Environ Earth Sci (2016) 75:921
DOI 10.1007/s12665-016-5691-5

THEMATIC ISSUE

Rise and decline of the fishery industry in the Aydarkul–Arnasay Lake System (Uzbekistan): effects of reservoir management, irrigation farming and climate change on an unstable ecosystem

M. Groll[1] · R. Kulmatov[2] · N. Mullabaev[2,3] · C. Opp[1] · D. Kulmatova[2]

Received: 26 January 2016 / Accepted: 2 May 2016

Abstract Originally, a shallow saline depression between the Kyzylkum and the Nurata mountain range the Aydarkul–Arnasay Lake System (AALS) was created in 1969 when a catastrophic flood event in the Syr Darya catchment exceeded the capacity of the Chardarya reservoir. Additional water diversions further increased the volume of the lakes to up to 42.2 mln m^3 in 2006. After the breakdown of the commercial fishing in the Uzbek part of the Aral Sea in 1983, the AALS became the most important fishery lake in Uzbekistan with an annual catch of more than 4600 tons (in 1988). In recent years, however, the fish catch experienced a sharp decline (down to 728 tons in 2006) due to the increased inflow of drainage water from the large Golodnaya Steppe (Hunger Steppe) irrigation scheme (e.g., 0.1 km^3 in 1960, 1.0 km^3 in 1970, 2.3 km^3 in 1980, 2.9 km^3 in 2000 and 3.6 km^3 in 2010) and a decrease in freshwater inflow from the Chardarya reservoir (e.g., 4.0 km^3 in 1995, 2.3 km^3 in 2005 and 1.8 km^3 in 2010). The increasing anthropogenic pressure, as well as the impacts of the climate change (+0.6–0.9 °C between 1950 and 2000, decrease in the long-term precipitation and increase in the variability), is threatening this ecological and economic important lake system. This article presents new data about the temporal dynamic of the lake hydrology (size, volume, water balance), the surrounding climate and its development as well as about the water quality of the lakes and the main drainage water collectors, and the development of the fish fauna over the last decades. This study, based on official data (Uzhydromet, Uzryba), online databases (GHCN) and extensive field work (water quality and fish sampling), provides a complete published analysis of the status quo of the AALS. Therefore, it is an important contribution to the establishment of a stable lake ecosystem system and a sustainable fishing industry.

Keywords Aydarkul–Arnasay Lake System · Chardarya reservoir · Collector drainage water · Fishery · Water quality

This article is part of a Topical Collection in Environmental Earth Sciences on "Water in Central Asia", guest edited by Daniel Karthe, Iskandar Abdullaev, Bazartseren Boldgiv, Dietrich Borchardt, Sergey Chalov, Jerker Jarsjö, Lanhai Li and Jeff Nittrouer.

✉ M. Groll
mgroll@gmx.net

✉ R. Kulmatov
rashidkulmatov46@gmail.com

1 Fachbereich Geographie, Philipps-Universität, Deutschhausstr. 10, 35037 Marburg, Germany

2 Department of Applied Ecology, National University of Uzbekistan, Vuzgorodok, Tashkent, Uzbekistan 100170

3 Laboratory of Hydrobiology and Ichthyology, Institute of Genofund of Flora and Fauna, Uzbekistan Academy of Sciences, Tashkent, Uzbekistan

Introduction

Water is a precious but heavily exploited resource in Central Asia (Karthe et al. 2015). It is used for the mining and processing of ores in the mountainous regions of the Pamir, Tien Shan, Altai and Alai, regulated and stored in reservoirs for the generation of hydropower and extracted from the rivers for the large-scale intensive irrigation farming (Groll et al. 2015a; Abdullaev and Rakhmatullaev 2015). Besides these anthropogenic activities of supra-regional relevance, the use of water bodies for fishery also plays an important role for the food security in the lowlands, especially in Uzbekistan (Petr 1995).

Published online: 20 May 2016

During the middle of the twentieth century, the Aral Sea became the center of the fishing industry in the Aral Sea basin with an annual fish catch of 50,000 tons in 1958 (Petr et al. 2004). Since the early 1960s, however, the annual catch drastically decreased until in 1983, the last year of commercial fishing in the Aral Sea, only 53 tons of fish were caught (Petr et al. 2004). Responsible for this sharp decline was the over-exploitation of the water resources in the Aral Sea basin, namely the water extraction from the Amu Darya and Syr Darya for irrigation purposes. As less and less water reached the Aral Sea not only did the water volume and lake surface decrease, but also the salinity of the lake's water increased to levels toxic to most fish species (from 10.2 g/l in 1947, to 11.0 g/l in 1970, to 17.0 g/l in 1980, to 21.0 g/l in 1985, to 30.0 g/l in 1990, to 80.0 g/l in 2005). This increase in salinity was accelerated by the anthropogenic pollution of the rivers supplying the Aral Sea. The extensive use of agrochemicals (fertilizers such as ammonium nitrate fertilizer, ammonium chloride fertilizer, ammonium sulfate fertilizer, nitrogen phosphorus fertilizer, potassium chloride fertilizer (FAO 2003); pesticides such as DDT, phosalone, lindane or toxaphene and salts leached from the salinized fields at regular intervals) in the Aral Sea basin has made the lake a sink for hazardous substances for many decades (Groll et al. 2013; Kulmatov and Hojamberdiev 2010; Létolle et al. 2005; Micklin 1988; O'Hara et al. 2000; Whish-Wilson 2002; Wiggs et al. 2003; Zetterström 1999). The desiccation of the Aral Sea has become known as the Aral Sea syndrome and was the largest man-made ecological disaster in the twentieth century and ranks among the largest catastrophes in human history, together with the deep water horizon oil spill in the Gulf of Mexico, the effects of microplastics on the aquatic ecosystems or the impact of the climate change (Opp 2007; Saiko and Zonn 2000; Shepherd et al. 2013; Micklin 2016). In order to meet the demand for fish products regardless of the shrinking Aral Sea, the Uzbek government developed the fishery industry in other water bodies and the Aydarkul–Arnasay Lake System (AALS, volume: 38.5 km^3, surface area: 3404 km^2) quickly became the most important of them, providing 56.7 % of the total Uzbek fish catch in 1988, even though the catch of 4616 tons in the AALS during that year was less than a tenth of the economic importance the Aral Sea had had 30 years before. After 1988, however, the fishery in the AALS experienced a sharp decrease in the annual catch itself (Fig. 1). Since then, the fish catch has remained on a much lower level roughly between 1000 and 1500 tons per year, which raises the question why the potential for economic income and food security of the largest freshwater lake in Uzbekistan remain underdeveloped.

Study area

The Aydarkul–Arnasay Lake System is located in the middle reaches of the Syr Darya River catchment in Uzbekistan, near the Uzbek-Kazakh border (Fig. 2). The climate in this region is continental and arid with average annual air temperatures between 14.4 °C (in Jizzakh) and 15.4 °C (in Yangikishlok), maximum average monthly temperatures between 29.2 °C (in Dustlik) and 33.2 °C (in Nurata) and an annual precipitation of 249 mm (in Nurata) to 388 mm (in Jizzakh). Until the 1950s, this region at the eastern fringe of the Kyzylkum and north of the Nurata mountain range was a mostly dry depression characterized by saline soils and the only water body in this region besides the Syr Darya was the small Tuzkan salt lake, which was filled with water from the Kli River (Kiyatkin et al. 1990; US Army Map Service 1955). The water of the Syr Darya had been used for the establishment of an irrigation scheme close to the river known as the Golodnaya Steppe (or Hunger steppe) for many centuries (Matley 1970).

During the Soviet period, this irrigation scheme grew significantly, drastically increasing the water demand for the cultivation of cotton and wheat. As the groundwater wells only provided brackish water unsuitable for irrigation (US Army Map Service 1955; Matley 1970), a network of irrigation canals was constructed (e.g., the Czar Nikolai I Canal from 1898 and the Romanovskiy Canal from 1913 (now known as the Northern or Kirov Canal, Fig. 2)), extending the irrigated area to 35,000 ha by 1916. As waterlogging and soil salinization became more and more problematic, a drainage system was developed and the saline drainage water was dumped into the Arnasay depression (approximately 2 km^3 of drainage water between 1957 and 1966, Kiyatkin et al. 1990). This leads to the formation of a small permanent (saline) water body in the Arnasay depression by 1957.

The modernization and extension of the irrigation and drainage network facilitated the continued expansion of the Golodnaya irrigation scheme (95,000 ha in 1939, 150,000 ha in 1948 and 206,000 ha in 1956) (Matley 1970). During the 1960s, a massive extension of the irrigated area by another 300,000 ha was planned based on the resolution "for the irrigation and reclamation of virgin lands of the Golodnaya Steppe […] for increasing the production of cotton" from 1956 (Matley 1970). Such a large irrigation scheme would require a much larger water supply, which could not only be provided by the Syr Darya itself or the small Farkhad reservoir (0.35 km^3) upstream of the Golodnaya Steppe near the Uzbek-Tajik border. That is why in 1965 the Chardarya reservoir (5.4 km^3) was established as a second tool for irrigation water

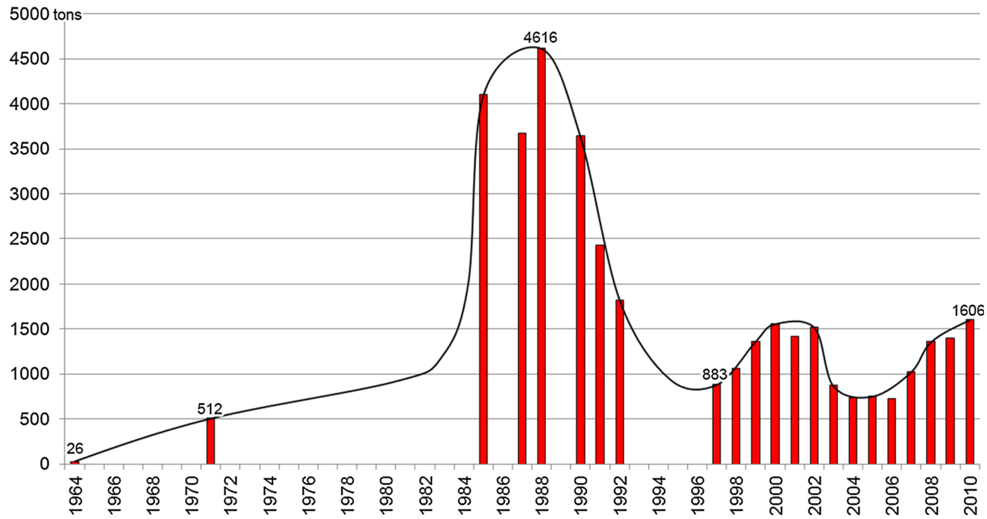


Fig. 1 Commercial fish catch (in tons per year) in the Aydarkul–Arnasay Lake System between 1964 and 2010 (data: Uzryba unpublished)

Fig. 2 Research area and sampling setup (own design)

management in the Golodnaya Steppe (Kulmatov et al. 2013, Fig. 2). In 1967 and 1968, considerable amounts of water were discharged from the Chardarya reservoir into the Arnasay depression (0.5 and 0.35 km^3), but most of that water infiltrated the saline soils and did not lead to an increase in the size or volume of the Arnasay water body. In 1969, however, the Syr Darya catchment was affected by a catastrophic flood event. Caused by winter and spring precipitation which had been three times the average, the discharge of the Syr Darya increased to 2000 m^3/s. As the Chardarya dam had not been designed to process such an amount of water (Ryabtsev 2001; Savoskul 2003), more than 25 km^3 of water was released from the Chardarya reservoir into the Arnasay and Aydarkul depression, leading to an increase in the water surface from 300 to 2300 km^2 and of the water volume from 1.16 to 20 km^3 (Kiyatkin et al. 1990, Fig. 3). Since then, the lake system has been a set of three permanent water bodies (Aydarkul, Arnasay and Tuzkan). Today the AALS has a water surface of 3600 km^2, a volume of 40 km^3 and a water depth of up to 25 m.

Data and methods

This study was conducted based on extensive field campaigns carried out between 2004 and 2010. During this period, the following data were collected:

- Taxa composition and abundances of the fish fauna at five sampling sites (Fig. 2) applying standard electrofishing methods (Abakumov 1983; Bohlin et al. 1989; Mullabaev 2006, 2010; Pravdin 1966);
- Hydrochemical analysis of the AALS water at four sampling points and of the drainage water collected in the Golodnaya Steppe at five sampling points (Fig. 2) assessing standard parameter (mineralization (WHO 1996), major ion concentration, heavy metal concentration, nutrients) by flame atomic absorption spectrometry and ion chromatography analytics at the Hydrometeorological Research Institute (NIGMI) in Tashkent;
- On-site determination of basic hydrochemical parameters (surface water temperature, pH, O_2, total hardness) at four sampling points on the AALS using multiparameter field equipment (WTW).

These data were complemented by

- Long-term (1881–2010) meteorological data (monthly average air temperature and monthly precipitation) from six stations surrounding the AALS (Fig. 2), provided by Uzhydromet and by the Global Historical Climate Network (GHCN, http://www.ncdc.noaa.gov 2015) database;
- Long-term (1936–2008) discharge data from five hydroposts along the Syr Darya and two of its tributaries (Fig. 2), provided by the Northern Eurasia

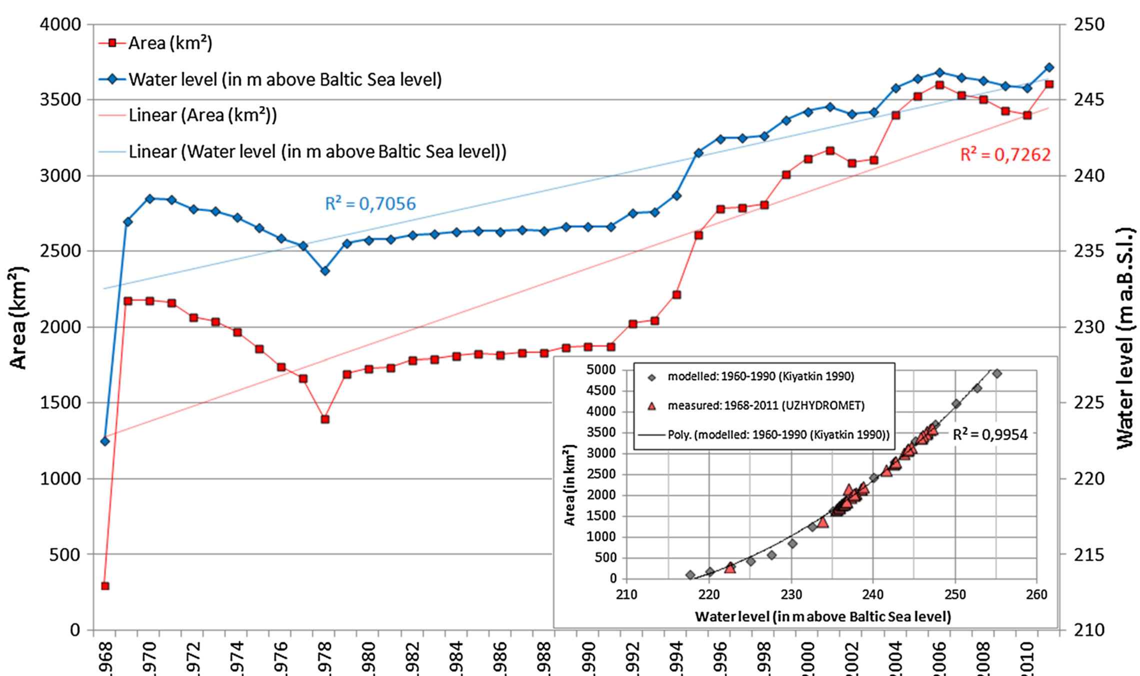


Fig. 3 Surface area (km^2) and water level (m above Baltic Sea level) of the Aydarkul–Arnasay Lake System between 1968 and 2011 (measured: Uzhydromet unpublished) and 1960 and 1990 (modeled: Kiyatkin et al. 1990)

Earth Science Partnership Initiative (NEESPI, http://neespi.sr.unh.edu/ 2014) and the Global River Discharge Database (GRDD, http://www.bafg.de 2015) as well as

- Uzbek fishery data from various literature sources and from Uzryba.

Results and discussion

The meteorological data collected from the six stations in the surrounding of the AALS (Dustlik, Jizzakh, Kushrabat, Mashikuduk, Nurata and Yangikishlok) provide a valuable inside in the long-term development of this arid region at the fringe of the Kyzylkum desert (Fig. 4). The annual average air temperature is characterized by strong variations and ranges at the station Jizzakh from 12.4 to 16.2 °C (with the average monthly air temperature ranging from −9.5 to 30.9 °C). Despite this variability, the long-term trend indicates a stable temperature regime during large parts of the twentieth century. A slight increase in the air temperature has been detected since 1980, and during the last 30 years, the average decadal air temperature has increased from 14.5 to 15.4 °C. The precipitation data show an even greater variability and ranged between 87 and 818 mm (with an average of 388 mm at the station Jizzakh). The long-term trend is thus less pronounced, but still shows a slight decrease since the early twentieth century (from 481 mm during the 1910s to 367 mm in the 2000s).

As the AALS is a relatively young but large water body, the meteorological data can also be analyzed with

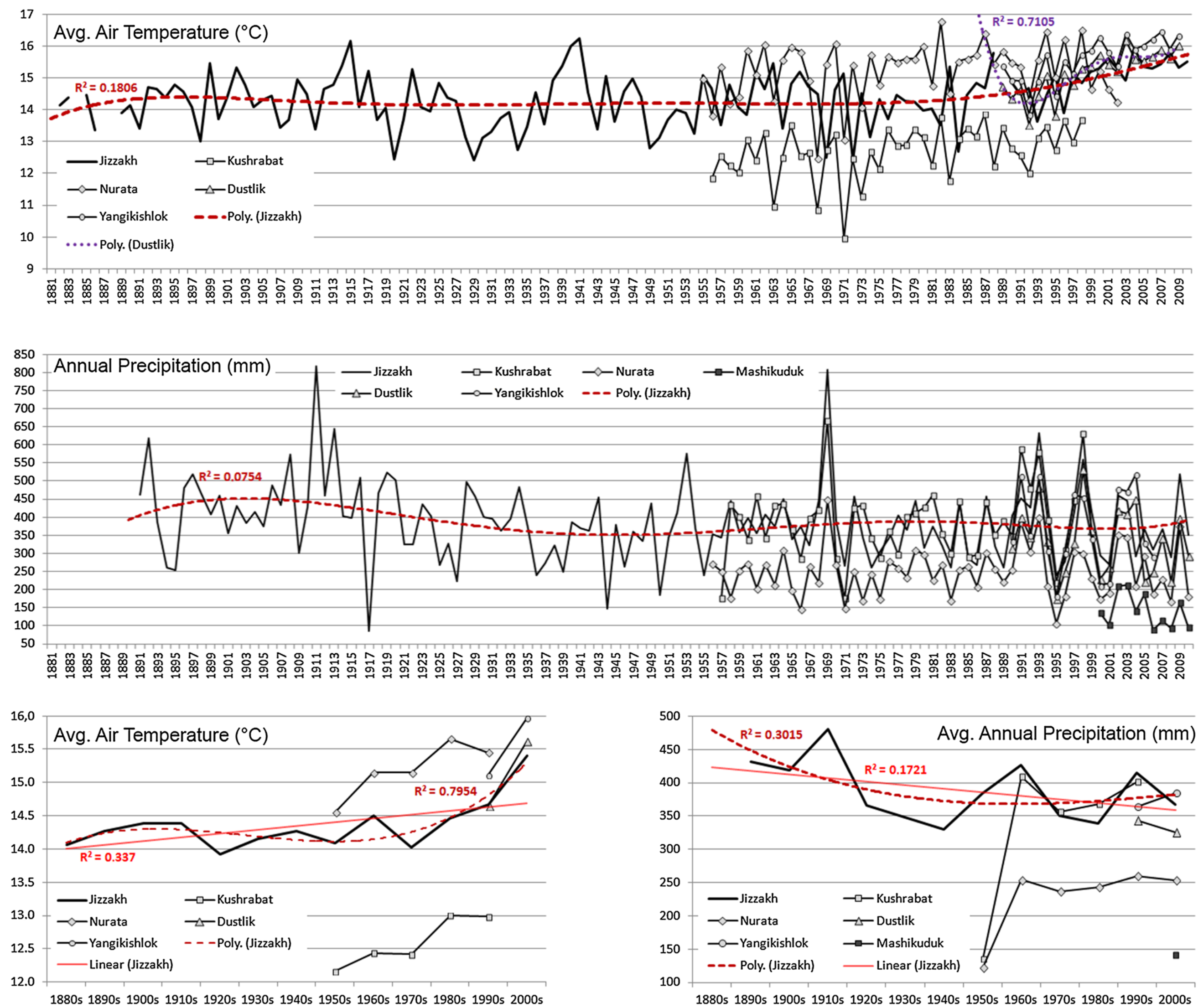


Fig. 4 Variability and development of the average annual air temperature (°C) and annual precipitation (mm) in the surrounding of the Aydarkul–Arnasay Lake System between 1891 and 2010 (data: GHCN; http://www.ncdc.noaa.gov 2015)

regard to the effect that the lake has on the local climate versus the impact of the global climate change. In order to do that, the average winter and summer temperatures and the precipitation data from the station Jizzakh (for which the longest time series is available) were analyzed and compared with the data from the meteorological station in Samarkand, which lies 120 km south of the AALS in the Zarafshan River catchment and is due to the Nurata mountain range not directly connected to the lake system. This comparison showed that especially the air temperature in the surrounding of the lake system has been significantly influenced by the creation of these new water bodies. While the average summer temperatures in Samarkand increased steadily since the 1930s (+0.35 °C per 10 years), the summer temperatures in Jizzakh have decreased by 1.1 °C during the same period (−0.15 °C per 10 years) (Fig. 5). This cooling in times of a global warming is caused by the buffer effect of the large lakes nearby. The winter temperatures, on the other hand, show a greater variability at both stations has increased during the twentieth century in a very similar way for both Jizzakh and Samarkand.

Due to this different behavior of the summer and winter temperatures, the temperature amplitude between maximum and minimum temperatures has also changed as a result of the newly formed lakes. At the station Jizzakh, the difference between summer and winter temperature dropped from 27.17 K in the 1930s to 23.15 K in the 2000s

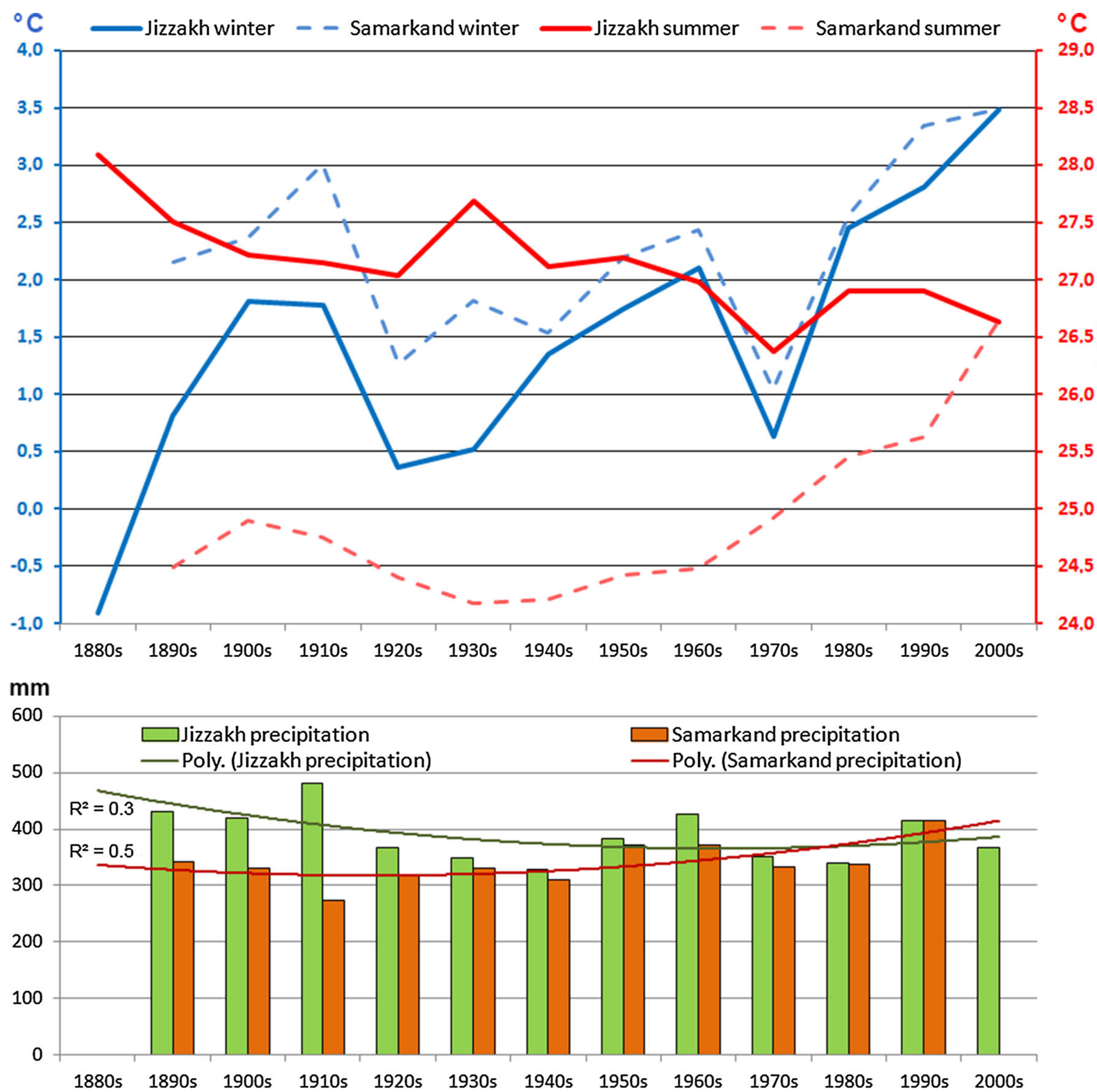


Fig. 5 Effect of the AALS on the decadal average winter and summer air temperatures (°C) and annual precipitation (mm) at the Jizzakh station (near AALS) and at the Samarkand station (in the Zarafshan River catchment, 120 km south of the AALS) between 1891 and 2010 (data: GHCN; http://www.ncdc.noaa.gov 2015)

(−4.0 K in 70 years), while the difference at the station Samarkand increased by 0.8 K during the same period.

The precipitation data, on the other hand, did not show any significant difference between the stations Jizzakh and Samarkand that could be related to the AALS. Both stations are characterized by a strong decadal variability, and the overall (weak) trends show a slight decrease in the average annual precipitation at Jizzakh (from 389 mm during the first half of the twentieth century to 383 mm during the second half of the twentieth century) and an increase at Samarkand (from 313 to 366 mm).

Overall, these meteorological data show that both climate change and the lake system itself are affected the local climate of the Golodnaya Steppe. But the high summer temperatures and the low precipitation also mean that the artificial water bodies of the AALS are not self-sustained, but depend on the inflow of water. Figure 3 shows how the discharge from the Chardarya reservoir during the catastrophic flood event in 1969 increased the water level, and since then, the AALS continuously received water both from agricultural drainage and from the Chardarya reservoir so that the water volume steadily increased during the last 50 years. Figure 6 shows the average annual surface water inflow into the AALS by its source, decade and month. The release of fresh water from the Chardarya reservoir into the Arnasay lake occurs only sporadic (e.g., no inflow between 1981 and 1990, which coincides with a severe drought in Central Asia during the first half of the 1980s (Bernauer and Siegfried 2012) but 27.4 km^3 between 1991 and 2000) and mostly during the winter and early spring months (on average 0.91 and 0.92 km^3 during February and March, Fig. 6), when more water is released from the upstream reservoirs in the Syr Darya catchment for the generation of hydropower (e.g., the Toktogul dam with an installed capacity of 1200 MW at the Naryn River in Kyrgyzstan, Bernauer and Siegfried 2012; Libert et al. 2008), and this released water cannot be used for the agricultural sector. The drainage water collected in the Golodnaya Steppe and discharged into the Arnasay and Tuzkan lakes, on the other hand, has been a much more constant inflow into the lake system. Throughout the year, the inflow of drainage water ranges between 0.22 km^3 in December and January and 0.31 km^3 in April, which means that the drainage water is during the summer and autumn months the sole source of water for the AALS. Furthermore, the total input of drainage water has increased from 4.1 km^3 in the 1960s (0.46 km^3/a) to 33.0 km^3 in the 2000s (3.3 km^3/a), reflecting the intensification of the irrigation farming in the Golodnaya Steppe.

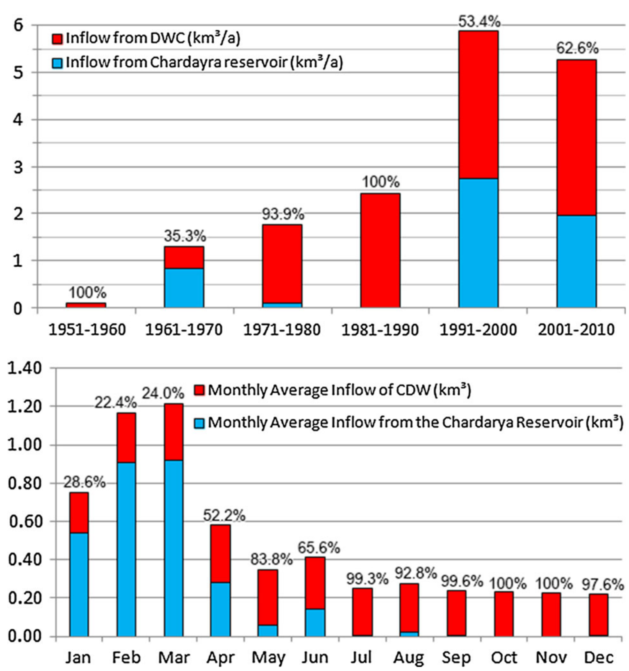


Fig. 6 Average annual and monthly inflow (km^3) of collector drainage water (CDW) and of water from the Chardarya reservoir between 1950 and 2009 and the percentages of the CDW in the total surface water inflow (data: Uzhydromet)

As a result of the irregular inflow of fresh water from the Chardarya reservoir and the increasing input of drainage water, which contains high concentrations of salts and nutrients, the overall mineralization of the AALS water increased from 2.4 g/l in 1970 (right after the massive inflow of freshwater from the Chardarya reservoir) to up to 13.7 g/l measured in 1990 in the Aydarkul (Fig. 7). Overall, the water mineralization is related to the lake system water balance as the mineralization increases during periods with a negative or insignificant water volume change (during which the evaporation and the inflow of drainage water are the main factors) and decreases after larger water releases from the Chardarya reservoir. But the three lakes of the AALS also show a different dynamic in this regard (Fig. 8). The Arnasay lake, which is located closest to the Chardarya reservoir, is characterized by the lowest water salinity, even though several of the drainage water collectors (including the Central Golodnostepskiy Collector (CGC), which is with an average discharge of 1.36 km^3/a the largest collector in the Golodnaya Steppe) dump their polluted water into this lake. Lake Tuzkan, which receives drainage water from several collectors (Akbulak, Pogranichniy and the River Kli (which also receives the water from the APK collector)) and is further away from the freshwater inflow from the Chardarya reservoir, is characterized by a much higher mineralization (up to 11.6 g/l in 1977). The Aydarkul, at the far end of the lake system, shows the highest mineralization, which also occurs with a delay of several years in relation to the other two lakes (Fig. 7). As the Aydarkul is not directly influenced by any drainage water inflow but has the largest

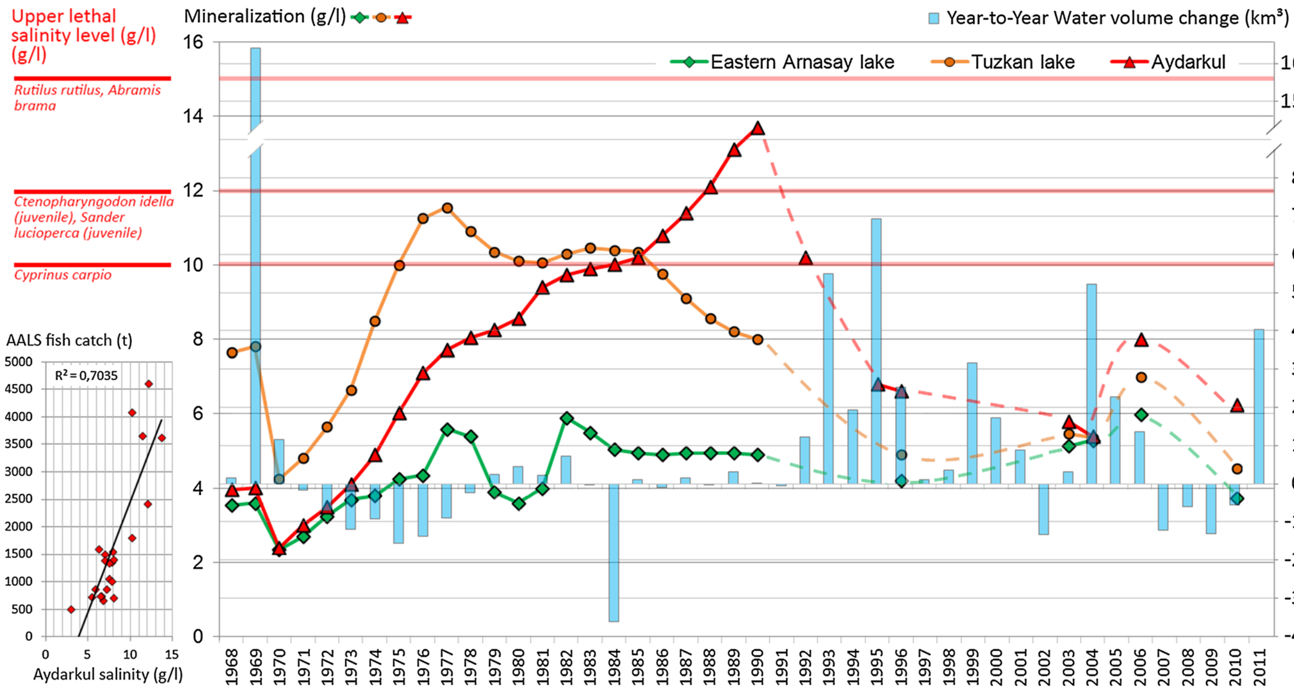


Fig. 7 Year-to-year water volume change and mineralization of the Aydarkul, Arnasay and Tuzkan lakes between 1968 and 2011 (hydrological data: Uzhydromet unpublished, Kiyatkin et al. 1990; Wahyuni et al. 2009; mineralization data: Kiyatkin et al. 1990; fish lethality data: Cudmore and Mandrak 2004; Küçük 2013; Wootton 1990; fish catch data: Uzryba unpublished)

surface area of the three lakes, the evaporation is the main process responsible for the high water salinity.

Of the five drainage water collectors (DWC) analyzed in this study, the APK collector showed the highest mineralization (5.4 g/l), followed by the collector Pogranichniy (4.9 g/l) (both discharging into the Tuzkan lake), the CGC (4.4 g/l; discharging into the Arnasay lake)), the Akbulak collector (4.1 g/l) and the River Kli collector (3.6 g/l) (both discharging into the Tuzkan lake). These values are very high, but not unusual for Central Asian irrigation farming schemes, as comparable mineralization values were detected in DWC in the neighboring Zarafshan River catchment (Groll et al. 2015a). The DWCs discharging into the Tuzkan lake are characterized by a high percentage of sulfate (47.9 %), followed by sodium (18.9 %), chlorine (15.3 %), calcium (6.9 %), magnesium (5.6 %) and hydrogen carbonate (5.5 %). The DWC discharging into the Arnasay lake shows a slightly different ion composition characterized by a lower percentage of sulfate (39.3 %), chlorine (14.4 %), magnesium (4.7 %) and hydrogen carbonate (3.9 %) and a higher concentration of sodium (32.0 %).

Based on the long-term average discharge of these DWCs, the average annual ion load discharged into the lake system is 8.12×10^6 tons for the Arnasay and 1.64×10^6 tons for the Tuzkan lake (Kiyatkin et al. 1990; Kulmatov et al. 2013). This load, in turn, increases the mineralization of the water in the three lakes and leads to a deterioration of the water quality as shown in Fig. 8. As the main input of pollutants occurs during the irrigation-intensive summer months, the mineralization increases during that season in all three lakes. During winter, the values drop again so that in spring the average mineralization is 0.1–0.8 g/l lower than during summer. An additional seasonal dynamic can be found in the vertical distribution of the water mineralization in the AALS, as during spring the values near the water surface are lower than in greater depth while during summer and autumn the surface water shows the highest mineralization (Fig. 8).

Even though fertilizers dissolved in the agricultural drainage water are the most important source of pollutants, the measured concentrations of the nutrients ammonium, nitrite, nitrate and phosphate remain well below the Uzbek thresholds for fishery water bodies (Fig. 8). Higher concentrations—and the excess of national thresholds—were detected for various other pollutants in the Aydarkul. Especially chrome VI, lead, phenols and fluorine exceeded their thresholds even with the average measured concentrations. The average concentration of copper stayed with 0.8 mg/l below the threshold of 1.0 mg/l, but the maximum value still exceeded this threshold by the factor x2.9 (Fig. 8). Zinc, chromium and petroleum, on the other hand, remained at all times below their maximum allowable concentrations, even though the values for zinc and chromium are elevated. The sources of the detected elements and compounds and the reasons for their high concentrations in the Aydarkul are threefold:

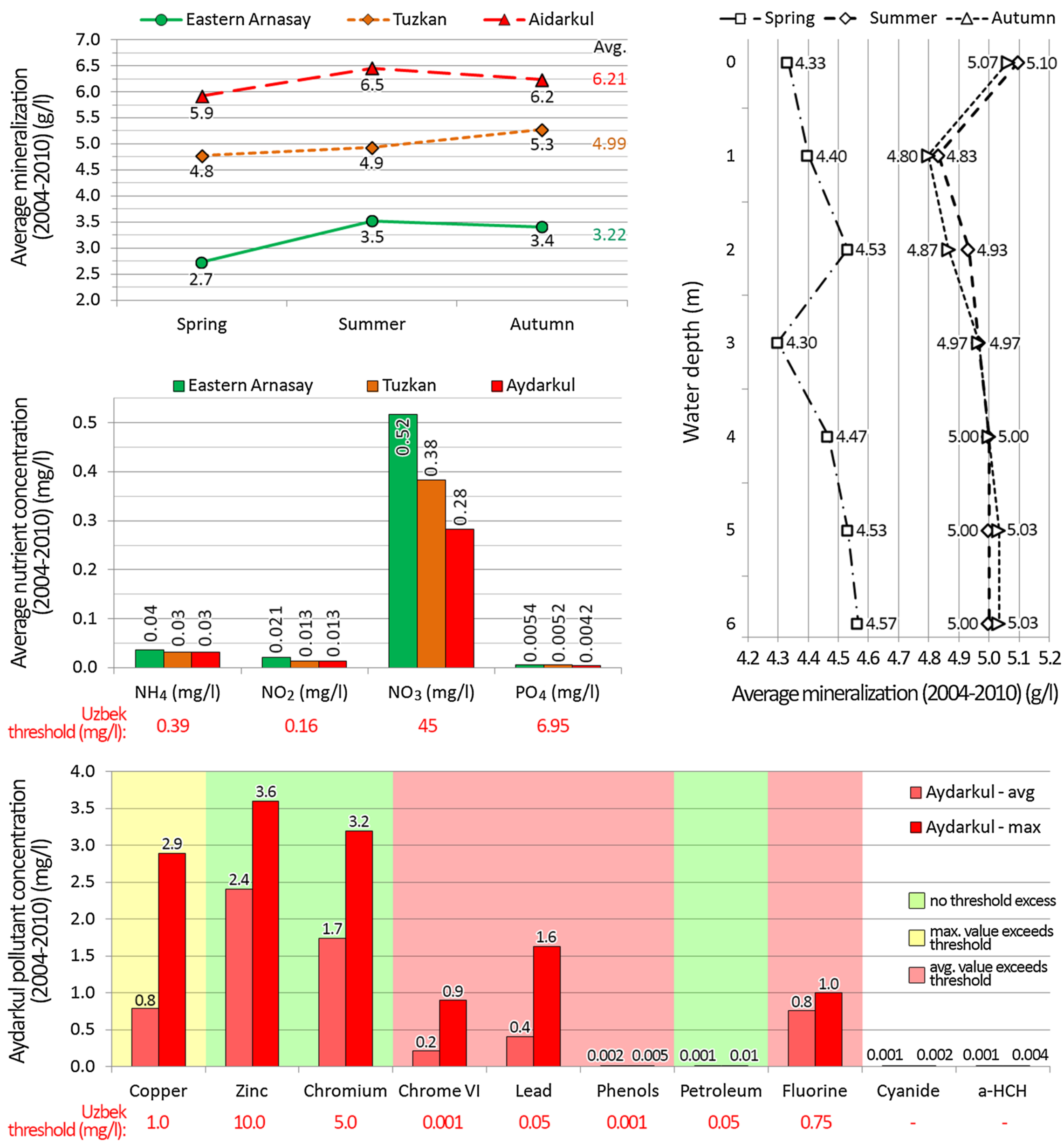


Fig. 8 Seasonal water mineralization and water pollution in the AALS

1. The Syr Darya itself—as the main source of water inflow via the Chardarya reservoir and the Golodnaya irrigation canal network—is characterized by elevated concentrations of various pollutants from ore mining and other upstream industrial sources (Kulmatov and Hojamberdiev 2010) so is the Keles River (a tributary flowing into the Syr Darya immediately upstream of the Chardarya reservoir) characterized by high heavy metal concentrations which lead to elevated pollution levels in the Chardarya reservoir sediments (Solodukhin et al. 2004).
2. The phosphate fertilizers applied in the Golodnaya Steppe irrigation scheme contain heavy metals as residual elements (Alihanov 2008; Aparin et al. 2006; Umarov 2013).
3. Due to the large surface area and the high evaporation of the Aydarkul, the pollutants contained in the water are enriched over time—a process very typical for terminal lakes in arid regions (Groll et al. 2013, 2015b; Kostianoy et al. 2004; Micklin and Williams 1996).

In summary, this means that the Arnasay and Tuzkan lakes are characterized by a higher pollution with nutrients as these are discharged into these two lakes via the drainage water collectors, while the Aydarkul, as the terminal lake of the system, shows the higher overall mineralization and enriched heavy metal concentrations.

Based on these water quality data, the assumption is plausible that the pollution and especially the increasing water salinity are the driving factors behind the decline of the fish catch in the lake system. After all, lethal salinity levels for several fish species (*Cyprinus carpio, Ctenopharyngodon idella* (juv.) and *Sander lucioperca* (juv.)) had been reached in the Aydarkul lake by the early 1990s and the fish catch shows a correlation to the Aydarkul salinity ($R^2 = 0.7$) (Fig. 7). But studies show that at least the vitality of pikes (*Esox lucius*) in the three lakes was greater during the period of the highest salinity than in other fishing water bodies (Amu Darya, Kairakkum reservoir, Yuzhnosurkhan reservoir, Talimardzhan reservoir) in the region (Amanov 1985; Fedorov 1973; Kamilov 1973; Kamilov and Urchinov 1995; Sagitov 1983). The body length of pikes caught in the AALS was, across all age classes (from 1 to 7 years), precisely the same as the average of pikes caught in the other analyzed water bodies (for a total average length of 37.8 cm), indicating that the higher salinity in the AALS did not affect the pike growth. The body length of pikes caught in the Aydarkul lake was even above that average, especially in the age classes 5–7 years, even though the salinity in the Aydarkul was much higher than in the Arnasay and Tuzkan lakes (60.1–54.6 cm). And a study by Ermakhanov et al. (2012) showed that pikes caught in the Aral Sea during the late 1960s and early 1970s had an average body length of only 29.4 cm across all age classes—at a time when the average salinity of the Aral Sea was between 10 and 12 g/l (Micklin 2007). But even if the salinity was not the main factor for the demise of the fishing industry, the water pollution did lead to changes in the fish fauna composition. Currently, there are 21 fish species found in the AALS and all but the Aral Barbel (*Barbus brachycephalus*) are commercially fished (Table 1). Roach and carp are the commercially most important species in the AALS, contributing 51.6 and 31.0 % of the total fish catch between 1987 and 2005 and between 1981 and 2007, the percentages of the more salt-tolerant roach (*Rutilus rutilus*) have increased from 25.7 % in 1981 to up to 84.9 % in 2002 (and back to 50.3 % in 2006), while the more salt-sensitive carp (*Cyprinus carpio*) was caught less often (from 47.7 % in 1981 to 14.9 % in 2007) (Fig. 9). In recent years, the grass carp (*Ctenopharyngodon idella*) has become the third strongest fish species in the AALS with a percentage of 20.9 % of the total catch in 2007, while it had been completely absent from the lake system between 1997 and 2005.

This strong fluctuation of the fish catch composition shows that the fauna composition in the lake system is an indicator for the changing water quality, but also for the strong anthropogenic influence in this commercially used water body. And it is this anthropogenic factor that can explain the decline of the fishing industry better than the water salinity or heavy metal concentrations. Figure 9 shows the total fish catch and the species composition of that catch in the AALS between 1987 and 2005, but it also shows the same data for Uzbekistan as a whole (based on the data from the Uzryba state corporation, the largest fishing company in Uzbekistan at that time). The Uzbek fishery industry experienced a drop of the annual fish catch from more than 8000 tons/year to well below 2000 tons/year in just 15 years. The decline of the fishing industry is thus not a phenomenon limited to the Aydarkul–Arnasay Lake System, albeit the development shows some slight differences. In the late 1980s, more than 50 % of the fish caught in Uzbekistan came from the AALS. This ratio dropped in 1997 to a minimum of 29.3 %, showing that the AALS was affected more heavily by the decline of the fishery industry. Toward the turn of the millennium, the industry in the lake system recovered better than in Uzbekistan as a whole so that by 2002 75.1 % of all fish was caught in the AALS. By 2005, the percentage of fish caught in the lake system was comparable to the values from the 1980s. The overall composition of the fish fauna also shows similarities between the lake system and the national average. Roach and carp are the dominant species in both cases, but both taxa are more frequently caught in the AALS while other species (especially grass carp and bream) are much rarer than in the rest of the country. Overall, the species composition in the Aydarkul–Arnasay Lake System is less diverse than on average, which could be an indicator for the impairment caused by the increased pollutant and salt input.

As the fishery industry in Uzbekistan as a whole has been affected by the decline in a similar fashion to the AALS, the main reason for this decline cannot be found in the catchment of the Aydarkul–Arnasay Lake System itself, but must be of a broader scope. And indeed, it is not pure coincidence that the drastic decline of the fish catch falls together with the breakdown of the Soviet Union and the formation of the newly independent states in Central Asia in the beginning of the 1990s.

The economic transition caused by the political breakdown led to a lack of maintenance of the fishing equipment and lack of funding required for the restocking of fish in the main fishery water bodies. This resulted in a drop of the fish yield in Uzbekistan by 77 % (from 20–27 kg/ha before 1990 to 4.1–6.4 kg/ha after 1990, Karimov et al. 2009). Furthermore, the newly independent states had to reposition themselves in a global market instead of the heavily intertwined economic community of the Soviet Union. Traditional trade connections were discontinued so that the demand for exporting fish products suddenly declined as well, which contributed to the sharp decline of the fish

Table 1 Fish species and their use in the AALS

No.	Fish species	Scientific name	Commercial fishing	Non-commercial fishing	Native species	Introduced species
1	Carp	*Cyprinus carpio*	+		+	
2	Zander	*Sander lucioperca*	+			+
3	Asp	*Aspius aspius*	+			
4	Wels Catfish	*Silurus glanis*	+		+	
5	Grass Carp	*Ctenopharyngodon idella*	+			+
6	Silver Carp	*Hypophthalmichthys molitrix*	+			+
7	Bighead Carp	*Aristichthys nobilis*	+			+
8	Roach	*Rutilus rutilus*	+		+	
9	Crucian Carp	*Carassius carassius*	+			+
10	Eastern Bream	*Abramis brama*	+		+	
11	Snakehead	*Channa argus* warpachowskii	+			
12	Caspian Shemaya	*Alburnus chalcoides*	+		+	
13	Sabrefish	*Pelecus cultratus*	+		+	
14	White-eye	*Abramis sapa* aralensis (Tiapkin)	+		+	
15	Pike	*Esox lucius*	+		+	
16	Aral Barbel	*Barbus brachycephalus*				
17	Hemiculter	*Hemiculter* sp.	+	+		
18	Mosquitofish	*Gambusia affinis* holbrooki	+	+		
19	Amur Bullhead	*Rhinogobius similes*	+	+		
20	Mikropercops	*Micropercops* sp.	+	+		
21	White Amur Bream	*Parabramis pekinensis*	+		+	

catch after 1990. Toward the end of the 1990s, the Central Asian countries had found their footing in the globalized world and their sovereignty and the fish catch started to increase again (from 7800 tons in 1996 to 8850 tons in 1998) (Fig. 10). At the start of the new millennium, however, the Uzbek and the AALS fish catch experienced another sharp decline and the reason for that can be found in the drop of the global fish prices as documented in the FAO Fish Price Index (Fig. 10, FAO 2014). Early in 2001, the global fish price started to drop significantly, and until the end of 2002, the FAO Fish Price Index had lost 20 %. The Uzbek fishing industry reacted to this development with lower fish catches, as both fish product imports got cheaper and the locally caught fish yielded less revenue.

After 2002, the fish price rose again and reached a high point in 2008 with a plus of 40 % compared with 2002. The Uzbek (and the AALS) fish catch again reacted to this development, but with a delay of two years. Since 2005, the fish catch has increased steadily and in 2010 reached a level comparable to the one before the Fish Price Index drop (Fig. 10). In the AALS, the lowest fish catch after the Uzbek independence was registered in 2004 (737.6 tons) and by 2010, the total catch had reached 1605.8 tons (compared with 1562.0 tons in 2000). Overall, however, the lake fishery in Uzbekistan remained on a very low level and has been largely replaced by aquaculture fishery, which had always been strong in Uzbekistan (see Fig. 10), and the drop of the yield per hectare after the breakdown of the Soviet Union had been smaller than for the lake fishery (−55 % in comparison with −77 %, Karimov et al. 2009). Despite this growth of the aquaculture in Uzbekistan, the lake fishery in the AALS seems to have reached its equilibrium in relation to the country as a whole. Today 66.9 % of all fish caught by lake fishery come from the Aydarkul–Arnasay Lake System. This is almost the same percentage as in 1990 (66.4 %), which suggests that the fishery industry in the AALS has reached its economic potential, even if the natural potential would be much higher.

Outlook

Looking from the status quo into the future, there are two aspects to consider—the climate change and the socioeconomic development.

The impacts of the global climate change affect Central Asia already today more than other regions (Groll et al. 2015a; Lioubimtseva 2015). In the surrounding of the AALS, the average annual air temperature has increased by 0.03 °C per year for the last 30 years (which equals +3 K

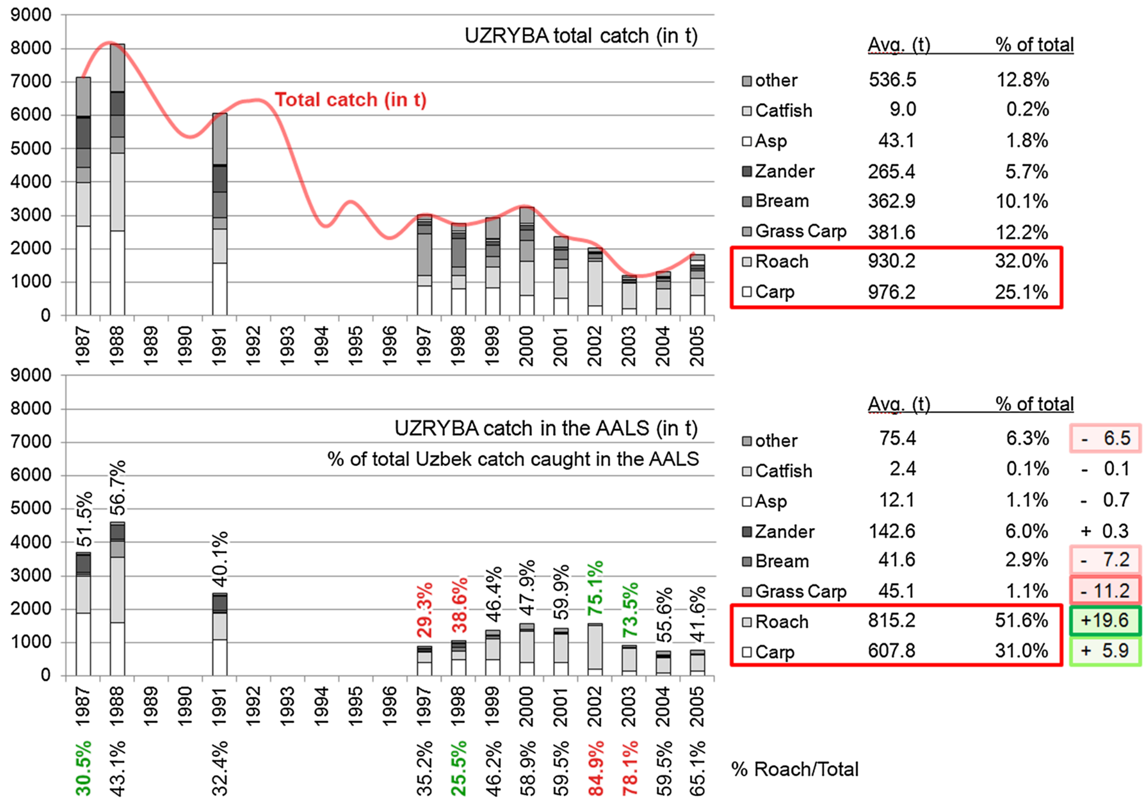
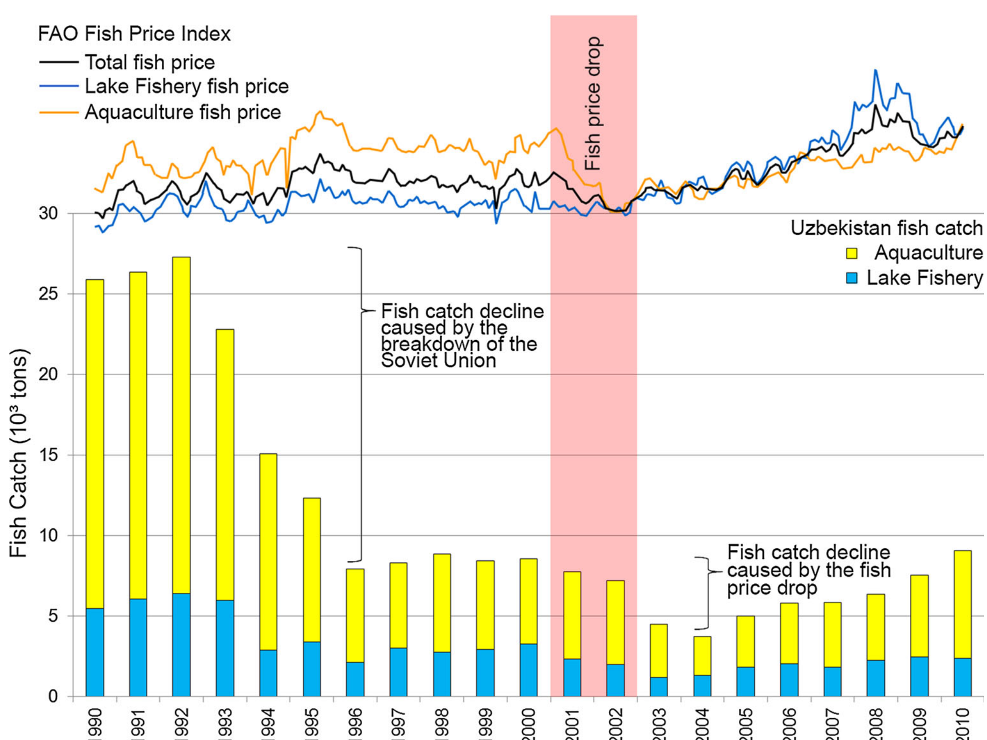


Fig. 9 Uzryba fish catch development and composition in the AALS compared with Uzbekistan

Fig. 10 Development of the Uzbek fish catch in relation to the FAO Fish Price Index fluctuations (data: FAO 2014; Karimov et al. 2009)



per 100 years), while the precipitation slightly decreased during the twentieth century (Fig. 4). The rise of the air temperature will continue during the twenty-first century (Aizen et al. 2006; Agaltseva 2004; Chub et al. 2002; Groll et al. 2015a; Ibatullin et al. 2009) so that by 2050 the average annual air temperature in Jizzakh could be between 16.5 and 17.0 °C. This will increase the evaporation rate in the lake system and increase the water demand for the irrigation farming (longer vegetative periods, higher transpiration activity). Combined with the reduced river runoff due to the receding and vanishing glaciers in the Tien Shan (Agaltseva 2008; Bates et al. 2008; Chub et al. 2002; Cruz et al. 2007; Hagg et al. 2007; Ibatullin et al. 2009; Konovalov and Agaltseva 2005; Kutuzov and Shahgedanova 2009; Lioubimtseva and Henebry 2009; Perelet 2008), the inflow of fresh water from the Chardarya reservoir into the lake system will be smaller than in recent years.

The continued strong population and economic growth in Uzbekistan on the other hand (+1.7 and +8 % per year, Djanibekov et al. 2010; http://www.cia.gov 2013; http://www.indexmundi.com 2013; http://www.worldbank.org 2013) will lead to an expansion of the irrigated farmland, further increasing the water demand and the amount of highly mineralized drainage water dumped into the Tuzkan and Arnasay lakes.

These climatic and anthropogenic factors will probably lead to a reduction in the lake's volume and to an increase in its salinity. The desiccation and finally the loss of the three lakes is a possibility and needs to be considered within any water resources management plan for the Syr Darya catchment. But if the AALS will in the end truly join the fate of the Aral Sea cannot be foreseen at this point.

The analysis of the fish catch also showed that the lake system has a great potential for the fishery. This potential could be utilized for improving the food security for the growing population if additional funds for the maintenance of the fishing equipment and for the restocking with fish spawn were available.

And finally does the lake system itself represent a valuable ecosystem, especially for migrating and wintering waterbirds at the crossroads of the Afro-Eurasian and Central Asian flyways. The Aydarkul is an ornithological protected area under the Ramsar Convention on Wetlands of International Importance since 1983, and the whole lake system is a key element of the proposed Nuratau-Kyzylkum Biosphere Reserve.

Protecting the Aydarkul–Arnasay Lake System—even if the lakes were created by human activities and an extraordinary flood event half a century ago—is thus a worthwhile endeavor. The services the AALS provides for the local climate, the Uzbek economy and as an ecosystem are very valuable. But the lake system is also a fragile system which requires an integrated management in order to acknowledge all interests involved.

Acknowledgments The Erasmus Mundus CASIA 3 Programme (EU) and the DAAD are acknowledged for funding the international short visits of Dr. R. Kulmatov to the University of Natural Resources and Life Sciences (BOKU) Vienna (Austria) and to the Philipps-University Marburg (Germany) to complete this study.

References

Abakumov BA (ed) (1983) Handbook of methods for the hydrobiological analysis of surface water and sediments. Gidrometeoizdat, Leningrad **(in Russian)**

Abdullaev I, Rakhmatullaev S (2015) Transformation of water management in Central Asia—from State-centric, hydraulic mission to socio-political control. Environ Earth Sci 73:849–861. doi:10.1007/s12665-013-2879-9

Agaltseva N (2004) Climate change impact on the mountains river runoff in the Central Asian region. Landschaftsökologie und Umweltforschung 47. In: Proceedings of the international conference on hydrology of mountain environments, Berchtesgaden, Braunschweig, pp 7–8

Agaltseva N (2008) Assessment of the river extreme runoff for climate scenarios conditions. Climate change effects, adaptation issues. NIGMI Bull 7:5–9

Aizen VB, Aizen EM, Joswiak DR, Fujita K, Takeuchi N, Nikitin SA (2006) Glacier changes in the central and northern Tien Shan during the last 140 years based on surface and remote-sensing data. Ann Glaciol 43:202–213

Alihanov BB (2008) About a condition of environment and use of natural resources in Republic of Uzbekistan (The Retrospective Analysis for 1988–2007). National Report of the State Committee for Nature Protection of the Republic of Uzbekistan, Tashkent **(in Russian)**

Amanov AA (1985) Fish ecology of water bodies in the south of Uzbekistan and neighbouring republics. Pub. FAN, Tashkent **(in Russian)**

Aparin V, Kawabata Y, Ko S, Shiraishi K, Nagai M, Yamamoto M, Katayama Y (2006) Evaluation of geoecological status and anthropogenic impact on the Central Kyzylkum Desert (Uzbekistan). J Arid Land Stud 15:129–133

Bates B, Kundzewicz ZW, Wu S, Palutikof J (eds) (2008) Climate change and water. Technical paper. Intergovernmental Panel on Climate Change, Geneva

Bernauer T, Siegfried T (2012) Climate change and international water conflict in Central Asia. J Peace Res 49(1):227–239. doi:10.1177/0022343311425843

Bohlin T, Hamrin S, Heggberget TG, Rasmussen G, Saltveit SJ (1989) Electrofishing—theory and practice with special emphasis on salmonids. Hydrobiologia 173:9–43

Chub VE, Agaltseva N, Myagkov S (2002) Climate change impact on the rivers runoff for the Central Asian River. In: Proceedings of the international conference on hydrology and watershed management with the focal theme on water quality and conversation, vol 2, pp 252–257

Cruz RV, H. Harasawa H, Lal M. Wu S, Anokhin B, Punsalmaa Y, Honda Y, Jafari M, Li C, Huu Ninh N (2007) Asia. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 469–506

Cudmore B, Mandrak NE (2004) Biological synopsis of grass carp (Ctenopharyngodon idella). Can Manuscr Rep Fish Aquat Sci 2705:44

Djanibekov N, Frohberg K, Djanibekov U (2010) Income-based projections of water demand for food consumption in Central Asia—the case of Uzbekistan. In: Merz B, Dukhovny V, Unger-Shayesteh K (eds) Water in Central Asia, volume of abstracts, international scientific symposium, November 2010. Tashkent, p 35

Ermakhanov ZK, Plotnikov IS, Aladin NV, Micklin P (2012) Changes in the Aral Sea ichthyofauna and fishery during the period of ecological crisis. Lakes Reserv Res Manag 17:3–9

FAO (2003) Fertilizer use by crop in Uzbekistan. FAO Land and Water Development Division, Rome, p 28

FAO (2014) The state of world fisheries and aquaculture—opportunities and challenges. FAO, Rome, p 223

Fedorov EA (1973) Morphological characteristics of the Crucian Carp of the Kairak-Kum Reservoir. IZV Akad Nauk Tadzh SSR OTD Biol Nauk 1:75–78 **(in Russian)**

Groll M, Opp C, Aslanov I (2013) Spatial and Temporal distribution of the dust deposition in Central Asia—results from a long term monitoring program. Aeolian Research 9:49–62. doi:10.1016/j.aeolia.2012.08.002

Groll M, Opp C, Kulmatov R, Ikramova M, Normatov I (2015a) Water quality, potential conflicts and solutions—an upstream-downstream analysis of the transnational Zarafshan River (Tajikistan, Uzbekistan). Environ Earth Sci 73:743–763. doi:10.1007/s12665-013-2988-5

Groll M, Opp C, Kulmatov R, Sun Z, Normatov I, Bernardi A, Ikramova M, Stulina G (2015b) Managing Central Asia's transboundary rivers—case studies from the Zarafshan (Tajikistan/Uzbekistan) and Tarim (Kyrgyzstan/China) River. In: Brebbia CA (ed) River basin management VIII. WIT transactions on ecology and the environment, vol 196, pp 149–160. doi:10.2495/WRM150131

Hagg W, Braun LN, Kuhn M, Nesgaard TI (2007) Modelling of hydrological response to climate change in glacierized Central Asian catchments. J Hydrol 332(1–2):40–53

http://neespi.sr.unh.edu/ (2014) Hydrological data provided by the Northern Eurasia Earth Science Partnership Initiative. Accessed 10 Dec 2014

http://www.bafg.de (2015) Hydrological data provided by the Global River Discharge Database. www.bafg.de/GRDC/EN/Home/homepage_node.html. Accessed 8 Nov 2015

http://www.cia.gov (2013) The world Facbook. http://www.cia.gov/library/publications/the-world-factbook/. Accessed 12 Mar 2013

http://www.indexmundi.com (2013) Worldwide statistical database. http://www.indexmundi.com/asia.html. Accessed 13 Mar 2013

http://www.ncdc.noaa.gov (2015) Meteorological data provided by the Global Historical Climate Network. www https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-data sets/global-historical-climatology-network-ghcn. Accessed 8 Nov 2015

http://www.worldbank.org (2013) Statistical data about countries and economies. http://data.worldbank.org/country. Accessed 2 Apr 2013

Ibatullin S, Yasinsky V, Mironenkov A (2009) Impacts of climate change on water resources in Central Asia. Sector report of the Eurasian development bank, p 42

Kamilov GK (1973) Fish in Uzbekistan Reservoirs. Pub FAN, Tashkent **(in Russian)**

Kamilov GK, Urchinov ZU (1995) Fish and fisheries in Uzbekistan under the impact of irrigated agriculture. In: Petr T (ed) Inland fisheries under the impact of irrigated agriculture—Central Asia. FAO Fisheries Circular 894 FIRI/v9529, Rome, pp 10–42

Karimov B, Kamilov B, Upare M, van Anrooy R, Bueno P, Shokhimardonov D (2009) Inland capture fisheries and aquaculture in the Republic of Uzbekistan—current status and planning. FAO Fisheries and Aquaculture Circular No. 1030/1, SEC/C1030/1, Rome, p 124

Karthe D, Chalov S, Borchardt D (2015) Water resources and their management in central Asia in the early twenty first century—status, challenges and future prospects. Environ Earth Sci 73:487–499

Kiyatkin AK, Shaporenko SI, Sanin MV (1990) Water and Salt Regime of the Arnasai Lakes. Gidrotekhnicheskoe Stroitel'stvo 3:172–177

Konovalov VG, Agaltseva N (2005) Projected change of glaciers size and river runoff in the different scenarios of future climate. Exch Intellect Prop 4(8):37–47

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 PP (eds) Dying and dead seas—climatic versus anthropogenic causes. NATO science series IV—earth and environmental sciences, vol 36, pp 1–48. doi:10.1007/978-94-007-0967-6

Küçük S (2013) The effects of salinity on growth of goldfish, *Carassius auratus* and crucian carp, *Carassius carassius*. Afr J Biotechnol 12(16):2082–2087. doi:10.5897/AJB12.430

Kulmatov RA, Hojamberdiev M (2010) Heavy metals concentration and speciation in Arid Zone Rivers (Amudarya and Syrdarya) of Central Asia. J Environ Sci Eng 4(8):36–45

Kulmatov R, Mullabaev N, Nigmatov A, Kulmatova D, Sobirov J (2013) Qualitative and quantitative assessment of water resources of Aydar Arnasay Lake System (AALS). J Water Resour Protect 5(10):941–952. doi:10.4236/jwarp.2013.510097

Kutuzov S, Shahgedanova M (2009) Glacier retreat and climatic variability in the eastern Terskey-Alatoo, inner Tien Shan between the middle of the 19th century and beginning of the 21st century. Glob Planet Chang 69:59–70

Létolle R, Aladin N, Filipov I, Boroffka NGO (2005) The future chemical evolution of the Aral Sea from 2000 to the years 2050. Mitig Adapt Strateg Global Change 10:51–70

Libert B, Orolbaev E, Steklov Y (2008) Water and energy crisis in Central Asia. China Eurasia Forum Q 6(3):9–20

Lioubimtseva E (2015) A multi-scale assessment of human vulnerability to climate change in the Aral Sea basin. Environ Earth Sci 73:719–729. doi:10.1007/s12665-014-3104-1

Lioubimtseva E, Henebry GM (2009) Climate and environmental change in arid Central Asia—impacts, vulnerability, and adaptations. J Arid Environ 73:963–977

Matley IM (1970) The Golodnaya Steppe—a Russian irrigation venture in Central Asia. Geogr Rev 60(3):328–346

Micklin PP (1988) Desiccation of the Aral Sea: a water management disaster in the Soviet union. Science 241:1170–1176

Micklin P (2007) The Aral Sea Disaster. Annu Rev Earth Planet Sci 35:47–72. doi:10.1146/annurev.earth.35.031306.140120

Micklin P (2016) The future Aral Sea: hope and despair. Environ Earth Sci 75(9):15. doi:10.1007/s12665-016-5614-5

Micklin PP, Williams WD (eds) (1996) The Aral Sea Basin. NATO ASI Series, vol 12, p 187. doi:10.1007/978-3-642-61182-7

Mullabaev N (2006) The Arnasay lake system fish products's development perspectives. In: Ecological Vestnik, pp 37–38 **(in Russian)**

Mullabaev N (2010) Hydrogeological condition and fish development potential of AALS and Mejdurrechinsk. PhD thesis, National University of Uzbekistan, Tashkent **(in Russian)**

O'Hara SL, Wiggs GF, Mamedov B, Davidson G, Hubbard RB (2000) Exposure to airborne dust contaminated with pesticide in the Aral Sea region. Lance 355(9204):627–628

Opp C (2007) Vom Aralsee zur Aralkum—Ursachen, Wirkungen und Folgen des Aralseesyndroms. In: Glaser R, Kremb K (eds) Asien (Reihe Planet Erde). Wissenschaftliche Buchgesellschaft, Darmstadt, pp 90–100

Perelet R (2008) Central Asia—background paper on climate change. In: UNDP (eds) Human Development Report 2007/2008 - Fighting climate change: Human solidarity in a divided world. Human Development Report Office. Occasional Paper, p 24

Petr T (1995) Fisheries in irrigated areas of Central Asia. In: Petr T (ed) Inland fisheries under the impact of irrigated agriculture—Central Asia. FAO Fisheries Circular 894 FIRI/v9529, Rome, p 62

Petr T, Ismukhanov K, Kamilov B, Umarov P (2004) Irrigation systems and their fisheries in the Aral Sea Basin, Central Asia. In: Robin L, Petr T (eds) Sustaining livelihoods and biodiversity in the new millennium. Proceedings of the FAO and Mekong River commission conference, 11.-14.02.2003, Phnom Penh. RAP Publication 17/2004, p 27

Pravdin IF (1966) Manual on study of fish. Pischevaya Promyshlennos, Moscow **(in Russian)**

Ryabtsev AD (2001) Threats to water security in the Republic of Kazakhstan: the transboundary context and possible ways to eliminate them. In: Madramootoo CA, Dukhovny VA, Baker RS, Fyles IH (eds) Water and food security in Central Asia. NATO science for peace and security series – c – environmental security, pp 69–75

Sagitov NI (1983) Fishes and fodder invertebrates in the middle and lower course of the Amu Darya. Pub. FAN, Tashkent **(in Russian)**

Saiko T, Zonn IS (2000) Irrigation expansion and dynamics of desertification in the Circum-Aral region of Central Asia. Appl Geogr 20:349–367

Savoskul OS (ed) (2003) Water, climate, food, and environment in the Syr Darya Basin. Adaptation strategies to changing environments. Report for the Stockholm Environment Institute, p 62

Shepherd A, Mitchell T, Lewis K, Lenhardt A, Jones L, Scott L, Muir-Wood R (2013) The geography of poverty, disasters and climate extremes in 2030. ODI report, London, p 72

Solodukhin VP, Poznyak VL, Kazachevskiy IV, Knyazev BB, Lukashenko SN, Khazhekber S (2004) Some peculiarities of the contamination with radionuclides and toxic elements of the Syrdarya river basin, Kazakhstan. J Radioanal Nucl Chem 259(2):245–250

Umarov NU (2013) About a condition of environment and use of natural resources in Republic of Uzbekistan (The Retrospective Analysis for 2008–2011). National Report of the State Committee for Nature Protection of the Republic of Uzbekistan, Tashkent **(in Russian)**

US Army Map Service (ed) (1955) Maps of Central Asia – NK42-7 (Chardara, U.S.S.R.), NK42-8 (Tashkent, U.S.S.R.), NK42-10 (Dzhizak, U.S.S.R.). Corps of Engineers, Washington

Wahyuni S, Oishi S, Sunada K, Toderich KN, Gorelkin NE (2009) Analysis of water-level fluctuations in Aydarkul-Arnasay-Tuzkan lake system and its impacts on the surrounding groundwater level. Annu J Hydraul Eng 53:37–42

Whish-Wilson P (2002) The Aral Sea environmental health crisis. J Rural Rem Environ Health 1:29–34

WHO (eds) (1996) Total dissolved solids in drinking-water—background document for development of WHO guidelines for drinking-water quality. WHO/SDE/WSH/03.04/16. Originally published in: Guidelines for drinking-water quality, Health criteria and other supporting information, 2nd edn. vol 2, World Health Organization, Geneva, p 3

Wiggs GFS, O'Hara S, Wegerdt J, Van Der Meer J, Small I, Hubbard R (2003) The dynamics and characteristics of aeolian dust in dryland Central Asia: possible impacts on human exposure and respiratory health in the Aral Sea basin. Geogr J 169:142–157

Wootton RJ (1990) Ecology of teleost fishes. Springer, Netherlands

Zetterström R (1999) Child health and environmental pollution in the Aral Sea region in Kazakhstan. Acta Paediatr Suppl 429:49–54