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Shrinking water bodies as hotspots of sand and dust storms: The role of land degradation and sustainable soil and water management

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ABSTRACT

Sand and Dust Storms (SDS) are a natural phenomenon with important impacts on ecosystems and human society. SDS hotspots are mostly located in drylands, however their impact goes beyond national and regional boundaries, making them a global issue. Factors affecting SDS occurrence include weather and climate, land cover and soil surface conditions, geomorphology and terrain types. "Playas", the exposed beds of shrinking water bodies, play a significant role in dust generation. Land degradation and desertification processes play an important role on dust emission from playa sources, which is frequently triggered or increased by human activities such as unsustainable land and water use upstream, reduced vegetation cover on and around playas, and mechanical disturbance of the playa surfaces.

It has been estimated that anthropogenic playa sources contribute 85% of global anthropogenic dust emissions. Anthropogenic playa sources are frequently located near human settlements, so that even relatively small dust sources can have severe socio-economic and environmental impacts, including soil salinization and soil pollution when playa sediments are salt-rich or polluted. In these contexts, the implementation of sustainable land and water management (SLWM) measures and integrated watershed planning is particularly urgent to reduce dust emission and its impacts. The United Nations Conventions to Combat Desertification (UNCCD) identified the mitigation of anthropogenic SDS sources as a major pillar towards combating SDS.

The number of scientific articles addressing this issue is rapidly increasing, but our understanding of SDS emitted from anthropogenic playa sources remains limited and fragmented. This article reviews the literature on playa sources that are recognized to be mainly anthropogenic in nature, with particular focus on the anthropogenic drivers, the SDS-related impacts, and the possible SLWM-based solutions to reduce SDS impact.

1. Introduction

Sand and Dust Storms (SDS) are a global phenomenon affecting large scale ecological processes such as the productivity of terrestrial and marine ecosystems, nutrient and hydrological cycles, and climate (Goudie and Middleton, 2006). A growing concern about the impacts of SDS on human society has driven the publication of an increasing number of papers, including several review articles, particularly addressing air quality and human health (Querol et al., 2019; Schweitzer et al., 2018; Goudie, 2014), as well as SDS impacts on a range of socio-economic sectors (Middleton, 2017; Middleton et al., 2019).

SDS are especially generated in drylands, where their occurrence is driven by climate, land cover, hydrology, and soil and geomorphological conditions; these factors affect erosion, transport, and deposition of sand and dust particles by wind. The global patterns of dust emission are linked to geomorphology and terrain types, and "playas", or the exposed beds of dried or drying up or ephemeral water bodies (also called pans, chotts, sabkhas, salars, saline lakes, or salt flats) are among the greatest dust sources (Prospero et al., 2002; Washington et al., 2003). A recent global scale study concluded that playas account for about 34% of the total dust emission (Parajuli and Zender, 2017). Studies conducted at finer scales show that playa dust sources can generate the highest

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amounts of dust per unit area, as observed by Baddock et al. (2016) and Kandakji et al. (2020) for the Chihuahuan Desert. A recent study conducted in the North African region over a two-year period found that playas and fluvial landforms were the main hotspot sources of dust events, although playas accounted for only 12% of the total dust sources (Bekin et al., 2020). The most important SDS playa sources include wide ephemeral water bodies located in desert regions (e.g., the Kati Thanda-Lake Eyre Basin in Australia, or the chotts and sabkhas in North Africa), and dry lakes with unconsolidated sediments (Bullard et al., 2011) including the fine-textured deposits of palaeolakes such as the Bodélé Depression in northern Chad, long recognized as one of the most important global dust sources (Middleton and Goudie, 2001; Bakker et al., 2019).

Some playa sources are anthropogenic. These include, for example, the beds of lakes that have been desiccated due to water diversion, like Owens Lake in southwestern USA (Gill, 1996) or that are drying-up due to unsustainable use of water resources upstream, changing the water balance and water cycle and resulting in reduced water flow to the lowland playas, such as the Aral Sea in Central Asia (Indoitu et al., 2015). Anthropogenic playa SDS sources are in some cases associated with saline lakes, many of which are shrinking at alarming rates (Wurtsbaugh et al., 2017). Apart from the effects of poor water management, dust and sand storm generation can also be influenced by other human activities in and on the margins of playas, including disturbance by off-road vehicle use, mining, the trampling of crusts by domestic livestock, and reduced vegetation cover due to heavy grazing (Gill, 1996). Ginoux et al. (2012) estimated that sources linked to the hydrological cycle ("hydrologic dust sources") contribute 85% of global anthropogenic dust emissions. In their model they classified as "anthropogenic-hydrologic" source each grid cell (0.1° size) of the SDS source map that, based on spatial overlay with relevant global datasets, contained at least 10% ephemeral water bodies and at least 30% agricultural land use.

The physical processes of dust emission from playa environments have been thoroughly studied, as recently reviewed by Goudie (2018). However, our knowledge about the anthropogenic playa sources, the drivers behind their recent expansion, and the impacts they have in terms of dust emission and SDS is fragmented. While many natural playa sources are located in remote desert regions, the anthropogenic ones are frequently located in populated arid to semi-arid areas. Here, relatively small hotspot playa sources can have severe short- to medium-distance environmental and socio-economic impacts. In these contexts, unsustainable land (soil and water) management plays the role of exacerbating desertification, especially degradation of soil and vegetation cover in the areas surrounding playas and on playa surfaces, and triggers or intensifies dust emissions and SDS generation.

These issues are being addressed by an increasing number of studies conducted locally in different regions, worldwide. The objective of this article is to review and synthesize such studies, to provide a clear and comprehensive understanding of the impacts of anthropogenic playa sources. This is very relevant to recent initiatives promoted by the United Nations Convention to Combat Desertification (UNCCD) which aim at identifying anthropogenic SDS hotspot sources in order to focus interventions to mitigate SDS at source, so helping to achieve land degradation neutrality (Middleton and Kang, 2017). This initiative is, in turn, related to recent attention given to SDS at the UN General Assembly, which between 2015 and 2020 has adopted 6 consecutive resolutions on "Combating sand and dust storms". These resolutions stem from recognition of the threats posed by SDS to livelihoods, the economy and the environment, and acknowledgement that they can hinder the achievement of several Sustainable Development Goals (SDGs).

This article reviews the studies on anthropogenic playa SDS sources to highlight i) the impacts of SDS from these sources, ii) the role of land degradation in dust emission from such sources, and iii) possible solutions to reduce impacts based on sustainable land and water management (SLWM).

2. Natural versus anthropogenic playa sources of SDS

Sometimes the distinction between anthropogenic and natural sources can be made only when based on specific diagnosis conducted at the local scale. Dust emission from playas is influenced by local hydrological cycles, water use, and climate variability. Water use may be linked to agriculture but also other uses (e.g., urban, industrial, mining), and can often take place upstream of the water body and far from it; so, causal relationships can be complex and scale-dependent.

The dry beds of palaeo lakes and rivers are the most widespread natural hydrological SDS source in hyperarid regions, as observed in North Africa (Gherboudj et al., 2017; Bakker et al., 2019). However, in other drylands, hydrological sources are most often ephemerally dry beds formed in depressions and endorheic plains (with limited drainage and no outflow). These can be local ephemeral systems like pans and riverbeds, which can be seasonally or periodically dry and are sometimes associated with local dune systems, indicators of active deflation and deposition (e.g., Prospero et al., 2002; Eckardt and Kuring, 2005; Goudie, 2008; Bullard et al., 2011; Lee et al., 2012; Previtali et al., 2014), or larger "lake" systems such as the Aral Sea in Central Asia or Lake Mega-Chad in North Africa. Being permanently dry does not necessarily mean higher dust emission. Dust emission may be more intense from wet playas than from dry ones (Reynolds et al. (2007), and is triggered by anthropogenic disturbance of playa surfaces (Gill, 1996), as discussed in Section 5.

Natural seasonal fluctuations, climate variability including periods of drought, and ultimately climate change play an important role. In many cases, dust emission from small scale ephemeral playas can be defined as mainly natural hydrological sources, as in the case of the southern High Plains in western Texas and New Mexico (USA), a region with one of the highest densities of playas on Earth, albeit that the fewer larger saline playas are major dust sources (Lee et al., 2012).

An example of a large endorheic basin that became a natural SDS hotspot due to climate fluctuations is the Mar Chiquita Lake, in Córdoba province of Northern Argentina. Thirty years of exceptional rainfall caused a three-fold expansion of the lake area, followed by its retreat starting in 2004–2006 (Bucher and Stein, 2016). A first large dust storm was observed in July 2004, originating from the wide salt playa surfaces left by the receding waters. These areas expanded after 2004 and reached 4500 km^2 in 2011. The annual number of SDS events, below five before 2008, peaked in 2010 with 36 events. From 2011 to 2013, their number ranged between 25 and 28, with wind threshold speeds of only $7.5\ m\ s^{-1}$ and dust plumes extending from between about 50 km to 800 km (Bucher et al., 2016).

A different example of a natural hydrologic source linked to climatic fluctuations was described by Gomez et al. (1992) in southern Saskatchewan, Canada, where several dry years contributed to the complete drying-up of Old Wives Lake. In 1988 this shallow alkaline lake became a source of dust with serious, although temporary, impacts on residents' health (including coughs, wheezing, eye and nasal irritation).

In inhabited regions, water use strongly contributes to making water deficits higher during dry periods and, for example, extending the exposed playa surface, for a longer duration. Furthermore, water demand tends to increase steadily and sometimes does not adapt flexibly to the fluctuations of natural availability. Even in largely hyperarid areas like the Tarim Basin in China, one of the regions with most frequent SDS in Asia – although most events are not severe (Shao and Dong, 2006) – several active point sources located along the edges of the basin can be associated with the anthropogenic desiccation of water bodies due to agricultural development and lake draining (Zhang et al., 2008). Irrigated agricultural areas in that region are usually considered as non dust-emitting islands, due to their nature as "artificial oases" (Wang et al., 2008); however, they can contribute indirectly to dust emission, by reducing water availability in the surrounding landscape.

The SDS sources addressed in this review (Table 1; Fig. 1) are cases where the human contribution is important or prominent, albeit often in

Table 1
Drivers, impacts, and possible SLM-based solutions reported for ephemeral and drying-up water bodies that are dust sources due to desiccation processes driven or enhanced by anthropogenic activities.

Water body (dust source)	Region, Country	Reference	Study focus	Drivers	Salient impact described	Suggested SLWM practices
Colhué Huapi Lake (Fig. 1.a)	Central Patagonia, Argentina	Montes et al. (2017)	Dust generation at source	Complex climatic and geomorphological interactions, along with recently increased water use in a closed hydrographic basin.	Active erosion and deposition forms are present around the lake.	Control livestock activity around the lake.
		Gasso and Torres, 2019	Dust generation and transport	Significant fluctuations in lake area correlate with dust observations. Drought is suggested as main driver, and water use.	Up 15 to 30 major or moderate SDS per year, in years of enhanced activity.	
Salton Sea (Fig. 1.b)	Southern California, USA	Johnston et al. (2019)	Dust generation at source; Air quality and health.	Recent lake bed exposure is human-made. "Competing water demands and changing climate, coupled with short-term planning and limited community engagement".	Surface of playa increased by 20 times in 2003–2016. Frequent local SDS, with PM10 much above health limits. Around 1 in 5 residents have asthma ("three times more pediatric asthma visits than elsewhere in California").	"Improved understanding of composition and toxicity of contaminated airborne particles, as well as of the geographic scope of dust emissions". "Dust management measures coupled with meaningful collaboration across agencies, government and community residents". Participatory forms of governance, community empowerment and generation of "collective knowledge to build resiliency and improve public health".
		Parajuli and Zender (2018)	Modeling future dust emission and air quality	Drivers not indicated.	PM10 is predicted to increase "on average by 11% and by nearly a factor of ten in localized source areas, with an estimated 38% exposure of the Salton Sea by 2030."	
Lake playas in Mojave Desert (Fig. 1.c)	Southern California, USA	Reynolds et al. (2007)	Dust generation at source	Human modification of playa surface and playa hydrology can trigger dust activity.	Surface erodibility changes following fluctuations in depth of the water table.	Avoid disturbance of dry playa surfaces.
Owens Lake (Fig. 1.c)	Southern California, USA	Gill (1996)	Dust generation at source	Water diversion from the Owens River into Los Angeles urban water distribution network began in 1913 and Owens Lake, left without inflow, soon desiccated into a 280 km^2 playa.	The exposed playa became one of the most intense single dust sources in North America, causing significant ecological and economic impacts	
		Breen and Richards (2008). National Academies of Sciences, Engineering, and Medicine (2020)	Reduction of dust emission	Same	Same	Notwithstanding the huge financial investments issue remains largely unresolved. Several methods have been applied with variable degree of success, including plantation of native halophytic shrub species.
		Gutrich et al. (2016)	Economic solutions for reduction of dust emissions	Same	Same	Economic approaches have been proposed assessing the trade-off between pumping groundwater and sustaining the native plant community that performs dust suppression.
Great Salt Lake (Fig. 1.d)	Utah (USA)	Wurtsbaugh et al. (2017)	History and drivers of like decline	Long-term decline of Great Salt Lake water levels was mainly due to water development and river diversions, with fluctuations driven by both climate and water use by human activities.		
		Carling et al. (2020)	Impacts of dust emission	Same	Dust emitted from the increasingly exposed playas affects downwind urban areas and ecosystems, including by darkening the mountain snowpack.	

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Table 1 (*continued*)

Water body (dust source)	Region, Country	Reference	Study focus	Drivers	Salient impact described	Suggested SLWM practices
Several playas (ephemeral lakes, open water and wetland surfaces) (Fig. 1.e)	Southern High Plains (western Texas, eastern New Mexico), USA	Li et al. (2018)	Transports; Highway safety	Dust emission from playas can increase strongly when soil surface is disturbed or vegetation cover is degraded.	Dust emission from playa hotspots can create hazardous conditions to ground transportation	Avoid soil surface and vegetation cover disturbance. Consider using "netting and reseeding to promote vegetation growth".
		Lee et al. (2012)	Dust generation at source, by geomorphology	Ephemeral lakes and wetlands (and related playas) are major SDS hotspots.	The Southern High Plains region "has one of the highest densities of playas on Earth". Playas occupy relatively limited surface area but produce the most dust per unit area.	Take into account inherent vulnerability (sandy river floodplains, playas). Protect soil during fallow Managing/ improving shrubland and grassland areas to maintain at least patchy vegetation cover.
Chad Lake Basin (Fig. 1.f)	Chad Lake basin; Chad, Nigeria	Orogade et al. (2016)	Dust composition, air quality, in Kaduna (northern Nigeria).	Drivers not indicated.	Mineral dust from Chad Basin makes 18% of the city air's PM2.5 and 21% of PM2.5–10.	
Mesopotamia marshes and other water bodies (Fig. 1.g)	Southern and central Mesopotamia, Iraq	Moridnejad et al. (2015)	Dust generation at source	The water bodies have been affected by the decreased river inflow, mainly due to the dams constructed on the main rivers, and occasionally to drought.	Dried Mesopotamian marshes and lakes indicated as part of the "newly desertified lands" of Iraq and a contributing source to increased SDS impacting both Iraq and downwind countries.	International collaboration to promote action for remediation and for prevention of additional desertification
		Sissakian et al. (2013)	Dust generation at source	Drought and changing water flow along the main rivers (influenced by human activities) are the main drivers of the drying-up of several water bodies.	Iraq has witnessed a drastic increase of the SDS frequency during last decade.	Restore agricultural lands and traditional "green zones" around the cities to reduce SDS impact; save and recycle water and restore the marshes.
	Southern Mesopotamia, Iraq	Al-Ansari et al. (2012)	History and impacts of marshes drying-up and restoration	The marshes used to cover 15–20,000 km2. Before 2003 the Iraqi government deliberately drained them for political and military reasons.	In 2000 less than 10% of the marshes surface remained. In 2008 restoration was achieved only 23 to 44%, then the surface declined again. 90% of marsh dwellers migrated. High biodiversity losses.	75% of the marshes area could be restored by letting substantial amounts of water (some 13,000 million m^3) flow into them.
	Southern Mesopotamia, Iraq (part of a West Asia regional study)	Cao et al. (2015)	Dust generation at source	Drivers not indicated.	Southern Mesopotamia is part of a major regional SDS source cluster, and is ranked among the most SDS-affected areas in West Asia, with more than 200 SDS in 2000–2013.	
Hawr-al-Azim Wetland (Fig. 1.h)	North Azadegan Plain. Along Iran/Iraq border).	Adib et al. (2018)	Dust generation at source	Wetlands are drying-up due to several human made reasons linked to military conflicts, development of oil industry, and construction of upstream dams.	The total area of the wetland was 307,000 ha in 1970 s, and is 102,000 ha now. The resulting playa is a dust source with average annual discharge above 2.5 tons per second, and above 3.5 in June-July.	Reduce effects of wind on soil erosion by planting shrubs, scattering mulch over source areas.
Urmia Lake (Fig. 1.h)	Northeastern Iran	AghaKouchak et al. (2015)	Extent and drivers of lake drying-up	Observed changes are mainly a consequence of inappropriate land and water planning, namely "intensive agricultural activities, anthropogenic changes to the system, and upstream competition over water".	Authors found that lake surface decreased by 88% during the past decades, far more than previously reported by other sources (around 25 to 50%).	"Develop sustainable restoration and new visions and strategies into practice before Lake Urmia falls victim to the Aral Sea syndrome"
		Mardi et al. (2018)	Dust generation at source; Air quality	Drivers not indicated.	Via a catastrophic desiccation process in recent years "the lake lost 90% of its area, now covered by playas and marshlands, and source of salt and dust".	
		Gholampour et al. (2015)	Dust generation at source; Salt transport	Drivers not indicated.	"Water soluble salts compose 3–20% of the total mass of total suspended solids (TSP) and PM10 from Urmia playas". Saline particulate is the main TSP source (57.6%).	

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Table 1 (*continued*)

Water body (dust source)	Region, Country	Reference	Study focus	Drivers	Salient impact described	Suggested SLWM practices
		Sotoudeheian et al. (2016)	Air quality (model predictions)	Simulations show that PM10 would increase up to 30–60% in Urmia city if the Urmia lake was fully desiccated.	Urmia Lake playas contribute to cause critically unhealthy conditions during SDS events in Northeastern Iran.	
Hamoun Lakes and marshes (Fig. 1.j)	Sistan Region of both Iran and Afghanistan	Rashki et al. (2018)	Dust generation at source and air quality in the Region in both countries	The drying-up of the lake system and the associated loss of vegetation around them caused a strong increase in SDS frequency and severity at stations located in the region (Zabol, Helmand, and Kandahar).	At some stations Kandahar, Elmand, and Zabol, stations the dust days are 86%, 65%, and 70%, with SDS days accounting to up to 15% of the dusty days.	Preserve vegetation cover on and around the exposed playas.
		Rashki et al. (2013; 2015)	Dust generation at source; Air quality in Sistan region of Iran	Drying-up events are linked to climate fluctuations coupled with use of water in upstream watersheds. The end result can even be the "complete dryness, as occurred in 2001".	During 2000–2004 drought, most lakes were mostly dry, and DS days increased from around 20 to 80–110 days per year. Dust affects southern Iran, SW Afghanistan (Helmand, Kandahar), and W and S Pakistan.	
		Miri et al. (2007)	Health; respiratory diseases in Zabol city (Iran)	Drought occurrence, climate aridity, Hamoon Lake drying up, agricultural land getting degraded ("wasteland"), lack of vegetation cover and strong winds.	During major SDS, up to 90% percent of patients visiting hospitals are respiratory patients; 63% of surveyed people in and around Zabol city are affected by respiratory diseases.	
		Miri et al. (2009)	Economic costs in Zabol city (Iran)	Sustained drought during more than four years.	DS occurred 338 days during 2000–2004 (including 18 intense and 51 moderate events), with cumulative losses of US $124.85 million (physical damage and loss of work hours).	
Jazmurian Lake (Fig. 1.k)	Jazmurian Basin, southeastern Iran	Rashki et al. (2017)	Dust generation at source; Air quality	The water of the two rivers that flow into the Jazmurian Basin (Bampur and Halil Rud) is "largely or even totally diverted for irrigation". Only "in some years during spring the central basin is flooded and a very shallow (20–30 cm) slightly saline lake forms."	The lake remained "totally dry for the last 15 years". SDS frequency very high in Iranshahr city, with 12.7 SDS days per year (around 5 to 15% of the dust days). Dust generated in the basin mainly affects southeastern Iran, southern Pakistan, and Oman.	
Ebinur Lake (Fig. 1.l)	Xinjiang, Northwest China	Abuduwaili et al. (2008)	Soil degradation; soil salinization in deposition areas	Human-induced. "Areas of irrigated lands have expanded significantly, which has led to an increased water consumption for domestic, industrial, and agricultural purposes".	Particularly after 1978 Ebinur Lake has shrunk drastically leaving a saline playa larger than 500 km^2. "About 4.8 M tons per year of salt-rich dust are carried away from the playa, containing 0.5–3.4 M tons of salts".	
		Ge et al. (2016)	Damage to mountain oases	Drivers generically indicated as climate change and human influence.	Up to 40% of dust load is deposited in proximity: "the entire oasis economic zone on the northern slopes of the Tian Shan Mountains suffered severe environmental and economic damages".	
Oases of Cele County (Fig. 1.m)	Xinjiang, Northwest China	Mao et al. (2014)	Dust generation at source	Human disturbance, including farm land reclamation, can accelerate wind erosion, in combination with vegetation cover and pattern, and with topography.	The "volume of wind erosion on bare newly reclaimed farmland is up to 6.96 times that of bare shifting sandy ground".	"Protect the oasis ecotone land against excessive reclamation and abusive levels of grazing"

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Water body (dust source)	Region, Country	Reference	Study focus	Drivers	Salient impact described	Suggested SLWM practices
Lakes of Ejina County (Fig. 1.n) and northeast Tarim basin	Western China, western Inner Mongolia (China) and southern Mongolia	Zhang et al. (2008)	Dust generation at source	All the 12 lakes of the Ejina basin became dry by 1992. In general, drivers are "agricultural development, overgrazing by livestock, and lake draining. Especially in the productive western Inner Mongolia, agricultural development in unsuitable areas and excessive water use".	These alluvial areas with dry lakes and river beds are major SDS sources in NW China: in Ejina County of Inner Mongolia these include Gashun Nor ake (dried in 1961), Sugu Nor lake (dried in 1992), and others. At the N and NE edges of Tarim Basin, an example is Lop Nor lake, a major SDS source.	Land planning; take into account land suitability for agriculture and inherent land vulnerability
Ulaan Nuur Lake (Fig. 1.o)	Omnogovi Province, Southern Mongolia	Zhang et al. (2008)	Dust generation at source	Endorheic shallow saline lake that used to be relatively large and permanent. It had a surface area of around 65 km^2 in the 1960 s. "The lake shrank in the early 1990 s when the main water inflow dried as a result of intensely increased gold mining and changing climate."	The lake playa has been identified as a major SDS hotspot.	Manage competing water uses in a context of increasing water scarcity.
Drying lakes of the eastern Mongolian Plateau	Mongolia and China's Inner Mongolia (Mongolian Plateau)	Tao et al. (2015)	Loss of lakes	Precipitation indicated as main driver of lake dry-up in Mongolia; in China's Inner Mongolia main drivers would be coal mining in rangelands and irrigation in cultivated areas.	Number of lakes larger than 1 km^2 decreased from 785 (late 1980 s) to 577 (2010), more in China's Inner Mongolia (34.0%) than in Mongolia (17.6%). Number of lakes greater than 10 km^2 declined by 30.0%. As a consequence the plateau has become one of the major SDS sources in northern China.	Reduce water use. Increasing coal mining in China and Mongolia, expected drier warmer climate, predicted to cause further lake shrinkage.
	Wetland patches of Songnen Plain, Northeast China (Fig. 1.p)	Gao (2019)	Ecosystem impact: impact of dust on wetland patches	Due to spreading farmland reclamation and residential water consumption the wetland surface area decreased and wind erosion and nutrient transport strongly increased. The remaining wetlands are impacted by dust deposition.	Since the 1920 s the easternmost wetland patches are affected by deposition of dust from surrounding farmland and grassland. Accumulation rates of pollutant and nutritional elements increased after the 1950 s and more after the 1980 s.	
	Ephemeral lakes of China's Inner Mongolia (Otintag -Fig. 1.p- and Horqin sandy lands) and of eastern Mongolia	Zhang B. et al (2015) & Du (2018)	Dust generation at source	Mostly anthropogenic. Dust hotspots "coincide with regions of expanding industry in Otintag Sandy Land and in parts of Mongolian Gobi, and with agricultural areas in Horqin Sandy Land and parts of Mongolian Gobi".	Most SDS hotspots in Horqin and Otintag sandy lands "are associated with ephemeral water bodies".	Apply land and water conservation in Horqin Sandy. Control water use by industry in Otintag Sandy Land. Adopt water conservation and protection measures in mining areas of SE Mongolia.
Ephemeral water bodies playas, and saline lakes of Central Asia (Fig. 1.r)	Central Asia; Uzbekistan, Kazakhstan, Turkmenistan	Issanova and Abuduwaili (2017)	Dust generation at source		Most major SDS "sources are located over topographical lows or on lands adjacent to strong topographical highs where fluvial action is evident by presence of ephemeral rivers and streams, alluvial fans, playas, and saline lakes".	

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Table 1 (*continued*)

Water body (dust source)	Region, Country	Reference	Study focus	Drivers	Salient impact described	Suggested SLWM practices
Aral Sea (Fig. 1.s)	Central Asia; Uzbekistan (UZB) and Kazakhstan (KAZ)	Indoitu et al. (2012)	Dust generation in UZB, KAZ, Turkmenistan	The essentially anthropogenic nature of the Aral Sea disaster, driven by reduced water inflow due to increased human uses by the concerned Central Asia countries, is accepted by all authors cited in this table.	After the 1980 s the northern Aral basin became the main SDS hotspot in Central Asia.	Besides Aral seabed, active DS source areas mainly coincide with sensitive ecosystems that suffered from human impact. Reduce disturbance.
		Groll et al. (2013; 2019)	Air quality, PM; dust composition across the Aral Basin (UZB, KAZ, Turkmenistan)		High concentrations of pollutants (agrochemicals and industrial pollutants accumulated in the seabed sediments) in seabed soils. High contents of sulphite salts and phosphate in Aralkum dust samples.	Promotion of more sustainable agriculture and irrigation practices in the watershed
		Lioubimtseva (2015)	Human vulnerabilities in Aral Basin (UZB, KAZ, Turkmenistan)		Due to increased salinity of the Aral system, in southern Aral region mineralization in ground water can be as high as 6 g L^{-1} (total dissolved solids, TDS) and up to 3.5 g L^{-1} in drinking water, “much higher compared to the national standard of 1 g L^{-1}”.	
		Indoitu et al. (2015)	Dust generation from Aral seabed (UZB and KAZ)		Most SDS events originate from north-eastern Aral seabed area. “Dust plumes often reach lengths of 150 km to over 600 km. Active emission site consists of sands (75%), Solonchaks (17%) and Takyrs/takyr-like soils (8%).”	
		Low (2013)	Dust generation from Aral seabed (UZB and KAZ)		In 2000–2008 water cover decreased from 40 to 20% of the Aral bed surface. “Sandy surfaces and salt soils having the greatest dust generation potential increased by more than 36%.” “Salt soils” like Solonchaks and Takyrs and “Salt crusts” increased from 15% to more than 25 % of the total surface area.	
		Semenov (2012)	Dust generation at source and long-distance transport from Aral seabed (UZB and KAZ)		Models predict an increase in size of the desiccated seafloor, and the transport and deposition at longer distance of smaller particles (below 10 µm) with higher salt content.	
		Shen et al. (2019)	Dust generation from Aral seabed (UZB and KAZ)		From 1977 to 2015 the Aral Sea shrunk by more than 66%, leading to the dramatic expanding of the salt soil and bare area. Projections for 2025 reveal more desertification with potential expansion of salt soils and bare area.	The vegetation cover showed increase in recent years that may be a good signal of spontaneous ecological recovery.
		Issanova et al. (2015)	Dust generation in south. KAZ		The most frequent SDS in southern Kazakhstan were observed in Pre-Aral Karakum and Kyzylkum deserts (40 to 110 days average per year).	An observed slight recent decrease in SDS activity may be explained by fixing sand control measures and other activities implemented in the region

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Water body (dust source)	Region, Country	Reference	Study focus	Drivers	Salient impact described	Suggested SLWM practices
		Mamyrbayev et al. (2016)	Health; adult cancer in north. Aral Basin (KAZ)		Increase in cancers (all cancers 2003 to 2014) around Aral Sea was 1.5 times higher compared to surrounding regions, likely due to higher Nickel and Cadmium inhalation/intake.	
		Turdybekova et al. (2015)	Health; reproduction in north. Aral Basin (KAZ)		Adverse effects on reproduction system of women living in Kyzylorda (Aral Sea) region, including menstrual and menopausal disorders, likely due to exposure to pollution.	
		Kislitskaya et al. (2015)	Health; reproduction in north. Aral Basin (KAZ)		Adverse effects on reproduction system of men living in disadvantaged areas of Kyzylorda (Aral Sea) region, likely due to exposure to pollution.	
		Kultanov et al. (2016)	Health; reproduction in north. Aral Basin (KAZ)		Adverse effects reproduction system ("disruption of reproductive function") of men residing in the area of the Aral disaster at the age of 18–29, likely due to exposure to pollution.	
		Opp et al. (2017)	Air quality; health implications, in south. Aral Basin (UZB)		Dust deposition very high near Aral (101.4 and 72.5 kg ha^{-1} per month in Jaslyk and Muynak), compared to farther away stations (15.7 in Yangibazar and Urgench, 20.5 in Takhiatash). "Near AralKum almost every second month (50.0% in Jaslyk and 45.5% in Muynak) is at health risk."	
		Aslanov et al. (2013)	Air quality, PM; dust composition in south. Aral region (UZB)		Karakalpakstan and Khorezm regions, in southern Aral, are especially impacted. Average dust deposition rate in 2007–2010 was 5–6 times higher than in 1982–1995. AralKum dust has higher salt content (Cl and SO_4) compared to dust from other regional deserts.	
		Kunii et al. (2003)	Health; child respiratory diseases in south. Aral Basin (UZB)		"Respiratory and pulmonary function" among school age children around Aral Sea more frequently affected compared to surrounding regions, likely due to dust exposure.	
		Bennion et al., (2007)	Health; child respiratory diseases in south. Aral (UZB)		This study did not find association of respiratory problems with exposure to Aral Sea bed dust.	
		Crighton et al. (2003a)	Health; psychological health and well-being in south. Aral (Karakalpakstan, UZB)		Exposure to environmental problems caused by Aral disaster generated psychological problems: 48% of 1118 people reported somatic symptoms associated with emotional distress.	
		Crighton et al. (2003b)	Health; self-rated health assessment in south. Aral (Karakalpakstan, UZB)		Residents around Aral Sea had "a poor perception of their own health", performed a low self-rating, "which is a strong predictor of morbidity and mortality."	
		Kaneko et al. (2002, 2003)	Health; child renal function in southern Aral Basin (UZB)		Renal function of children around the Aral Sea region "is profoundly impaired" compared to distant areas, likely as a result of intoxication by heavy metals due to inhalation/intake.	

(*continued on next page*)

Table 1 (*continued*)

Water body (dust source)	Region, Country	Reference	Study focus	Drivers	Salient impact described	Suggested SLWM practices
		Wiggs et al., (2003)	Air quality, PM, in Karakalpakstan, UZB		Monthly fine PM are "extremely high, comparable to US EPA standards of 150 µg m^{-3} in 24 h and 50 µg m^{-3} average during a year."	
		O'Hara et al. (2000)	Air quality and health implications in Eastern Turkmenistan		Dust deposition rates among the highest worldwide, with considerable organophosphate phosalone content (up to 126 mg/kg in the main irrigation zone near the Aral Sea). "In eastern Turkmenistan respiratory diseases are a major cause of illness and death, and 50% of all reported illnesses in children are respiratory".	

conjunction with natural drivers of water variability. They include the exposed beds of dry or receding water bodies such as natural or artificial lakes, wetlands, and oases, and sometimes with nearby bare and/or salinized agricultural fields. In some cases, these water bodies are ephemeral and their dry periods are becoming longer, or more frequent, or even permanent. Less water is due to increased water use for human activities, climate change and/or variability, or to a combination of the two. The studies selected for this study include different spatial scales, from local (e.g., the small playas in SW USA) to sub-regional (e.g., Aral Sea Basin). Studies addressing dry or dried up water bodies located in hyperarid desert regions and ephemeral water bodies long documented as permanently dry have not been considered.

3. Anthropogenic SDS sources: Drivers and impacts

Although playas are most often point sources of SDS, and sometimes relatively small, their socio-economic and ecological impacts are important, and a growing number of scientific articles focus on them.

A major SDS source in Central Patagonia (Argentina) is the Colhué Huapi Lake playa (Fig. 2a), where, during years of enhanced SDS activity (e.g., 1989–1994 and 2006–2017) 15 to 30 major or moderate SDS were observed each year (Gasso and Torres, 2019). The desiccation of the lake is linked to complex climatic and geomorphological interactions, and to increasing water use: water within this closed hydrographic basin supports human consumption for more than 350,000 inhabitants living in the surrounding towns; it is used for irrigation in the rural areas around Sarmiento city, and for drilling by the hydrocarbon industry and connected operations (Montes et al., 2017).

In southwestern USA, playas are well-studied as SDS sources (e.g., Lee et al., 2012; Reynolds et al., 2007; Li et al., 2018). Owens Lake, California, is an archetypical case. Water diversions from the Owens River into a pipeline for urban use in Los Angeles began in 1913 and Owens Lake, left without inflow, soon desiccated into a 280 km^2 playa which became one of the most intense single dust sources in North America, causing significant ecological and economic impacts (Gill, 1996). The history of the Great Salt Lake (Utah) has been marked by important fluctuations of the water levels driven by both climate and water use by human activities, with a long-term decline mainly due to water development and river diversions (Wurtsbaugh et al., 2017). Dust emitted from its increasingly exposed playas affects downwind urban areas and ecosystems (Carling et al., 2020).

The Salton Sea, a highly saline lake in southern California, is another major example of an anthropogenic source. The modern lake is artificial, created in the early 1900s on a late Pleistocene lake bed by diverting the Colorado River and to fill the dry salt bed that was not an active dust source. Subsequently the lake was sustained by irrigation wastewaters from surrounding croplands, which accounted for over 95% of the annual inflows (Johnston et al., 2019). Recently, the lake started drying up leaving an exposed playa that increased from 349 ha to 6658 ha between 2003 and 2016. As a consequence, the down-wind agricultural areas located southeast of the lake faced frequent SDS, with recorded peak daily PM10 (Particulate Matter $\leq$ 10 µm) "nearly 10 times the state and federal limits", and with 23,000 residents in the area, around 20% of the total population, having been diagnosed with asthma: "3 times more pediatric asthma visits than elsewhere in California" (Johnston et al., 2019, page 814). The recent desiccation process has been interpreted as the combined effect of competing water demands and climate change, aggravated by short-term planning and poor community engagement (Johnston et al., 2019). Parajuli and Zender (2018) predicted that the Salton Sea bed exposure will be as wide as 38% by 2030, and that the PM10 values in the adjacent areas will increase by 11% on average, and by up to ten times in localized areas.

In Iran, the desiccation of lakes appears to be perhaps the most important direct cause of SDS. Urmia Lake in northern Iran used to be the second largest hypersaline lake in the world, covering up to 6000 km^2 till the mid-1990s, but quickly dried-up in recent years, losing

Fig. 1. Location of the case study sites documented in Table 1. (a) Colhué Huapi Lake (Argentina); (b) Salton Sea (USA); (c) Mojave playas and Owens Lake (USA); (d) Great Salt Lake (USA); (e) Southern High Plains playas (USA); (f) Lake Chad playas (Chad); (g) Southern Mesopotamia marshes (Iraq); (h) Hawr-al-Azim Wetland (Iran); (i) Urmia Lake (Iran); (j) Hamoun Lakes and marshes (Iran); (k) Jazmurian Lake (Iran); (l) Ebinur Lake (China); (m) Oases of Cele County (China); (n) Lakes of Ejina County (China); (o) Ulaan Nuur Lake (Mongolia); (p) Wetland patches of Songnen Plain, Horqin sandy lands (China); (q) Ephemeral lakes of Otintag sandy lands (China); (r) Ephemeral and saline water bodies of Central Asia (Kazakhstan); (s) Aral Sea (Uzbekistan).

90% of its water surface, exposing large playas and dry marshlands that became sources of saline dust (Mardi et al., 2018). The water level decreased by up to 6 m during 2005–2015 reducing the surface to less than 1000 km^2 and thus creating a saline playa with a surface area of more than 5000 km^2. In 2013, dust sampling stations along the shore recorded 24 h average PM10 as high as 140–220 $\mu g\ m^{-3}$ (Gholampour et al., 2015), a high value if compared, e.g., to the air quality standards set by EU legislation (daily PM10 limit value of 50 $\mu g\ m^{-3}$, not to be exceeded more than 35 times per year). Simulations show that PM10 would increase by up to 30–60% in Urmia city if Urmia Lake was fully desiccated (Sotoudeheian et al., 2016), although the water level increased between 2015 and 2020 (Rashki et al., 2021). According to AghaKouchak et al. (2015), the drastic lake-level changes are a consequence of inadequate water resource planning, particularly the introduction of intensive agriculture, and of upstream competition over water. Schulz et al. (2020), however, suggest that climatic changes have also played a role in Urmia's declining water level.

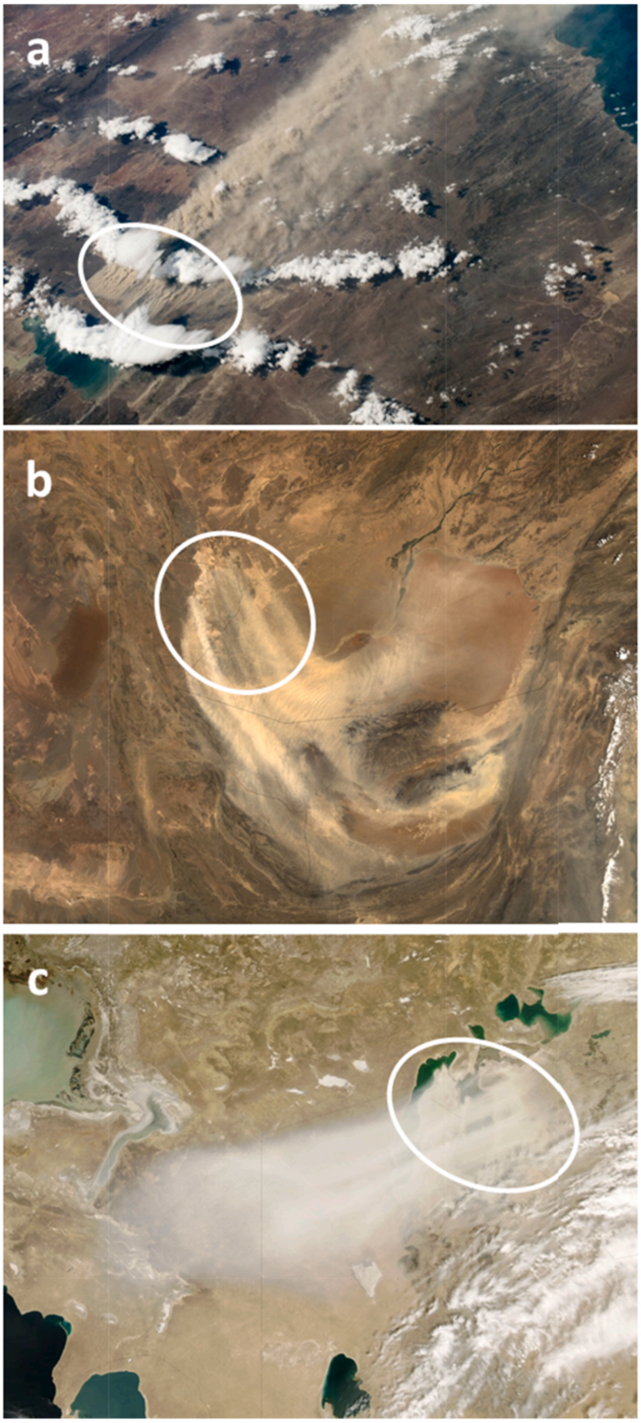
The Sistan region of eastern Iran (Fig. 2b) is a regional SDS hotspot from which the dust reaches southeastern Iran, southern Afghanistan, southern Pakistan, and farther downwind areas, due to the periodic desiccation of the shallow marshy Hamoun Lakes located on the Iran-Afghanistan border (Rashki et al., 2015; 2018). These lakes are naturally dry from April to September, a duration sometimes extended by a combination of droughts and regional water abstraction (Rashki et al., 2015; Middleton, 2019). Drying was particularly intense during the 2000–2004 drought, when some of the lakes became completely desiccated, and SDS days increased from around 20 to 80–110 days each year in Zabol city (Rashki et al., 2013; Miri et al., 2020). In Zabol, during major SDS events, up to about 90 % of the patients visiting clinics and hospitals are respiratory patients (Miri et al., 2007), and the cumulative financial loss over a five-year period, calculated as physical damages and loss of work hours, has been estimated at US$124.85 million (Miri et al., 2009).

Dust from the dry playa of the Jazmurian Lake in southern Iran frequently affects Iranshahr city and the surrounding regions including southeastern Iran, southern Pakistan, and Oman (Rashki et al., 2017). The water of the two rivers flowing into the Jazmurian Basin is largely withdrawn for irrigation use, and the lake has been totally dry since the early 2000s, a period also characterized by widespread drought (Rashki et al., 2017).

The northern Azadegan Plain (western Iran, along the Iran/Iraq border) is suffering from similar problems due to the drying up of the Hawr-al-Azim Wetlands, which used to be partly permanent and partly seasonal. These desiccated wetlands are one of the most important dust sources affecting Ahwaz city (the others are located in Iraq), with the consequence that Ahwaz is considered a "capital of dust" in Iran (Adib, 2018; Javadian et al., 2019). The total area occupied by the wetlands in Iran was 64,100 ha in 1970s, and decreased to 29,000 ha by 2018, a reduction due to several human activities linked to military conflicts, oil industry developments, and construction of upstream dams and related agricultural development on the Tigris tributaries and Karkheh river in Iran (Adib, 2018).

Similar issues have been described on the other side of the border with Iraq, in southern Mesopotamia, where famous marshes that used to be a food basket and an important biodiversity reserve extensively dried-up during the 1980s and 1990s. Al-Ansari et al. (2012) suggested that the wetlands had been deliberately drained by the Iraqi government for military and political reasons and that later restoration efforts were made difficult by reduced water flows due to construction of dams upstream, as well as by increased water consumption by agriculture. In 2000, less than 10% remained of the original 15–20,000 km^2 of marshes.

Other authors (Sissakian et al., 2013; Moridnejad et al., 2015) mention the desiccation of the marshes in the context of the recent drying of most Iraqi wetlands and reservoirs, caused by reduced water flows in the main rivers, increased use by agriculture, and drought. As an example the Rezzaza Lake (sometimes spelled Razzaza) and other water



(caption on next column)

Fig. 2. (a) A dust storm passing over Patagonia region of southern Argentina on March 7, 2020. The main dust source is Lago Colhué Huapí (-45.5 Lat, −68.7 Long), a shallow lake adjacent to the deeper Lago Musters. In the photograph the lake is largely obscured by dust and clouds. NASA Image courtesy, astronaut photograph ISS062-E-85589 taken by a member of the Expedition 62 crew.https://earthobservatory.nasa.gov/images/146681/patagonian-dust-streamers (b) Dust plumes originating from the almost completely dry bed of the Hamoun Lakes (30.8 Lat, 61.6 Long), in the Sistan Region of Iran, cover the arid terrains of southern Afghanistan (top), Iran (left), and Pakistan (bottom right), as shown by true color images by the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's Terra satellite, on August 20, 2003. NASA Image courtesy Jacques Descloitres, MODIS Land Rapid Response Team at NASA GSFC https://earthobservatory.nasa.gov/images/3724/dust-storm-over-afghanistan-and-pakistan(c) A large dust storm blowing westward from the Aral Sea, crossing the border between Uzbekistan and Kazakhstan, as captured by Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite on April 29, 2008. NASA image courtesy Jeff Schmaltz, MODIS Rapid Response Team at NASA GSFC. https://earthobservatory.nasa.gov/images/19853/dust-storm-over-the-aral-sea

bodies in central and eastern Iraq are also undergoing desiccation processes and becoming part of the so called "newly desertified lands of Iraq", which are important regional SDS sources (Moridnejad et al., 2015; Cao et al., 2015).

The well-known human-induced ecological disaster in the Aral Sea is by far the best studied case among the SDS sources connected to lake desiccation (Fig. 2c). During the last few decades the Aral Sea shrunk by more than 66%, primarily as a result of the excessive water use by agriculture, the construction of reservoirs and hydropower stations along the Amu Darya and the Syr Darya rivers, and climate change (Shen et al., 2019). The desiccation exposed the seabed as large bare areas characterized by saline soils, now known as the Aralkum desert (Low et al., 2013; Indoitu et al., 2015), which have become a significant regional SDS source (Indoitu et al., 2012; Issanova et al., 2015; Opp et al., 2017; Orlovsky et al., 2013; Groll et al., 2019).

The seabed soils have high concentrations of pollutants (agrochemicals and industrial pollutants that accumulated in the seabed sediments), and have become a special threat for human health if dust is inhaled or swallowed due to water and food contamination (Issanova et al., 2015). Several studies conducted since the late 1990s highlighted severe health issues affecting the populations living around the lake although most medical studies did not investigate the relationships between the observed increased morbidity and mortality and the exposure to dust. Some of the observed health problems are adult and children respiratory diseases in Turkmenistan (O'Hara et al., 2000); children respiratory and pulmonary diseases (Kunii et al., 2003) and renal functions (Kaneko et al., 2002; 2003) in Uzbekistan; psychological health and well-being in Uzbekistan (Crighton et al., 2003a; Crighton et al., 2003b); adult cancer (Mamyrbayev et al., 2016) and reproduction diseases affecting both men and women in Kazakhstan (Kislitskaya et al., 2015; Turdybekova et al., 2015; Kultanov et al., 2016).

A study addressing all of Central Asia stressed that most 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 indicates that the Aral may not remain a unique case in the region and that similar SDS sources could be activated or intensified in connection with climate change and water management.

A case study addressed by several articles is the dramatic desiccation of the Mongolian Plateau lakes. Here the number of lakes with surface area above 1 km^2 declined from 785 in late 1980s to 577 in 2010, particularly in China's Inner Mongolia (34.0%), less in Mongolia (17.6%). In Inner Mongolia the decrease was marked since the late 1990 s. The number of lakes with surface area above 10 km^2 also declined by 30.0% (Tao et al., 2015). This created a number of small, but very active dust hotspots, both in the eastern (e.g., Jilin Province; Fig. 3) and in the western regions (e.g., Ejina County; Fig. 4) of Inner Mongolia, significantly contributing to regional dust generation (Zhang et al., 2008; Zhang et al., 2015; Du et al., 2018). According to Tao et al. (2015), in Mongolia the observed lake changes were mainly driven by declining rainfalls, followed by water use by humans, whereas in China's Inner Mongolia coal mining and irrigation were the leading factors in grassland and cultivated areas respectively. Du et al. (2018) also found that in some areas of the Mongolian Gobi such dust hotspots coincided with zones of expanding industry and mining activities.

Another interesting case from China was documented in Xinjiang's Cele County, in northwestern China (southern margin of Taklimakan Desert) by Mao et al. (2014). Here, farmland reclamation around the wetlands affected the fragile oasis-desert ecotone, significantly accelerating wind erosion processes. The intensity of wind erosion on newly reclaimed bare lands was up to seven times higher than that of the bare shifting sand areas.

A well-documented larger scale case from the Xinjiang region of northwestern China is Ebinur Lake. About 4.8 million tons of dust are generated every year from the dry lake bed, which contain 0.5–3.4 million tons of salts, or 0.6–4.2 kg m^{-2} (Abuduwaili et al., 2008). Up to 40% of the dust load is deposited nearby: the oasis economy on the northern slopes of Tian Shan mountains suffered important environmental and economic damages (Ge et al., 2016). Aeolian input has been recognized as the main cause of the salinity increase observed in the soils of the downwind piedmont plain, where the thickness of the aeolian deposit layer ranges from several centimeters to meters (Abuduwaili et al., 2008).

A lesser known case is Ulaan Nuur, a dry lake located in the Gobi desert of Mongolia. As reported by Natsagdorj et al. (2003) and Zhang et al. (2008), the lake playa is the focus of one of Mongolia's three main SDS source areas. This endorheic saline lake was relatively large and shallow. It used to have a surface area of 65 km^2 in the 1960s and up to 175 km^2 after exceptional precipitation events. Since 1995 the permanent lake has been replaced by a playa that is only occasionally and partly flooded (Mischke et al., 2020; Sternberg and Paillou, 2015). The available literature about the causes of the lake's desiccation indicates that climate change and mining have both been influential (Holguin, 2019). Mischke et al. (2020) support the thesis that the lake dried up during the early 1990s "when the main inflow dried as a result of intensely increased gold mining activities in the middle reaches of Ongin River". Temperatures in the region have been increasing since the 1980s, while there has been a decrease in precipitation since the 1990s (Kang et al., 2015). Ulaan Nuur's major source of water, the Ongi River, has flowed with a much-reduced discharge since the 1990s, so that in more recent times the river often vanishes before it reaches the lake. The Ongi's reduced flow has been attributed to both climate change and mining activities upstream (Holguin, 2019).

The quickly drying-up Lake Chad is already an SDS source, and is much closer to densely inhabited Sahelian regions (e.g., northern Nigeria is just downwind) than the above-mentioned and much studied Bodélé Depression, so the impacts of its SDS are potentially more important. Wind-blown dust from the Sahara is the major contributor to

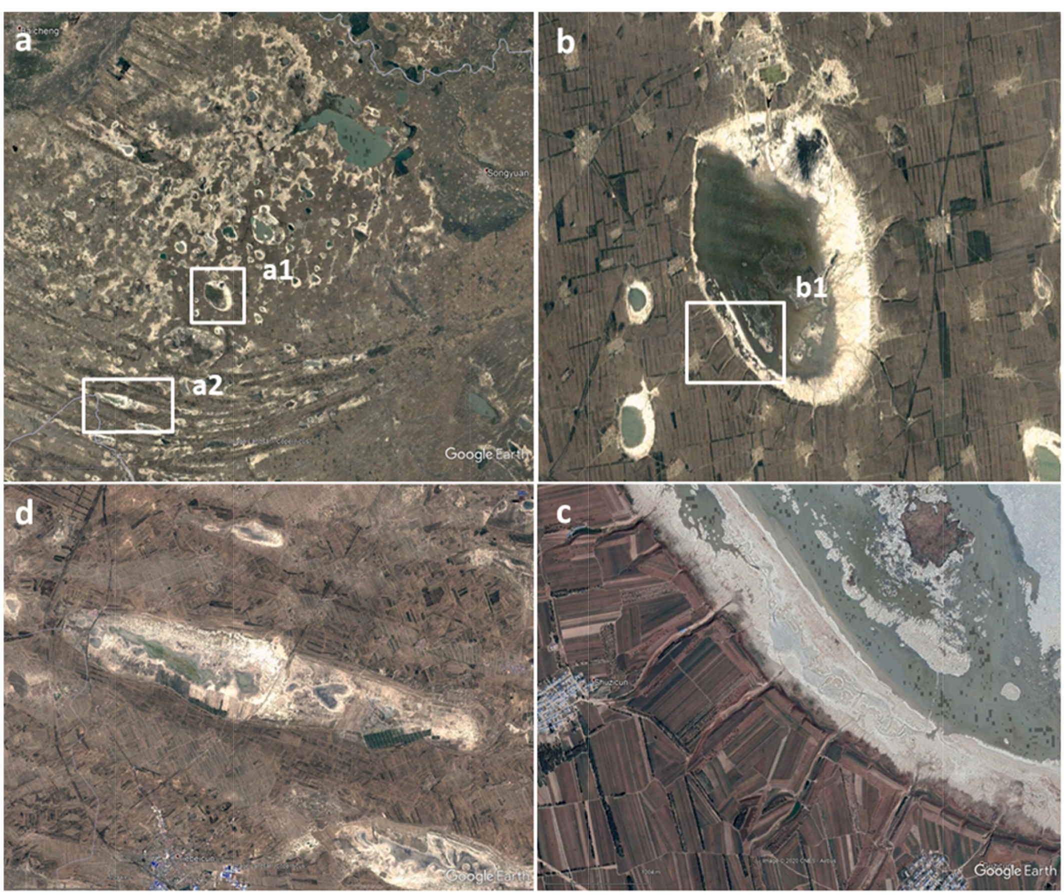


Fig. 3. (a) A Google Earth image dated December 2006 shows two water bodies (a1 and a2; between 44.5 and 44.8 Lat and between 123.2 and 123.7 Long) that were identified as SDS sources Zhang et al. (2015), on MODIS images dated 24 March 2007, in Horqin sandy land (Jilin Province) of China's Inner Mongolia (Fig. 5.b of the cited article). (b) Detail view of dust source (a1), showing that the lake is surrounded by agricultural fields and that the bare lake bank is deeply incised by erosion channels. (c) Enlarged view of detail (b1), showing the intensive land and water use. The lake appears to be fed by drainage water, which flow towards the lake seems to be systematically intercepted by small dams located near the lake shore. (d) Detail view of dust source (a2), showing irrigated farming around the water body and encroaching on the lake playa.

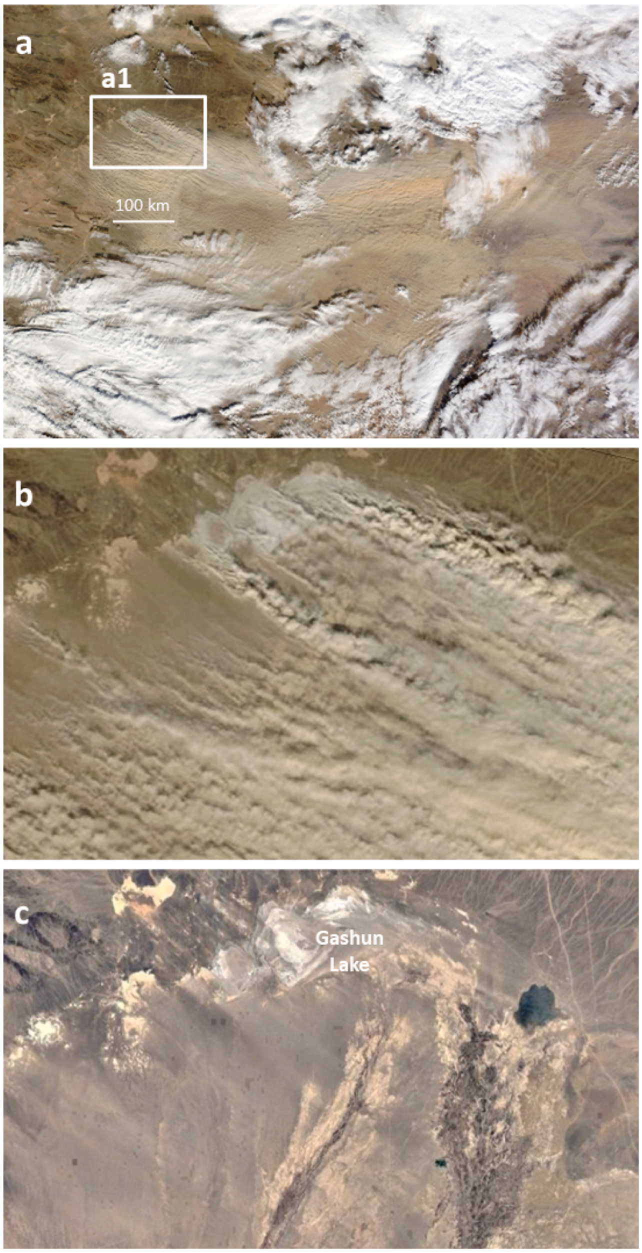


Fig. 4. (a). Dust storm, with long plumes traveling eastward, which sources are located close to the Mongolia-China border, on November 10, 2010. Natural-color image by Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite. NASA image courtesy by Jeff Schmaltz, MODIS Rapid Response Team at NASA GSFC. https://earthobservatory.nasa.gov/images/46908/gobi-dust-storm (b). Detail view of the same image as (4a), showing that plumes are mostly fed by fine sediments generated from around an ephemeral lake system. (c). Google Earth image showing the same geographical extent as in (4b), with clear atmosphere conditions, showing the drying lake system of the Ejina County (Zhang et al., 2008), centered around Gashun Lake (42.4 Lat and 100.7 Long) in the Gobi Desert of Inner Mongolia, China.

PM loads in northern Nigeria (Orogade et al., 2016; Offor et al., 2016), which during the Harmattan season is impacted by northeasterly winds blowing over the Chad basin. However, the available literature in this region focuses on dust deposition and air quality at target sites and does not indicate source areas precisely.

Other playa sources identified in West Africa, such as Lac Faguibine in Mali, are poorly documented by scientific articles; the observed levels of dust emission from those sources appear to be linked to interactions of varying river discharge and water use by human activities in a context marked by climate variability and local and regional conflicts (UNEP, WMO, UNCCD, 2016).

The potential human impact on dust emission from some Southern African playas such as Sua Pan and Makgadikgadi Pans (Botswana), which are impacted by mining, water diversion by dams, and other types of land degradation processes, should also be carefully evaluated (Eckardt et al., 2008; Bhattachan et al., 2012).

4. Salinity and pollution of playa sediments, aggravating SDS impact on soils and on human health

4.1. Dust salinity

An important feature of the SDS originating from hydrologic sources is that dust from saline playas often carries important amounts of fine-grained saline and alkaline material, particularly sodium sulfate and sodium chloride. These, together with other potentially toxic components, can cause soil salinization, poison ground vegetation, stimulate glacier melt and threaten the ecological security of the surrounding regions (Abuduwaili et al., 2010). Salt-rich dusts also affect radiative properties of dust plumes, atmospheric chemistry, and amounts of windborne nutrients (Reynolds et al., 2007), and can impact precipitation and air pollution patterns downwind (e.g., Gaston et al., 2017). The Aral Sea and the Ebinur and Urmia lakes are among the most important case studies worldwide, although saline playas that are dust sources exist in most dryland regions.

In the exposed bed of the Aral Sea the sandy surfaces and salt-affected soils increased by more than 36% between 2000 and 2008, and the surface occupied by Solonchaks, Takyrs soils, and salt crusts, soils considered to have highest dust generation potential, spread from 15% to more than 25% (Löw et al., 2013). Furthermore, for decades the Aral sediments accumulated pollutants transported by the Amu Darya and the Syr Darya, which included large amounts of salts leached from fields affected by widespread salinization (Groll et al., 2013). The dust generated by the dry bed is very rich in salt. High salt concentrations were found at dust sampling stations located near and south to the Aral SDS sources, in Karakalpakstan and Khorezm regions, with particularly high values of chloride and sulphite salts, and phosphate, also indicating anthropogenic inputs via agrochemical compounds (Aslanov et al., 2013; Groll et al., 2019). Dust emissions come not only from the lake bed, but also from salinized and abandoned agricultural fields upstream. Additionally, degraded salinized surfaces are prone to runoff washing out the salt and accumulating them into the river waters and eventually into the playa deposits during heavy rainfall events. Thus, land degradation upstream contributes to increase salt content in playas, which become a more dangerous source of SDS.

The increased salinity levels in the Aral system are detrimental to both surface and groundwater quality. In the southern Aral Sea region (Uzbekistan) total dissolved solids, TDS, can be as high as 6 g L^{-1} in groundwater, and up to 3.5 g L^{-1} in drinking water, "much higher compared to the national standard of 1 g L^{-1}" (Lioubimtseva, 2015, page 726). Besides direct inhalation with wind-advected dust, the contamination of drinking water is another major vehicle of ingestion of salts and pollutants by human and animals, and likely connected to the already mentioned renal dysfunctions observed in the region (Kaneko et al., 2002; 2003).

In the case of Lake Ebinur (Abuduwaili et al., 2008), the amount of dust deposition is quite high, ranging from 600 g m^{-2} per year (near the lake) to 70 g m^{-2} per year (at a distance of 100 to 200 km from the lake). The amounts of transported salt are very high, ranging between 14 and 27 g m^{-2} per year (with a maximum of 77 g m^{-2} per year). Salts are mainly sodium and calcium chlorides and sulfates, and the composition of the dust changes with distance: at increasing distances from the lake, the amount of sulfate and calcium increases and the chloride and sodium content decreases (Abuduwaili et al., 2008), so the ecological impacts, notably the alkalinization processes of the soils in the deposition areas, are more intense near the lake.

The dust emitted by the Urmia Lake playas has a high salinity content, since Urmia Lake is hyper-saline and the desiccation process further increased salt concentrations. Water soluble salts constitute 3 to 20% in mass of the total suspended solids (TSP) and of the total PM10 mass in dust, with the following percentages of dominant ions: $SO4^{2-}$ (29%), NO^{3-} (20%), Na^{+} (15%), Cl^{-} (12%), and Ca^{2+} (12%) (Gholampour et al., 2015).

4.2. Dust pollution

Polluted anthropogenic dust sources, typically associated with playa sediments that were exposed to waters polluted by intensive agriculture or by industrial activities, are often located close to inhabited areas and can contribute high concentrations of harmful elements to settlements downwind. However, this aspect is addressed by relatively few studies, and further research is needed to fully understand the role of these dust sources on human health. Dust generated by polluted source soils and sediments may be particularly harmful to human health and natural ecosystems. The level of pollution of the dry beds of lakes and reservoirs can be higher when intensive agricultural activities are present in the watersheds, or when they are close to urban and industrial areas.

The Aral basin is probably the best-known case. Several studies conducted since the late 1990s observed that contaminants from past agricultural and industrial activities upstream and the surrounding areas, accumulated in the sea bed in large quantities, including high concentrations of heavy metals from unprocessed wastewaters, radioactive particles from mining industry in the upstream regions, urban and industrial waste water discharges from the numerous inhabitants of the basin, and highly concentrated agrochemicals in polluted drainage water from irrigated areas (Groll et al., 2013). These contaminants, via the dust generated by the exposed seabed, now contaminate the air and the surrounding ecosystems, resulting in severe health risks for the populations living in the region. A highly cited article by O'Hara et al. (2000) describes very high dust deposition rates in southwestern Aral Basin (Eastern Turkmenistan) and considerable contamination of such dust with phosalone, an organophosphate pesticide (up to 126 mg/kg in the main irrigation zone along the Amu Darya River). In a more recent study by Mamyrbayev et al. (2016) the increase in cancers (all cancers, between 2003 and 2014) around Aral Sea was found to be 1.5 times higher compared to more distant areas, and this was hypothetically ascribed to inhalation and/or intake of Nickel and Cadmium. A literature review on children's health (Crighton et al., 2011) found that "anemia, diarrheal diseases, and high body burdens of toxic contaminants were identified as significant health problems for the children in the area". These in some cases were associated directly with the environmental disaster, in other cases indirectly, "via the deterioration of the region's economy and social and health care services". However, this paper found no clear evidence of causal linkages between dust exposure and respiratory diseases, indicating this as a knowledge gap for future research.

Another case is the above-mentioned Salton Sea. Here, measurements conducted over forty years found that "concentrations of lindane, dieldrin, and other persistent organochlorine pollutants like total polychlorinated biphenyls (PCBs) in shoreline sediments exceeded PELs (probable effect levels) for sediment quality in freshwater". It was also found that the "levels of organochlorine pesticides on the southern edge of the Sea were higher in air-exposed sediments compared to submerged sediments", and that "in addition to pesticides, toxic metals such as arsenic, cadmium, copper, molybdenum, nickel, zinc and selenium have also been measured in playa sediments at levels of ecological concern" (Johnston et al., 2019, page 810). The cited article warns that research is only starting to study the potential health risks for the residents associated with the inhalation of dust generated from these sediment mixtures (Johnston et al., 2019).

An interesting study conducted along the southern Iraq-Iran border, in an area including several drying wetlands and frequent dust storms, highlighted the health risks connected to the presence of war-polluted ground. Broomandi et al. (2017) measured high values of anthropogenic Br, Cl, Mo, S, Zn and Hg in airborne dust samples, and suggested, after reviewing other work in the region, that the detected high values of Cl and S could be "the result of using chemical warfare (Mustard gas) in Iraq-Iran war during 1980–1988". The high values of Hg were of major concern.

5. Sustainable land and water management (SLWM) solutions to mitigate anthropogenic SDS

The UNCCD supports mitigation of SDS impacts and anthropogenic dust sources by affected countries, through a three pillar approach: 1) Early warning systems; 2) Preparedness and resilience; and 3) Anthropogenic source mitigation. This section focuses on the third pillar. Mitigation at source (reduction of wind erosion and SDS generation) particularly addresses anthropogenic sources, which are linked to the unsustainable management of land and water.

In this section, the term sustainable land management (SLM) is extended to sustainable land and water management (SLWM), a term often used by international organizations such as the World Bank and Global Environment Fund (GEF) to highlight the role of the water and watershed component in combination with soil and plant/vegetation management.

Most of the reviewed papers mainly address the processes of dust generation, and subsequent transport, from playa sources. In some cases they report quantitative estimates of the related impacts, but causal factors of lake desiccation are frequently not discussed. SLWM practices are often advocated by authors to mitigate impacts, however in many cases these are just mentioned, without indicating specific practices and without presenting examples (Table 1). To integrate our analysis we thus reviewed the World Overview of Conservation Approaches and Technologies (WOCAT) database on sustainable land management practices (wocat.net) to identify concrete examples of SDS-relevant SLWM practices.

5.1. Identifying areas of interventions to tackle drivers and impacts of SDS from playa sources

In order to mitigate anthropogenic SDS and their impacts, three different areas of SLWM intervention are proposed (Fig. 5): 1) the water-consuming and sediment and pollutant-feeding zone upstream of the shrinking water bodies, 2) the playa zone subject to wind erosion, and 3) the impact zone located down-wind of the playa.

Indirect drivers of SDS mainly act in the upstream zone. Here, water abstraction for irrigation and other uses reduces the water flow in the rivers and the inflow of water into the lakes. Furthermore, many irrigation practices lead to accumulated salt content in the water returned to the rivers, increase salinity and pollution of rivers and lakes and the toxicity of accumulated sediments in the playas. Land degradation and desertification in the upstream zone are also connected to playa processes. Intensive crop production and overgrazing areas with reduced soil cover, or abandoned bare land formerly irrigated but degraded through salinization, are vulnerable to runoff and erosion. Runoff collects agrochemicals, other pollutants and salt from the salinized surfaces and accumulates them, along with the eroded sediments, in downstream rivers, lakes and playas (e.g., Rivera Rivera, 2010; Kandakji et al., 2020).

The expanded bare areas along riverbeds and around shrinking water bodies are highly vulnerable to wind erosion. Here, direct SDS drivers affect the erodibility of playas, which may be enhanced by human activities and livestock movement leading to destabilization of the river and lake floors and by the disturbance and reduction of vegetation cover around the playa areas (e.g., on the former lake shore). The latter provide improved protection of the soil against wind and water erosion, further salinization and pollution. The anthropogenic influence can be further aggravated by increasing irrigation water withdrawals on the lake shores resulting in lower water levels.

The areas impacted by SDS are those located downwind of the wind erosion-affected playas, which may be affected by sand encroachment and/or dust deposition (which may reach far outside the watershed boundaries). Impacts include deposition of sand and dust on agricultural fields and natural ecosystems, deposition of contaminants and salts on soil and water bodies if dust is polluted and/or salt-rich, and, certainly, impacts on human health and safety and on economic activities (e.g., deposition of sand and dust on productive structures and facilities, on roads, and in buildings).

5.2. SLWM practices addressing different areas of interventions

Reducing the formation of SDS and mitigating their impacts within the three areas of intervention can be achieved through a virtuous integration of sustainable irrigation water management and sustainable land management. The literature review identified the most frequently reported practices and their use in the three areas of intervention (Table 2), which are described in the following sections.

5.2.1. Irrigation water management upstream

Experience indicates that once upstream water is committed to other uses and ecological damage is done, it is difficult to reverse. This is clearly shown by Owens Lake. Huge financial investments have been made during recent decades by the city agencies of Los Angeles in an attempt to mitigate the dust issue at the Owens Lake playa, but the issue remains largely unresolved. A recent book summarizes the efforts deployed and their variable degree of success (National Academies of Sciences, Engineering, and Medicine, 2020). It is thus not surprising that dryland developing countries are struggling to save their shrinking water bodies among increasing and competing water demands, and that anthropogenic playa SDS sources are increasingly widespread and hard to mitigate.

The most frequently advocated approaches involve actions to prevent or reduce playa exposure, particularly by means of improved water use efficiency in irrigation to reduce water demand and, at the same time, salinization and pollution of irrigated soils. Common solutions indicated in various case studies, at different scales, from the shrinking small lakes in the Mongolian Plateau to the Aral Sea basin, include practices such as drip irrigation (Fig. 6) and rehabilitation of infrastructure for the distribution of irrigation water to reduce water losses (Fig. 7).

However, this is not always realistically feasible. As an example, in terms of water and watershed management, the Aral Sea case has generated considerable international debate. Several authors advocated for urgent international actions targeting the anthropogenic drivers of the Aral Sea disaster, including the political and economic factors driving large-scale cotton production, especially in Uzbekistan and Turkmenistan (e.g., White et al., 2013). Other authors (e.g., Breckle and Geldyeva, 2012) think that “restructuring the economy of the region will not be possible in the near future”, that “irrigation will remain the most important resource for agriculture in Central Asia”, and that water demands will even increase, considering population growth. In any case, it is understood that even diverting more water to the lake, only a partial recovery of the pristine conditions could be achieved and in a relatively

Table 2
Sustainable Land and Water Management (SLWM) practices by intervention zone (Upstream; Playa; Downwind). + = minor importance; ++ = important relevant; +++ = highly important.

SLWM Practice	Upstream	Playa	Downwind
Approaches			
Integrated watershed management planning and implementation	+++	+++	+++
Irrigation water abstraction, monitoring and regulation of water use	+++	+++	
Technologies related to water			
Improved Water use efficiency: rainfed	+++	+++	+
Improved Water use efficiency: irrigation	+++	+++	
Reducing saline and polluted return water flow from irrigated fields into the rivers	+++		
Reducing salinization and pollution in irrigated fields (prevention)	+++	+	
Reducing salinity in Playas (restoration)		+++	
Reducing salinity/pollution in soils where wind transported sand and dust is being deposited	+	+	+++
Technologies related to wind and water erosion			
Windbreaks		+++	+++
Improved and perennial cover	+++	+++	++
Reduced physical disturbance of topsoil	++	+++	++
Distribution of water points in rangelands to reduce animal movement and concentration	++	+++	++

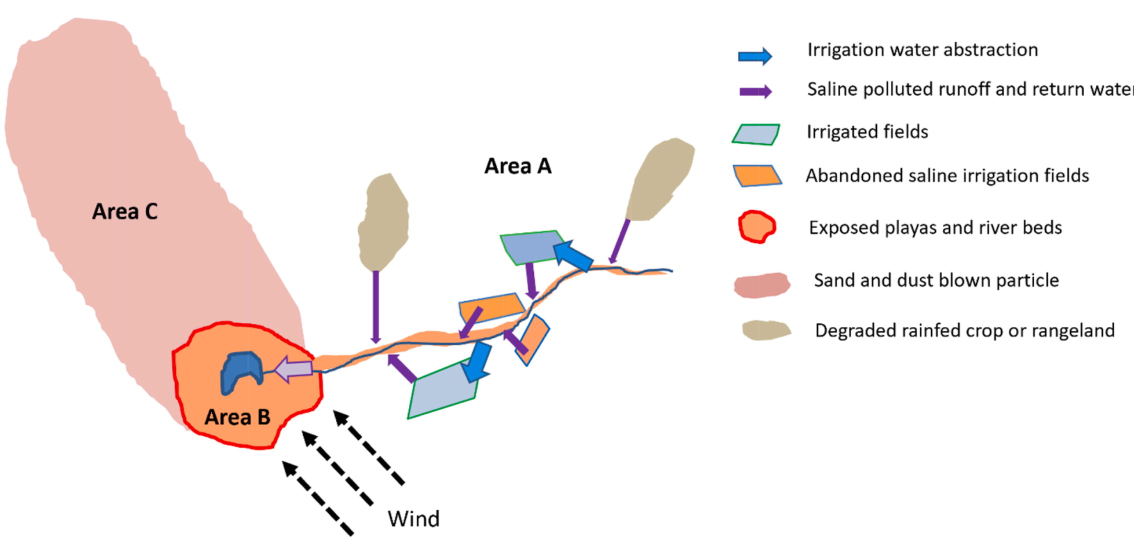


Fig. 5. Authors’ drawing showing the three areas of intervention for the mitigation of anthropogenic SDS playa sources: the water-consuming and sediment and pollutant-feeding zone upstream of the shrinking water bodies (A), 2) the playa zone subject to wind erosion (B), and 3) the impact zone located down-wind of the playa (C).

long time, so strategies need to cope with the situation and reduce the SDS impacts.

5.2.2. *Mitigating land degradation through improved land management upstream and around playas*

Poor vegetation cover on playa shores and on surrounding agricultural fields and rangelands is often considered a key factor driving dust emissions because it increases the exposure of bare playa surfaces to wind action (Table 1). As an example, control of livestock activity around the drying Colhué Huapi Lake in Argentina is recommended by Montes et al. (2017) to favour the increase of vegetation cover and reduce erodibility.

In the playa-rich southwestern USA, Lee et al. (2012) recommend managing/improving shrublands and grasslands to preserve at least a patchy vegetation cover during extreme droughts, particularly on the most vulnerable areas (e.g. sandy river floodplains, playas), also to reduce transport of fine sediments into playas, that then become dust. In the same environment, in a study focused on dust storm impacts on highway safety, Li et al. (2018) suggest using netting and reseeding to actively assist vegetation development to reduce dust generation.

Rashki et al. (2018), discussing the SDS affecting cities such as Zabol, Helmand, Kandahar, and Zahedan in the Sistan region of Iran and Afghanistan, point out that the loss of vegetation around the Hamoun ephemeral lakes causes a strong increase in frequency and severity of dust emission from the exposed lake playas. According to Adib et al. (2018), the most useful approach to reduce the SDS impacts around the shrinking wetlands in Khuzestan Province of southern Iran could be planting shrubs and scattering mulch over hotspot source areas.

To mitigate the ecological impacts of oases silting in Xinjiang's Cele County, Mao et al. (2014) underline the urgency to protect the natural vegetation of the oasis-desert ecotone against inadequately conducted reclamation activities and abusive grazing, and to actively restore vegetation cover (e.g. plants supported with irrigation in summer or cultivated in more even spatial distribution) with supporting measures aiming to improve soil moisture conditions. Degradation, salinization and abandonment of oasis systems is generally studied in terms of economic loss for local communities, and as a loss of precious water resources. However, abandoned oases can easily become vulnerable to wind erosion. Another example of intervention to restore threatened oases, a technique adopted by the farmers to prevent salinization in the Djerid region of Tunisia, is documented by WOCAT. It aims to amend the soil around palm trees by mixing fresh sand to improve soil drainage and reduce salinity (Fig. 8).

Fig. 6. Integrated farming with drip irrigation is applied to reduce water losses by runoff and evaporation, salinization and soil organic matter loss in Tajikistan, Aral Sea basin. (WOCAT entry n. 4307; https://qcat.wocat.net/en/wocat/technologies/view/technologies_4307/).

Fig. 7. Rehabilitation of water gates to improve distribution of irrigation water. The breakdown of obsolete water infrastructure caused immense water losses along the canals and the distribution systems in in Tajikistan, Aral Sea basin (WOCAT entry n. 1444; https://qcat.wocat.net/en/wocat/technologies/view/technologies_1444/).

As mentioned above, improved land management and reduced erosion of rainfed crops and rangelands located in upstream watershed areas would generate indirect benefits by reducing the load of sediment and salts reaching the water bodies and ultimately the playa floor. However, this linkage is not directly addressed by most of the reviewed scientific articles.

An important example is documented by WOCAT, involving rehabilitation of degraded irrigated land in Uzbekistan through afforestation by multi-purpose salinity and drought tolerant tree species (Fig. 9). Improved drainage and control of groundwater level can be achieved by intercropping trees and establishing agroforestry systems, which also contribute to reducing wind impact and creating an improved microclimate. This case is particularly relevant for the Aral Sea watershed where large irrigated areas located along the lower Syr Darya (Qyzylorda district) and Amu Darya (Karakalpakstan Republic) valleys, respectively in Kazakhstan and Uzbekistan, have degradation and salinization problems. These areas contribute to salt-rich river sediments flowing to the Aral, and are also dust sources themselves.

5.2.3. *Improving vegetation cover on playas*

Playa surfaces are often bare, which make them extremely exposed to wind erosion. Thus, the most frequently advocated practices are to improve the vegetation cover and stabilize the loose exposed sediments of the playas with salinity resistant grasses, shrubs and trees, and through the establishment of windbreaks (mostly vegetative and some enforced with structural measures). Selected plants may also have the capacity to reduce the salinity and toxicity of surface soils.

Several projects conducted on the Aral Sea dry bed indicate that planting native species adapted to salinity and drought facilitate a faster and more effective increase of vegetation cover and a subsequent reduction of dust generation (Wucherer et al., 2012b; Novitzkiy et al., 2012; Kuzmina and Treshkin, 2012). Plant species need to be tested and selected to match specific land conditions (salinity, soil texture, moisture), and based on their suitability to be used as pastures and fodder crops. Additional benefits of these interventions would include the generation of new pasture land. Furthermore, the use of native species, by maintaining the main elements of pristine flora, would make it easier to restore or rehabilitate the original ecosystems in case of a future

Fig. 8. Degrading oases can become dust sources. The figure shows degraded and salinized palm groves targeted for amendment in Kébili Oasis, Tunisia (WOCAT entry n. 3732; https://qcat.wocat.net/en/wocat/technologies/view/technologies_3732/).

increase in natural moisture conditions or of improved water management (Kuzmina and Treshkin, 2012). Among the species tested for this purpose, *Haloxylon* spp. (Saxaul) proved to be most effective (Fig. 10). Another example, documented by WOCAT, is the plantation of *Apocynum pictum* and *Apocynum venetum* in the Tarim Basin of north-west China to regreen barren saline lands and make them productive again (Fig. 11). Native halophytic shrub species have been tested also on the Owens Lake playa to explore best methods to increase seedling growth and survival on saline playas (e.g., Breen and Richards, 2008).

5.2.4. *Reducing physical disturbance of playa surfaces*

Reducing anthropogenic disturbance of playas is another simple but effective measure (Gill, 1996; Gillette, 1999). In fact, human disturbance of the soil surface is a major factor in wind erosion in arid ecosystems. Studies conducted at the scale of the whole Central Asia region indicate that the active SDS sources are mostly located in sandy and other types of deserts, including playas, “where the sensitive ecosystems suffered from human impact” (Indoitu et al., 2012). Several of the reviewed articles stress this aspect. Reynolds et al. (2007) underline that the dry playas of the Mojave desert generally have a hard surface that produces limited amounts of dust (mainly made of “transient silt and clay deposited on surfaces by wind and water”) unless the surface is disturbed by human activity. In a study addressing ways to minimize dust impacts on highway safety in southeastern USA, Li et al. (2018, page 1030) recommend avoiding soil surface and vegetation cover disturbance, particularly in playas and other ecosystems “where the physical soil crust may be disturbed by recreational vehicles, cattle grazing and trampling, and land use change”. Zhang et al. (2015) recommend reducing disturbance of playa surfaces by mining and industrial activities that contribute to enhance dust generation in Otintag Sandy Land, in China’s Inner Mongolia.

Reducing disturbance is critical for playa sources located near settlements. As an example, Mardi et al. (2018) claim that dust emission from Urmia Lake playas is worsened by disturbance generated by grazing and salt harvesting on the lake playa, which can produce severe

Fig. 9. Degraded irrigated land targeted for rehabilitation through afforestation by multi-purpose salinity and drought tolerant tree species including oleaster (Elaeagnus angustifolia), Turanga poplar (Populus euphratica), and Siberian elm (Ulmus pumila) in Uzbekistan. (WOCAT entry n. 1533; https://qcat.wocat.net/en/wocat/technologies/view/technologies_1533/.

Fig. 10. The halophyte Saxaul tree planted along rows as windbreak to stabilize the exposed Aral Sea floor in Kazakhstan (WOCAT entry n. 1089; https://qcat.wocat.net/en/wocat/technologies/view/technologies_1089/).

pollution impacts, the magnitude of which is not balanced by the limited immediate economic benefits generated by these activities.

It is also worth mentioning that in semi-arid environments, undisturbed saline playas have the potential to recover spontaneously. As an example, in parts of the Aralkum a process of natural soil desalinization would take place within 4–8 years due to the leaching action of precipitation (Low et al., 2013), with a slow, spontaneous recovery of vegetation following (Dimeyeva, 2007; Wucherer et al., 2012a).

5.2.5. Mitigating SDS impact in downwind areas

In downwind areas, SLM practices to mitigate the impact of SDS are challenging as on the one hand they should help reduce wind speed and trap dust particles while on the other hand these particles may be detrimental to the soil due to their salt or pollutant content.

The reviewed scientific articles mostly focus on reduction of dust generation and do not address this aspect. However, many available techniques could be applied to reduce SDS impacts on local communities. Some examples documented in the WOCAT database include reed protection strips around houses, along with sand dune stabilization by shrub plantation and by structural measures (Figs. 12-13), used to protect houses and orchards against wind and dust in Central Karakum, Turkmenistan.

5.2.6. Integrated land and water management

The long-term mitigation of dust emissions from playa sources would primarily require keeping to a minimum the surface of the exposed playas and regulating water use in the upstream areas and the whole watershed. This requires local and watershed-scale management plans and the implementation of integrated sustainable land and water management (SLWM) practices.

Integrated approaches to land and water management are advocated by the Global Assessment of SDS (UNEP, WMO, UNCCD, 2016; page 17), which states that “the key to containing anthropogenic dust emissions is through sustainable management of all land uses and water across whole landscapes including both natural and human-dominated ecosystems”. It also states that “control of anthropogenic sources of SDS is synonymous with sustainable land and water management”.

SLWM is increasingly seen as a solution to achieve SDS impact reduction in the short and longer term. In this context, SLWM should include and combine together measures addressing the dust-generating areas, such as regreening (Abuduwaili et al., 2010), as well as approaches to mitigate the drivers, such as by promoting sustainable agriculture and irrigation practices in the watershed (e.g., Groll et al., 2013), and practices to reduce dust impacts on communities.

Fig. 11. Apocynum spp., profitable indigenous drought tolerant plants used to improve soils salinized due to inappropriate irrigation management of cotton, in a highly SDS-prone region of Xinjiang Province, China, (WOCAT entry n. 1721; https://qcat.wocat.net/en/wocat/technologies/view/technologies_1721/).

SLWM is indicated as a possible solution by few papers. To reduce SDS impacts in Iraqi cities located near the drying marshes, Sissakian et al., 2013 proposes restoring agricultural lands and “green zones” around the cities, which could be achieved by using drip irrigation, treated waste-water and water harvesting techniques. This would at the same time allow saving water, and would contribute to restoration of the marshes. Similar integrated approaches worked well in stabilizing the desiccated Lake Texcoco, a major source of dust storms affecting Mexico City in the 1960s and 1970s (Goudie and Middleton, 1992). Zhang et al. (2008) and Lee et al. (2012) recommend taking a planning-oriented approach, considering the inherent vulnerability of the land, particularly the playa surfaces, in land planning to reduce dust emissions.

However, the potential benefits of the synergistic integration of multiple SLWM technologies appears to be a relatively poorly explored topic by scientific articles, which mostly focus on either dust generation from playas, or on dust impacts, with little or no discussion about the possible integrated solutions. Also, this review did not reveal the existence of recent projects aimed at implementing integrated watershed planning or management interventions to reduce SDS from anthropogenic playas. This should be considered as a major knowledge gap in both science and practice, possibly requiring pilot projects and further research and discussion.

The WOCAT database provides a variety of examples of SLWM practices that could be applied, individually or in combination, to generate synergistic benefits and become elements of integrated approaches for the different areas of interventions and that could be strategically deployed at the watershed scale.

The three areas of intervention are interlinked. Integrated watershed management covers large areas if the whole connected system from the upstream degraded lands to the playas and the downwind areas is included, and it may cover ecological gradients and geo-political boundaries. Integrated approaches may also involve mechanisms from SDS-affected areas to support investments in the upstream areas and the source areas within and around the playas, in what would be a type of payment for ecosystem services. This approach has been used in an effort to revive the Jazmurian Lake wetlands in Iran (Eskandari-Damaneh et al., 2020). An economic approach has also been proposed in the case of Owens Lake, assessing the economic trade-off between pumping groundwater and sustaining the native plant community that performs dust suppression (Gutrich et al., 2016).

6. Conclusions

Sediment blown from exposed playas of shrinking water bodies strongly contributes to global dust emissions. Dust emission in most hydrologic dust hotspots is a consequence of the worsening conditions of the water bodies in many of the world’s drylands, and the drivers of this process are commonly at least in part anthropogenic. The so-called Aral Sea “syndrome” is contagious.

Playas that are anthropogenic SDS sources are at the centre of a complex system of interactions under the influence of human activities that involve unsustainable water and land management, and land degradation in areas located upstream and around the playas, and of climate change.

An increasing number of articles address this issue, as shown by this review. The emerging picture is that of a global problem, although the geographical coverage of the review in terms of number of articles and cases studies is unbalanced, with a much higher number of anthropogenic playa source cases documented in Asia and North America than elsewhere.

The review of the possible solutions proposed by the articles to mitigate SDS impacts from playa sources shows that actions mainly target three different geographical zones of intervention: the water-consuming and sediment and pollutant -feeding upstream zone; the

Fig. 12. A package of technologies is used to mitigate SDS around the Bokurdak village, in the Central Karakum region of Turkmenistan, including dune stabilization by bundles of reed (left) and plantation of adapted plant species such as Haloxylon persicum on the stabilized sand (right) (WOCAT entry n. 1529; https://qcat.wocat.net/en/wocat/technologies/view/technologies_1529/).

Fig. 13. Protection strips made of Arundo donax reed used in the Bokurdak village, in the Central Karakum region of Turkmenistan, as protection against wind and dust around the households (left) and to create favorable micro-climate conditions for crop production (right). WOCAT entry n. 1531 (https://qcat.wocat.net/en/wocat/technologies/view/technologies_1531/).

playa zone subjected to wind erosion; and the downwind impact zone. Some studies also recognize the need for integrated land planning strategies, which may involve the integration of multiple sustainable land and water management (SLWM) techniques, but with limited discussion of the possible approaches.

As advocated by the UNCCD, the sustainable management of land and water across landscapes is crucial to mitigate anthropogenic dust emission. In order to reduce the SDS-related impacts downwind of playa sources, SLWM practices should be applied, individually or in combination, to generate synergistic benefits and strategically deployed at the watershed scale to become elements of integrated planning approaches. Optimized blending of approaches and methodologies across intervention zones can be defined through reiterative consultation and coordination engaging diverse stakeholders and relevant sectors.

To achieve this goal, appropriate combinations of SLWM techniques applicable to the varying contexts and zones of intervention need to be identified, their synergistic effectiveness and contribution to the mitigation of SDS assessed, and their upscaling potential evaluated. However, these aspects are not sufficiently explored in the scientific literature, which mostly addresses either dust generation or dust impacts, and remain a major knowledge gap both in science and in practice.

Under the UNCCD framework, nonetheless, countries with SDS sources are invited to explore anthropogenic SDS source mitigation in national voluntary land degradation neutrality (LDN) target-setting and options to integrate source mitigation measures into LDN process. Achieving LDN (Sustainable Development Goal target 15.3) through adoption of SLM, and measures to reverse degradation by rehabilitating and restoring degraded land can deliver multiple benefits including the reduction of wind erosion and dust emission. This is globally relevant for anthropogenic SDS source mitigation, considering that 151 UNCCD country Parties (77% of the total) are affected by sand and dust storms and 45 (23%) are identified as source areas (Middleton and Kang, 2017). Successful integration of anthropogenic playa sources into the LDN process and implementation of related voluntary targets can contribute to achieving restoration commitments including LDN from national to global level as part of the UN Decade on Ecosystem Restoration 2021 to 2030.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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