Chapter 17
Impact of Climate Change on the Aral Sea and Its Basin

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Abstract Climatic and environmental changes in the Aral Sea Basin represent a complex combination of global, regional, and local processes of variable spatial and temporal scales. They are driven by multiple interconnected factors, such as changes in atmospheric circulation associated with global warming, regional hydrological changes caused by mountain-glacial melting and massive irrigation, land-use changes, as well as hydrological, biogeochemical, and meso- and microclimatic changes in the Aral Sea and its quickly expanding exposed dry bottom. Human vulnerability to climate change involves many dimensions, such as exposure, sensitivity, and adaptive capacity and affects various aspects of human-environmental interactions, such as water availability and stress, agricultural productivity and food security, water resources, human health and well-being and many others at various spatial and temporal scales.

Keywords Climate change • Climate variability • Land use • Human vulnerability • Arid environments • Adaptations • Aral Sea

17.1 Introduction

Society and environment of the Aral Sea Basin have been increasingly affected by climate change and variability that occur at multiple temporal and spatial scales. Climate, land-use, and hydrology are interconnected in complex ways. Any change in one of these systems induces a change in the other. For example, basin-wide hydrological and land cover changes have caused changes in temperature patterns and a decrease of precipitation, when local boundary conditions dominate over the large-scale circulation. On the other hand, global and regional climate change

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affects hydrological processes with respect to mean states and variability as well as land-use options. Water use is impacted by climate change, and also, more importantly, by changes in population, lifestyle, economy, and technology; in particular by food demand, which drives irrigated agriculture, globally the largest water-use sector. Significant changes in water use or the hydrological cycle (affecting water supply and floods) require adaptation in the management of water resources (IPCC and WGII 2007).

Climatic and environmental changes in the Aral Sea Basin represent a complex combination of global, regional, and local processes of variable spatial and temporal scales. They are driven by multiple interconnected factors, such as changes in atmospheric circulation associated with global warming, regional hydrological changes caused by mountain-glacial melting and massive irrigation, land-use changes, as well as hydrological, biogeochemical, and meso- and microclimatic changes in the Aral Sea and its quickly expanding exposed dry bottom. To understand the problem requires a nested multi-scale conceptual model addressing multiple natural and human-induced processes of various scales, their interrelations, and feedbacks. The purpose of this paper is to discuss climate change and human vulnerability in the Aral Sea Basin at several interconnected scales.

Human vulnerabilities to climate in drylands are strongly correlated with climate variability and changes, and especially variability of precipitation and runoff. These vulnerabilities are particularly high in the Aral Sea Basin, where stream flow is generated by the mountain glaciers and concentrated over a short period of time measured in months, and year-to-year variations are significant. A lack of deep groundwater wells or reservoirs leads to a high level of vulnerability to climate variability, and to the climate changes that are likely to further increase climate variability in the future. In addition this region, already stressed due to local, regional and global climatic changes, is likely to be vulnerable to non-climatic stresses (e.g. political, economic, institutional, etc.).

Climate change impacts and human vulnerability involve many variables, such as impacts of climate change on food security, water resources, health, security and other aspects of human life. Regional development factors contribute to the global climate change both through greenhouse emissions and the interactions between land cover and the boundary layer of the atmosphere. Exposure, sensitivity, and adaptive capacity of different regions and sectors also vary depending on spatial and temporal scales.

This chapter consists of four sections. Section one provides a brief discussion of the study area, overview of the essential terminology and provides the key references to the seminal bibliography. Section two describes the climate and climate change in the Aral Sea Basin at four scales: from the global to regional. This section is based on an extensive literature review, meteorological records, and climate change scenarios generated by the Atmosphere–ocean General Circulation Models (AOGCMs). Section three provides a discussion of the key aspects of human vulnerability, such as exposure, sensitivity and adaptive capacity, with regard to climate change impacts on water resources, agriculture, and human health. Finally, section four draws conclusions and offers some reflections on potential mitigation and adaptation policies for the Aral Sea Basin countries.

17.2 Climate Change in the Aral Sea Basin: A Multi-Scale and Multi-Dimensional Problem

The Aral Sea drainage basin area is approximately 1,874,000 km^2, of which the individual Amu Darya and Syr Darya catchments constitute a major part, and smaller catchment areas amount to about 321,000 km^2 (Shibuo et al. 2007). Afghanistan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan share the basin of the Amu Darya River. Kazakhstan, Kyrgyzstan, Tajikistan and Uzbekistan share the basin of the Syr Darya. The Aral Sea Basin comprises the Turan Lowland including the Kara-Kum, Kyzyl-Kum, and Muyun-Kum deserts and is bordered by the Kazakh Hills in the north and the ranges of Kopet-Dag, Tian Shan and Pamir mountains in the south.

Numerous biostratigraphic, geomorphological and archaeological data indicate that the climate of the Aral Sea Basin has been experiencing natural fluctuations for many thousands of years (Vinogradov and Mamedov 1991; Boomer et al. 2000; Sorrel et al. 2007). In addition, the global climate change of the past century associated with enhancement of the greenhouse effect, has contributed to much faster changes in meteorological and hydrological regimes, causing shifts in the major circulation systems, temperature and precipitation regimes and accelerating melting of the mountain glaciers in Central Asia (Thompson et al. 1993; Oerlemans 1994). The major controls on precipitation change in the Aral Sea Basin include latitudinal shifts of the westerly cyclonic circulation and position of the Siberian high. The level of the Aral Sea entirely depends on the run-off of the Syr Darya and Amu Darya, starting in the Pamir and Tian Shan mountains, and ultimately depends on the rhythm of mountain glaciation. Temporal variability of precipitation is very high and precipitation has a distinctive spring maximum in most of the region. Very high daily temperature variance is recorded with frequent sand storms and intense sunshine. As in many other arid and semi-arid regions, the climate of Central Asian deserts and semi-deserts is highly variable. The major controls on precipitation change in Central Asia include latitudinal shifts of the westerly cyclonic circulation and position of the Siberian high (Lioubimtseva 2003). The North Atlantic Oscillation (NAO) exerts an important control over the pattern of wintertime atmospheric circulation variability over arid and semi-arid zones of Central Asia. Over the past four decades, the pattern captured in the NAO index has altered gradually from the most extreme and persistent negative phase in the 1960s to the most extreme positive phase during the late 1980s and early 1990s.

At a regional scale, two interconnected anthropogenic factors have been increasingly contributing to climate change in Central Asia: basin-wide land-use and land-cover changes (Lioubimtseva and Henebry 2009; Kariyeva and van Leewuven 2011) and rapid degradation of the Aral Sea itself (Micklin 2010). Therefore, current and future climatic trends in this region can best be addressed as a combination of nested interconnected processes and feedbacks operating at several spatial and temporal scales. I will discuss four groups of such factors:

(a) Natural long-term global climate change and variability;
(b) Anthropogenic global climate change (global warming);
(c) Regional land-use and land cover changes in the Aral Sea Basin;
(d) Meso-climatic changes caused by the Aral Sea degradation.

17.3 Natural Long-Term Climate Changes

The landforms of this region carry relict features both of relatively short humid intervals with runoff higher than modern, and long arid periods (Boomer et al. 2000; Lioubimtseva 2003; Lioubimtseva et al. 2005; Boroffka et al. 2006). Pollen and archaeological data from the Aral Sea Basin suggest that climate change was followed by significant ecosystem changes. Marine fossils, relict shore terraces, archaeological sites, and historical records point to repeated major recessions and advances of the Aral Sea (Varuschenko et al. 1987; Kes et al. 1993). Although the structure of the Aral Basin can be traced back to the late Neogene, the Sea has only existed in its present form for the past 10,000 years and its Holocene history has been shaped by regional climatic variations, the development of the associated drainage system and anthropogenic forces (Boomer et al. 2000). Significant cyclical variations of regional climate and sea level during this period resulted from major changes in river discharge caused by climatic changes and several natural diversions of the Amu Darya River away from the Aral Sea (Micklin 1988; Kes et al. 1993; Vinogradov and Mamedov 1991; Boomer et al. 2000).

Paleoenvironmental reconstructions based on pollen and archaeological data suggest that the Aral Sea experienced a period of almost complete desiccation during the Late Glacial Maximum (around 20–18,000 years before present) and again in the Younger Dryas (12,800 and 11,500 years before present), when the climate of Central Asia was characterized by colder winter temperatures, cooler summers and greater aridity (Boomer et al. 2000; Lioubimtseva et al. 2005; Tarasov et al. 2007). The Djanak arid phase of the Younger Dryas was followed by an increase in temperatures and precipitation during the Early and Mid-Holocene (Sorrel et al. 2007; Tarasov et al. 2007). A trend towards greater humidity during the Holocene culminated around 6,000 years ago, a phase known in Uzbekistan and Turkmenistan as the Liavliakan pluvial (Vinogradov and Mamedov 1991; Lioubimtseva et al. 1998). According to Vinogradov and Mamedov (1991) mean annual precipitation in the deserts of Central Asia could have been three times higher than at present and desert landscapes were possibly entirely replaced by mesophytic steppes, with well-developed forest vegetation along the river valleys. Climate variations resulted in multiple shifts from hyper-arid to semi-arid steppe vegetation (Varuschenko et al. 1987; Tarasov et al. 2007). A general aridization trend that started approximately 5,000 years ago was interrupted by multiple minor climatic fluctuations in this region at a finer temporal scale (Esper et al. 2002; Sorrel et al. 2007).

17.4 Impacts of Global Climate Change: Current Trends and Projections

In addition to the natural climatic variability, more recent and shorter-term climatic changes have been observed in the Aral Sea Basin and are likely to be caused by global and regional anthropogenic factors. Recent climate trends and variability in Central Asia are generally characterized by increasing surface air temperature, which is more pronounced during winter than in summer. Meteorological data series available in the Aral Sea Basin since the end of the nineteenth century show a steady increase of annual and winter temperatures in this region. Studies of climate data (Neronov 1997; Chub 2000; Lioubimtseva et al. 2005; Lioubimtseva and Henebry 2009) indicate a steady warming trend of 1–2 °C per century throughout the region. Steady temperature increases during the past century might be an indication of a general spatial shift in the atmospheric circulation in Central Asia (Lioubimtseva et al. 2005). The recorded increases in both mean annual and seasonal temperature trends are likely to result from the decreasing intensity of the southwestern periphery of the Siberian high in winter and the intensification of summer thermal depressions over Central Asia.

Reliable and well-distributed climate observations are essential for monitoring and modeling climate change and developing informed adaptation policies. Unfortunately, the climate observing system in Central Asia is currently the worst in the former Soviet Union and continues to deteriorate. Meteorological stations that operated before collapse of the USSR have been closed or operate sporadically. For example, out of nine stations that existed during the Soviet time, now there are only three stations that still collect data near the former shore of the Aral Sea: Aralskoye Morye near Aralsk on the north, Muynak on the south, and Aktumsyk on the Ust-Urt Plateau on the west (Philip Micklin, 9 May 2012, personal communication).

Warming of the global climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level (IPCC, WGI 2007). The last two decades appear to be the warmest years in the instrumental record of global surface temperature since 1850. The temperature increase is widespread over the globe and is greater in the Northern hemisphere and at high and mid-latitudes. While meteorological data consistently indicate the warming trend throughout Central Asia since the beginning of the nineteenth century, the precipitation trends are much more variable (Neronov 1997; Chub 2000; Lioubimtseva et al. 2005). Precipitation records show a slight decrease during the past 50–60 years in the western part of the region, no change or slight increase throughout most of the region, and much more significant local increase in precipitation recorded by the stations surrounded by irrigated lands (Lioubimtseva and Henebry 2009).

Based on the multi-model (MMD) simulations discussed in the IPCC Fourth Assessment report, Central Asia is likely to warm by a median of 3.7 °C by the end of this century (IPCC, WGI 2007). The seasonal variation in the simulated warming is modest. This author conducted several comparative studies of climate change scenarios produced by the Atmosphere Ocean Global Climate Models (AOGCMs) used by the IPCC (Lioubimtseva et al. 2005; Lioubimtseva 2007; Lioubimtseva and Henebry 2009). Annual, seasonal and monthly AOGCM scenarios for Central Asia used in the Third and Fourth IPCC Reports (TAR IPCC 2001 and AR4 IPCC and WGI 2007) indicate a generally good agreement among the models suggesting that the current trend of temperature increase in arid Central Asia is likely to continue through the entire Aral Sea Basin. Lioubimtseva and Henebry (2009) analyzed the regional scenarios derived from 23 AOGCMs using MAGICC/SCENGEN 5.3 software developed by the National Center for Atmospheric Research (Wigley 2008). Annual and seasonal temperature and precipitation scenarios were examined under A1FI-AIM and A1B-MES IPCC SRES scenarios (Nakicenovic et al. 2000). Temperature changes in the Aral Sea Basin are projected to increase by 3–5 °C by 2080 and all AOGCMs agree that the warming is very likely to be accompanied by a further intensification of aridity. Climate change scenarios significantly differ across seasons, with much higher temperature changes generally predicted by all models during the winter months.

The range of precipitation projections produced by AOGCMs is much more uncertain. Precipitation over central Asia increases in most MMD-A1B projections for winter but decreases in the other seasons. The median change by the end of the twenty-first century is −3 % in the annual mean, with +4 % in winter and −13 % in summer (IPCC, WGI 2007). This seasonal variation in the changes is broadly consistent with the earlier multi-model study of Meleshko (2004), although they find an increase in summer precipitation in the northern part of the area. The majority of climate models project a slight decrease in precipitation rate over most of the region (~1 mm/day by 2050) with a stronger decrease in the western and southwestern parts of the region and a very slight increase in the northern and eastern part of Central Asia (~1 mm/day) (Lioubimtseva and Henebry 2009). Average MMD projections for the annual temperature and precipitation changes driven by the A1FI SRES scenario by the middle of this century are summarized in Table 17.1.

The majority of the AOGCM experiments used in the IPCC AR4 (2007) suggest a high probability of increasingly dry conditions with a slight increase in winter rainfall, but decreases particularly in spring and summer. This trend towards higher aridity is projected to be more significant west from 70 °E to 72 °E latitude. According to the IPCC, the western part of Central Asia (area between the Caspian and Aral Seas) is very likely to become drier during the coming decades, while the central and eastern part might experience a slight increase in precipitation (IPCC and WGII 2007). The MMD scenarios appear to be consistent with the observed temperature and precipitation trend over the past decades in most of the region. Given the low absolute amounts of precipitation and high inter-annual, seasonal, and spatial variability of precipitation across the region, the changes in precipitation rate projected by the AOGCMs cannot be deemed very reliable. Due to the complex topography and the associated mesoscale weather systems of the high-altitude and

Table 17.1 MMD -AF1 climate changes scenario for the Aral Sea basin by 2050, relative to 1961–1990

Seasonal changes	Winter	Spring	Summer	Fall
Mean temperature, °C	1.5–4.95	2.87–3.99	3.24–7.36	3.05–3.99
Maximum temperature, °C	1.9–4.5	2.33–3.99	2.88–9.33	2.88–3.99
Minimum temperature, °C	1.7–4.95	1.88–3.30	3.99–5.33	2.69–3.91
Precipitation, mm/day	0.01–0.1	0–0.09	−1.11–0.09	−0.5–0.09

Climate change scenarios were generated by the author with MAGICC/SCENGEN5.3.2 model (Wigley 2008)

arid areas, AOGCMs typically tend to overestimate the precipitation (IPCC and WGI 2007).

It is the change in the temporal and spatial variability of precipitation and its seasonal distribution – rather than absolute precipitation values – that are more important for the assessment of human vulnerability in this arid region, but they are also more difficult to project. It is uncertain the extent to which the observed and projected trends result primarily from the global restructuring of atmospheric circulation and changes in the teleconnections controlling macroclimatic conditions over Central Asia versus mesoclimatic changes induced by regional land use change. There are several sources of uncertainty associated with the AOGCM scenarios. The resolution of these models is quite coarse (a horizontal resolution of between 250 and 600 km and 10–20 vertical layers in the atmosphere). Many physical processes, such as those related to clouds, occur at more detailed scales and cannot be adequately modeled; instead, their known properties are averaged over a larger scale in a technique known as parameterization (IPCC and WGI 2007). Other uncertainties relate to the simulation of various feedback mechanisms in models concerning, for example, water vapor and warming, clouds and radiation, ocean circulation and ice and snow albedo (Arnell 2004; IPCC and WGI 2007).

17.5 Regional Land-Use and Land-Cover Changes in the Aral Sea Basin

At the regional scale, effects of the global climatic changes might appear insignificant compared to the superimposed land changes and processes, such as irrigation, overgrazing, wind erosion, ground water depletion etc. Arid areas all over the world have shown themselves to be highly susceptible to the effects of human intervention (de Sherbinin 2002; Glantz 2005). Conversion of desert and semi-desert rangelands into irrigated cropland made many parts of this region particularly vulnerable to recent environmental, economic, and political changes. The most dramatic land use changes were driven by two factors. First, is the rapid and massive expansion of irrigation, water diversion, and conversion of desert rangelands into irrigated croplands that occurred primarily under the Soviet regime from the mid-1950s to the mid 1980s (Micklin 1988, 2007; Glantz 2005). Second, is the decline of agriculture and livestock in the 1990s due to the collapse of the USSR at the end of 1991 (Lioubimtseva and Henebry 2009).

Irrigated arable land, principally for cotton monoculture, increased by 60 % in the region from 1962 to 2002 (Lioubimtseva et al. 2005). The total irrigated area in the study area increased by over half a million hectares (5.2 %) just from 1992 to 2002 (Lioubimtseva and Cole 2006). Turkmenistan alone accounted for 59 % of the change, increasing its irrigated area by 300,000 ha (20 %). Total water withdrawals (all uses) were 125 % of the average annual water resources in 1988 (Glazovsky 1995). Such dramatic human-induced changes in the hydrological cycle led not only to a significant decrease of river runoff, changes in the number and area of lakes and rise of groundwater levels, but also to significant changes in evapotranspiration and precipitation.

The dissolution of the Soviet Union had a dramatic impact on the agricultural sector of the newly independent Central Asian states. With little or no access to fertilizers, pesticides, subsidies, and markets, a substantial amount of land was idled with longer fallow periods. Furthermore there were significant shifts in crop composition that differed among the Central Asian states as a result of internal policies regarding land reform and farm restructuring (Sievers 2003). Across the Central Asian States, the impact of the political and economic transition on agricultural production was very severe (Chuluun and Ojima 2002; Lioubimtseva and Cole 2006). In Kazakhstan, sheep numbered 33.9 million in 1992. By 1999 that figure had dropped 74 % to 8.6 million, but by 2005 had risen 11.4 million. In 1992 Kazakhstan had 57 % of the sheep in Central Asia; in 2005 that share was only 29 %. The total number of sheep in Central Asia in 2005 was 40 million or 67 % of what it had been in 1992 (Lioubimtseva and Henebry 2009). The sheep stock time series indexed to 1992 show the divergence among the Central Asian States from collapse and slow recovery in Kazakhstan to steady growth in Turkmenistan (Fig. 17.1). From a 9 % share of the regional sheep stock in 1992, Turkmenistan reached a 36 % share in 2005 with 14.3 million sheep (Lioubimtseva and Henebry 2009).

The decline of agriculture was sufficiently great to be captured by the Normalized Difference Vegetation Index (NDVI) derived from the red and near-infrared channels of the NOAA AVHRR imagery, despite the high climatic inter-annual variability (de Beurs and Henebry 2004; Lioubimtseva 2007; Kariyeva and van Leewuven 2011).

The principle behind NDVI is that the red-light region of the electromagnetic spectrum is where chlorophyll causes considerable absorption of incoming sunlight, whereas the near-infrared region of the spectrum is where a plant's spongy mesophyll leaf structure creates considerable reflectance (Tucker et al. 1991). As a result, vigorously growing healthy vegetation has low red-light reflectance and high near-infrared reflectance, and hence, high NDVI values. This relatively simply algorithm produces output values in the range of -1.0 to 1.0. Increasing positive NDVI values, shown in increasing shades of green on the images, indicate increasing amounts of green vegetation. NDVI is calculated from these individual measurements as follows: $\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{RED})/(\mathrm{NIR} + \mathrm{RED})$, where RED

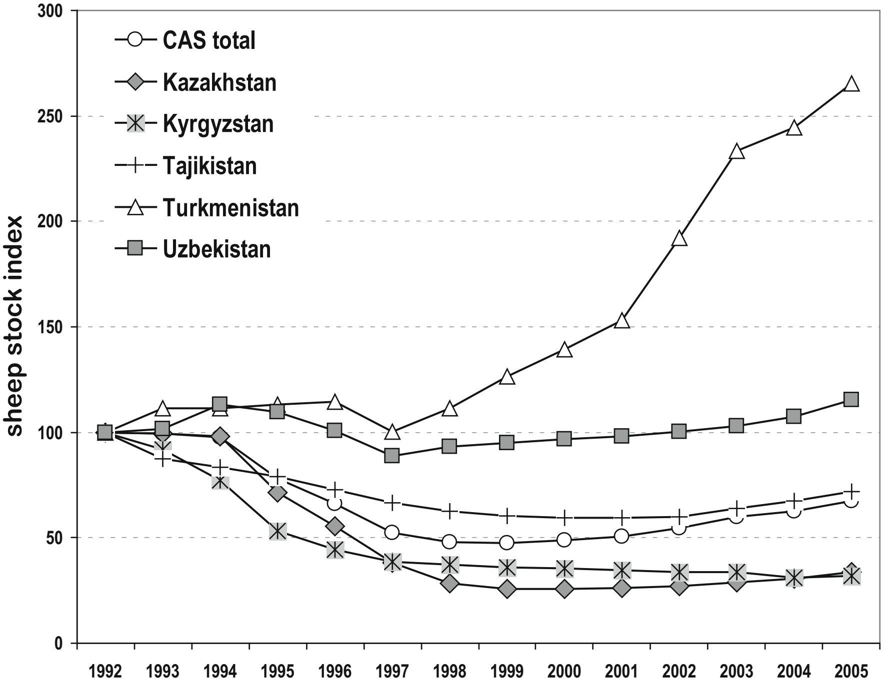

Fig. 17.1 Sheep stocks indexed to 1992 reveal divergent trajectories: collapse in Kazakhstan, Kyrgyzstan, and Tajikistan; little change in Uzbekistan; and significant growth in Turkmenistan (Lioubimtseva and Henebry 2009)

and NIR stand for the spectral reflectance measurements acquired in the red and near-infrared regions, respectively. NDVI values near zero and decreasing negative values indicate non-vegetated features such as barren surfaces (rock and soil) and water, snow, ice, and clouds.

First, a significantly higher NDVI was observed at the start of the growing season. Second, the peak NDVI values occurred at significantly fewer accumulated growing degree-days indicating a shift toward an earlier seasonal peak in vegetation. De Beurs and Henebry (2004) interpreted these changes as resulting from increases in fallow area and fewer herbicides available to control weeds during the 1990s. In the irrigated areas of Kazakhstan, there were no significant shifts toward earlier peaks, but there were higher NDVI values at the beginning of the observed growing season, that were likely to reflect the changes in land management practices, including crop types and composition.

The overall regional trend in this region indicates a slight decrease in rainfall throughout the western part of the region and a slight increase in the eastern part of the Aral Sea Basin. However, data series from meteorological stations located in quasi-pristine ecosystems significantly differ from those reported by the stations located on irrigated lands (Neronov 1997; Lioubimtseva et al. 2005). Stations located in the major oases indicate precipitation increase over the past decades (Lioubimtseva 2007). These trends are a result of the hydrological and albedo changes due to the expansion of irrigation. Modeling experiments (Wang and Eltahir 2000) and field studies (Pielke et al. 2007) show that changes in albedo and other biophysical parameters of vegetation cover caused by massive irrigation might establish totally new equilibria in the climate-vegetation relations and reverse previously existing feedback mechanisms. While a desert environment is featured by strong negative biosphere-atmosphere feedbacks, perturbation of a large area by irrigation induces a positive feedback that brings the system to more humid climatic conditions with new climate-vegetation equilibria (Lioubimtseva et al. 2005).

17.6 Mesoclimatic Changes in Vicinity of the Aral Sea

The Aral Sea degradation has resulted in significant changes in surface albedo, soil temperature and moisture, evapotranspiration, cloud cover, precipitation patterns, wind speed and direction, atmospheric transparency, and many other mesoclimatic parameters in the immediate vicinity of the Sea (Varuschenko et al. 1987; Small et al. 2001; Micklin 2007; Shibuo et al. 2007). The surface area of the Aral Sea declined from ~65,000 km^2 in 1960 to 10,317 km^2 in 2011 (Micklin, Table 15.1, Chap. 15 this volume). During the same period of time the lake volume decreased by 90 %, its level dropped by 23 m, area shrunk by 75 % and salinity increased from 10 g/l to more than 100 g/l (Micklin 2007; Micklin, Table 15.1, Chap. 15 this volume). Desiccation of the Aral Sea has resulted in an extensive, massive modification of land cover both of its barren bottom and the immediate vicinity. The thermal capacity of the remaining lake has substantially decreased due to reduction of its surface, volume and depth. Significant changes in the interactions between the land and boundary layer of the atmosphere have resulted in dramatic air temperature changes in this area. Several studies (Chub 2000; Small et al. 2001; Micklin 2007) identified significant mesoclimatic changes resulting from the desiccation of the Aral Sea, as opposed to the impacts of global changes.

The climate records from around the sea show dramatic temperature and precipitation changes since 1960. Mean, maximum, and minimum temperature near the Aral Sea have changed by up to 8 °C, increasing both seasonal and diurnal amplitudes (Small et al. 2001), as the lake effect has diminished. The magnitude of such changes decreases with distance from the coast, with effects extending about 200 km from the original 1960 shoreline. Precipitation records also show a shift in seasonality. The Aral Sea desiccation has caused significant climate change not only in the coastal area but affected the entire system of atmospheric circulation in its basin. Summer and winter air temperatures at the stations near the seashore increased by 1.5–2.5 °C and diurnal temperatures increased by 0.5–3.3 °C (Glazovsky 1995; Chub 2000). Near the coast the mean annual relative humidity decreased by 23 % and recurrence of drought days increased by 300 % (Glazovsky 1995). The annual cycle of temperature and precipitation has also changed. A sevenfold rise in the albedo of the area previously occupied by the Aral Sea caused a threefold increase in reflected solar radiation and increased overall continentality of the climate (Glazovsky 1995). Some regional modeling scenarios suggest that rise of the air temperature in Central Asia should cause a further 8–15 % increase in evaporation both from the sea and the land surface (Small et al. 1999; Chub 2000).

According to a study by Small et al. (2001), an increase in diurnal temperature range of 2–3 °C is observed in the Aral Sea area in all months. These authors examined the Aral Sea surface temperature (SST) trends between 1960 and 1996 using in situ buoy and boat SST measurements from the State Oceanographic Institute of Russia, combined with Multi-Channel SST derived from the Advanced Very High Resolution Radiometer satellite imagery. They found that the highest change in the Aral SST occurred in spring – a 4–5 °C increase in April and May. SST increase in summer was about 3 °C, and there were no changes between August and October. During the same period of time SSTs decreased by 4–5 °C in November and December.

Basin-scale water diversion and irrigation, along with the desiccation of the Aral Sea have considerably increased evapotranspiration and thereby decreased net water flux from the atmosphere to the surface. Increased evaporation cools the irrigated areas, and the decrease of net atmosphere water influx is likely to affect the entire basin. Modeling studies by Shibuo et al. (2007) indicate important effects of water diversion on the regional climate. The excessive irrigation in the southeastern part of the Aral Sea Basin appears to have significantly increased evapotranspiration and cooled this area in the process. By contrast, temperature increases are considerable in non-irrigated areas, where hydro-climatic changes reflect local effects of the Aral Sea shrinkage itself in addition to the regional manifestation of global climate change. The main reported precipitation increase in the Aral Sea Basin is also localized to the southeastern part of the basin. It is probably an effect of the local evapotranspiration increase due to irrigation. By contrast all stations in the immediate vicinity of the Aral Sea have experienced precipitation decreases during the same period of time (Lioubimtseva and Cole 2006). Such influence of the local land-cover changes has been reported in many studies in other arid and semi-arid regions (Pielke et al. 2007).

In addition, exposure of the former lakebed areas, especially on the eastern side of the Aral Sea, represents an enormous source of highly saline wind-blown material (up to 1.5 % salt in the total mass of hard particles transported by the wind). According to Semenov (1990) the amount of aeolian redeposition from the former Aral seabed is exceeding 7.3 10^6 t per year, comprised of between 5 and 7×10^4 t of salt per year. Today the drying bed of the Aral Sea has become one of the biggest sources of dust aerosols in the world. Salty dust blown into the atmosphere is another important factor that needs to be considered in model simulations of both global and regional climates. Dust tends to cool the earth by reflecting sunlight back into space, and it decreases rainfall by suppressing atmospheric convection (Lioubimtseva et al. 2005).

Restoration and conservation efforts in Kazakhstan have recently resulted in improvement of microclimatic conditions in the vicinity of the Small Aral (former northern part of the Aral Sea). Separated by a dike from the Large Aral, the Small Aral Sea is now showing steady signs of water level increase and decline of water salinity (Micklin and Aladin 2008). In the early 1990s Kazakhstan constructed an earthen dike to block outflow to the south but in April 1999 the dike collapsed. The second 13-km earthen dike with a gated concrete dam for water discharge was completed in November 2005. Heavy runoff from the Syr Darya in the ensuing winter jump-started the Small Aral's recovery. The water rose from 40 to 42 m – the intended design height – in only 8 months. Area increased by 18 %, and salinity has dropped steadily, from roughly 20 to about 10 g/l today. Fishers are once again catching several species in substantial numbers – most important, the highly prized pike perch and carp (Aladin et al. 2005; Micklin and Aladin 2008). As the restoration of the Small Aral continues it is likely that its moderating impact on the local climate will continue to increase.

17.7 Human Vulnerability to Climate and Environmental Change

Although different authors have proposed many definitions of human vulnerability, it is usually understood as a function of the character, magnitude, and rate of climate change and the exposure, sensitivity and adaptive capacity of the human-environmental system (Schröter et al. 2005; Parry et al. 2007; Adger 2006; Polsky et al. 2007; Adger 2006; Lioubimtseva and Henebry 2009). One of the key dimensions of human vulnerability to climate change is exposure – the degree to which a system is exposed to a hazard, perturbation or stress caused by climatic change and variability. The second dimension is sensitivity; it can be defined as the degree to which a system is affected by, or is responsive to, climate change stimuli (Smit and Skinner 2002). The third dimension of vulnerability is adaptive capacity. Adaptive capacity or adaptability is understood as the potential or capability of a human-environmental system to adapt to climatic stimuli (Smit and Skinner 2002; Schröter et al. 2005; Polsky et al. 2007). The capacity of a sector or region to adapt to climatic changes depends on many non-climatic factors, such as level of economic development and investment, access to markets and insurance, social and economic policies, access to education and technology, cultural and political considerations, the rule of law regarding private and public properties, including natural resources, etc. Vulnerability can also be regarded as a function of potential impact of climate or other environmental change that can be in turn defined as all implications of the projected environmental change, without considering adaptations (Schröter et al. 2005). Therefore, impact depends primarily on exposure and sensitivity of a system. There is compelling evidence from around the world that there is a strong relationship between vulnerability to climate change and sustainable development. As the Fourth Report of the IPCC Working Group II states, "…sustainable development can reduce vulnerability to climate change, and climate change could impede nations' abilities to achieve sustainable development pathways" (Parry et al. 2007).

Due to their common environmental, political and economic legacy, countries of the Aral Sea Basin represent together a complex macro-regional system. Development of effective and realistic adaptation strategies would benefit from an integrated macro-regional approach reaching beyond the national borders, especially because adaptation measures are rarely undertaken in consideration of the impacts of climate change alone and are typically imbedded within other initiatives such as land-use planning, water resource management, drought warning, desertification control, health care programs, and diversification of agriculture.

Many non-climatic stresses might be increasing vulnerability of the Aral Sea Basin countries to climate change and reduce its adaptive capacity because of resource deployment to competing needs. For example, political isolation, low living standards and significant social inequality, limited access to sanitation, insufficient infrastructure and health care system in many parts of the region and many other non-environmental stresses generally decrease the adaptive capacity of Central Asian countries. When the region is increasingly exposed to climate-related stresses, such as increases in surface temperature and frequency of droughts in the Aral Sea Basin, decline of precipitation, and mesoclimatic changes caused by the Aral Sea, and other environmental stresses, such as soil salinization and degradation, water loss due to inefficient irrigation practices, chemical runoff from agriculture, its sensitivity to environmental impacts is very high while adaptability is low. In the context of the arid climate of Central Asia, short-term, unplanned reactive coping strategies that aim to address separately some of these stresses usually provide only an immediate solution for limited areas or groups of the population, but in the long-term they only exacerbates the problem.

Focusing on effects but not on the causes of the problem they risk aggravating the ongoing adverse environmental changes. For example, there is a continuous migration of the population from Karakalpakstan, an autonomous republic within Uzbekistan, adjacent to the Aral Sea, to eastern Uzbekistan and Kazakhstan. During the first years after collapse of the USSR the estimated number of environmental migrants from the Aral Sea area was more than 100,000 people and in the recent decade the net emigration from the areas adjacent to the Aral Sea has doubled from over 3,000 to over 6,000 persons per year (Akiner 2000). Between 5 % and 10 % of the working-age population of this region is leaving Karakalpakstan every year (Elpiner 2003; Elpiner, 2011, personal communication). Considering that these environmental refugees are usually individuals who had the best skills, opportunity, and psychological aptitude to migrate and adjust to different lifestyles in other regions or countries, there is concern that the population left behind would have even lower capacity, skills and potential to adapt to regional climate change.

17.8 Human Vulnerability and Water Resources

Significant temporal variability in the runoff of the Amu Darya, Syr Darya and smaller rivers of the Aral Sea Basin is largely controlled by hydrometeorological changes in the Pamir, Tian Shan, and Altai mountains. A regional modeling study driven by five AOGCMs under a business-as-usual scenario conducted by Uzhydromet (Hydrometeorological Service of Uzbekistan) suggests that by 2030–2050 the temperature in the mountains of southeastern Uzbekistan is likely to increase by 1.5–2.5 °C causing higher runoff of the Amu Darya, Zeravshan, and Syr Darya due to accelerated melting of the mountain glaciers and precipitation will increase by 100–250 % (Miagkov, 2006, personal communication). Glacial melt in the Pamir and Tian Shan ranges is projected to increase, initially increasing flows in the Amu Darya, Syr Darya, and Zeravshan systems for a few decades, followed by a severe reduction of the flow as the glaciers disappear (Glantz 2005). Field data indicate that significant changes in the seasonality of glacial flows have already occurred as a result of warming (Braithwaite 2002). Rapid melting of glaciers has increased runoff, which has led to an increase in the frequency of glacial lake outbursts that can cause devastating mudflows and avalanches in the mountainous regions of Tajikistan, Uzbekistan, Kazakhstan, and Kyrgyzstan.

Growing demand for water for irrigation, high levels of water pollution, and frequent droughts and widespread land degradation are among the key water-related issues that already threaten human development and security of the Aral Sea Basin countries. Overall water withdrawals in the Central Asia States have increased from 37 km^3/year in 1950 to 102 km^3/year in 2000 and are projected to reach 122 km^3/year by 2025 (Shiklomanov and Rodda 2001). The core regional problem, however, is not the lack of water resources but rather their management and distribution. A lack of coordination among irrigation systems, pervasive soil degradation, and inter-basin transfers are the persistent water problems in the region. The surface water resources of Central Asia are primarily generated in mountain glaciers.

Although differences in water stress at the country level are considerable, these are smaller than differences among the geographic regions within the basin. Kazakhstan and Uzbekistan are impacted by mesoclimatic changes directly caused by the reduction in water volume of the Aral Sea, sea-bottom exposure, and the associated toxic salt and dust storms. The salt content of the Southern Aral Sea now ranges between 100 and 150 g/l, which is more than triple the salinity of the open ocean (Micklin 2007). The quality of water for human consumption is poor in many parts of Central Asia. The same processes that contributed to the Aral Sea degradation – excessive irrigation and mismanagement of water – have also resulted in the rise of the groundwater table, contamination of groundwater with high levels of salts and other minerals. Groundwater quality ranges in the region from a minimum of 1.5 g/L TDS (total dissolved solids) to 6 g/L TDS and drinking water reaches levels of up to 3.5 g/L TDS. In Karakalpakstan (an autonomous republic of Uzbekistan adjacent to the Aral Sea) about 65 % of drinking water samples tested did not meet national standards of 1 g/L TDS (AQUASTAT 2011). There is a growing concern that water stress in Central Asia may lead to open conflicts over water, weakening the states to such an extent that they lose their capacity to address other threats to stability and development (Sievers 2003; Glantz 2005).

Water availability and water stress are expected to be highly sensitive to projected climate change scenarios (Shiklomanov and Rodda 2001; Alcamo and Henrich 2002; Arnell 2004). Assessment of water stress can be depicted as the current average annual withdrawals-to-availability ratio, where stress is indicated by a ratio of withdrawals to availability greater than 40 %. Water stress is a useful measure of human vulnerability to climate change as it measures the degree of demand on water resources by the users of these resources, including agriculture, industries, and municipalities. A larger increase in water stress represents a greater sensitivity of the water resources to global change. The future impacts of climate change on water resources are strongly dependent on the current conditions of existing water supplies and water control systems. A study by Alcamo and Henrich (2002) based on the WaterGAP model indicates severe water stress already occurring in all Central Asian countries. Given the very high level of water stress in many parts of the Aral Sea Basin, projected temperature increases and precipitation decreases in the western part of Kazakhstan, Uzbekistan, and Turkmenistan are very likely to exacerbate the problems of water shortage and distribution.

During the past 10–12 years, a series of droughts affected Turkmenistan, Uzbekistan, Tajikistan, Iran, Afghanistan, and Pakistan. These droughts have amply demonstrated the very high human vulnerability of this region to precipitation deficits. Agriculture, animal husbandry, water resources, and public health have been particularly stressed across the region as a result of the recent drought (Lioubimtseva and Henebry 2009). Climatic changes, projected by the models, are likely to impact regional hydrometeorology and hydrology and further exacerbate the human vulnerability of this region by reducing its overall water supply.

17.9 Human Vulnerability and Agriculture

Most croplands in Turkmenistan, Uzbekistan and southern Kazakhstan are irrigated and agriculture is potentially highly vulnerable to climate change because of the degradation of limited arable land and shortage of water available for irrigation. Almost two-thirds of domestic livestock are supported on grazing lands, although in Kazakhstan a significant share of animal fodder also comes from crop residues (Lioubimtseva and Henenbry 2009). Aridity is the primary constraint limiting the portion of land available for agriculture and livestock production in the Aral Sea Basin. The results of modeling studies suggest that at least some parts of the Central Asian region might benefit from an increase in winter temperatures and a longer growing season, the CO_2 fertilization effect and the projected increase in the water-use efficiency by agricultural crops, and probably also a winter rainfall increase in the eastern part of the region (Parry et al. 2007; Fischer et al. 2005). According to an agro-ecological zoning study by IIASA (International Institute for Applied Systems Analysis), almost 90 % of the land in Central Asia that was part of the former USSR has constraints for rain-fed crops: almost 76 % of the area is too arid, 4 % too steep, and about 7 % has insufficient soils. Out of the total 414 million ha approximately 45 million ha are currently used for cultivation of food and fiber crops and more than 14 million ha require irrigation (Fischer et al. 2005). The IIASA Basic Linked System models driven by the HadCM3-A1FI scenario suggest that, due to regional climate changes, by 2080 the total area with constraints will decrease to 84 %. On the other hand, the area in Central Asia deemed unsuitable for agriculture due to insufficient soils is projected to reach 17 % by 2080 (Parry et al. 2007; Fischer et al. 2005). The same studies suggest that the potential for rain-fed cultivation of major food and fiber crops in this region might increase by 2080 (primarily due to the CO_2 fertilization effect on C_3 plants).

The MMD experiments used in the IPCC WGII Assessment Report (2007) suggest that most of the Aral Sea Basin is likely to become more arid and probably less suitable for agriculture. AOGCM scenarios also revealed substantial geographic differences across the region. The major differences in the magnitude of projected temperature changes, however, result from the wide range of the SRES socio-economic pathways. The climate change scenarios discussed in the previous section of this chapter project temperature increases between 2.4 °C and 4.7 °C under B1 scenario and from 3.9° to 7.1° under A1 by 2080 with a particularly notable increase in winter temperatures. Precipitation scenarios vary, suggesting a slight increase in the eastern part of the region and a decrease in the west. However, even the wettest scenarios, do not seem to be sufficient to offset the aridity caused by elevated temperatures, especially in the southern and western sectors of the region (Turkmenistan, Uzbekistan and southwestern Kazakhstan). CGCM3 and HadCM3 scenarios suggest a risk of even higher levels of aridity in the southwestern part of Central Asia and a very insignificant increase in the northeast under all socio-economic scenarios. The CSIRO model projects the greatest increase of aridity throughout the entire region. The MMD assessments discussed by the IPCC (IPCC AR4 and WGII 2007) also indicate that the median precipitation change in Central Asia by the end of the twenty-first century is −3 % in the annual mean, with −13 % in summer (dry season) and +4 % in winter (IPCC and WGI 2007, Chap. 11). Combination of elevated temperatures and decreased precipitation in the deserts and semi-deserts of Central Asia could sharply increase potential evapotranspiration, leading to very severe water-stress conditions with dramatic impacts on agriculture and livestock production.

Climate models agree that the western part of the region (deserts of Turkmenistan and Uzbekistan and the Caspian coast) would be particularly vulnerable to the increase in potential evapotranspiration. Yet, perhaps of bigger concern in estimating impacts from temperature and precipitation changes on agriculture are the potential changes in variability and extreme events, such as frosts, heat waves, droughts, and heavy rains. Extreme events are responsible for a disproportionately large part of climate-related damages and sensitivity of extremes to climate change may be greater than one would assume from simply shifting the location of the climatological distribution. The global-scale study of Tebaldi et al. (2006), based on analysis of ten indicators of temperature and precipitation-related extremes computed by nine AOGCMs used in the IPCC-AR4, suggests that agricultural production in the Central Asian region could benefit from fewer frosts and an increasing length of the growing season. It could also be negatively affected by the increasing variability of precipitation and number of dry days, particularly at higher elevations and for rain-fed crops and orchards (Tebaldi et al. 2006).

Another factor that is likely to affect agricultural productivity in the Aral Sea Basin and adjacent areas is increasing surface runoff in the adjacent mountain systems of Tian Shan and Pamir-Alai. The projected increase in runoff could potentially accelerate soil erosion, especially in case of increasing frequency of catastrophic precipitation. Several multi-model assessments (Shiklomanov and Rodda 2001; Arnell 2004), suggest that the volume of runoff from glaciers in Central Asia may increase three-fold by 2050 leading to significant changes in the regional pattern of water and land use. In the long term, however, after decades of accelerated melting, the glacial runoff will dramatically decline as glacial mass significantly declines.

17.10 Human Vulnerability and Health

Changes in the regional climate and ecosystems might both increase or reduce the risk of some infectious diseases. Increase of temperature and climate variability can also increase the exposure of populations to heat stress, extreme weather events, such as droughts, dust-storms and floods, contribute to the already existing water stress, and also stress the existing institutional systems of public health (Confalonieri et al. 2007).

Epidemic malaria, including the tropical form of malaria, caused by *Plasmodium falciparum*, returned to Uzbekistan, Kyrgyzstan, Turkmenistan, and Tajikistan in the 1990s (World Health Statistics 2011). In 1994, the number of malaria cases reported in Tajikistan quadrupled compared to 1993 and peaked in 1997, when nearly 30,000 cases were registered (WHO 2011). In 2002, the explosive resumption of malaria transmission produced an epidemic situation with an incidence much greater than that reported in the past years in Kyrgyzstan, and a total of 2,267 autochthonous (i.e. endemic to the region) cases were reported in the southwestern regions of the country (Fig. 17.2). The explosive resumption of malaria transmission in Kyrgyzstan started as a result of immigration of a number of infected people from Tajikistan into the Batken region where the Anopheles vector exists and conditions for malaria transmission are very favorable (Abdikarimov 2001). In 2004–2005, as a result of the application of epidemic control measures, there was a significant decrease in the reported number of autochthonous malaria cases.

However, in 2004 the first autochthonous case of *P. falciparum* malaria was reported in the southern part of Kyrgyzstan and in 2005 the number of

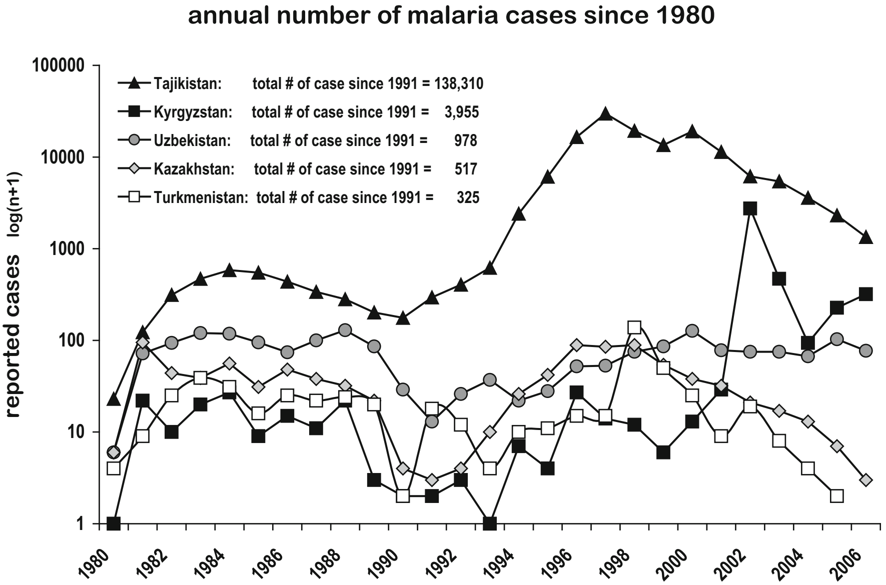

Fig. 17.2 Total number of malaria cases reported to WHO, 1980–2006 (Lioubimtseva and Henebry 2009)

autochthonous cases of *P. vivax* malaria increased in the capital city Bishkek. The resumption of *P. falciparum* cases in Tajikistan and Kyrgyzstan and the expansion of the territory in which this type of malaria is spread is a matter of particular concern. Endemic malaria has now returned to the southern part of Tajikistan (Sabatinelli 2000). Surveys conducted by WHO personnel in the southern part of Tajikistan bordering Afghanistan identified about 10,000 malaria-infected individuals in the Khatlon Region (WHO 2011).

The observed and predicted climate changes in Central Asia, such as the temperature increase, changes in climatic variability, and seasonal shifts might be responsible for creating more favorable mesoclimatic conditions for vectors and parasites. The last decade of the twentieth century was marked by a series of particularly warm years. Climate change has a direct impact on mosquito reproduction, development rate and longevity, and the rate of development of a parasite, as the parasites develop in the vector within a certain temperature range, where the minimum temperature for parasite development lies between 14.5 °C and 15 °C in the case of P. vivax and between 16 °C and 19 °C for *P. falciparum* (Martens et al. 1999). According to the study by Kayumov and Mahmadaliev (2002), the zone of potential malaria development in Tajikistan is likely to increase during the coming years up to an elevation of more than 2,000 m due to the continuous temperature increase. Climate change is also affecting malaria transmission indirectly through such factors as changes in vegetation, agricultural practices, desertification, migration of populations from areas in which vector-borne diseases are endemic into receptive areas (Kovats et al. 2001; Van Lieshout et al. 2004). Large irrigated areas and river valleys within these chiefly arid and semi-arid countries provide perfect habitats for mosquitoes. Increasing climate aridity and variability and increasing summer temperatures can increase the reliance of local agriculture on irrigation and cause an increase in the areas suitable for vector development.

Many non-environmental factors, such as migrations caused by war in neighboring Afghanistan, deterioration of national health systems, economic decline, reduction of the use of pesticides, and land use change have all contributed to the regional health crisis (Abdikarimov 2001; Razakov and Shakhgunova 2001). The number of malaria cases in Central Asia has gone down in recent years as a result of governmental programs involving widespread application of insecticides but the crisis that recently occurred here clearly indicates that climate change is likely to increase the risk of future outbreaks of malaria in parts of this region.

17.11 Conclusions

The Aral Sea Basin represents an area with diverse and overlapping environmental, social and economic stresses. It is projected to become warmer and probably drier during the coming decades. Aridity is expected to increase across the entire region, but especially in the western part of Turkmenistan, Uzbekistan, and Kazakhstan. The temperature increases are predicted to be particularly high in summer and fall, but lower in winter. An especially significant decrease in precipitation is predicted in summer and fall, while a modest increase or no change in precipitation is expected in winter months, particularly in the eastern part of Kazakhstan and in adjacent Kyrgyzstan and Tajikistan. These seasonal climatic shifts are likely to have profound implications for agriculture. Some parts of the region will be winners, while others will be losers (particularly western Turkmenistan and Uzbekistan, where frequent droughts will negatively affect cotton production, increase already extremely high water demands for irrigation, and exacerbate the already existing water crisis and human-induced desertification). The severe and ongoing droughts of the past decade have already resulted in multiple water disputes and increased tensions among the states of the Aral Sea Basin. Given that the aridity and water stress are likely to increase, new political and economic mechanisms are necessary to ease such tensions in the future.

The ability of the Aral Sea countries to adapt to hotter and drier climatic conditions is limited by the already existing water stress and the regional land degradation and poor irrigation practices. Central Asia inherited many environmental problems from Soviet times but many years after independence, the key land and water-use related problems remain the same. A decline in the intensity of agriculture after independence, documented by agricultural statistics, was significant enough to produce a signal in the temporal series of remote sensing data. Agricultural transformation had extremely high social costs but to date agricultural reforms and the transition to market conditions remain problematic in most of the region.

Increasing rural poverty and unemployment, particularly among females, growing economic inequality, and shortage of adequate living conditions, medical care and water management infrastructure have significantly increased human vulnerability of the majority of population in the region.

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