A multi-scale assessment of human vulnerability to climate change in the Aral Sea basin

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A multi-scale assessment of human vulnerability to climate change in the Aral Sea basin

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Abstract Vulnerability to climate change impacts is defined by three dimensions of human–environmental systems, such as exposure, sensitivity, and adaptive capacity. Climate change affects various aspects of human–environmental interactions, such as water stress, food security, human health, and well-being at multiple spatial and temporal scales. However, the existing protocols of vulnerability assessment fail to incorporate the multitude of scales associated with climate change processes. Changing trends in the Aral Sea basin are driven by multiple interconnected factors, such as changes in the global atmospheric circulation associated with the GHG-enhanced warming, regional hydrological and hydrometeorological changes caused by mountain-glacial melting and massive irrigation, land-use and land-cover changes, as well as hydrological, biogeochemical, and meso- and microclimatic changes in the remains of the Aral Sea and its exposed dry bottom. This review examines the role of scale in the assessment human vulnerability to climate change and offers a multi-scale approach to vulnerability assessment. In addition to the global climate change impacts, it takes into account regional and local land-use and land-cover changes, social, cultural, political, and institutional factors.

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Introduction

Human vulnerability to climate and environmental changes in the Aral Sea basin are directly linked to the global, regional, and local factors of climatic and hydrological variability and changes. Vulnerability of human–environmental systems to climate change involves at least three different components, such as exposure, sensitivity and adaptive capacity (Polsky et al. 2007), determined by multiple biophysical and social, political and economic factors, including terrain, water resources, population pattern, ecosystems, governance structure, access to technology, food systems, wealth distribution, and many others. Exposure, sensitivity, and adaptive capacity are scale dependent because various processes caused by climate change and environmental changes occur at multiple temporal and spatial scales.

Climate, land use, and hydrology of the Aral Sea basin are tightly interconnected. 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 affects hydrological processes in the basin with respect to mean states and variability as well as land-use options (Lioubimtseva 2014). 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.

Many existing publications that address climate change in the Aral Sea basin focus primarily on the regional and local processes caused by the land-use changes and associated hydrological and meso-climatic changes caused by Aral Sea degradation (Aladin et al. 2005; Micklin 2007, 2010). However, environmental changes in this region represent a complex combination of global, regional, and local processes driven by multiple interconnected factors, such as changes in atmospheric circulation associated with growing GHG emissions, regional hydrological changes caused by mountain-glacial melting and massive irrigation, land-use changes, as well as hydrological, biogeochemical, and meso- and microclimatic changes over the exposed dry bottom of the Aral Sea. Therefore, a nested multi-scale conceptual model is needed to address human vulnerability to multiple environmental changes of various scales, their inter-connections, and feedbacks.

Geography and climate of the Aral Sea basin

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. Most of the Aral Sea basin has continental climate (Köppen classification BWh and BWk—subtropical or mid-latitude desert). The annual amount of precipitation is 344 mm in Kazakhstan, 533 mm in Kyrgyzstan, 691 mm in Tajikistan, 191 in Turkmenistan, and 264 mm in Uzbekistan (FAO AQUASTAT 2013). Summers are typically hot and dry, with the daytime highs exceeding 40 °C in the plains of Uzbekistan and Tajikistan. The winters are cold in Kazakhstan, Kyrgyzstan, and Uzbekistan and milder in Turkmenistan and Tajikistan. The patterns of temperature and precipitation demonstrate high spatial variation: e.g., despite the average winter air temperature in Tajikistan of about 7 °C, the absolute minimum temperature recorded for the country is −49 °C (Kirilenko and Dronin 2011). This spatial heterogeneity is chiefly determined by the region's topography.

The major controls on precipitation change in Central Asia include latitudinal shifts of the westerly cyclonic circulation and position of the Siberian high (Lioubimtseva 2002). The North Atlantic Oscillation (NAO) exerts an important control over the pattern of wintertime atmospheric circulation variability over the 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. The patterns of precipitation in Central Asia have been also linked to El Niño-Southern Oscillation (ENSO) phases (Barlow et al. 2002). Cold ENSO phases generally result in drought conditions in the region, while warm ENSO phases result in an increased precipitation (Barlow et al. 2002; Syed et al. 2006).

Two groups of regional factors have been increasingly contributing to climate change of the region: (a) basin-wide land-use and land-cover changes (Lioubimtseva and Henebry 2009; Kariyeva and van Leewuven 2011) and (b) degradation of the Aral Sea itself (Micklin 2010). Therefore, current and future climatic trends in this region can be best addressed as a combination of interconnected processes and feedbacks operating at several spatial and temporal scales. They include natural climatic variability, anthropogenic global climate change (decades to millennia), regional land-use changes in the Aral Sea basin (decades to centuries), and meso-climatic changes caused by the Aral Sea degradation and exposure of its dry bottom (years to decades) (Table 1; Fig. 1).

Global scale

Anthropogenic warming of the global climate system is now evident from observations of increases in global average air and ocean temperatures, widespread melting of

Table 1 Spatial and temporal scale dependence of climate and environmental changes in the Aral Sea basin

Global changes decades to millennia, primarily linked to global circulation changes, changes in the global hydrological balance, possibly CO_2 fertilization effect on plant	*Regional changes* decades to centuries, primarily linked to land-use changes and irrigation at the scale of entire Central Asia	*Local changes* years to decades, primarily linked to the Aral Sea degradation and exposure of its dry bottom
Temperature increase, aridization, increase of drought frequency, increase of glacial melting and runoff due to warming (in the short-term future), decline of runoff (in the long term)	Decrease of river runoff, changes in the number and area of lakes, rise of groundwater levels, changes of the evapotranspiration and precipitation rates, desertification, land-cover changes due to economic deintensification and changes in crop preferences after 1991	Sea surface temperature changes, increase of continentality in the vicinity of the sea, increase of frequency and intensity of dust storms, ecosystem changes, improvement of microclimate in the vicinity of the Small Aral since 2005

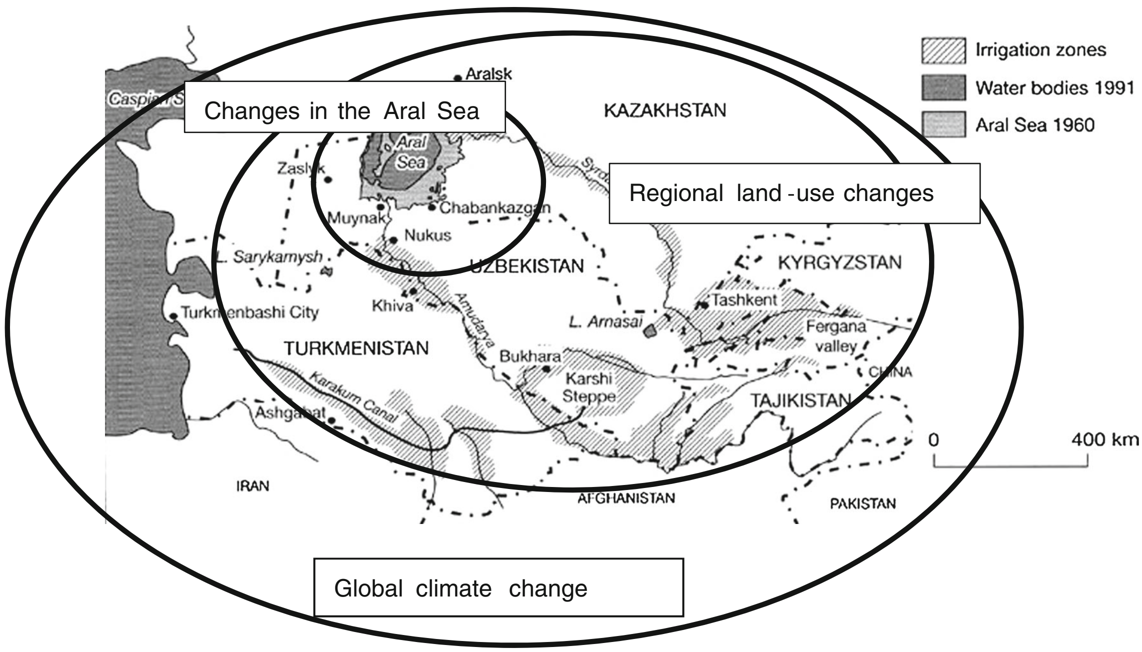

Fig. 1 Multi-scale changes in the Aral Sea basin (modified from http://www.rusnature.info/env/f22-3.jpg)

snow and ice, and rising global average sea level (IPCC WGI 2007a, b). Meteorological data, available from the end of the nineteenth century, clearly demonstrate a steady and significant warming trend in the region, especially pronounced during the winter season (Chub 2000; Lioubimtseva et al. 2005). This trend may indicate a general shift in the atmospheric circulation, namely decreasing intensity of the southwestern periphery of the Siberian high in winter and the intensification of summer thermal depressions over Central Asia (Lioubimtseva and Henebry 2009).

We have examined annual, seasonal, and monthly temperature and precipitation scenarios for Central Asia under A1F and A1B policy scenarios (Nakicenovic et al. 2000) derived from 20 GCMs using the NCAR (National Center for Atmospheric Research) MAGICC/SCENGEN 5.3 model (Wigley 2008). Detailed discussion of climate change scenarios for Central Asia can be found in Lioubimtseva and Henebry (2009) and Lioubimtseva et al. (2013). Based on the GCM projections, temperature changes in the Aral Sea basin are likely to increase by 2–3 °C by 2050 and by 3–5 °C by 2080. All scenarios generally agree that the warming is very likely to be accompanied by a further intensification of aridity, particulary in the western sector of the region. Higher temperature changes are predicted by all models during the winter months (Table 2; Lioubimtseva 2014). The range of precipitation projections by different models is quite broad. Most of the precipitation decline is expected to happen between May and October when precipitation is already very low. Analysis by Kirilenko and Dronin (2011) of gridded GCM simulations of precipitation and temperature change in Central Asia projects rather similar temperature increase of 2.5–3.6 °C by 2,050 s and a small increase or decrease in precipitation. The multi-model GCM scenarios are in line with the observed temperature and precipitation trends over the past decades in most of the region.

Table 2 Climate change projections for the Aral Sea basin by the middle of the twenty-first century, relative to 1961–1990

Seasonal changes	Winter	Spring	Summer	Fall
Mean temperature (°C)	1.5–4.95	2.87–4	3.24–7.36	3.05–4
Precipitation (mm/day)	0.01–0.1	0–0.09	−1.11 to 0.1	−0.5 to 0.1

Climate change projections are computed with MAGICC and SCENGEN 5.3.2 software suites Wigley (2008)

Global climate change directly affects water resources. According to Groll et al. (2014, this issue) by 2030 the available water resources will be 30 % lower than today. Population and economic activity of the Aral Sea basin is almost controlled by hydrometeorological conditions in the Pamir, Tianshan, and Altai mountains. 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. Accelerated melting of the mountain glaciers may favor flash flood occurrences (Fort 2014, this issue). During 1973–2000, accelerated glacier melting increased the flow of Kyrgyzstan rivers by 6.3 %, with an additional 10 % increase projected for the next 20 years (Kirilenko and Dronin 2011). The increased runoff 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.

Deserts and semideserts are expected to respond positively to increased CO_2 concentrations in the atmosphere because they are water limited and thus, in theory, responsive to the effects of CO_2 on water balance (Lioubimtseva and Adams 2004). Several studies based on chamber experiments, the Nevada Desert Free-Air CO_2 Enrichment (FACE) Facility (Smith et al. 2000), and indirect evidence derived from remote sensing data have shown increased leaf-level photosynthetic rates, water-use efficiency, leaf area index, and plant growth under elevated CO_2. It is uncertain, however, how significant these changes will be under future climatic conditions and no direct studies on CO_2 fertilization have been conducted to date in the Aral Sea basin. A recent study by Newingham et al. (2013) in Mojave Desert in the USA suggests that the positive response of vegetation to CO_2 might have been overestimated. During the 10-year FACE experiment in Nevada, most vegetation responses occurred in wet years, but did not lead to sustained increases in community biomass. It is likely that increase of aridity and more frequent droughts may constrain cumulative biomass responses to elevated CO_2 in desert environments.

Regional scale

The most dramatic land changes in Central Asia were driven by two historical events: the rapid and massive expansion of irrigation in 1960–1980s (Micklin 1988, 2007; Glantz 2005) and the decline of agriculture in the 1990s after the collapse of the USSR (Lioubimtseva and Henebry 2009; Lioubimtseva et al. 2013). Between 1962 and 2002 irrigated arable land, principally for cotton monoculture, increased by 60 % in the region (Lioubimtseva et al. 2005) and the total water withdrawals (all uses) were 125 % of the average annual water resources in 1988. Such dramatic human-induced changes in the hydrological cycle led to a significant decrease of river runoff, changes in the number and area of lakes and rise of groundwater levels, transformation of the evapotranspiration and precipitation rates at the scale of the entire basin (Micklin 2007), and decreased net water flux from the atmosphere to the surface. Modeling studies by Shibuo et al. (2007) suggest that the excessive irrigation in the southeastern part of the Aral Sea basin has caused a significant increase in 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. Precipitation increase is likely to be caused by the local evapotranspiration increase due to irrigation.

Deintensification of agriculture caused by the dissolution of the USSR was significant enough to cause significant "greening" trend captured by vegetation indices derived from coarse- and medium-resolution satellite imagery, such as AVHRR and MODIS products (Lioubimtseva 2007; Kariyeva and van Leewuven 2011). By analyzing the Pathfinder AVHRR Land (PAL) data from 1981 to 1999, found three distinct patterns of significant difference in land surface phenology (LSP) models that linked the NDVI with accumulated growing degree-days to describe the seasonal course of vegetation activity. Kariyeva and van Leewuven (2011) also found significant LSP changes following institutional changes using a different modeling approach, namely, phenological metrics extracted from the GIMMS NDVI data set using the Timesat algorithm (Jönsson and Eklundh 2004). They found significant differences in land-cover trends in Central Asia before and after the USSR collapse due to changes in crop preferences.

Local scale

Desiccation of the Aral Sea has resulted in massive changes of land cover and hydrometeorological regimes 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 region. Several studies (Chub 2000; Small et al. 1999; Micklin 2007) identified meso-climatic and micro-climatic changes resulting from the desiccation of the Aral Sea, as opposed to the impacts of global and macro-regional changes.

The climate records from around the sea show significant increase of annual and diurnal temperature amplitudes and decline of precipitation since 1960, as the lake effect has diminished. According to a study by Small et al. (2000), 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 and found that the highest change in the Aral SST occurred in spring—a 4 to 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.

In addition, the exposure of over 36,000 km^2 of the former lakebed, especially on the eastern side of the Aral Sea, represents a vast source of highly saline wind-blown material (Wiggs et al. 2003). Today, the drying bed of the Aral Sea has become one of the biggest sources of dust aerosols in the world. Dust tends to cool the earth by reflecting sunlight back into space, and it decreases rainfall by suppressing atmospheric convection (Lioubimtseva et al. 2005).

All meteorological stations in the immediate vicinity of the Aral Sea have experienced slight precipitation decrease since the 1960s, which coincides with drastic reduction in the water surface of the Aral Sea. On the other hand, restoration and conservation efforts in Kazakhstan have been a source of moderating impact on microclimate in the vicinity of the Small Aral (Micklin 2010). Water rose from 40 to 42 m in less than a year since the completion of the project in 2005. Water area increased by 18 % and salinity 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 2010). As the restoration of the Small Aral continues, it is likely that its moderating impact on the local climate will continue to increase.

Human vulnerability to climate and environmental change

Vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes (IPCC 2001). It is usually understood as a function of exposure, sensitivity, and adaptive capacity of a human–environmental system to impacts of climate change or other environmental hazards (Schröter et al. 2005; Polsky et al. 2007). *Exposure* is defined as the nature and degree to which a system is exposed to a hazard, perturbation, or stress caused by environmental change (Polsky et al. 2007). Therefore, factors of exposure include characteristics of physical landscapes (local climate, terrain, soils, water, ecosystems), distance from the hazard, size of exposed population, etc. *Sensitivity* is typically defined as the degree to which a system is affected by, or is responsive to, either adversely or beneficially, to climate change stimuli or environmental impact (Polsky et al. 2007). Sensitivity of a human–environmental system depends on its many biophysical, social, and economic variables including population demographics, occupations, livelihoods, agricultural crops, land-use practices, food and water availability, and many other factors. The third dimension of human vulnerability is *adaptive capacity*. Adaptive capacity or adaptability is understood as the capacity of a human–environmental system to adapt to climatic and environmental stimuli (Smit and Skinner 2002; Schröter et al. 2005; Polsky et al. 2007) or as the potential to implement adaptation measures. Adaptive capacity of a system primarily depends on social and economic factors, such as level of economic development and investment, access to markets, insurance, education and technology, social, cultural and political considerations, governance, regulations of private and public properties including natural resources, etc.

The most pressing aspects of human vulnerability to climate change in the Aral Sea basin countries include water stress and water availability, food security, and health issues (Sayko 1998; Lioubimtseva and Henebry 2009; Abdolvand et al. 2014, this issue). Variables that determine exposure, sensitivity, and adaptive capacity are scale-dependent, ranging from local to global and may have various temporal frames. Therefore, vulnerability assessment requires a scale-dependent conceptual framework that can accommodate several hierarchical levels of indicators of exposure, sensitivity, and adaptive capacity of human–environmental systems within the Aral Sea basin (Table 3).

Human vulnerability to the global processes

Considering the scale of vulnerability to global climate change, useful measurable indicators of exposure include spatial distribution and density of the population, location of agricultural lands, frequency of droughts, distance from and quality of water sources, and other geographic parameters (Table 3).

Information about basin-wide sensitivity to the global impacts of climate change can be gathered through such proxy indicators as population demographic data (age, gender, ethnicity, occupation, and health), food sources, water availability and water stress, types of dwelling, irrigation infrastructure, healthcare availability, and others.

Adaptive capacity of the population at this scale can be assessed based on availability and feasibility of basin-wide and national climate change adaptation plans and emergency management plans, feasibility of the existing basin-wide international agreements, stability of national governments, access to education and information, availability of financial resources and technology, and international coordination of water resources within the Aral Sea basin.

Currently, a lack of coordination among irrigation systems, pervasive soil degradation, and poorly regulated inter-basin transfers are the persistent water problems in the region (Rakhmatullaev et al. 2010). Water availability and water stress are expected to be highly sensitive to projected

Table 3 Scale-dependent indicators of human vulnerability to climate change

Indicators	Sector	Exposure	Sensitivity	Adaptive capacity
Impacts of the global climate change	Water availability	Distance from water sources Population density and distribution Surface runoff	Population demographics and wealth Groundwater depth and quality	Financial resources Access to technology National and international water regulation
	Food and agriculture	Population occupation and location Proximity to water resources Terrain and landscape	Agricultural crops and livestock species Irrigation techniques Wealth National and international land use and water regulations	Financial resources Access to agricultural machinery Modern irrigation techniques Chemicals
	Human health	Distance from mosquito breeding grounds Water quality	Population demographics Wealth Type of dwelling	National health-care infrastructure Education Access to information Emergency management
Regional land-use and land-cover changes and related hydrometeorological changes	Water availability	Population density and distribution Distance from water supply	Irrigation and water supply infrastructure Land management practices Population demographics Water mineralization	Financial resources Water treatment technology
	Food security	Population density and distribution Terrain Soils Food vs. non-food crop ratio Livestock density and distribution	Food crops Livestock Land management and irrigation techniques and infrastructure Food market flexibility Regional land-use policy	Access to education, information, funding, drought-resistant seeds, drip irrigation Machinery Availability of affordable food imports
	Human health	Population density and pattern distance from malaria endemic areas Size of areas affected by malaria Water contamination by pollutants and bacteria	Population demographics (gender, age) Occupation Dwelling Income Education Equality	Access to health care Mosquito spraying Drainage improvement Water treatment and sanitation measures
Local environmental changes caused by the desiccation and exposure of the Aral Sea bottom	Water availability	Population density and pattern Groundwater salinity and depth Distance from Amu Darya and Syr Darya delta Distance from the remaining parts of the Aral Sea	Age of irrigation and water supply infrastructure Drinking water mineralization Water management policies Local governance, community engagement in water conservation practices	Community and family-scale material resources Access to loans Access to education Mobility

Table 3 continued

Indicators	Sector	Exposure	Sensitivity	Adaptive capacity
	Food security	Population density and pattern Distance from the Aral Sea dry bottom Distance from the remaining parts of the Aral Sea Wind direction Terrain	Population age and gender Income Occupation Water mineralization Soil salinization levels Land use Crops Livestock Food market	Availability of food imports Potential for the local fishery restoration Agricultural subsidies Local environmental restoration, wind erosion control measures
	Human health	Population pattern and its distance from the Aral Sea remains and dry bottom Atmospheric pollution Water pollution Wind direction	Age Gender Income Mobility Education Equity	Local health infrastructure Immunization Access to information Income

climate change scenarios (Shiklomanov and Rodda 2001; Alcamo and Henrich 2002; Arnell 2004; Abdolvand et al. 2014, this issue). 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. A study by Alcamo and Henrich (2002) based on the WaterGAP model indicates severe water stress already occurring in all countries of the Aral Sea basin. In addition, current projections of water availability based on hydrological and water-use models are highly uncertain (Malsy et al. 2014, this issue).

During the past decade, 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).

Aridity is the primary constraint limiting the portion of land available for agriculture and livestock production in the Aral Sea basin and exposure to droughts is already extremely high. The MMD experiments used in the IPCC AR4 suggest that most of the Aral Sea basin is likely to become more arid. In the short term, the agriculture of this region may benefit from the increasing runoff from the melting mountain glaciers, increase in winter temperatures, fewer frosts and a longer growing season, CO_2 fertilization effect, and increased crop water-use efficiency (Fischer et al. 2005). In the long term, however, temperature increase combined with eventual reduction of glacial runoff is likely to have devastating impact on agriculture. The potential changes in variability and extreme events, such as frosts, heat waves, droughts, and heavy rains are even more important in estimating the vulnerability of agricultural systems to climate change. 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 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 threefold 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.

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, has returned to Uzbekistan, Kyrgyzstan, Turkmenistan, and Tajikistan, but it is unclear if the recent outbreaks of malaria should be attributed to climate change, land-use changes, or changes in the infrastructure and health-care systems of the region (Lioubimtseva 2014). 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. 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.

Human vulnerability to the regional processes

At the regional scale, shorter-term changes are linked primarily to land use, and hydrological and hydrometeorological changes associated with agricultural practices within the Aral Sea basin. In Kazakhstan only 13 % of the land under cultivation is currently irrigated, but the rest of the region highly depends on irrigation: 76 % of arable land is equipped for irrigation in Kyrgyzstan, 68 % in Tajikistan, 87 % in Uzbekistan, and in 100 % in Turkmenistan (Kirilenko and Dronin 2011) 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. Growing demand for water for irrigation, high levels of water pollution, and frequent droughts and widespread land degradation are among the key water stress and food security-related issues that already threaten human development and security of the Aral Sea basin countries. Land-use changes and expansion of irrigated lands are also the major factors contributing to the spread of water-borne and vector-borne diseases.

At this scale, exposure of human–environmental systems to environmental impacts is primarily determined by proximity of the population to water sources, type of water sources, as well as other aspects of physical geography, such as terrain, vegetation, and soils. The major factors of sensitivity include population demographics, prevailing agricultural practices and crops, livestock and small stock species, as well as market flexibility, alternative food supplies, access to health care, strength of the local and national institutions, and many other factors that determine management of land and water resources and the regional scale.

Many variables of adaptive capacity to the regional processes associated with land-use and land-cover trends are similar to those relevant to human vulnerability to the global climate change: financial and institutional stability, access to education, technology, and other resources. However, more detailed indicators are necessary to capture these factors at a finer scale of individual administrative units and communities. Some other scale-specific factors include access to modern irrigation techniques and more sustainable agricultural practices, introduction of more diverse and less water-demanding food crops, improvement of water supply and water purification systems, mosquito control, and other health-related preventive measure (Table 3). Unfortunately, significant rural poverty and unemployment, particularly among women, growing economic inequality, shortage of adequate health care, and deteriorated infrastructure have significantly reduced adaptive capacity of the majority of the population in many parts of the Aral Sea basin.

Human vulnerability to the local processes

In the direct proximity to the Aral Sea, its own suite of anthropogenic climate change and environmental problems has emerged. Of all countries of the Aral Sea basin, western Kazakhstan and Karakalpakstan Republic in western Uzbekistan have been directly impacted by the micro- and meso-climatic changes caused by the desiccation the Aral Sea, sea-bottom exposure, and the associated toxic salt and dust storms. The salt content of the Southern Aral Sea ranges between 100 and 150 g/L, which is more than triple the salinity of the open ocean (Micklin 2007). The same processes that contributed to the Aral Sea degradation have also resulted in the rise of the groundwater table and contamination of groundwater with high levels of salts and other minerals. Groundwater mineralization in this region can be as high as 6 g/L TDS and drinking water reaches levels of up to 3.5 g/L total dissolved solids (compared to the national standard of 1 g/L) (Lioubimtseva et al. 2005).

At the local scale, food security and human health issues in these areas are directly linked to water availability and water stress. All croplands in the surroundings of the Aral Sea rely on irrigation. The depletion of surface and groundwater sources, high concentration of salts and other chemicals in water, increasing wind and water erosion, increasing temperature extremes caused by the Aral Sea disappearance, and frequent salt storms from its barren salty bottom have devastating impact on the local agricultural productivity. In the past, regions adjacent to the Aral Sea used to have a vibrant fishing industry. Today, fishing is non-existent in Karakalpakstan, but is coming back to the Small Aral in Kazakhstan. As the micro-climate of the area adjacent to the Small Aral continues to improve, it will most likely have positive impact on the local food security, water availability, and livelihoods of the local communities. The situation is much less hopeful in the neighboring Karakalpakstan, where both the sheer size of the Large Aral dry bottom and persistent lack of financial resources represent insurmountable challenges for any potential restoration project. The case of the Small and Large Aral clearly illustrates that human vulnerability is a function of both biophysical and socioeconomic variables.

At this scale, human vulnerability is largely determined by the local and, to some extent, national factors. Exposure to direct impacts of the micro- and meso-climatic changes caused by the Aral Sea degradation chiefly depends on the location of the population: distance from the exposed bottom of the sea, distance from water sources, and water salinity in the remaining lakes. Exposure to dust storms is one of the major factors affecting population health in the vicinity of the Aral Sea and several studies conducted in this region have established that the exposure to dust contaminated by fertilizers, defoliants, pesticides, heavy metals, and other chemicals is a direct cause of pneumonia, asthma, gastritis, liver and pancreatic diseases, pyelonephritis, and various types of cancer (Jensen et al. 1997; Wiggs et al. 2003). Total dust deposition is extremely high, in the range of 50–1679 kg per hectare with the highest deposition rates at sites located in the desert (O'Hara et al. 2000; Wiggs et al. 2003).

Sensitivity to adverse (or beneficial) processes in the vicinity of the Aral Sea is shaped by population mobility, skills and demographic parameters, such as age and gender. For example, there is substantial evidence that anemia and certain types of cancer in this region primarily affect women. Children are particularly vulnerable to respiratory and eye diseases, and kidney and liver problems caused by the toxic dust storms. There is a high child mortality rate of 75 in every 1,000 newborns and maternity death of 12 in every 1,000 women (Jensen et al. 1997; Sayko 1998; Micklin 2007). Psychological health of the population is another important measure of its vulnerability to economic or environmental stresses. Environmental exposures may impact not only on the physiological, but also on the psychosocial health of individuals. Studies by Crighton et al. (2003a, b) have uncovered a wide range of physiological health problems and somatic symptoms due to environmental stress in the Aral Sea area's population. Factors, such as gender and ethnicity of respondents seem to influence their psychological and physiological sensitivity to environmental changes.

The adaptive capacity of the population at this scale depends on the availability of financial, technological, educational, and many other resources at the scale of individual communities, families, and even individuals. Frequently, these types of resources shape the individual and community-wide decisions and adaptation strategies, such as to stay or to migrate, to continue with the same economic activity or to switch job, and to cultivate the land in the same way as before or to adopt new crops, new methods, new technologies, and so on. Low resources mean low adaptive capacity and unplanned reactive adaptation measures. During the first years after the 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 decades the net emigration from the areas adjacent to the Aral Sea has continued (Akiner 2000), with 5 to 10 % of the working-age population of this region leaving Karakalpakstan every year (Elpiner 2003; Crighton et al. 2003a, b). Considering that these environmental refugees are usually individuals who have 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 adaptive capacity. The difference between the Small Aral in Kazakhstan and Large Aral in Uzbekistan provides an insightful example of how resources shape the adaptation capacity and adaptation strategies. In the early 1990s the situation in both regions was quite similar and the population had very few adaptation choices besides emigration. Yet, Kazakhstan has nonetheless tried to partially restore the northern Aral and was able to attract massive international aid to follow up with this project. Twenty years later, the Small Aral levels are climbing up, the local micro-climate has improved, freshwater fish is back, the coastal vegetation has been restored, and the population of the Kazakh coast of the Aral Sea has significantly more economic opportunities. The proactive efforts of Kazakhstan have clearly demonstrated that water level could be raised and salinity lowered and the local climate change can be mitigated.

Conclusions

The Aral Sea basin represents an area with diverse environmental, social, and economic stresses that occur at several spatial and temporal scales. The entire basin is projected to become warmer during the coming decades and precipitation is likely to increase slightly in its eastern part and to decrease in the west. Aridity is expected to increase across the entire region, but especially in the western part of Turkmenistan, Uzbekistan, and Kazakhstan, areas that are also affected by significant land-use and hydrological changes and Aral Sea degradation. 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 the 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 water resources, food security, and health. Climatic changes 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 drying Aral Sea itself. 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 proposed multi-scale approach to human vulnerability assessment offers an effective framework to quantify and evaluate variables of exposure, sensitivity, and adaptive capacity of human–environmental systems that often have very different spatial extent and duration: from macro-regional to local and from long-term to short term. Once all variables are identified and collected, they can be weighed based on their relative importance and a comprehensive multi-scale multi-criteria model can be developed for mapping human vulnerability of the basin.

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References

Abdolvand B, Winter K, Mirsaeedi-Gloßner S (2014) The security dimension of water: insights from Central Asia. Environ Earth Sci (this issue)

Akiner S (2000) Central Asia: a survey of the region and the five republics. UNHCR Centre for Documentation and Research, WRITENET Paper No. 22/1999, United Nations High Commissioner for Refugees, Geneva, p 50

Aladin N, Crétaux J-F, Plotnikov IS, Kouraev AV, Smurov AO, Cazenave A, Egorov AN, Papa F (2005) Modern hydro-biological state of the small Aral Sea. Environmetrics 16(18):375–392

Alcamo J, Henrichs T (2002) Critical regions: a model-based estimation of world water resources sensitive to global changes. Aquat Sci 64:1–11

Arnell NW (2004) Climate change and global water resources: SRES emissions and socio-economic scenarios. Glob Environ Change 14:31–52

Barlow M, Cullen H, Lyon B (2002) Drought in central and southwest Asia: La Niña, the warm pool, and Indian Ocean precipitation. J Clim 15:697–700

Chub VE (2000) Climate change and its impact on the natural resources potential of the Republic of Uzbekistan. Gimet Tashkent (in Russian)

Confalonieri U, Menne B, Akhtar R, Ebi KL, Hauengue M, Kovats RS, Revich B, Woodward A (2007) Human health. 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 391–431

Crighton EJ, Elliott SJ, van der Meerc J, Small I, Upshur R (2003a) Impacts of an environmental disaster on psychosocial health and well-being in Karakalpakstan. Soc Sci Med 56(2003):551–567

Crighton EJ, Elliott SJ, Upshur R, van der Meerc J, Small I (2003b) The Aral Sea disaster and self-rated health. Health and Place 9:73–82

Elpiner LI (2003) A scenario of possible effect of changes in the hydrological conditions on the medical and environmental situation: on the problem of global hydroclimatic changes. Water Resour 30(4):434–444

FAO AQUASTAT (2013) AQUASTAT FAO's information system on water and agriculture. http://www.fao.org/nr/water/aquastat/main/index.stm. Accessed Dec 2013

Fischer G, Shah M, Tubiello FN, van Velhuizen H (2005) Socioeconomic and climate change impacts on agriculture: an integrated assessment, 1990–2080. Philos Trans Royal Soc B 360: 2067–2073

Fort M (2014) Natural hazards versus climate change and their potential impacts in the dry, northern Himalayas: focus on the Upper Kali Gandaki (Mustang District, Nepal). Environ Earth Sci (this issue). doi:10.1007/s12665-014-3087-y

Glantz MH (2005) Water, climate, and development issues in the Amu Darya basin. Mitig Adapt Strat Glob Change 10(1): 1381–2386

Groll M, Opp C, Kulmatov R, Ikramova M, Normatov I (2014) Water quality, potential conflicts and solutions—an upstream–downstream analysis of the transnational Zarafshan River (Tajikistan, Uzbekistan). Environ Earth Sci (this issue). doi:10.1007/s12665-013-2988-5

IPCC (2001) Climate change: the scientific basis. In: Houghton JT, Ding Y, Griggs M (eds) Contribution of working group I to the third assessment report of the intergovernmental panel on climate change (IPCC). Cambridge University Press, Cambridge, UK

IPCC WGI (2007) Climate Change 2007: the physical science basis. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK and New York, NY, USA

IPCC WGII (2007) Climate Change 2007: impacts, adaptation and vulnerability. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK and New York, NY, USA

Jensen S, Mazhitova Z, Zetterstr R (1997) Environmental pollution and child health in the Aral Sea region in Kazakhstan. Sci Total Environ 206(1997):187–193

Kariyeva J, van Leewuven W (2011) Environmental drivers of NDVI-based vegetation phenology in Central Asia. Remote Sens 3(2):203–246. doi:10.3390/rs3020203

Kayumov AK, Mahmadaliev BU (2002) Climate change and its impacts on climate change. Avesto, Dushanbe (in Russian)

Kirilenko A, Dronin N (2011) Climate change and adaptations of agriculture in the countries of the Former Soviet Union. In: Yadav SS, Redden B, Hatfield JL et al (eds) Crop adaptation to changing climates. Wiley-Blackwell, Hoboken, NJ, pp 84–106

Jönsson P, Eklundh L (2004) TIMESAT—a program for analyzing time-series of satellite sensor data. Comput Geosci 30(8): 833–845

Lioubimtseva E (2002) Arid environments. In: Shahgedanova M (ed) Physical geography of northern Eurasia. Oxford University Press, Oxford, UK, pp 267–283

Lioubimtseva E (2007) Possible changes in the carbon budget of arid and semi-arid Central Asia inferred from land-use/landcover analyses during 1981–2001. In: Lal R, Suleimenov M, Stewart BA, Hansen DO, Doraiswami P (eds) Climate change and terrestrial carbon sequestration in Central Asia. Taylor & Francis, London, pp 441–452

Lioubimtseva E (2014) Impact of climate change on the Aral Sea and its Basin. In: The Aral Sea: the devastation and partial Rehabilitation of a Great Lake: anatomy of an environmental disaster. In: Micklin P, Aladin N, Plotnokov I (eds) Chapter 17, (Springer Earth System Sciences), Springer, Praxis

Lioubimtseva E, Adams JM (2004) Possible implications of increased carbon dioxide levels and climate change for desert ecosystems. Environ Manag 33(S1):S388–S404

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

Lioubimtseva E, Cole R, Adams JM, Kapustin G (2005) Impacts of climate and land-cover changes in arid lands of Central Asia. J Arid Environ 62(2):285–308

Lioubimtseva E, Kariyeva J, Henebry GM (2013) Climate change in Turkmenistan. In: Zonn IS, Kostyanov AG (eds) The Turkmen Lake Altyn Asyr and water resources in Turkmenistan, handbook on environmental chemistry. Springer, Heidelberg. doi:10.1007/698-2012-175

Malsy M, Aus der Beek T, Flörke M (2014) Uncertainties in hydrological modelling and its consequences for sustainable water management in Central Asia. Environ Earth Sci (this issue). doi:10.1007/s12665-014-3107-y

Micklin P (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 (2010) The past, present, and future Aral Sea. Lakes Reserv Res Manag 15:193–213

Nakicenovic N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, La Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner H–H, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, van Rooijen S, Victor N, Dadi Z (2000) IPCC special report on emissions scenarios, IPCC special reports. Cambridge University Press, Cambridge

Newingham BA, Vanier CH, Charlet TN, Ogle K, Smith SD, Nowak RS (2013) No cumulative effect of 10 years of elevated [CO_2] on perennial plant biomass components in the Mojave Desert. Glob Change Biol 19(7):2168–2181. doi:10.1111/gcb.12177

O'Hara S, Wiggs GFS, Mamedov B, Davidson G, Hubbard RB (2000) Exposure to airborne dust contaminated with pesticide in the Aral Sea region. Lancet Res Lett 355:627–628

Polsky C, Neff R, Yarnal B (2007) Building comparable global change assessments: the vulnerability scoping diagram. Glob Environ Change 17(3–4):472–485

Rakhmatullaev S, Huneau F, Kazbekov J, Le Coustumer P, Jumanov J, El Oifi B, Motelica-Heino M, Hrkal Z (2010) Groundwater resources use and management in the Amu Darya River Basin (Central Asia). Environ Earth Sci 59(6):1183–1193. doi:10.1007/s12665-009-0107-4

Sayko TS (1998) Geographical and socio-economic dimensions of the Aral Sea crisis and their impact on the potential for community action. J Arid Environ 39:225–238

Schröter D, Polsky C, Patt AG (2005) Assessing vulnerability to the effects of global climate change: an eight step approach. Mitig Adapt Strat Glob Change 10:573–596

Shibuo Y, Jarsjo J, Destouni G (2007) Hydrological responses to climate change and irrigation in the Aral Sea drainage basin. Geophys Res Lett 34:L21406. doi:10.1029/2007GL031465

Shiklomanov IA, Rodda JC (2001) World water resources at the beginning of the twenty-first century. Cambridge University Press, Cambridge

Small EE, Sloan LC, Hostetler S, Giorgi F (1999) Simulating the water balance of the Aral Sea with a coupled regional climate-lake model. J Geophys Res 104(D6):6583–6602

Small EE, Giorgi F, Sloan LC, Hostetler S (2000) The effects of desiccation and climatic change on the hydrology of the Aral Sea. J Clim 14:300–322

Smit B, Skinner MW (2002) Adaptation options to climate change: a typology. Mitig Adapt Strat Glob Change 7:85–114

Smith SD, Huxman TF, Zitzer SF, Charlet TN, Housman DC, Coleman JS, Fenstermaker LK, Seemann JR, Nowak RS (2000) Elevated CO_2 increases productivity and invasive species success in an arid ecosystem. Nature 408:79–82

Syed FS, Giorgi F, Pal JS, King MP (2006) Effect of remote forcings on the winter precipitation of Central Southwest Asia, Part 1: observations. Theoret Appl Climatol 86(1–4):147–160

Wiggs GFS, O'Hara SL, 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(2):142–157

Wigley TML (2008) MAGICC/SCENGEN 5.3: USER MANUAL (version 2) NCAR, Boulder, CO, September 2008, http://ncar.ucar.edu/