecol 234:304–327

51. Bryson RA (1996) Proxy indications of Holocene winter rains in southwest Asia compared with simulated rainfall. In: Dalfes HN, Kukla G, Weiss H (eds.) Third Millennium BC: Climate change and Old World collapse. NATO ASI Ser. I, Global environ change, vol. 49. Springer, Berlin Heidelberg New York
52. Landmann G, Reimer A et al. (1996) Dating late glacial abrupt climate changes in the 14,570 yr long continuous varve record of Lake Van, Turkey. Palaeogeogr Palaeoclimatol Palaeoecol 122:107–118
53. Schilman B, Ayalon A et al. (2002) Sea-land palaeoclimate correlation in the eastern Mediterranean region during the Late Holocene. Isr J Earth Sci 51:181–190
54. Schmidt B, Gruhle W (2003) Klimaextreme in römischer Zeit. Eine Strukturanalyse dendrochronologischer Daten. Archäol Korresp.bl. 33(3):421–426
55. Yagodin VN (2006) The medieval Aral Sea Crisis. Archäol. Mitt Iran Turan 37:307–322
56. Melville C (1980) Earthquakes in the history of Nishapur. Iran 18:103–120, pls. 1–2
57. Smagulov E (2001) Nakhodka i issledovanie mazara na dne Aral´skogo moria. Otan Tarikhi 4:77–81

Creeping Environmental Disasters: Central Asia's Aral Seas

Michael H. Glantz

Abstract The Aral Sea is dead. What does exist in its place are the Aral Seas, that is there are in essence three bodies of water, one of which is being purposefully restored and its level is rising (the Small Aral), while the other two, though marginally still connected, continue to decline in level (the Large Aral West and the Large Aral East). In 1960 the level of the sea was about 53 m above sea level. By 2006 the level had dropped by 23–30 m above sea level. This was not a scenario generated by a computer model. It was a process of environmental degradation played out in real life primarily as a result of human activities. Despite wishes and words to the contrary, it will take a heroic global effort to save what remains of the Large Aral. It would even take a significant degree of sacrifice to restore the Large Aral to a previous acceptable level, given that the annual rate of flow reaching the Amudarya River delta is less than a tenth of what it was several decades ago.

Keywords Aral Sea, Central Asia, Critical zones, Disaster, Environment

Contents

M.H. Glantz
CCB (Consortium for Capacity Building), INSTAAR, University of Colorado, 1560 30th St., Campus Box 450, Boulder, CO, 80309-0450, USA
e-mail: glantz@mail.ucar.edu

A.G. Kostianoy and A.N. Kosarev (eds.), *The Aral Sea Environment*,
Hdb Env Chem (2010) 7: 305–315, DOI 10.1007/698_2009_19,

1 The Aral Sea Crisis Is a Global Problem, or Is It?

The demise of the Aral Sea did not occur overnight, but it did not take centuries either. It happened over a period of four to five decades. The discussions about whether to exploit the sea's waters took a bit longer – about 50 years – than did the sea's decimation. In 1908 Russian geographer Berg first spoke of tapping the sea's waters for "useful" purposes (read that as using the water for purposes suited to the needs of the Russian Empire) [1]. In the 1950s Soviet leaders decided to sharply expand the amount of land that would be devoted to cotton production in the basin, which in turn required a major increase in water diversions from the region's two major rivers. In that decade plans were finalized that put into practice the process of what would lead to a doubling of the land devoted to cotton production. It was at about 4 million ha in 1960 and was planned to increase to almost 8 million ha.

From 1960 on, increasing amounts of water were diverted from the Amudarya and the Syrdarya primarily to irrigate cotton fields. Cotton has been the major crop in Central Asia, as the climate and soils are perfect for it. The missing ingredient, however, was water. The rate at which diversions were made, up to the 1950s, was apparently below a threshold of adverse impacts on streamflow reaching the sea in amounts adequate to maintain the hydrological balance. Aside from its normal annual, decadal fluctuations, human activities began to impinge on the quantity of water able to reach the sea.

Government leaders in Central Asia have in the past constantly referred to the demise of the Aral Sea as a global problem. That implies that its solution will require global involvement. There are many good reasons for the involvement of the international community in addressing the consequences of the >23 m drawdown of the Aral Sea's level since 1960. (It is in fact a drawdown in the sense that it is the result of human actions that are undertaken with full knowledge of their ecological and social consequences). However, reasons for international concern about the fate of the Aral Sea are for the most part humanitarian and voluntary and are in no way obligatory.

Clearly, the Aral Sea situation, per se, is a problem that is *neither global in cause nor global in effect*. It is the result of decisions made by political leaders of the Former Soviet Union (not necessarily just those who were based in Moscow). They had knowingly chosen to pursue certain economic development strategies at the expense of environmental quality and, as we now know, at the expense of human health conditions. Thus, one could argue that the direct and indirect effects of the disappearance of the Aral Sea have been local and regional, not global. The disappearance of the sea, however, has created an environmental and humanitarian situation that is of global interest.

Recall that international interest in the Aral region sharply increased when Gorbachev's newly imposed policy of *glasnost* exposed to the international public the serious level of environmental degradation and its impacts on human health. The plight of people, culture and environment captured the attention of many who at the time most likely knew little about the region. A *National Geographic* article in February 1990 served to enlighten the general public worldwide to the difficult situation faced by inhabitants near the sea, especially the Karakalpak people. The article provided vivid photographs of abandoned, rusting hulls of fishing vessels resting on desert sands where a vibrant sea had once flowed. The photos also showed the anguish on the faces of affected inhabitants of the former fishing town of Muynak. Once an important port on the Aral Sea, Muynak is now more than 100 kilometers from the Sea's shoreline.

Unfortunately, the drying out of the Aral Sea is a perfect example of a "creeping" environmental change that has ended up as a crisis. These are environmental changes that are low grade, incremental but cumulative over time for which no obvious thresholds of change of state (step-like or irreversible change) can be identified in advance of crossing that threshold. Such changes almost always become creeping environmental problems (CEPs), which eventually demand the full attention of policy makers from the local to the national level [2].

2 Coping with Creeping Changes

Few societies are well prepared in their decision-making processes to cope with incremental environmental changes that have no readily identifiable thresholds of adverse changes in the short-term. For example, as with air pollution, today's air quality, though incrementally worse, is still quite similar to that of the previous day. And today's pollution level is not much different from tomorrow's, though tomorrow's air quality has also incrementally worsened. After a few years have passed, however, those incremental changes pose an urgent problem for government decision makers, as the air's quality and its impacts on human health as well as on visibility have become easier to discern.

While policy makers, for a variety of reasons, often demand quantitative proof for thresholds of irreversible environmental change, such thresholds are hard to identify in advance of having crossed them. By then, the environmental change and its step-like consequences have become more severe and more difficult and costly to address. This is the case in rich and poor countries alike, industrial and agricultural, and without regard to the type of political system (democratic or authoritarian). I would venture to say that there is a high risk of degradation wherever human activities and ecosystems intersect.

Thus, the combination of policy-making processes and creeping environmental changes are at the heart of the matter. One could effectively argue that high rates of change cause alarm and spark quick responses by policy makers, whereas slow rates of change tend to foster a *laissez-faire* attitude toward that change. Just as people tend to discount the value of future goods and services, so too do they tend to discount the value to society of past goods and services extracted from their environments.

Generations change and current generations only hear about the "good old days" in stories but may not have had first-hand experience with those days that were free of water and air pollution or days that were once relatively free of water scarcity problems in, for example, the lower reaches of the Amudarya and the Syrdarya. To a majority of the current Aral Basin population, there was always a Karakum Canal (begun in 1954) taking water out of the Amudarya. Most likely, they do not know what life was like before the canal was constructed, except by way of history, documentaries, visits to the local museums and the reminiscence of their elders.

3 Was the Construction of the Karakum Canal a Bad Idea?

We need to take a few steps back in time on this highly charged issue to get a better perspective on the reasons for and value of the Karakum Canal. When consideration of the construction of the canal was first discussed in the early 1930s, one of the reasons was to transport water from the mighty Amudarya to the declining Caspian Sea. In the 1930s the level of the Caspian Sea began to drop and continued to do so until 1977. It had dropped 3 m in that relatively short period of time. Another reason for its construction was to bring water to the potentially fertile but dry soils of the Karakum desert in Turkmenistan. Cotton, wheat, fodder and vegetable crop production would benefit from the water diversions, as the water passed westward across Turkmenistan to the Caspian Sea. People have forgotten the role of the Caspian in the consideration of diversion from the Amudarya by way of the Karakum Canal. At the time this could not have been considered a bad idea. It was an attempt to maintain a stable sea level in the Caspian. The location along the Amudarya for diverting water to Turkmenistan was a politically sensitive issue. Turkmenistan was clever to draw water near Kerki as opposed to near the sea. That gave the republic more control over its diversions.

The bad idea with regard to the canal's construction was the way in which it was eventually done. For the most part, water loss was high because the canals were open and unlined. Therefore, excessive amounts of water would be lost because water would seep into the adjacent soils as well as evaporate. In addition, there were no controls (prices or otherwise) on either the amount used or on the way the water was used.

Today, there is concern about the amount of water that has been withdrawn annually from the Amudarya to the canal by Turkmenistan. With a relatively small population, it withdraws an inordinate amount of water.

There is, in fact, a family of such changes of which the demise of the Aral Sea is but one more example. To date, few societies, if any, know how to deal with creeping changes in a timely, effective way.

Making explicit the notion of CEPs in the Aral Sea basin to decision makers and the public can raise their awareness and concern about environmental changes that currently exist or are likely to adversely affect present and future generations. For example, one can only wonder what decision makers in the Aral region might have done had they had been able to get a glimpse of the impacts of the CEPs they had caused (adverse health effects, desiccated sea, exposed sea bed, toxic dust storms, collapse of the fishing industry and rusting ships trapped by desert sands).

4 Aral Sea: From Science to Policy

Many studies over at least half a century have provided researchers with considerable amounts of data relating to the climate, water and soils [3]. The hydrological balance is known, as are the many ways that settlements have interfered with or disrupted it. Clearly there is more water leaving the Aral Sea than entering it (through sea water evaporative processes and water diversion to an adjacent basin).

Cotton has been blamed for the demise of the sea and the poisoning of the water and agricultural lands. Fertilizers, herbicides and pesticides were applied to the cotton fields in great amounts, based on the assumption that if a little amount did some good, then a lot would do even greater good for cotton production. It was revered as a crop and for the high level of its production in the region.

Little, if any, political attention was paid, however, to the environmental costs associated with the long-term environmental and societal consequences of cotton production. Quotas set in Moscow drove regional political leaders and collective farm managers to push hard on the workers to meet the unrealistic quotas, quotas that were often met only on paper. There are many documented accounts about how the cotton production statistics were manipulated to please the Politburo thousands of kilometers away from Central Asia.

Admittedly, it is easy to sit in an armchair far away from Central Asia and advise the leaders of the Central Asian republics about the need to break their dependence on cotton or to use water more efficiently. It is also easy to tell them that they must cooperate on issues related to the efficient management and use of basin-wide water resources and water supply issues. But making the needed drastic changes is much easier said than done.

To be fair to policy makers in these relatively new countries, problems related to the Aral Sea and its environment were not the only ones that these leaders had to face. Recall that the sea had been dropping slowly over time and not changing in notably sharp, step-like increments. While these hardly noticeable changes were underway, these leaders also had to contend with many urgent issues. Under "normal" conditions, the five Central Asian Basin states (and Afghanistan) were clearly operating in a multistressed political and economic environment. The following list is illustrative and is not in order of priority.

Diverted streamflow	Pesticide and fertilizer use
Declining water quantity	Declining water quality
Shortened life expectancy	Ethnic conflicts
Rapid sea level drop	Contaminated aerosols
Loss of biological productivity	Dust storms
Loss of biological diversity	Karakum Canal
Loss of wildlife and forests	Five Central Asia competing nations
Islamic fundamentalist threat	Terrorism and corruption
Upstream–downstream issues	Dictatorships
Oil and gas haves and have-nots	Global warming
Hotter summers, colder winters	Loss of cultural heritage

5 The Aral Seas: Ethics and Equity

It is easy to identify numerous ethical and equity issues that surround the half-century decline in the level of the Aral Sea, in the degradation of the water and soil quality, in the decline in human well-being and health conditions, in the choices made as to how, what and why to develop the Central Asian republics the way that Soviet and post-Soviet leaders have done.

One of the most obvious equity issues centers on upstream versus downstream users of streamflow of the Amudarya and the Syrdarya. In the Aral basin the upstream users are Tajikistan and Kyrgyzstan. To these, however, we must add Afghanistan even though its demands on water withdrawals from the Amudarya to date have been minimal. Turkmenistan could also be viewed as an upstream country in the sense that its significant withdrawals from the Amudarya start where the river begins its descent toward the Sea. Aside from politically feel-good platitudes about sharing water resources in a river, whether in Central Asia or in other parts of the globe, those who are situated downstream are in reality at the mercy of the upstream countries (users) when it comes to water quantity and water quality.

This is not just an international transboundary problem but is a problem within countries as well. In Uzbekistan, for example, Amudarya water flows through much of the Uzbek territory before it reaches Karakalpakstan. It is the Autonomous Republic of Karakalpakstan that suffers most from water shortages and poor water quality, as the river's water is withdrawn well before it can reach the sea's receding shoreline. Kamalov, founder of the Union for the Defense of the Aral Sea and the Amudarya, recently asserted that it was within the rights of the Karakalpak people to have their sea and their livelihoods that were dependent on a healthy sea [4].

Equity and ethical concerns also center on intergenerational issues. To what extent should land and water resources be exploited by the present generation of users, if its use impinges in a negative way on the ability of future generations to maintain their livelihoods? To what extent does the concept of "sustainable development" play in the decision-making processes of current leaders in the region? Aside from the human issues of equity, one can ask "Who speaks on behalf of

Nature?" Who represents the interests of the sea, the fish, the soils, the rivers, the deltas? It is now clear that the cotton-related Aral Basin development policies were going to destroy the Aral Sea's natural environment and ultimately its productive capabilities. To many regional scientists, it was clear since the 1960s.

6 The Impacts of Society on the Sea

Society's impacts on the Aral have for the most part been negative. Increasing streamflow diversions over the past five decades have led to a sharp and relatively rapid decline in not only level, but also in societal and ecological well-being. The diversion from the Karakum Canal has contributed to that decline. The drying out of the deltas has caused a loss in wetlands, an increase in salinity, a decrease in biodiversity and an attendant loss in revenue and the destruction of various economic activities dependent on delta habitats for flora and fauna. As the sea's coastline shrunk fishing ports and their supporting settlements moved farther from the sea. The image the world has of this drying sea is conveyed in photos of fishing vessels trapped by desert sands, destined to rust away or to have their metal parts salvaged.

In a last-ditch effort to save the livelihoods of the workers at fish-processing factories, fish were shipped into the region for processing from the Pacific Ocean and from Baltic seaports in the early 1990s.

All of the above adversely affected settlements in Karakalpakstan, especially livelihoods and human health. As Lindgren [5] has noted maternal mortality, respiratory and diarrhea diseases are worse than in the rest of the region. The level of tuberculosis is the highest in Europe as well as in the former Soviet Union and anemia is among the highest in the world. Other adverse health effects in the Karakalpak Republic include hepatitis, malnutrition, high infant mortality, kidney dysfunction, neurological disorder and cancer.

7 Is There a Way Forward?

The Aral Sea situation is a perfect example of the consequences of the disregard of precaution, of a blind faith in the ability of science and engineering to extract on demand Nature's bounty and of how short-term gains can have deleterious impacts if they are pursued without consideration of or care for the adverse impacts in the long-term.

All is not lost, however. The government of Kazakhstan has moved forward to restore the Small Aral Sea. After several attempts to build earthen barriers to arrest the flow from the Small Aral to the Large Aral, a concrete wall now helps to return water in the Small Aral. Its level has steadily risen, as the government assures a steady flow of Syrdarya water into its delta. The fishing industry, too, has been resurrected in this region.

It is time now to consider partially restoring the Large Aral Sea and maintaining it as a partially restored inland body of water. This would serve to show future generations what can happen if one does not respect the limits to the exploitation of nature, it also demonstrates what happens when one has a blind faith that whatever is done to the environment, can be undone by human ingenuity and science and technology. A partial restoration of the Aral Sea to a previous higher sea level also has tangible positive aspects: Some ideas include, but are not limited to, the following [6]:

- Restoration of the Large Aral. Because it has been done for the Small Aral, it can be done again.
- Maintains international interest in a unique feature in the region.
- Improves health conditions.
- Restores delta productivity. Restores wetland ecosystems.
- Improves inter-ethnic relationships.
- Encourages Siberian River diversions to Central Asian republics for drinking water.
- By making it a World Heritage site, governments might take stronger interest in a partial restoration.
- Encourages tourism.
- Encourages additional international development support.
- Demonstrates government commitment to a healthy Karakalpak people and environment.

8 Have Government Placed a High Priority on Saving the Aral Sea?

One can judge the beliefs of government leaders either by assessing words or by assessing their deeds. The words of Central Asian Republic leaders clearly suggest their support for saving the Aral Sea, though there is no explicit policy towards the sea. “Saving the sea,” however, can take on many forms. It can mean, for example, preserving the sea at its present reduced level; it can mean restoring the sea to a previous level of, say, 1960. Saving the sea could take on a different twist by letting it further reduce until it breaks up into several small highly saline ponds. It could mean that all the drainage water from irrigated fields would eventually collect in the sea, while at the same time protecting the Amudarya and Syrdarya deltas. All of these suggestions have been made over the past few years by someone discussing how or whether to save the sea.

Looking only at the actions of governments instead of just assessing the statements of their political leaders, one is left with the impression that the desire to “save the sea” seems to have waned considerably. It appears that the plight of the sea and the inhabitants in the surrounding regions (e.g., the disaster zone) has been used to some extent to encourage international development efforts in the region. Funds provided to Central Asian governments in the name of “Saving the Aral Sea” or in "rehabilitating Karakalpakstan" are often shared with (some say diverted to) those areas outside of the designated disaster zone. People in this zone have complained that their situation has neither improved nor have the prospects for improvements in the near future increased. Suggestions such as dumping drainage water into the sea, while saving the rivers' deltas, must not be considered as saving the sea because it would become a biological "dead zone", like those that exist in several regions of the Caspian Sea or in the Gulf of Mexico off the coast of Louisiana. There are still some decision makers who privately state that the sea is of little interest or of little value to Central Asia. The water that flows into the sea would be more valuable, they have argued, if its waters were to be used to irrigate cash crops for sale in the marketplace. This argument has been made at least since the turn of the century in opposition to those who argued to preserve the "integrity" of the Aral Sea. This appears to be a lingering feeling among many Central Asian decision makers, despite their vocal pronouncements to the contrary.

9 The Aral Sea as an Environmental "Hotspot"

Environmental degradation has a starting point. One can present the process in pyramid form where the base of the pyramid represents a pristine environment (Fig. 1). Humans enter the scene and begin to transform nature to meet their needs. The process of change begins, as suggested in Fig. 1.

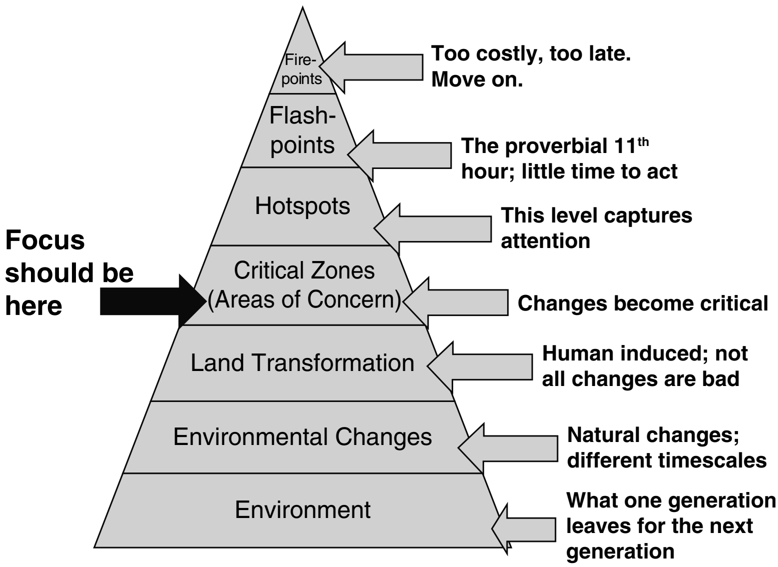


Fig. 1 Hotspots pyramid of environmental change [6]

Soon relatively harmless changes to the environment become areas of concern to observers, especially to local affected inhabitants. Over time, degradation becomes increasingly visible: too many trees harvested on mountain slopes, too many livestock grazing the rangelands, too many fish being caught, and too many natural habitats being destroyed in the name of progress, and too much water being diverted from rivers. Soon, areas of concern, if left unaddressed, can evolve into locations where the human activities are destroying the ecosystems on which they depend for their livelihood and for sustainable development prospects beyond their ability to recover without serious intervention by society, i.e., hotspots.

If the hotspots continue to be neglected, the degradation becomes so severe that it becomes prohibitively costly to repair, which means that many people would have to learn to live within the new ecological boundary conditions created by that degradation. The environment is then considered to be at a "flashpoint," the proverbial "Eleventh hour." This would leave very little time for a society to act to avoid reaching the final stage of degradation and human responses to it, the stage labeled "firepoint." Firepoint is the point of no return. The situation requires an abandonment of the land or perhaps just the end of the exploitation of the resources used for industrial and societal metabolism.

While there is considerable interest in and fascination with the hotspots, the focus of societies, especially governments, should be on "areas of concern." Environmental changes related to the Aral Sea have become so severe that they are at the flashpoint stage for some locations and at the firepoint stage for others. Figure 2 suggests the levels of creeping change in an Aral Sea context.

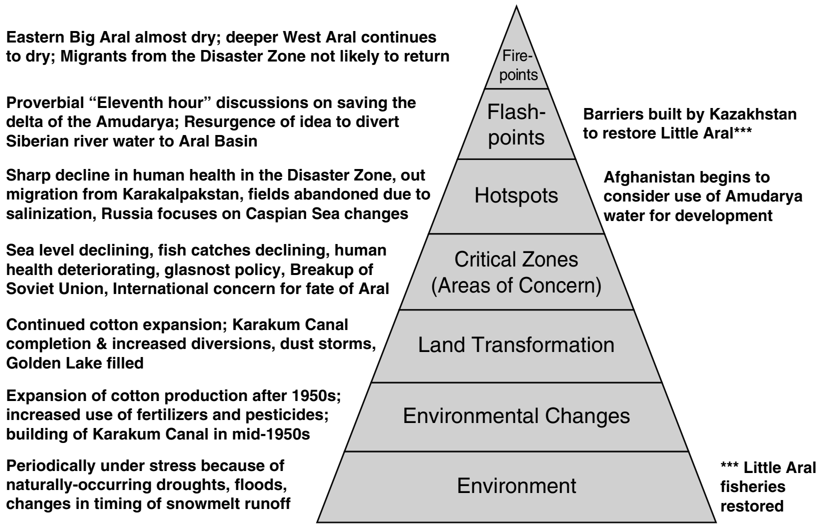


Fig. 2 Hotspots pyramid applied to the Aral Sea situation [6]

10 Conclusions

The Aral Sea's impacts on ecosystems and societies have been positive over time. With regard to ecosystems it has produced a rich environment for a range of flora and fauna, terrestrial and aquatic [7]. The region's two major rivers produced two highly productive inland deltas. The stream ecosystems were also abundant in species of aquatic life at different stretches of the river. The sea had a steady supply of water each spring from the melting glaciers in the mountains.

The positive aspects of the sea for society include the availability of abundant river water for human settlement and economic development purposes, for example, fertile but dry soils can rely on the water supply in the region. There has been, until recently, a sustainable balance of the Aral Basin, and therefore the sea's hydrological cycle; that is, before human intervention disrupted that cycle.

Providing the Aral Sea with World Heritage Status can serve to encourage governments in the region to seek ways to restore the sea to a usable level. Bringing back healthy deltas can restore biodiversity. It can restore a level of fishing and other economic activities, and therefore livelihoods. It can provide a modicum of hope for the future for the Karakalpak people who have been left with few options short of migrating to other parts of Uzbekistan. There are examples of heritage sites that serve as memorials to sad experiences in human history. The Aral Sea, once the world's fourth largest inland sea and now not even on the list, deserves Heritage Status as well as restoration. It will take a long time to accomplish this task. Better, then, to get started now.

References

1. Berg LS (1908) The Aral Sea. An experience of physics-geographic monography. Izv Turkestanskogo Otd Russk Geogr Obshchestva 5(9):580 pp (in Russian)
2. Glantz MH (ed) (1999) Creeping environmental problems and sustainable development in the Aral Sea basin. Cambridge University Press, Cambridge, UK
3. Nihoul JCJ, Kosarev AN, Kostianoy AG, Zonn IS (eds) (2002) The Aral Sea: selected bibliography. Noosphere, Moscow 232 pp
4. Kamalov Y (2006) Why do we have to save the sea? Paper presented at the international conference Central Asia in crisis: who speaks for the Aral Sea?, Royal Swedish Academy of Sciences, Stockholm, Sweden, 18 October 2006
5. Lindgren E (2006) The human health situation in the Aral region: causes and concerns. Paper presented at the international conference Central Asia in crisis: who speaks for the Aral Sea?, Royal Swedish Academy of Sciences, Stockholm, Sweden, 18 October 2006
6. Glantz MH (2007) Aral Sea basin: a sea dies, a sea also rises. Ambio 36(4)
7. Zonn IS, Glantz M, Kostianoy AG, Kosarev AN (2009) The Aral Sea encyclopedia. Springer, Berlin 292 pp

Conclusions

Aleksey N. Kosarev and Andrey G. Kostianoy

Abstract Herein is presented a review of the content of the chapters written by specialists from different institutions in Russia, Uzbekistan, France, Germany, and USA, devoted to different aspects of the Aral Sea problem – from paleohistory and archaeology of the Aral Sea region, to the present physical, chemical, and biological state of the sea, analysis of the Amudarya and Syrdarya river runoff and their deltas, description of regional climate change, as well as discussion of socio-economic conditions in the Aral Sea regions and reasons for the environmental and socio-economic crisis.

Keywords Amudarya, Aral Sea, Environmental crisis, Syrdarya

The Aral Sea by its natural features represents a unique water body that for many centuries of its history has been in the focus of attention of researchers and scientists. This is shown by the numerous historical data, cartographic documents, and treatises of authors who lived in different times beginning from Ancient Greece and Rome. The exploration of the Aral Sea has a long history. The treatises of the antique Chinese, Greek, Arab, and Venetian scholars contain the first written allusions to the rivers of Central Asia that flow into the sea. But all these data were very fragmental, confused and, at times, even fantastic.

The main investigations of the Aral Sea region started in the early eighteenth century by Russian officers, cartographers, geographers, geologists, and zoologists

A.N. Kosarev
Geographic Department, M.V. Lomonosov Moscow State University, Vorobjovy Gory, Moscow 119992, Russia

A.G. Kostianoy (✉)
P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, 36 Nakhimovsky Pr., Moscow, 117997, Russia
email: kostianoy@online.ru

A.G. Kostianoy and A.N. Kosarev (eds.), *The Aral Sea Encironmental*, Hdb Env Chem (2010) 7: 317–327, DOI 10.1007/698_2009_34,

who produced true maps of the region and data on the climate, relief, physico-geographical conditions, geological structure, and biodiversity of the Aral Sea, Amudarya and Syrdarya rivers, and their surroundings [1].

By the mid-nineteenth century thanks to the efforts of Russian naval officer and investigator A.I. Butakov and his predecessors the Aral Sea hydrography was already rather well studied. Investigations of the Circum-Aral area and Aral Sea were intensified to a great extent in 1873 when Khiva was joined to Russia. From 1874 occasional level-gauge observations were carried out on the sea shores. Soon it was found that its level was subject to perceptible fluctuations: after a very low level in the 1880s it rose rather sharply and quickly (over 10–15 years by nearly 3 m), stabilizing by the 1950s.

In 1897 the Turkestan Branch of the Russian Geographical Society was set up in Tashkent and this event was very important for further studies of the Aral Sea. A great contribution to the activities of this society and into investigations of the sea was made by L.S. Berg who later became an outstanding Russian scientist, geographer and zoologist. In 1900–1903 he organized the Aral expedition which conducted geographical and hydrologic surveys of the sea and nearby territories and leveling surveys of the sea surface [2].

Another important sphere of Aral development was connected to the study and use of its fish resources. In the 1930s the fish catches were about 40,000–50,000 tons per year. The opening in 1929 of the Aral Research Fishery Station facilitated hydrobiological and ichthyological investigations that were conducted by V.Ya. Nikitinsky, A.L. Bening, G.V. Nikolsky, and others [3, 4].

In the mid 1930s–1940 a network of hydrometeorological stations (nine by the late 1940s) was acting in the Aral region. Regular observations of the sea water level, water temperature and salinity, waves and ice phenomena, as well as meteorological parameters were conducted [5, 6].

In the post World War II years due to construction of the Karakum canal and after governmental resolutions on irrigation development in the Amudarya and Syrdarya river basins there was a need for wider-scale research of the sea which was mainly conducted by the State Oceanographic Institute (GOIN) and other organizations of the USSR. They studied the water and salt balances of the sea, its hydrometeorological and hydrochemical regimes, biology of fish multiplication, and adaptation of fish from other basins [6]. Studies of the Amudarya and Syrdarya deltas became very important.

Since 1960 the natural and stable period of the Aral Sea's evolution changed to an anthropogenic one, related to irrational use of riverine water resources for irrigation purposes. The water balance of the sea was disrupted so much that during the last 50 years we have observed a progressive desiccation of the Aral Sea and degradation of its environment. The anthropogenic history of the Aral Sea is regarded as one of the "largest ecological disasters of the twentieth century."

The Aral investigations attracted still more attention in the 1960s in connection with the economic development and irrigation of large land areas in the Amudarya and Syrdarya basins, and construction of unique canals and reservoirs with large storage capacity. Also, the drop in water level in the Aral Sea that started in the

1960s attracted additional attention from many researchers of various organizations. There was an urgent need to analyze and generalize the materials on natural conditions of the sea for the time of its "natural" existence and to assess the likely future changes caused by anthropogenic factors. In the early 1960s the standard network of "century" oceanographic stations of the open sea was introduced which conducted seasonal surveys of the water body including a complex of standard hydrometeorological and hydrochemical observations [6]. Also in winter ice airborne surveys were conducted systematically.

By the mid-1980s the Aral crisis had been acknowledged by the whole world and became one of the most significant environment protection issues [7–10]. The Aral Sea crisis redoubled when after the disintegration of the USSR in 1990–1991 the investigations and monitoring of the sea practically ceased. Almost all hydrometeorological stations have been closed, sea expeditions stopped, there has been no more assessment of ongoing rapid changes in the Aral Sea environment. At the same time interest in the Aral Sea problem has risen sharply on the international level [8–12]. The Aral problem is not global, but nevertheless it stirs global interest. Under the auspices of a number of international organizations and funds a set of important projects on different aspects of the Aral Sea problem were funded [1].

The 1980s–1990s were years of wide-scale investigations of consequences of the Aral Sea desiccation, desertification, effect of climate variations on natural resources, water and salt balance, general variations of the sea ecosystems and biodiversity, salt and dust transfer, etc. By 2010 we observe a decrease of interest in the Aral Sea problem due to a set of different scientific, economic, and political reasons and problems, including a general pessimism regarding the possibility to revive the Aral Sea to the state it was in during the 1960s–1970s. Many of the above-mentioned projects produced a lot of interesting scientific results, which traced in detail the development of the environmental crisis, but unfortunately did not result in real measures promoting salvation of the Aral Sea. Scientists, researchers, designers, and politicians could not come to a consensus on a strategy for the preservation and restoration of the Aral Sea.

In mid 2009 we can state that the main progress made towards saving of the Aral Sea occurred only in Kazakhstan with the construction of the Kokaral dam in August 2005. Thus, the Small Aral Sea is now slowly reviving, while the Large Aral Sea continues to disappear progressively. Today, the Aral Sea has lost its economic importance completely, and the aftermath of its degradation represents a serious threat to local populations due to a lack of fresh water and its quality loss, salinization of soils, dust and salt storms, climate deterioration, various diseases, etc.

This book combines the results of investigations performed by specialists in different fields of the natural sciences, giving a comprehensive description of the evolution of the Aral Sea and the peculiarities of its behavior in terms of its natural condition and the present anthropogenic period.

The book contains two chapters devoted to the paleohistory of the Aral Sea with a description of the geological evolution of the sea and its coasts, and archaeology of the Aral Sea region. It was noted that the Aral Sea basin was formed as a result of joint action of tectonic subsidence and processes of arid denudation. The first stage of the Aral dates back to the Late Pliocene when its basin was filled with water of the Akchagylian and Apsheronian seas; this was followed by a long period of subaerial environments persisting in the basin through the Pleistocene. In the mid-Holocene the Amudarya river water turned from the Sarykamysh depression and began to flow into the Aral basin via the Akchadarya channel, thus starting the recent (last) stage of the Aral Sea's history. At that time the Aral was a vast freshened brackish-water body of marine type subjected to drastic fluctuations of sea level (within 20 m) and noticeable changes of salinity (up to 10‰) and it was inhabited by the mollusk *Cerastoderma glaucum*.

Further evolution of the Aral Sea basin was controlled by a number of factors, including climate, hydrology, and human impact (irrigation). It seems, however, that the climate was of primary significance, as it controls the hydrologic cycle within the Aral drainage basin, evaporation from the sea surface, and runoff of the Syrdarya and Amudarya rivers; the latter was of prime importance in turning the poorly inundated Aral depression into a large lacustrine–marine basin.

The chapter on the archaeology of the Aral Sea region shows that a collaboration between geosciences and archaeological–historical sciences can be fruitful for both disciplines. The geosciences provide data on the environment and climate, while archaeology dates historical periods or specific events. When man was dependent on surroundings during early prehistory data on the environment can explain settlement patterns. Later, when humans began to exert influence, information on these activities helps to understand changes in the environment. In the case of the Aral Sea basin this was demonstrated very well by shifting habitation centers and analysis of irrigation history. A brief review of archaeological data is given and their relevance to the reconstruction of climate and sea level changes is discussed.

The characteristics of the Amudarya and Syrdarya river flow, which determines the water inflow to the Aral Sea and its water balance and level regime, are presented in a special chapter on the basis of a 75-year (1932–2006) long series of hydrological observations on the mentioned rivers and their tributaries. Information about water withdrawal from both river watersheds for economic reasons, including irrigation, is summarized. Until the 1960s the deltas of the Amudarya and Syrdarya rivers which received a lot of water and sediments, were among the most dynamic in the world, were notable for their high biodiversity and biological productivity, and resisted well against the deserts of Central Asia. As a result of dramatic man-induced reduction of river flow and a drop of the Aral Sea level the deltas of the Amudarya and Syrdarya rivers, their hydrographic network, and landscapes have undergone severe degradation. The volumes of annual inflow to the delta summits and to the Aral Sea during different periods in the last 45 years are critically less than those before 1961.

The ongoing desiccation, shallowing, and salinization of the Aral Sea have resulted in profound changes of its physical, chemical, and biological regime [11–14]. This was traced in several chapters of the book. We logically start with a description of the Aral Sea characteristics in its natural condition before 1960. The main hydrological peculiarities of the Aral Sea are discussed based on the multiyear data of in-situ observations and scientific publications. General information on the morphometry, hydrological and meteorological characteristics, water balance, sea level, and currents of the sea is provided. The main hydrological conditions of the sea: temperature and salinity distribution, convective mixing, and deep water formation are analyzed. Marine chemistry includes general information on the salinity, salt content and balance, dissolved oxygen and nutrient concentration in the Aral Sea. Distinctive features which specificate the Aral Sea as a special water body type – a lake-sea – are shown.

In this chapter we show the peculiarities of the Aral Sea and its distinction from typical sea-like water bodies. The main factors in the formation of the hydrological structure of the Aral Sea are heat exchange with the atmosphere and river runoff. Physico-geographical conditions (location in the desert area, continental climate, ice formation, small depth of the sea, etc.) are also very important. The main process responsible for the formation of the sea structure was an intensive autumn-winter convection that reached the sea bottom. A subduction process – horizontal advection of cold and dense waters from shallow eastern regions into the deep parts of the Aral Sea was also very important. Namely this mechanism led to the formation of deep waters in the western trough. During the cold season due to strong cooling water temperature was low and vertical gradients of temperature, salinity, and density were very small. Interannual variability of water temperature near the bottom marked variations in the conditions of convective mixing. In the warm season due to strong warming of the upper layer a thermocline was formed, which was strongest in July and August. The upper limit of the thermocline was located at 10–15 m depth. Seasonal variations of water temperature were observed in all layers, but with a decrease from the sea surface to the bottom.

Distribution of salinity over the sea and its seasonal variations were dependent, largely, on the river water inflow and evaporation. Lower salinity was found in the Amudarya and Syrdarya mouth offshore areas. The greater part of fresh waters came in with the Amudarya flow into the southern part of the sea and was spread via the anticyclonic circulation along the western coast. High salinity was observed in shallow areas near the eastern coast with their impeded water exchange with the sea. The salinity field in the open sea was rather monotonous.

The specific feature of the oxygen regime of the Aral Sea was maintenance of the permanently high oxygen content in space and time. Oversaturation with oxygen in deeper layers might reach 120–150%. Oxygen content below 80% was never registered. Such high concentration of dissolved oxygen in waters of the Aral Sea may be attributed, on the one hand, to high water transparency and small depths creating good conditions for benthos development and, on the other, relative insufficiency of pelagic organisms and organic matter which restricts consumption of dissolved oxygen for oxidation.

Waters of the Aral Sea were characterized by low concentrations of nutrients – phosphorus, nitrogen, and silicate – that suppress photosynthetic activity of bioorganisms. The greater part of the Aral possesses the features of the typical oligotrophic water body. Insufficiency of nutritive mineral substances in the sea waters may be explained both by the nature of input and cycling of these substances in the water body and also by morphological and hydrological peculiarities of the sea. High transparency of water combined with small depths ensured sufficient illumination of all water layers and development of photosynthesis in all water layers from top to bottom, in particular, development of the higher underwater vegetation consuming the regenerated mineral nutritive salts. Therefore, there were no morphological conditions for accumulation of nutrients in the sea proper. The "biological filters" of deltas, including higher benthos and overwater vegetation well developed in river mouths consuming the greater part of nutrients from river waters, played a rather significant role in restricting the input of nutritive salts into the sea. This is why the Aral Sea was always relatively poor in flora and fauna, though several fish species had commercial importance.

The information gathered in the above-mentioned chapter may be regarded as a reference point for further changes that occurred in the Aral Sea.

The objective of the chapter on physical oceanography is to summarize the up-to-date knowledge of the present hydrological state of the Large Aral Sea and quantify the profound changes to its physical regime. The discussion is mainly based on the original observations in several field surveys of the sea conducted between 2002 and 2008 by P.P. Shirshov Institute of Oceanology, Moscow, Russia. During the last 50 years the sea shrank from 66,100 km^2 (1961) to 10,400 km^2 (2008), its volume decreased from 1,066 to 110 km^3, the sea level dropped by 24 m, its salinity (mineralization) rose from 10 to 116 ppt and about 210 ppt (2008) in the western and eastern Large Aral Sea accordingly [15]. The decrease in area of the Large Sea occurred mainly through its shallow eastern part, the area of which in 2008 (3,200 km^2) became for the first time less than that of the western part (4,000 km^2).

Starting from the mid-1990s, the penetration of saltier and denser water from the shallow eastern basin into the deeper western basin played a major role in the build-up of the vertical stratification in the sea. Since 1960 the sea has evolved from brackish and low stratified waters into a hyperhaline and strongly stratified water body. The interbasin exchanges, however, tended to become less significant as the strait connecting the basins became shallower and narrower with the sea level drop. An important finding of the recent field research is the discovered "self-deepening" of the strait, i.e., the formation of a channel whose depth in 2008 was about 5 m, associated with the erosion of the bottom by currents [15].

A special chapter is addressed to spatial and temporal variability of ice conditions in the Aral Sea from historical observations and recent satellite microwave observations. The lack of reliable in-situ measurements and time series for ice cover parameters since the mid-1980s may be successfully replaced by using active and passive microwave satellite observations, that provide reliable, regular, frequent, and weather-independent data. An ice-discrimination methodology, based on the synergy of active and passive data from radar altimeters TOPEX/Poseidon, Jason-1, ENVISAT and GFO satellites, as well as the SMMR and SSM/I radiometers is presented. This methodology has been applied to the entire satellite dataset to define specific dates of ice events (first appearance of ice, formation of stable ice cover, and appearance of open water and the complete disappearance of ice) for both the

Small and Eastern Large Aral Sea. Finally, temporal variability of ice regime parameters in the context of air temperature, bottom morphology, and salinity changes is discussed.

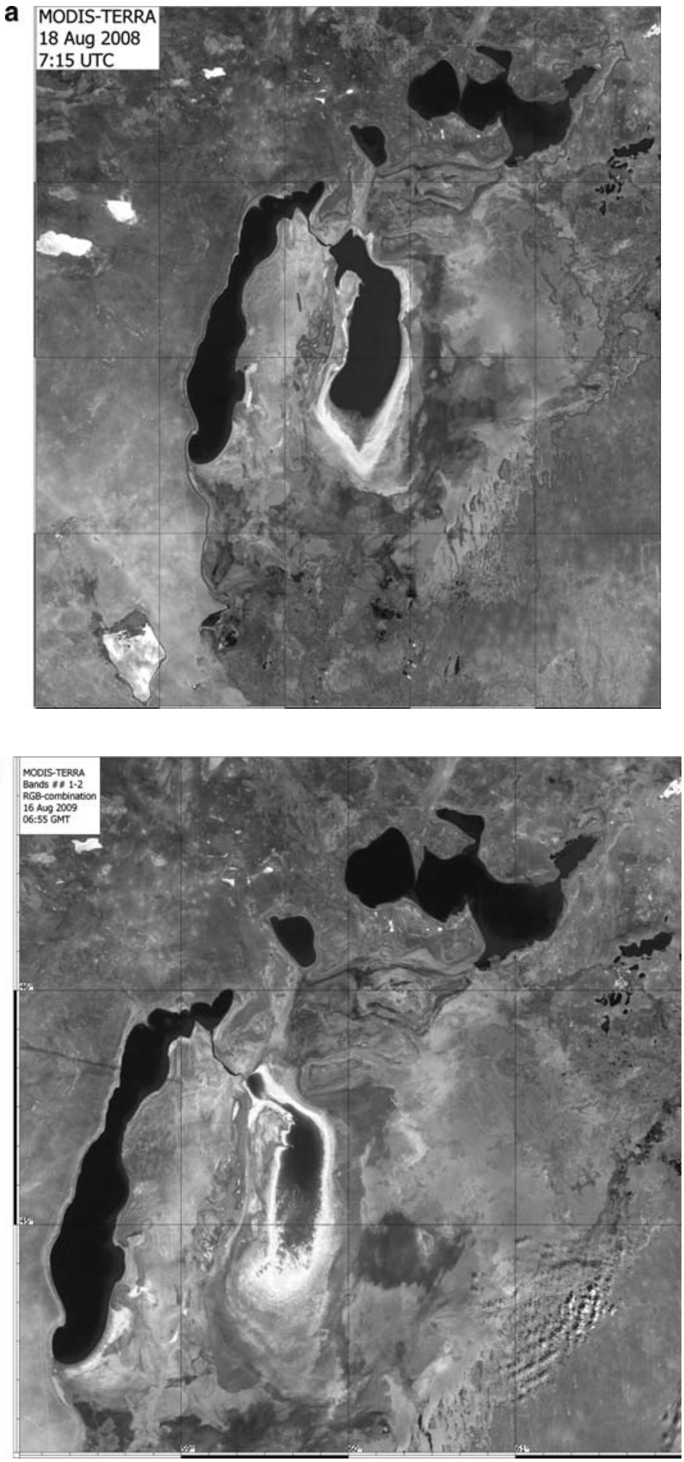
Before desiccation the Aral Sea waters chemically belonged to the so-called modified sulfate–sodium type, intermediate between the chloride–sodium-type ocean water and bicarbonate–calcium-type continental waters. During the period of desiccation, the salt composition of the Aral Sea has been subject to continuous changes because of chemical precipitation accompanying the salinity build-up. Precipitation of calcium and magnesium carbonates, gypsum, and, possibly, mirabilite and halite successively occurred as the salinity increased by an order of magnitude. Accordingly, compared with the pre-desiccation period before 1960, the sulfate-to-chloride mass ratio decreased by about 40% (in the western basin of the sea), whilst the relative content of calcium decreased by a factor of 9 in the western basin and a factor of 40 in the eastern basin. Hence, because of the desiccation, the Aral Sea water's relevance to the sulfate-type waters became less pronounced, and its waters became somewhat closer to the chloride type [16].

The progressive alterations of the ionic composition are also evident at the interannual scale over the period of the recent observational campaigns performed in 2002–2009 by P.P. Shirshov Institute of Oceanology [16]. The tendencies are characteristic for both basins of the Large Aral. The shallow eastern basin, where the most intense evaporation occurs and the salinity is generally higher, is expected to exhibit the chemical alteration to a larger extent, and, indeed, the reduction of calcium content is more pronounced in this part of the sea.

The ongoing desiccation of the Aral Sea has resulted in significant changes in the distributions of dissolved gases in the residual water body. In particular, the once fully oxygenized sea developed anoxic conditions and intermittent hydrogen sulfide contamination in the bottom layers. The sulfide content depends on the density stratification and is mainly controlled by the physical regime of the sea. However, H_2S is a variable rather than a permanent feature of the present Aral Sea [16].

In the first half of the twentieth century in the Aral Sea 33 species of fishes, 61 of bottom invertebrates, 49 species of zooplankton, 306 species of phytoplankton (including bento-planktonic microalgae), and 37 species of macrophytes were found. The Aral Sea accounted for 7% of the total internal waters fishery of the USSR. The main trade species were roach, sazan, and bream [17]. The first essential changes to the ecosystem occurred in the 1950s and it was driven by the installation of some species of fish and invertebrates. From 1960 till 2008 the fauna of the Aral Sea evolved from mainly fresh-water to hyperhalinic with the increase in water salinity. During the first decade of salinization more than 70% of the species of fish and invertebrates vanished. By 2004, when mineralization had reached 90 ppt in the Large Aral Sea, fish fauna of the Large Aral had progressively disappeared: at first autochthonous, and then introduced species. In 2008 zooplankton was represented by only one hypersaline species *Artemia parthenogenetica*, installed into the Aral Sea in 1996 [17].

The flora of macrophytes had reduced in the period 1960–2008 from 37 to just three species. At salinities up to 116 ppt in the Aral Sea only *Cladophora fracta*,


a
MODIS-TERRA
18 Aug 2008
7:15 UTC
b
MODIS-TERRA
Bands ## 1-2
RGB-combination
16 Aug 2009
06:55 GMT

Cladophora glomerata, and *Vaucheria cf. dichotoma* were observed. At 134 ppt *Vaucheria* was absent. By 2008 phytoplankton and microphytobenthos still included tens of species. In 2002–2008 regular installation of one species of microalgae and extinction of others was observed. Only five species lived there permanently [17]. Despite considerable impoverishment of flora and fauna, the Aral is still a forage reserve for many species of birds of passage.

It is generally accepted that the main reason for desiccation of the Aral Sea has been irrational use of Amudarya and Syrdarya waters for development of irrigation of agricultural lands and the filling of artificial water reservoirs. But it seems that regional climate change (at least in the form of rising air temperatures and decrease of atmospheric precipitation) also plays an important role in this process. According to estimates of the Intergovernmental Panel on Climate Change (IPCC), the trend of the mean annual air temperature in the Aral region in 1901–2005 was 1.1–1.7°C per 100 years and only in 1979–2005 it was 0.3–0.7°C per 100 years. The results of these estimates presented in the last report of the IPCC have indicated that by the late twenty-first century the air temperature in the Aral region depending on the emission scenarios may become 2–7°C higher compared to 1981–2000 [18]. Our estimates of the amount of water precipitated from the atmosphere over the catchment areas of the Amudarya and Syrdarya rivers for the period 1979–2001 revealed a marked decreasing trend for the Amudarya catchment area from 7–8 to 4–5 km^3 per month on average [19]. Thus, both the effects of regional climate change significantly influenced the water balance of the Aral Sea in the past 30 years leading to its supplementary desiccation.

Desiccation of the Aral Sea in the so-called anthropogenic period (since 1961) led not only to considerable changes in its morphometric, physical, chemical, biological and other parameters, but to disappearance of the infrastructure in the coastal zone as well, including meteo and sea-level gauge stations, ships, ports, villages, roads, etc. The current lack of reliable in-situ measurements and time series for sea surface temperature, sea level, ice cover, and morphometric characteristics since the mid-1980s may be successfully replaced by using corresponding satellite information available directly from satellites or through the World databases. Images from AVHRR NOAA and MODIS (onboard Terra and Aqua satellites) radiometers provide a possibility to follow the changes in the sea's coastline and observe interesting phenomena in the water, atmosphere and on the dried parts of the Aral Sea. This is discussed in a special chapter devoted to the application of remote sensing data to the monitoring of the Aral Sea.

Unfortunately, today we must say that within a lifespan of only one generation the Aral Sea as a single natural water body practically ceased to exist, and the main reason for this should be sought in man's economic activities. In the 2000s the Aral

Fig. 1 The MODIS-Terra satellite image of the Aral Sea on: (**a**) 18 August 2008 and (**b**) 16 August 2009. Image courtesy of D.M. Soloviev, Marine Hydrophysical Institute, Sevastopol, Ukraine, based on the data provided by the LAADS Web, NASA-Goddard Space Flight Center (http://ladsweb.nascom.nasa.gov/). *Solid line* in figure part (**a**) shows the Aral Sea coastline in 1960

Sea existed in the form of three survived water bodies: the Small Aral Sea, the Western Large Aral Sea, and the Eastern Large Aral Sea. But in 2009 we observe a rapid change in the Eastern Large Aral Sea's configuration leading to a complete desiccation probably in summer 2010 due to a progressive drop of the sea level in a very shallow area. We can follow this dramatic process based on the satellite imagery of the Aral Sea region from August 2008 to August 2009 (Fig. 1). Thus, in the 2010s the Aral Sea will exist in the form of two very distinct water bodies, which will no longer remind us of its usual configuration.

Nevertheless due to further rapid changes in the Aral Sea's regime, and development and design of water management and engineering actions related to regime regulation in some of its parts, it is still necessary to continue work on integrated monitoring of the Aral Sea environment aimed at possible optimization of its regime and environmental protection.

References

1. Zonn IS, Glantz M, Kostianoy AG, Kosarev AN (2009) The Aral Sea Encyclopedia. Springer, Berlin, p. 292
2. Berg LS (1908) The Aral Sea. An experience of physics-geographic monography. Izv Turkestanskogo Otd Russk Geogr, vol 5(9). Obshchestva, St.-Petersburg, p. 580 (in Russian)
3. Nikol'sky GV (1940) Fish in the Aral Sea. In: Materialy k poznaniyu flory I fauny SSSR (Materials to Knowledge of Flora and Fauna of the USSR), vol 1 (XVI). MOIP, Otd. Oolog., Moscow, p. 115 (in Russian)
4. Zenkevich LA (1963) Biology of the seas of the USSR, Izd. AN SSSR, Moscow, pp. 507–524 (in Russian)
5. Kosarev AN (1975) Hydrology of the Caspian and Aral Seas. Moscow University Publishing, Moscow, p. 272 (in Russian)
6. Bortnik VN, Chistyaeva SP (eds) (1990) Hydrometeorology and hydrochemistry of the USSR seas. V. VII – The Aral Sea. Leningrad, Gidrometeoizdat, p. 196 (in Russian)
7. Glazovsky NF (1990) The Aral crisis. Causative factors and means of solution. Nauka, Moscow, p. 136 (in Russian)
8. Letolle R, Mainguet M (1993) Aral. Springer, Paris, p. 357
9. Glantz MH (ed) (1995) Creeping environmental problems and sustainable development in the Aral Sea basin. Cambridge University Press, Cambridge, p. 291
10. Micklin PhP, Williams WD (eds) (1996) The Aral Sea basin. Springer, Berlin, p. 186 Published in cooperation with NATO Scientific Affairs Division
11. Kostianoy AG, Wiseman W (eds) (2004) The dying Aral Sea. Special issue of J Mar Syst 47(1–4):152
12. Zavialov PO (2005) Physical oceanography of the dying Aral Sea. Springer Praxis Books, Chichester, p. 146
13. Aladin NV, Filippov AA, Plotnikov IS (2000) Zoobenthos and zooplankton of the Aral Sea. Tr Zool Inst, 200 (in Russian)
14. Dukhovny VA, Navratila P, Ruzieva I, Stulina G, Roshenko E (eds) (2008) Integrated remote sensing and ground investigations of the dried Aral Sea bottom. Scientific-Information Center of Intergovernment Coordination Water Commission, Tashkent (in Russian)
15. Zavialov PO (2010) Physical oceanography of the Large Aral Sea. In: Kostianoy AG, Kosarev AN (eds) The Aral Sea environment. The handbook of environmental chemistry. Springer, Berlin

16. Zavialov PO, Ni AA (2010) Chemistry of the Large Aral Sea. In: Kostianoy AG, Kosarev AN (eds) The Aral Sea environment. The handbook of environmental chemistry. Springer, Berlin
17. Sapozhnikov PhV, Arashkevich EG, Ivanishcheva PS (2010) Biodiversity. In: Kostianoy AG, Kosarev AN (eds) The Aral Sea environment. The handbook of environmental chemistry. Springer, Berlin
18. IPCC (2007) Climate change 2007: the physical science basis. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
19. Nezlin NP, Kostianoy AG, Lebedev SA (2004) Interannual variations of the discharge of Amu Darya and Syr Darya estimated from global atmospheric precipitation. J Mar Syst 47:67–75

Index

S

T