SAND-AND-DUST STORM IMPACTS AND BENEFITS FROM REDUCTION.
ARAL SEA BASIN REGIONAL OVERVIEW

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DISCLAIMER

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Foreword

The Aral Sea crisis is one of the biggest environmental disasters in the world. During the last decades, it has shrunk to around 10% of its original size, disrupting the water cycle and creating dangers to human health. The exposed seabed has become a regional hotspot source of sand and dust storms (SDS). Contaminants from past agricultural and industrial activities, residing in the sea bed, are now exposed and, aided by sandstorms, contaminate the air and the surrounding ecosystems.

Urgent strategies including interventions for reduction of dust generation at source and mitigation of impacts on society need to be designed. The World Bank (WB) has undertaken initiatives to achieve reduction of dust generation from the Aral Seabed in Uzbekistan by means of targeted forestation interventions.

In collaboration with the WB, ICARDA (International Center for Agricultural Research in the Dry areas) is conducting a study aimed at measuring and valuating the effects of soil retention interventions on ecosystem services. This literature review on the impacts of SDS in the Aral region is aimed at setting the stage for the study.

1. Background

Sand and Dust Storms (SDS) are a global transboundary phenomenon with important impacts on ecosystems and society. SDS influence ecosystem processes affecting nutrient and hydrological cycles and biomass productivity, and impact human society by affecting a range of sectors, including health, transport, agriculture, as well as sanitation and water and air quality (Middleton et al., 2019, Querol et al., 2019). For this reason, coping with SDS requires a multi-hazard risk assessment and alert system (UNESCAP, 2018).

The occurrence of SDS is depends on climate, weather, soil conditions, and land cover, which determine erosion, transport, and deposition of sand and dust particles by wind. Unsustainable use of agricultural land, deforestation, overgrazing, depletion of water resources, can all contribute to SDS by accelerating wind erosion. Potential drivers of increased future wind erosion and SDS occurrence include desertification, land degradation and climate change (e.g., more extreme wind events, greater aridity in some areas, and greater drought frequency, severity and duration).

Globally, SDS are considered as a largely natural phenomenon. The Global Assessment1 of Sand and Dust Storms (UNEP, WMO, UNCCD (2016) reviewed the scientific estimates of the relative contribution of human activity to current levels of global dust emissions, and indicated 25% as the most likely estimate. Desertification and land degradation are typical drivers of human-driven, or anthropogenic SDS (UNCCD, UNEP, UNESCO, FAO, ESCAP, 2001; UNESCAP, 2018).

The international community is aware that even if dust sources are located in remote areas, their impact can be felt thousands kilometers away. On the other hand, an important feature of the anthropogenic source areas is that they are often not located in remote desert regions, but closer to the inhabited areas, or within them. In some cases, source soils and sediments can be polluted, or enriched in salts or other potentially toxic compounds, which makes anthropogenic dust more harmful.

In view of the relevance of land degradation and desertification to SDS, in 2017 the 13th Session of the UNCCD Conference of the Parties (COP) adopted Decision 31/COP.13[2] on SDS and invited countries to use the UNCCD Policy Advocacy Framework to address the impact of SDS. The UNCCD supports countries in the mitigation of SDS impacts and anthropogenic dust sources by advocating a three pillars approach: 1) Early warning systems; 2) Preparedness and resilience; and 3) Anthropogenic source mitigation.

In regions where anthropogenic sources have a prominent role, like in Central Asia, source mitigation may be the only way to reduce SDS impacts substantially. Despite historically, Kizilkum and Karakum deserts were major sources of SDS in the region. Appropriate measures, including, e.g., prevention, restoration, or sustainable land management (SLM) need to be identified and scaled up (Middleton and Kang, 2017).

However, much remains to be done to identify effective source-mitigation actions. A comprehensive assessment of the impacts of SDS and a greater understanding of the benefits that would come from the reduction of the anthropogenic dust sources are needed to design strategies and to justify the investments needed to reduce both dust generation and SDS impacts.

[1] https://public.wmo.int/en/resources/library/global-assessment-of-sand-and-dust-storms. Accessed in May 2020.

[2] https://www.unccd.int/sites/default/files/sessions/documents/2019-08/31COP13_0.pdf

2. Purpose and approach

The main purpose of this work is to review the available scientific literature on the SDS impacts in Central Asia (CA), with particular focus on the SDS generated by the dried and exposed Aral seabed, and to outline their impacts according to the CAPITALS model adopted within the Sustainable Livelihoods and Vulnerability to Disasters framework (Twigg, 2001).

SDS are the subject of a large number of articles from several scientific disciplines, including atmosphere circulation and chemistry, climate and climate change, glaciology, soil science, geomorphology and sedimentology, environmental pollution, socio-economy, technological and military applications, microbiology, allergology and several other medical disciplines. Several global review papers also exist that address the dust sources (e.g., Ginoux et al., 2012; Bullard and Baddock, 2019), summarize multiple SDS impacts (Middleton et al., 2019) or review impacts on specific targets, e.g., on health (Querol et al., 2019), on solar energy systems (Costa et al., 2016), on civil structures (Raffaele and Bruno, 2019), etc.

Many articles define the Aral Basin as a highly SDS-impacted region. However, a comprehensive regional review of the SDS impacts in Central Asia is still missing and the picture provided by literature is fragmentary. Thus, the main purpose of this work is to contribute to fill this gap based on the scientific articles accessible online.

In addition, in view of the fact that the evaluation of the benefits of SDS-reduction and the quantification of the socio-economic damages caused by SDS are poorly addressed by regional literature, this review will also include examples of studies that documented the benefits of SDS-reduction interventions from other regions of Asia, and will provide methodological references useful for the quantification of the socio-economic damages caused by SDS.

The next section (section 3) describes the conceptual framework adopted by this review to categorize the SDS impacts. Section 4 summarizes the review findings, outlining drivers and impacts of the SDS in the Aral basin and in CA. Section 5 and 6 provide, respectively, literature examples of evaluation of the SDS financial impacts and of the effectiveness of the SDS-reduction interventions at source.

3. Conceptual framework

3.1. Type of impact

The information contained in the reviewed articles has been analyzed in order to categorize, among other, the type of data and methods used by the authors of the studies, the type of impact and damage caused by the SDS, and the SDS source areas.

The Capitals model has been used to categorize the impacts. To this aim, the SDS impacts have been grouped according to four main categories: Human, Physical, Natural, and Financial. The Social capital as defined by Twigg (2001) was not considered because the reviewed studies do not address the impacts of SDS on personal connections (e.g., extended family, associations, and other support mechanisms). Some sub-categories were also defined (health, air quality, structures, productive assets, activities, soils, water, ecosystems, and economic costs) as shown in Table 1.

Human	Physical	Natural	Financial

Health Increased morbidity and mortality.	Structures Damage to integrity or functioning of buildings, structures.	Soil Soil loss, degradation, or pollution. Water degradation.	Economic cost Costs of various types of damage.
Air quality (indirect human impact) Higher PM concentrations; lower visibility, dust load.	Productive assets Damage to crop fields, livestock, solar panels, etc.	Ecosystems Impact on fragile ecosystems and on climate.	
	Activities Disruption of transport systems and other open-air activities.		

Table 1. The main SDS impact types categorized according to the impacted Capitals.

A detailed list of the specific impacts under each category would be long. As an example, health impacts can include (as reported by various studies):

- increased mortality or morbidity (higher for more at-risk population) linked to respiratory, cardiovascular, and allergological effects;
- disease transmission and triggering of the onset of epidemics;
- ingestion of advected toxic chemicals or radiation;
- eye and skin problems (e.g., lacrimation, irritation); and
- reduced psychological wellness.

Impacts on economic activities include:

- increased operating expenditures of production facilities in the form of higher cleaning and maintenance costs;
- additional costs for emergency units of hospitals to keep functionality, safety, and efficiency under SDS;
- damages to electrical transmission systems and to solar panel efficiency and integrity;
- reduction in construction and mining and other open-air activities due to health and safety issues; and
- high recurrent costs for household cleaning, and repairs and maintenance to structures and vehicles.

Negative impacts on ecosystems can involve effects on local and regional climate (e.g., atmosphere cooling/warming), on high altitude snow fields (darkening), and on oligotrophic ecosystems (nutrient cycle unbalance).

Impacts on soil encompass reduced soil depth, nutrient and carbon content, fertility, and soil water holding capacity due to erosion; contamination and alkalinisation in case of polluted and/or salt-rich dust deposition.

3.2. Onsite and offsite impacts

The SDS impacts can be observed both on-site and off-site. The distinction between on- and off-site impacts cannot be rigid in view of the continuity of the spatial scales involved.

Inside the source area (onsite), where both soil particle detachment and entrainment happens, all possible types of impacts can be observed, associated with erosion (soil loss, undermining of structures, etc.), transport (air quality, visibility, etc.), or deposition (sand encroachment, d) of particles.

Moving away from the source area (offsite), depending on the distance and on wind speed, some types of impacts can still be possible. As an example, at regional to global scale, the impacts caused by transport and deposition of very fine particles can be observed along with the consequences it can lead to.

4 Review findings

Forty-seven articles in English language addressing SDS generation and impacts in the Aral basin and in CA have been identified and reviewed. Most of them (36) are articles published in peer reviewed scientific journals, 9 are book chapters, 1 is a conference paper, and 1 is a technical report.

Most documents are recent: 22 were published between 2012 and 2015, 11 after 2015. A majority of them (36) are mainly based on ground observations, including works relying on data series from meteorological and air quality station networks, from field measurements and experiments, and from statistical records (mortality, morbidity, socio-economics, etc.). Relatively few studies are based on remote sensing and modeling, which appear to be still poorly exploited in CA compared to other regions.

Fifteen of the 43 studies address dust generation at source, mainly through the analysis of multi-annual series of climatologic data from meteorological stations, to evaluate, e.g., the location of the source areas and their changing features and extent, and the spatial and temporal dynamics of SDS frequency and severity (Figure 1).

Nine studies address dust deposition (Figure 1), 8 of which focus on the impacts of SDS on air quality and on ecosystems based on the measurement of dust deposition, by means of networks of stations equipped with dust traps. An additional one analyses the long-distance dust deposition on high-altitude mountain ecosystems.

Thirteen studies assess the impacts of the ecological disaster on the health of the people living around the Aral, although only some of these papers link, explicitly, the observed effects with SDS.

Three papers discuss various aspects related to the impacts of the Aral disaster on the human and physical capital including economic activities and agricultural production, and explore nature-society linkages and human vulnerability factors. Finally, 7 studies provide evidence on how the SDS source areas located in the Aral seabed could be reduced by means of adaptation or restoration interventions based on the use of native halophytes and on a more efficient use of the available water resources.

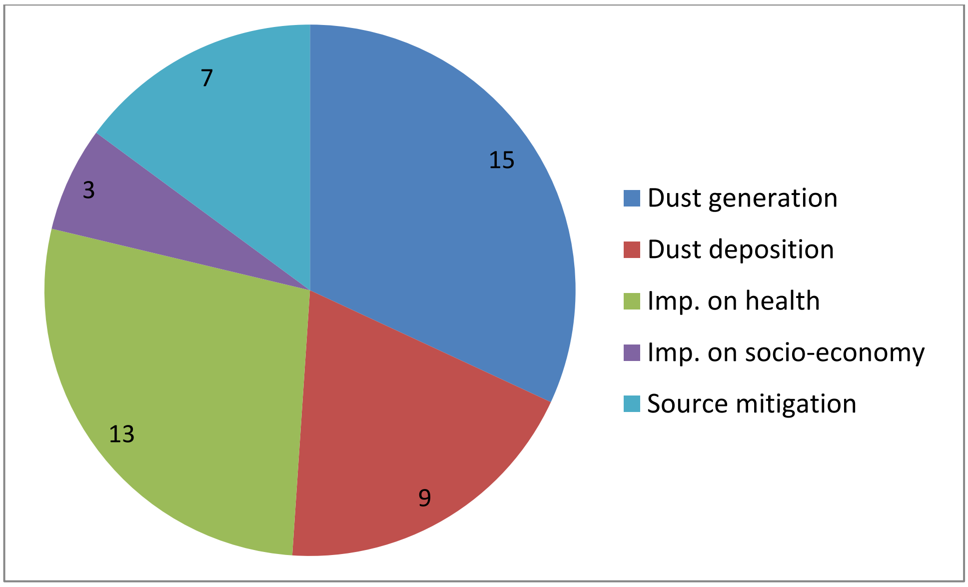

Figure 1. Thematic focus of the 47 studies reviewed.

4.1. Drivers and implications of the Aral Sea ecological disaster

Aral Sea is considered as one of the biggest environmental disasters in the world. During the last decades it has shrunk dramatically compared to its original size. Aside from the loss of fishery as a source of living for local communities, the drying up of the sea disrupted the water cycle and created dangers to human health. The exposed seabed has become a regional hotspot source of sand and dust storms (SDS). Contaminants from past agricultural and industrial activities, residing in the exposed sea bed contaminate the air and the surrounding ecosystems.

The water level of the Aral Sea has known significant historical oscillations, with at least two very severe regression events during the last two millennia (Breckle and Geldyeva, 2012). About 400 AD the water level sank to only 25–30 m a.s.l., most probably because of a deviation of the Amu Darya River. During the 15th and 16th centuries the water level was about 43–44 m a.s.l. most of the time. Only since the 18th century the water level got stabilized at around 53 m a.s.l.

The recent drop of the water level started during the 1970s (Table 2), bringing about the quick shrinking of the water body and its sharp salinity increase.

Year	Water level (m asl)	Water surface, without islands (km^2)	Volume of water (km)	Salinity (% NaCl)
1960	53.4	67,100	1,080	0.9
1970	51.2	60,200	950	1.2
1980	45.4	50,800	630	1.7
1990	38.2[a]/40.5[b]	36,400	310	3.2
2000	≈ 33.5[a]/39.8[b]	26,000	160	6–8[a]/2.0[b]
2005[c]	≈ 30.7[a]/41.0[b]	19,000	110	7–15[c]/1.9[b]
2009	25[a]/42[b]	7,000	< 100	≈ 10–20[c]/1.5[b]

After (Bortnik 1996; Dukhovny et al. 2008)
[a]The South Aral Sea
[b]The North Aral Sea
[c]In 2005, the shrinking South Aral Sea was subdivided into two lakes, the western and the eastern basins, with almost no water exchange between them

Table 2. Aral Sea level changes since 1960. Source: Breckle and Geldyeva, 2012.

Remote sensing evidence shows that between 1977 and 2015 the Aral Sea shrunk by more than 66% (Shen et al., 2019). This was the result of the over-exploitation of water resources for agriculture and of the construction of water reservoirs and hydropower stations along the two main feed rivers (the Amu Darya and the Syr Darya), as well as a consequence of climate change (Shen et al., 2019). The main driver was the enormous increase of irrigation in the whole region for intensive production of cotton, rice, wheat and vegetables, in a region where the annual mean precipitation is of only 100–150 mm (Breckle and Geldyeva, 2012).

The hydrological and aeolian processes leading to the degradation of the Aral Sea ecological complex have been summarized as follows (INTAS and RFBR, 2001):

- Reduced inflow from the rivers and seaside and related reduction of flooded areas;
- Ground water lowering;
- Increased salt content in surface and ground water;
- Desertification - aeolian processes, salt and dust transport.

The socio-ecological linkages driving the above process are very complex. They are linked to the international water use in the region and to climate change, and there is an understanding that it would be very difficult to revert the process (Lioubimtseva, 2014; White et al., 2013; Erdinger et al., 2011, Squires and Qi, 2018). Some authors think that recovering the pristine conditions of the Aral Sea may be impossible in the medium term, and that irrigation will remain the most important resource for agriculture in Central Asia, also to sustain population growth (Breckle and Geldyeva, 2012).

The socio-ecological implications are manifold. The above-mentioned study by INTAS and RFBR (2001) addressed them in four regions of Karakalpakstan (Muinak, Bozatauz, Kungrad and Tahtakupyr), the most severely affected area in southern Aral region, and outlined them as follows:

- Intense development of desertification processes in the territories adjacent to the Aral Sea. The most serious factors of desertification are aeolian processes, salt and dust transport from the dried sea bottom and other parts of surrounding deserts.
- Acute decrease of the AmuDarya runoff, termination of spring floods and floodplain inundation, the number of lakes and their area has sharply reduced.
- Lower inflow to the delta and seaside and related reduction of the flooded area.
- Lower level of ground water.
- Progressing process of soil salinization in irrigated areas (about 94% of irrigated land in Karakalpakstan salinized by 1997).
- Intense degradation of the soil and natural complex, and related variations in vegetation cover and natural landscapes including areas of native reed and forest.
- Local climate modified considerably (average summer and spring air temperature increased, winter and autumn temperature, diurnal amplitude of temperature increased, and relative air humidity decreased, particularly in the warm season).
- Loss of habitat for migratory bird species, for muskrat and other animal species.
- The amount of fish catch in the Sea and adjacent lake systems reduced tenfold.
- Starting from 1994-95 the used irrigated lands throughout the Aral Sea zone have reduced by 25%, causing reduced crop productions (particularly affected were grain crops, rice, forage, maize, cotton, vegetables and cucurbits).
- Decreased river runoff and drying of vast areas of former sea bottom resulted in acute reduction of natural productive rangelands and hay mowing areas affecting cattle breeding and the number of sheep and goats, particularly in Tahtakupyr region.

The study also noted that the rapid withdrawal of the coastline has hampered the rehabilitation activities in the coastal zone.

4.2. Dust emission from the exposed seabed's soils

The desiccation of the Aral Sea exposed the seabed, forming large bare areas characterized by saline soils (Figure 2; Shen et al., 2019), and creating a mosaic of sand desert and salt desert ecosystems (the new "Aralkum" desert), the characteristics of which are influenced by the variable and complicated geological and geomorphological structure of the desiccated seafloor.

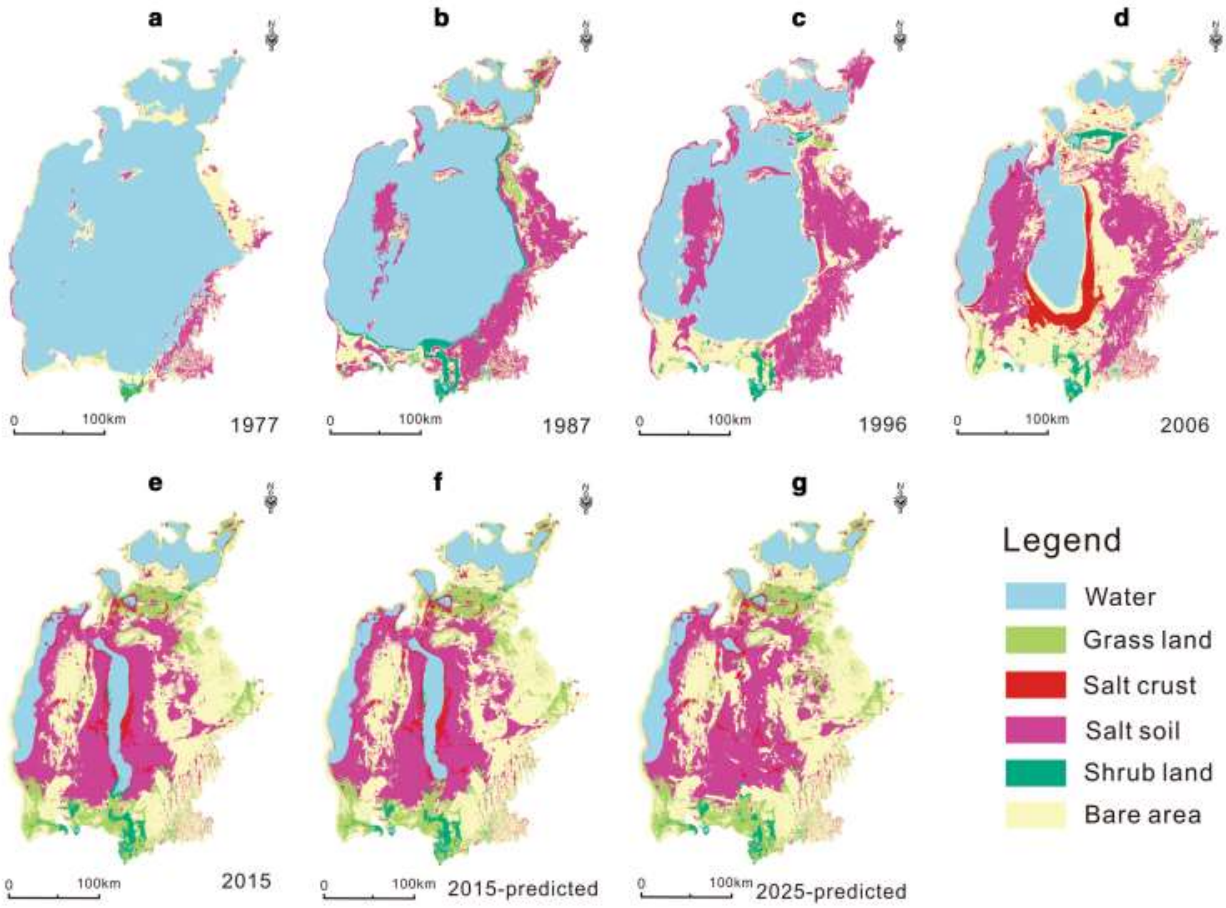

Figure 2. Land cover change on Aral seabed, 1977-2015. Source: Shen et al., 2019.

According to Löw et al. (2013) the sandy surfaces and the salt-affected soils increased by more than 36% between 2000 and 2008. According to the authors the latter are the soils with the greatest DS generation potential. Particularly, the Solonchak and the Takyr soils, and the "Salt crusts" expanded from 15 to more than 25%.

Indoitu et al. (2015) state that the exposed heavy Takyr, Takyr-like and Solonchak surfaces have high potential to be a source of severe SDS events: the most active emission site consists of sands (75%), Solonchaks (17%) and Takyrs/Takyr-like soils (8%). In fact, most of the SDS events in the Aral basin originate from the north-eastern Aral seabed area, mostly under the action of winds from the East (57%) and more in general from eastern quadrants (80%). This area is responsible for high aerosol concentrations in the atmosphere. From there, dust plumes often reach lengths of 150 km to more than 600 km (Indoitu et al., 2015).

Semenov et al. (2012) developed a physical model to evaluate the amount of aerosols transported from the desiccated seafloor of the Aral Sea, finding evidence that the increase in size of the desiccated seafloor will make available higher amounts of smaller size (less than 10 µm) particles, with higher salt content, increasing the distance over which the particles are transported by wind. The salt-dust clouds can be up to 400 km long and finer particles can travel up to 1,000 km away.

Bare sediments started to be colonized by native vegetation species, with colonization patterns and rates depending on the salinity and texture of the newly formed soils (Wucherer et al., 2012a; Dimeyeva, 2007). Although the rate of the spontaneous vegetation cover increase is not enough to reduce dust generation significantly, the observed process is of great ecological interest, and a learning opportunity for restoration scientists, because it has transformed the Aralkum into the largest area worldwide where a primary succession is taking place (Wucherer et al., 2012a).

4.3. SDS occurrence and contribution to the regional SDS activity

The dust generation processes activated by the exposed seabed have transformed the Aral into a regional SDS hotspot, as clearly showed by several studies.

Indoitu et al. (2012) analyzed all SDS events for Central Asia between 1936 and 2005 and found that after 1980s the northern Aral basin becomes the main regional hotspot, with up to more than 40 SDS days per year (Figure 3). At the broader regional scale, active source areas of DS are located mainly in deserts where sensitive ecosystems suffered from human impact, and show a general decrease in frequency after the 1980s, along with changes in the active source areas. Decreasing trends were most obvious for Karakum Desert (from an average above 30 days per year to less than 20 days per year). Main spatial changes were clear in the Northern Caspian deserts, also showing a shift of few hundred kilometers to the East. The Kyzylkum Desert and the south Balkhash Lake area underwent an important surface reduction of the major source areas. So, the Aralkum dynamics contrasted the regional ones.

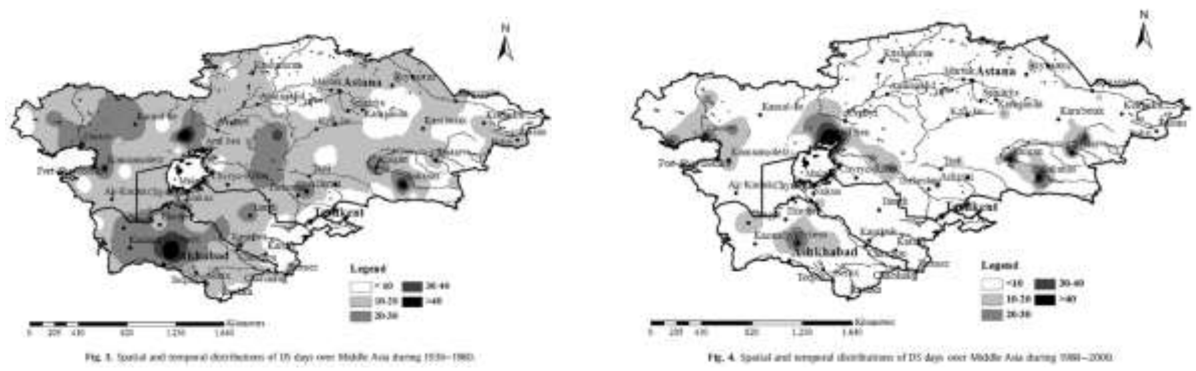

Figure 3. SDS occurrence in CA in 1936-1980 (left) and 1980-2000 (right). Source: Indoitu et al., 2012.

A recent research on the diffusion of dust aerosol originating from the Aral Sea Basin by Ge et al. (2019) found strong increasing trends of aerosol indices after 2005 and until 2013, associated with the continuous decrease in the water level.

A study addressing southern Kazakhstan (long-term meteorological data, from the 1960s) found that the newly formed Aralkum desert was the dominant source of aeolian sand, dust and salt aerosols (Issanova et al., 2015). In the broader Aral Sea region the same study found the highest SDS occurrence in Pre-Aral Karakum and Kyzylkum deserts. Most meteorological stations found three maximums of sand and dust transportation, namely in 1966–1970, 1984–1986, and 2000–2002, with a general overall slight decrease in sand and dust transportation, and with dominant winds from eastern and north-eastern quadrants.

Spivak et al. (2012) also highlighted the very high probability of occurrence of dust storms on the dried bottom of the sea due to the surface structure and instability. Focusing on the eastern part of the Aral Sea, they studied the temporal dynamics of the aerosol development and described the SDS frequency (an average of 13 event per year) and patterns between 2000 and 2009.

A continental-scale study by Shao et al. (2006) showed that in CA, during 1998-2003, only in two stations located along the Syr Darya River in QyZylorda region (east to the Aral Sea, in south-western Kazakhstan), the SDS severity and frequency were comparable to those observed in the SDS hotspots areas of the Mongolian plateaus.

A recent study addressing all of CA stressed that almost all major SDS sources are located over topographical lows or on lands adjacent to strong topographical highs where fluvial action is evident by the presence of ephemeral rivers and streams, alluvial fans, playas, and saline lakes (Issanova and Abuduwaili, 2017). This shows that the Aral is not a unique case in the region and that similar SDS sources could be activated or intensified in connection with climate change and water management.

The spread of the Aral dust to the surrounding CA regions, and its contribution to the local dust load, are not well quantified by the available literature yet.

In a study conducted in Turkmenistan, Orlovski et al. (2005) studied all SDS events using a 60 year-long (1936–1995) series of data from 56 meteorological stations across the country. They observed a drop in SDS occurrence after 1980-1985, possibly due to global atmospheric circulation dynamics. The highest mean annual SDS frequency was found in spring in the sandy Central Karakum Desert (67 days), and the maximum number of SDS days was registered in western Turkmenistan (146 days). They also noted contrasted patterns, with persistence of SDS generation from areas affected by active rangelands degradation and sharp decrease from areas where irrigated agriculture has been developed. However, although they reported an increase by 3 times of the frequency of dust storms in the Aral Sea region during 1960–1980, they did not discuss the possible effects of this increase on the SDS activity observed in Turkmenistan, downwind.

Conversely, a recent study investigated the trajectories of the SDS affecting south-western Asia, including southern Turkmenistan, and found that north and northeast strong surface winds over the Usturt Plateau in the west of the Aral Sea are mostly responsible for the SDS observed in downwind locations like Ashgabat and Mary (southern Turkmenistan), and Sarakhs (north-eastern Iran), suggesting that more research based on RS and modeling would be needed to map and quantify the offsite impacts of the Aral dust (Rashki et al., 2018).

Issanova et al. (2014) addressed SDS in southern Pre-Balkhash desert regions and found that sand/dust transport occurs mainly in the east, south-east, and north-east directions, suggesting no significant inflows from the Aral basin. In the region, the Taukum and Moiynkum deserts, the Ili river deltas and valleys, and the southern coast of Lake Balkhash are the most prone to SDS generation.

4.4. Impacts on air and ecosystems: dust loads and dust deposition

The transport and fall-out of the dust particles generated from the Aral sources affects the air quality of the downwind regions. Furthermore, the seabed soils have high concentrations of soluble salts and pollutants (agrochemicals and industrial pollutants that accumulated in the seabed sediments) that can affect the health of both people and ecosystems. Several studies have investigated the atmospheric dust loads and dust deposition rates in the Aral basin.

Simulation modeling based on MODIS[3] and AERONET[4] data for the period April 2008–July 2009 showed that dust was the largest component of the particulate matter (both PM2.5, up to 2.5µm size, and PM10, up to 10µm size) mass in CA in all seasons except winter, as well as the driver of the seasonal PM and AOD (Aerosol Optical density) cycles (Kulkarni et al., 2015). The second most important contribution came from anthropogenic sources. On an annual basis, power and industrial sectors were the most important contributors to the anthropogenic PM2.5. Residential combustion and transportation were instead the most important sources for black carbon (BC). Biomass burning within and outside the region also contributed to raise of the PM and BC concentrations.

Groll et al. (2013) collected 426 dust deposition samples, covering all dust events during the 2003-2010 period, from 21 stations located in Uzbekistan, Kazakhstan, and Turkmenistan (Aral Sea basin; Figure 4). Stations located at the southern fringes of the AralKum, the KyzylKum or the KaraKum yielded the highest dust deposition intensities. Potentially harmful conditions were registered more frequently close to the KaraKum, but with less severe intensity of the SDS events. In the central lowlands of the Aral Sea basin the dust was instead mostly deposited in few but intense events. The meteorological station of Buzubay, close to the KyzylKum, showed highest maximum deposition intensity (9,616 g m^{-2} in September 2009), and highest median monthly deposition (61.78 g m^{-2}). High deposition rates were registered close to the Aral shoreline, in Karakalpakstan and Khorezm regions, where the maximum rate was 4,660 g m^{-2} (recorded in Jasliq in July 2009; second highest after Buzubay). Here, the highest median monthly deposition was 8.45 g m^{-2}. Overall, the impact of AralKum as dominant source seemed to be limited to a region of approximately 500,000 km^2 surrounding the former Sea (Groll et al., 2013).

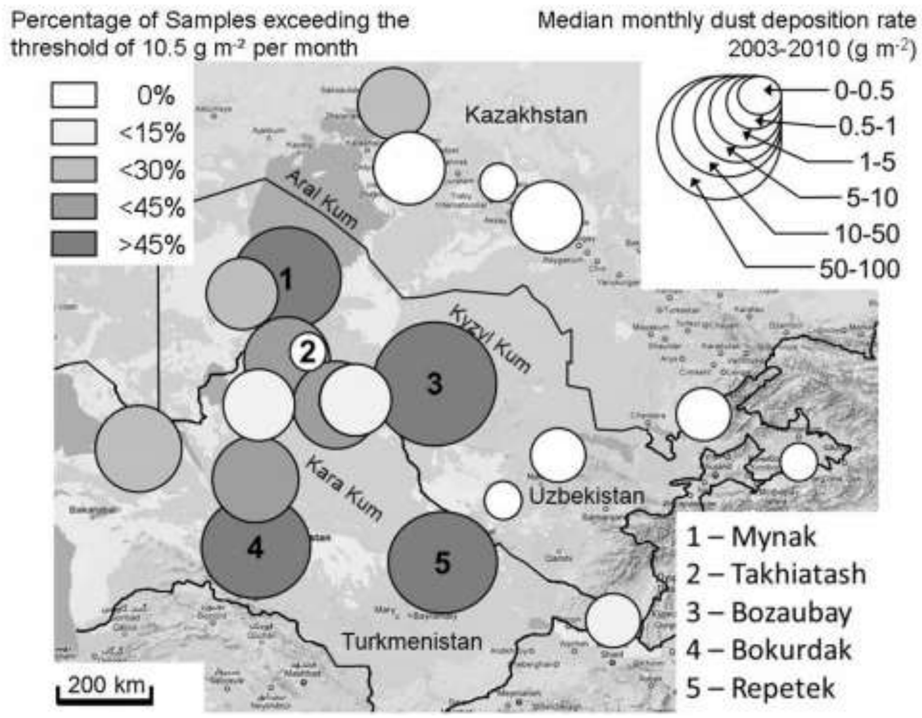

Figure 4. Spatial distribution of dust deposition in CA based on ground measurements at 21 meteorological stations, 2003-2010. Source: Groll et al., 2013.

3 Moderate Resolution Imaging Spectrometer (MODIS). https://modis.gsfc.nasa.gov/

4 AErosol RObotic NETwork (AERONET) project. https://aeronet.gsfc.nasa.gov/

A more recent work on dust deposition in the Aral Sea basin (Turan lowlands, including Aralkum, Kyzylkum, Karakum, and Khorezm) was conducted by Opp et al. (2019), using data from 23 dust sampling stations distributed across the region, between 2006 and 2012. The study confirmed highest deposition intensity in the Kyzylkum region (247.7 kg ha^{-1} per month), where 52% of all samples collected exceeded the long-term dust deposition threshold of 10.5 g m^{-2} per month (a health-related threshold defined by the German Clean Air Act and used as reference by the authors). The man-made Aralkum ranked second with an average deposition intensity of 151.5 kg ha^{-1} per month, with 45% of all samples exceeding the same health threshold. The exceedance rate was lower for the Karakum region, with 41% of exceeding days, and in Khorezm (21%). Overall, dust deposition increased over time, in association with a decreasing trend in precipitation, increasing wind speeds and a shift towards northern winds.

Some studies took a closer look to the southern Aral region, and focused particularly on western and central Uzbekistan.

Based on all SDS events during May–October 2000 and monthly dust deposition at 16 sites in Karakalpakstan, Wiggs et al. (2003) had observed extremely high monthly fine PM concentrations, comparable to the US EPA quality standards of 150 µg m^{-3} in a 24 h period and 50 µg m^{-3} as yearly average, and deposition rates as high as about 2.5 tons ha^{-1}. High levels of dust deposition were observed throughout the country in the summer months, but with particularly high rates of deposition in the north of the country close to the shore of the former Aral Sea in July, August and September.

For seven sites located in western and central Uzbekistan (Muynak, Jaslyk, Takhiatash, Yangibazar, Beruniy and Buzubay,) Aslanov et al. (2013) found that the average dust deposition rates during the 2007-2010 period was 5 to 6 times higher than during 1982-1995. On the other hand, they also found a lower average deposition rate near the AralKum than near the KyzylKum (e.g., 450 kg ha^{-1} per month in Muynak and 1,200 kg ha^{-1} per month in Buzubay).

A recent work by Opp et al. (2017) was focused on the southern Aral Sea region (autonomous republic of Karakalpakstan, and Khorezm oblast, Uzbekistan). They monitored all SDS events at 7 sampling stations of the Uzbek meteorological survey equipped with passive deposition samplers, between 2003 and 2012. Buzubay and Beruniy stations, near the KyzylKum, had very high median dust deposition (617.8 kg ha^{-1}per month and 164.0 kg ha^{-1}per month), followed by Jaslyk and Muynak, near the AralKum (101.4 kg ha^{-1}per month and 72.5 kg ha^{-1}per month). Stations farthest away showed a less intense deposition (15.7 kg ha^{-1}per month in Yangibazar and Urgench and 20.5 kg ha^{-1}per month in Takhiatash). The percentage of months exceeding the health threshold of 10.5 g m^{-2} ranged from 4% in Takhiatash to 86.7% in Buzubay. Near the AralKum, almost every second month (50.0% in Jaslyk and 45.5% in Muynak) had to be considered at health risk.

Other studies addressed the long-range fine-dust deposition processes and their potential impacts on the fragile mountain ecosystems of CA, showing clear impact of SDS on local dust deposition, but no direct linkage to the Aral sources.

Kulmatov et al. (2010) studied the dust deposition on the Abramov Glacier (Kyrgyzstan), the Sary-Chelek Reserve (Kyrgyzstan), and the Chatkal Reserve (Uzbekistan), considering all events during the summer season 1996-1997. Almost double concentrations of heavy metals (Cr, Sb, Sc, Fe, Co) were observed in the PM in Abramov Glacier in summer season, which was interpreted as contribution of soil dust from the drylands. However, no direct link to the Aral Sea sources was demonstrated.

Chen et al. (2013) observed that the monthly average PM2.5 and a coarser PM fraction at Bishkek and at the Teplokluchenka Lidar station (Tien-Shan region of Kyrgyzstan), in 2008-2009, were always below 25 μg m^{-3} in both stations, and below 20 in most of the year, except in August and September. They also quantified the number of dust days at the 2 stations as between 0 and 3 per month.

In the same sites and during the same period Miller-Schultze et al. (2015) found that mineral dust and organic matter (OM) were the dominant contributors to PM10 and PM2.5. OM contributed more to the PM10 levels in winter (December to February), on a percentage basis, at both sites and for both size fractions, when combustion sources likely influenced the sites more than dust transported from the deserts. Mineral dust was instead the dominant contributor during summer, the period with highest observed PM and highest SDS frequency. At the Lidar site, mineral dust contributed an average of 42±29% of the observed coarse PM during high PM days, and an average of 20±16% during the low PM events. On the other hand, based on the available evidence, the authors indicate the Taklimakan desert in Western China as most likely dust source.

4.5. Dust salinity

White or "salty" storms were rare in the Aral region before the 1960s, and recorded mainly in the low and middle part of the Volga River. According to in the Aral region they appeared with the intensive development of irrigation during the 1960s, when significant areas of newly salinized lands and anthropogenic saline soils (Solonchaks) formed, but unusually strong DS were first recorded in 1975.

Orlovsky and Orlovsky (2001) report that the soils formed on the sandy and sandy loamy exposed marine sediments are marked by a content in sulfate-chloride and chloride-sulfate salts that may be as high as 8-10% and more, corresponding to about 2,200 tons per hectare in the aeration zone of the soil. The same authors review early estimates done by different researchers of the volume of salt and dust removal during SDS events, noting that they are very contradictory. They indicate in 1.6 million tons per year the most likely value of the total dust volume from Kazach source areas (former Saryshigonak Bay area and larger eastern coast) during the 1966-1979 period. By 1992 the Aral Sea level had decreased by 15 m and new sources of aerosols were formed, with an average annual removal of topsoil particles estimated at 5 different locations (Lazarev island, Barsa-Kelmes island, Eastern island, and Saryshygonak Kokaral) ranging between 0.05 and 0.5 million tons per year.

Orlovsky and Orlovsky (2001) also report that the total amount of deposited aerosols in the southern Aral zone, as studied between 1982 and 1991 at 43 sites, was 1.5-6.0 tons/ha and included about 170-800 kg/ha of soluble salts, with maximum values of up to 1,600 kg/ha in the dried bottom of the Aral Sea. This value was lower (150-300 kg/ha) in the irrigated lands of Karakalpakstan. The salt content in deposited aerosols in the Amudarya delta was estimated at 5-6%, and up to 20-30% in areas close to Solonchaks soils. Figure 5 illustrates the spatial distribution of the salt deposition around the exposed dried bottom of the Aral Sea.

Some of the recent studies cited in the previous sections assessed the current physical and chemical nature of the collected dust samples. Groll et al. (2013) and Opp et al. (2017) found that the dust from the AralKum was characterized by a more balanced distribution of hydrogen carbonate (35%), sulfate (22%), calcium (15%) and a high concentration of chloride (12–21%) compared to the other regions. Higher salt concentrations (Cl and SO_4) at AralKum stations were also observed by Aslanov et al. (2013). On the other hand, apart from Zinc, concentrations of heavy metals were not found to be higher in Aralkum dust (Opp et al., 2017).

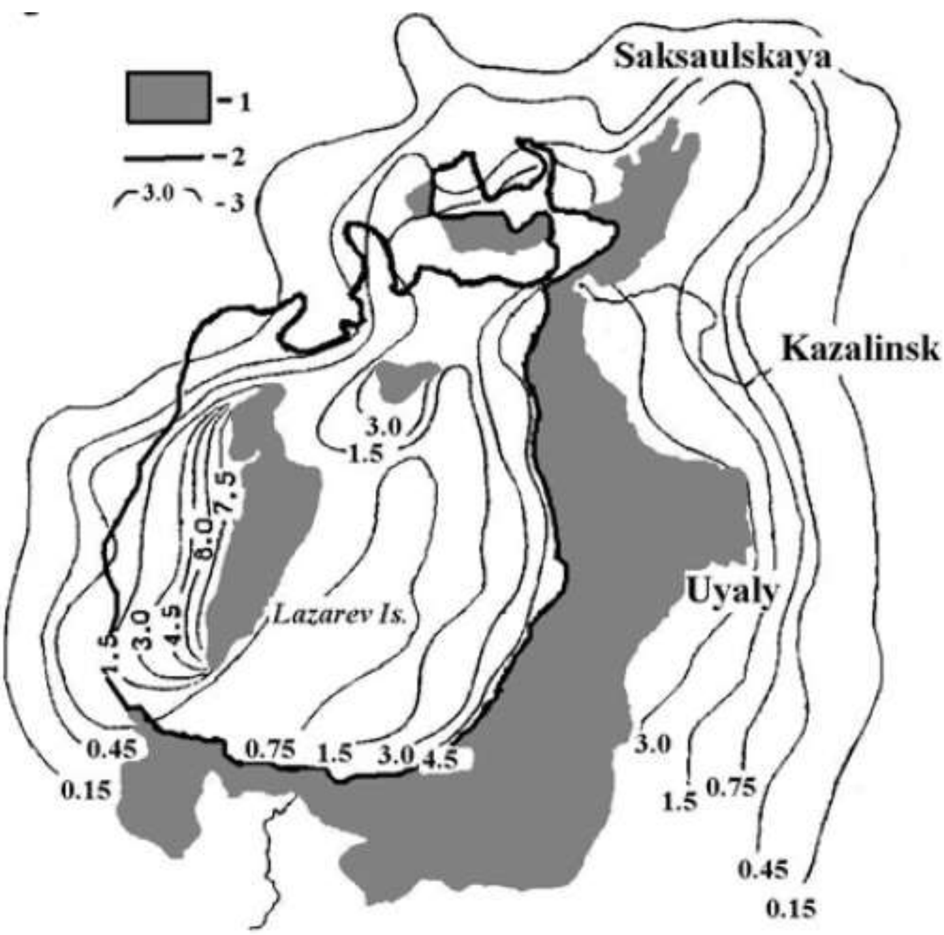

Figure 5. Spatial distribution of salts originating from the dried bottom of the Aral Sea in tons/km^2 per year (Orlovsky and Orlovsky, 2001).

Groll et al. (2019) analyzed dust deposition samples collected during 2003-2012 from 23 meteorological stations in four regions of the Aral Sea basin (Aralkum, Khorezm, Karakum and Kyzylkum). They observed that the majority of the material deposited in 3m height (85.8%-97.6%) in the study area was part of the PM5 group (fine silt and clay particles; <0.0063 mm) and that the Aralkum dust samples were characterized by a much higher concentration of SO_3^{2-} compared to the Karakum and Kyzylkum (2,365 ppm vs. 232 ppm and 512 ppm). Khorezm also showed high SO_3^{2-} content (1,681 ppm) and had the highest concentration of P_2O_5 (1,857 ppm compared to 1,074 ppm in the Aralkum 866 ppm in the Karakum and 465 ppm in the Kyzylkum). The high concentrations of phosphorus in Khorezm and Aralkum samples reflected the strong anthropogenic impact of local agricultural dust sources (Khorezm) and the accumulation of agrochemicals in the Aral Sea sediments.

4.6. Impacts of Aral dust on human health

As stated above, along the southern fringes of the Aral seabed a high number of days is at health risk due to the high dust concentrations (Opp et al, 2017). It has to be added that the soils of the Aral seabed (and of the surrounding formerly irrigated areas) have high concentrations of pollutants (agrochemicals and industrial pollutants accumulated in the sea sediments): these can become a special threat for human health when they get inhaled with the dust, or swallowed due to water and food contamination. Several studies conducted since the late 1990s highlighted severe health risks for the populations living in the area. However, most of the studies are not recent and some results are contrasted, possibly suggesting the need for further research with more harmonized approaches and methods.

Adult and children respiratory diseases were studied in Turkmenistan by O'Hara et al. (2000). Dust deposition rates in this part of the Aral Sea basin were quantified as among the highest in the world (50–1,679 kg ha^{-1}, 23% of which PM10 or smaller). There, respiratory diseases were a major cause of illness and death among all age groups, and 50% of all reported illnesses in children were respiratory in nature. A considerable contamination of dust with phosalone, an organophosphate (up to 126 mg kg^{-1} in the main irrigation zone close to the Aral Sea), was also observed, despite systematic spraying with pesticides was reportedly no longer carried out in the area because of economic constraints.

Conversely, in a study conducted in Karakalpakstan (Wiggs et al., 2003), respiratory health surveys conducted on children (aged 7 to 11) from communities (approx 90 children in each) living within a 5 km radius from 16 dust sampling sites did not show significant relationship between occurrence of respiratory health problems and proximity to the dust sources.

Respiratory and pulmonary diseases of children (aged 6-15 years) were also studied by Kunii et al. (2003), who used clinical and questionnaire-based observations on 383 children living in the heavily affected disaster zone (within 200km from the Aral seabed) and 432 living farther away (500km). They found significant increase of cough and wheezing, lower forced vital capacity (FVC%), and prevalence of restrictive pulmonary function closer to the shore.

Instead, after conducting a survey of respiratory and lung function in 1499 children aged 7-10 in 18 communities located in 6 geographical regions, Bennion et al. (2007) did not observe significant relationship between major respiratory problems and exposure to Lake dust. They suggested, however, that the higher dust loads observed during the peak of the dust season may have adverse effects on lung functions.

Other studies showed that the populations living near the former Aral shore suffer from the exacerbation of several diseases. However, the linkage between the pathology and the direct exposure to dust was in most cases not demonstrated. In fact, a combination of air and water/food contamination may be the cause of the observed effects. Some examples are given below.

Clinical studies from the north of Aral sea in Kazakhstan on the incidence of hypercalciuria and renal tubular function on 205 children living in Kazalinsk (near the shore) and 187 children living in Zhanakorgan (far) demonstrated much higher effects near the shore, likely in association with intake of toxic chemicals (kaneko et al., 2003 and 2007).

Cancer cases (all cancer types, 2003 to 2014) around the north of Aral sea in Kazakhstan were 1.5 times more frequent compared to distal areas, likely due to higher Nickel and Cadmium levels, according to Mamyrbayev et al. (2016), based on a statistical study conducted in 3 regions differently affected by the Aral Sea disaster (ecological disaster area, ecological crisis zone, and pre-critical condition zone).

Severe men and women reproduction diseases were documented in Kazakhstan. Clinical and laboratory studies on 1406 women living in the ecological impact area highlighted younger age of menopause onset, inflammatory diseases of genital organs, and, in the zone of high ecological impact, fetal losses, and spontaneous pregnancy termination or non-developing pregnancies in anamnesis (Turdybekova et al., 2015). Clinical and laboratory studies done on 1010 men aged 18 to 29 and living in 5 settlements near the northern Aral coast showed that the Aral pollution can have adverse effects on the reproductive function of men residing in the ecological disaster area (Kultanov et al., 2016). Similar studies performed on 251 men who lived in the ecological catastrophe area for at least 5 years confirmed adverse effects on the reproduction system (Kislitskaya et al., 2015).

A literature review on the effects of the Aral Sea disaster on children's health uncovered 26 peer-reviewed articles and four major reports published between 1994 and 2008 (Crighton et al., 2011). Anemia, diarrheal diseases, and high body burdens of toxic contaminants were identified as being among the significant health problems for the children in the area. These are associated either directly with the environmental disaster or indirectly via the deterioration of the region's economy and social and health care services. No clear evidence for the link between dust exposure and respiratory function was identified. But the review unequivocally illustrates the seriousness of the Aral public health tragedy. It also underlines that important knowledge gaps are still present, and the need for further specific research.

Finally, the psychological effects of the ecological disaster have been investigated. Interview-based studies conducted in 3 communities of Karakalpakstan affected by the consequences of the Aral drying-up revealed environmental concern in 41% of all respondents; 48% of them reported levels of somatic symptoms (SCL-90) associated with emotional distress (Chrighton et al., 2003a and 2003b).

4.7. Impacts of Aral SDS on economic activities

The economic impacts of the SDS generated by the Aral disaster seem to be poorly explored by the scientific literature. Several recent papers address the concurrent uses of the water resources in the region and the related scenarios and impacts (e.g., availability of drinking water and irrigation water, crop yields, fishery, etc). A valuation of actual historical and current impacts in the Basin does not seem to be available.

Two relatively outdated documents (Orlovsky and Orlovsky, 2001 and INTAS and RFBR, 2001) address the issue explicitly and give some quantitative estimates.

Orlovsky and Orlovsky (2001), citing regional sources, report that the intensity of transpiration from dust-laden leaf in the daylight time could decrease by around 62-69%, while transmission of solar radiation through dust-laden leaf to the lower strata could decrease to 50-60%, with an increase of the leaf surface temperature. Losses of cotton and rice yields resulting from aerosols influence reached 5-15% and 3-6% respectively.

Furthermore, salinization of the soil in areas adjacent to Aral Sea regions sharply increased as a result of aeolian salt transfers resulting in a five-fold increase in the area of "halomorphic geosystems" after 1970.

The salt content of the rain is also reported to have increased to 100-150 mg per liter as compared to 30-100 mg per liter in 1975. In springtime such rains create salty crusts, which affect seed germination and shortens the lifetime of the supporting structures of high-voltage transmission lines. Additional expenditures to repair transmission lines in the Raushan-Beiney of the Kungrad railway section for the period 1981-1990 raised to USD $15 million, and property damage as a result of power breaks raised to USD $9 million, with the consequence that total capital expenditures increased budgeted investments for the same period by 2.8 times.

INTAS and RFBR (2001) provide an interesting overview of the actual economic impacts with a tentative estimation of the costs. The assessment is based on a multi-sectoral approach addressing both land and water resources and can constitute an example and a baseline. The impacts identified are summarized by Table 3.

The costs of some of these direct losses were estimated, for the whole Aral Sea area, in 99.28 million USD per year (58.68 million for agriculture and USD 40.6 million for industry).

Sector	Issues	Costs, Million USD
Fishery	Amount of fish catch in the Sea and adjacent lake systems reduced tenfold	28.57 (fishery and fish breeding) 9.0 (fish industry)
Hunting	Muskrat habitats sharply diminished resulting in lower muskrat numbers and decreased catch by hunting	4.0 (hunting) 18.0 (pelt processing)
Cane	Reduction of habitat for cane growing	12.6 (cane processing)
Irrigated farming	Starting from 1994-95 the used irrigated lands throughout the Aral Sea zone have reduced by 25%, causing reduced crop productions. The most affected crops were grain crops, rice, forage, maize, cotton, vegetables and cucurbits	6.55 (crop production)
Rangeland	Decreased river runoff into the Amudarya delta and drying of vast areas of former sea bottom resulted in acute reduction of natural highly productive rangelands and hay mowing areas affecting cattle breeding and sheep and goat numbers, particularly in Tahtakupyr region	8.4 (cattle breeding)
Wool production	Production of wool and Astrakhan pelts dropped to almost a half, driven by the drop in sheep and goats number and by the deteriorated conditions of pasture and rangelands	N/A
Tourism	Number of tourists attracted by hunting and fishing sharply decreased	11.16
Cost of rehabilitation	Rapid withdrawal of coastline hampering rehabilitation activities in the coastal zone	N/A

Table 3. The economic impacts of the Aral disaster as identified by INTAS and RFBR (2001).

In addition to the direct costs, 16.74 USD million of indirect losses and 28.81 USD million as social losses were also estimated. Thus the total direct and indirect losses caused by the environmental disaster in the Aral Sea region were USD 144.83 million per year. It is worth noting that this was quantified in 2001, when the level of impact on land and water resources was much lower than now.

4.8. Restoration options and effectiveness

There is a spatial sequence of land cover classes around the shoreline of the Aral that can be summarized as follows: “Water”>“Salt crust”>“Salt soils”>“Bare areas and desert soils” (Low et al., 2013). The water recession first resulted in a quick build up of extensive salt crusts directly adjacent to the sea. Then, most of these salt crusts converted into a series of different Solonchaks and Takyr types (comprised in the class “Salt soil”) and afterwards, in some parts of the study area, into "Bare areas" reflecting a gradual landscape evolution under arid conditions, with the transformation of the salt soils into desert soils types and the formation of sand dune due to deflation processes.

In parts of the Aralkum, under the leaching action of precipitations, the process of natural desalinization of the soils was found to take place within 4–8 years (Low et al., 2013). So, there is potential for long- to medium- term spontaneous recovery of the vegetation, which is actually happening (Wucherer et al., 2012a; Dimeyeva, 2007). This is however a slow process, marked by different speed and success depending on many factors, including the intensity of wind erosion.

Active restoration options are advised to achieve a faster and more effective increase of the vegetation cover and a subsequent reduction of dust generation. Additional direct benefits would include the establishment of additional pasture land and subsequent contribution to the reduction of poverty. The practices already tested in the region include the plantation of various native species adapted to salinity and drought conditions.

The first experiments on phyto-amelioration in the southern part of the dried seabed were carried out during the 1980s using native shrubs growing on the coast and taking part in the process of natural colonization of the dried bottom, and about 70 species were identified and recommended for phyto-reclamation and afforestation (Orlovsky and Orlovsky, 2001). Plants were selected based on properties such as desalinization, landscape stabilization, and sand fixing capacity, but also in view of establishing green belts around settlements to protect them against strong winds, transport of salts, dust devils, and fixate shifting sands.

Further studies were conducted to identify sets of measures and species adapted to the different environmental conditions of the regions surrounding the Aral.

Northern Aral region (Wucherer et al., 2012b)

For the northern Aral region best results were obtained with the Black Saxaul tree (*Haloxylon aphyllum*). The establishment and the growth of this tree is dependent on the weather and hydrological conditions and on the planting season. It proved to be successful on slightly to moderately saline sandy soils and on loamy coastal Solonchaks with sand cover and a low salinity degree of the topsoil. On the crusty-puffy coastal Solonchaks, however, the list of species to select for planting should be extended to more euhalophytic species, which can withstand higher soil salinity, such as *Halocnemum strobilaceum*. In the region there are other perennial euhalophytes from the genera *Halostachys*, *Kalidium*, *Salsola* and *Suaeda*. However, the planting technology for them is still not fully known and should be further investigated.

Southern Aral region (Novitzkiy et al., 2012)

The southern Aral region is characterized by a complex mosaic of soil/sediment texture and salinity conditions and groundwater depth. Various species have been tested in a network of sites reflecting those edaphic typologies, such as the following woody plants: *Haloxylon aphyllum*, *Salsola richteri*, and *Calligonum caput-medusae*. Other plants that are used as pastures and fodder crops are *Ceratoides* *papposa*, *Salsola orientalis*, *Aellenia subaphylla*, *Kochia prostrata*, *Salsola arbuscula*, and *Aristida karelinii*. A more extensive, substantial use of these species would be possible by increasing the capacity to establish and manage the plantations.

Pre-Aral region (Kuzmina et al., 2012)

A possible approach suited to the Uzbekistan pre-Aral region is to assist the transformation of the former tugai ecosystem, destroyed by the man-made regulation of the flow of the Amu Darya and the Syr Darya Rivers, into productive halophytic pastures on the desiccated delta sites. Planting shrubs such as saxaul, cherkez, and teresken would be recommended in this context to improve the plant communities under degradation. The mixed halophytic–tugai ecosystems formed in such a way (turanga–saxaul, tamarisk–black saxaul, and others) will be conducive to maintaining the ecosystem productivity and the main elements of tugai flora, to become human-modified analogues of the relict tugai halophytic ecotones. In the case of a future increase of the natural moisture conditions or improvement of water management situation, they could be restored or rehabilitated into the typical tugai ecosystems.

If active restoration of the desiccated Aral floor is a logical and urgent action to reduce dust generation, it is also important to prevent the extension of the dust source areas, e.g., by avoiding further salinization and wind erosion of the irrigated land. This could be achieved through better planning.

Kumar et al. (2019) highlighted that a more efficient use of the current water resources in the lower Amudarya Basin (Khorezm region, Uzbekistan) would make much water available for both crop production and afforestation of degraded land. Actually, part of the productive croplands has a surplus of water availability, while much (67%) of the marginally productive croplands still have enough water availability to support the establishment of salt-tolerant tree plantations.

4.8.1. Restoration effectiveness

An et al. (2019) investigated the effects of Black Saxaul afforestation interventions conducted on the desiccated bed of the Aral Sea near Kazalinsk (southern part of the north Aral Sea). They sampled the topsoil in sites planted in different years (1991 to 2013) and observed a soil improvement trend along the plantation chronosequence, namely a decrease in soil salinity and an increase in soil enzyme activities. According to the authors the latter can be considered as an early indicator of soil amelioration, and might convert soil nutrients into plant-available forms. However, the study does not seem conclusive due to the limited number of the samples and to the lack of information on the experimental setup (soil types and initial soil conditions in the different sites, thus site-to-site comparability). No data is presented about soil organic carbon and nitrogen, fundamental indicator to monitor restoration effects. Furthermore, a negative trend in CEC was observed, which may in fact reflect a difference in initial soil conditions across the sites.

In the same study area Khamzina et al. (2020) found an increase in species richness and self-propagation in the sites afforested with Saxaul, indicating successful afforestation. Along the plantation chronosequence, an increase in foliar ^{13}C was also observed, suggesting a trend towards higher water-use efficiency in older plantations, possibly in response to declining water availability on the sandy substrate. As a non-phreatophytic plant, Saxaul’s ability to maintain sufficient water supply to the foliage is attributed to the efficient morphological adjustment of the rooting systems and to the strong stomatal control.

5. Literature examples from other regions

5.1. Financial impacts of SDS

Despite the importance of the damages caused by SDS, the valuation of their financial costs is relatively poorly investigated in scientific literature.

A comprehensive approach, cited as reference by most recent works, was implemented by CSIRO in Australia more than 20 years ago (Williams and Young, 1999). The study found that 85% of the cost share was related to health (basically asthma) and 13% to household costs. A more recent study conducted in Australia by Tozer and Leys (2013) estimated the impact on the state of New South Wales of a single large SDS of September 2009 and found a total cost is A$299 million (with a range of A$293–A$313 million) with most of the cost being associated with household cleaning and associated activities.

Other examples of studies on the financial impacts of SDS come from few other countries: China, Iran, Korea, Iraq, Kuwait, and UK. They are methodologically very different and in some cases the SDS costs are only partially quantified.

Most of them address multi-sectoral economic impacts (Ai et al., 2008; Yeong et al., 2008; Ekhtesasi and Sepehr, 2009; Miri et al., 2009; Meibodi et al., 2015; Cheng et al., 2018). An article from Cheng et al. (2018) is an interesting critical review on previous estimations of the costs of desertification in China, also considering government assessments. SDS costs are generally referred as “indirect” costs of desertification (damages caused by siltation of rivers, reservoirs and irrigation canals, transportation losses, and health).

Other studies have a more specific focus such as the economic damage to the tourism sector in an Iranian city (Almasi et al., 2016), the economic losses for the oil industry in Kuwait (Al Hemoud et al., 2019), the farmer income losses due to sand deposition on the crops in eastern England (Riksen et al., 2001), and the damage to the oasis agricultural system in the Tianshan region (Ge et al., 2016; economic impact not quantified).

A work by Liu et al. (2012) adopted an original approach to quantify the risk connected with severe SDS in Inner Mongolia, by identifying SDS peak zones and the related time of return of the events. They analyzed the risk of occurrence of severe dust storm under different return period scenarios (5-, 10-, 20-, and 50-years) finding that the risk decreases from west to east across Inner Mongolia. They also identified hotspot zones for which the severity of dust storms will be intolerable in the 50-year or in the 20-year return period scenarios respectively..

5.2. Effectiveness of interventions for SDS-reduction at source

Restoration programs to reduce desertification and SDS have been documented by scientific articles in Canada, China, India, and South Africa.

In Canada, the government policies to promote conservative farming (avoid summer fallow, apply direct seeding) dramatically reduced SDS occurrence in the Canadian Prairies (Fox et al., 2012). This happened because after 1990, farms practicing summer fallow decreased from 70 to 40% in Saskatchewan, from 30 to 15% in Alberta and Manitoba; areas under direct seeding increased from less than 10% in all states to 20, 40 and 60% in Manitoba, Alberta, and Saskatchewan respectively.

In China the debate on the effectiveness of the Great Green Wall (GGW) has engaged various scientists.

Wang et al. (2010) argue that although the large-scale afforestation program may have had beneficial effects on SDS and desertification in China, their importance have been overstated. A relatively small area of the region was improved, and the survival of trees and shrubs was low. Cao et al. (2011) claimed that afforestation practiced as the primary method to combat desertification and to control dust storms in China's dry northern and central regions was not successful. Fast-growing, short-lived species that offer attractive short-term gains were often preferred. Deeply rooted woody vegetation transpires large quantities of water, lowering the water table and making it harder for native grasses and other species. Most of the actual increase in vegetation cover came instead from grazing control highlighting the importance of management practices.

In contrast with the two articles cited above, Tan et al. (2015) showed that in the GGW region vegetation has greatly improved, while it varies dramatically outside the GGW region. They said that, discounting the effects of climatic change and human pressures, the GGW greatly improved vegetation and effectively reduced dust in northern China. Based on modeling, Long et al. (2018) stated that the GGW remarkably decreased the dust concentration in downwind regions. The reduction (predicted) ranged from −5 to −15 %, with a maximum reduction of −12.4 % in Beijing, Tianjin, and Hebei cities. Especially effective was the grass component that was established on the edge of the dust source regions, decreasing the bare surface with dust emitting potential.

Another study supporting the positive role of afforestation in East Asia was published by An et al. (2018). Their long-term (2007-2016) regional study observed SDS reductions over the region, which they interpreted as result of both climatic changes (variation in surface temperature and precipitations increasing soil moisture and vegetation cover; decreasing decadal trend of strong winds) and afforestation interventions conducted in marginal areas of deserts source areas.

In India, in the Thar Desert region, several afforestation programs have been implemented, with overall good level of success but with several technical difficulties (Dhir et al., 2018). As of 2018, 0.36 Million ha have been covered (including general afforestation, road-side plantations, and fuel plantations), with increasing use of native species (Prosopis cineraria, Azadirachta indica, Tecomella Undulata (rohida). On the other hand, in the same region of India, the abandonment of the traditional practices has been considered as a major cause of land degradation and SDS. In the same region, Gaur et al. (2004) made a comprehensive review of the abandoned traditional measures to combat desertification. These measures have been practiced for longtime, but changing socio-cultural contexts and a greater need of the small farmers for monetary income has led to their abandonment..

In the lowland of Namaqualand, in southwestern South Africa, land was degraded by longtime open air mining and to a lesser extent by farming, and land degradation was direct cause of wind erosion and dust generation (Botha et al., 2008). A participatory study revealed that restoration attempts had limited success due to poor protection of planted species from strong winds and drought. The participatory evaluation identified possible techniques such as shade-cloth wind-nets (the most effective for reducing wind speed and stabilizing mobile sand on mined areas), transplanting of leaf-succulent species from undisturbed soils to rehabilitated areas (considered a successful restoration method for re-introduction of indigenous vegetation).

In the Western Cape Province of South Africa, widespread land degradation had been historically caused by the 1930s policies to substitute wheat imports with local production. The initial mainly extensive stock-based system of the late 19th century was replaced by intensive winter wheat production against a background of progressive farm subdivision (Meadows et al., 2003). Substantial improvements in erosion reduction (mainly water erosion, but also wind erosion) took place starting from after the 1970s through better land use planning and by introducing improved practices respecting land potential (improved rotations and tillage systems, reintegration of livestock, contour plowing and walls, etc.).

Active interventions including restoration of vegetation cover are recommended by various authors to prevent dust emission from contaminated soils (e.g., war-contaminated soils, Broomandi et al., 2017; radioactivity, Ogorodnikov et al., 2011).

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