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Sand and Dust Storms: Recent Developments in Impact Mitigation

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Abstract: Sand and dust storms (SDS) pose a wide range of hazards to human society, affecting people in drylands and beyond. This paper, based on a wide-ranging review of the scientific and grey literature, presents, for the first time, a comprehensive synthesis of mitigation and adaptation interventions designed to manage the risks involved and thus build resilience to these SDS hazards in line with the Sendai Framework for Disaster Risk Reduction 2015–2030 (Sendai Framework) and the Sustainable Development Goals. It highlights case studies and good practice examples of measures available to reduce the risks and impacts associated with SDS beyond SDS source areas. These measures, which are interrelated and complementary, are summarized under education initiatives (for schools, specific sectors and vulnerable groups), risk/impact assessments (involving information on hazard, exposure and vulnerability), vulnerability assessment/mapping, integrated monitoring and early warning (using the World Meteorological Organization's Sand and Dust Storm Warning Advisory and Assessment System, or SDS-WAS) and emergency response and risk reduction plans (including contingency planning). Many of these measures are developed for other hazards, but not for SDS. Data availability is an important issue in this regard, and the example of Kuwait illustrates that even with a relatively good understanding of SDS, many aspects of impact mitigation remain poorly understood. Developing appropriate responses to SDS hazards is a matter of some urgency given climate change projections that indicate more frequent and intense SDS emissions due to increased aridity and worsening drought conditions (frequency, severity and duration).

Keywords: dust storm; sand storm; drylands; climate hazards; Sendai Framework; disaster risk reduction

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1. Introduction

Sand and dust storms (SDS) are common phenomena, particularly in the world's drylands (deserts and semi-deserts). These events take place when strong turbulent winds lift fine material from dry land surfaces with little or no protective vegetation cover. SDS play a part in the functioning of the Earth system, affecting the lithosphere, atmosphere, hydrosphere and biosphere in numerous ways [1], but they also have a range of adverse socioeconomic effects [2,3]. Important sectors affected include transport [4], agriculture [5], electricity generation [6] and the oil and gas industry [7]. Numerous associations have been identified between SDS and human health [8,9]. Links have also been made between SDS and violent crime [10], human well-being [11] and suicide risks [12]. During major SDS events, impacts are also felt in education, construction and leisure [13]. Desert dust is frequently transported great distances from source areas (Figure 1), often across national boundaries, so that the effects are felt not only within drylands but also far beyond [14,15].

However, although these socioeconomic impacts are recognized, SDS have a low profile in mainstream natural hazard or disaster research, meaning that there are major gaps in hazard and risk data availability, as well as management capabilities, all over the world [16,17]. For instance, detailed analyses of road transport accidents associated with SDS are very largely confined to the USA [18], despite occurring in many other countries [19]. In the field of human health, many studies have demonstrated that SDS events correlate with the number of hospital admissions and daily deaths for a variety of ailments, particularly those associated with the heart (including stroke, arrhythmia and ischemic heart disease) and lungs (including asthma, pneumonia, chronic obstructive pulmonary disease) [20,21]. Rather less is known about other health disorders associated with SDS, such as meningococcal meningitis [22]. In geographical terms, some SDS source areas and affected areas are much better studied than others [23], and the variety of methods used for epidemiological investigations needs to be standardized [24]. Standardization is also required for economic impact assessments, which have been conducted for just a few places and events [25,26], although a guideline on the monitoring and reporting of the impacts of SDS through the Sendai Framework has now been developed [27].

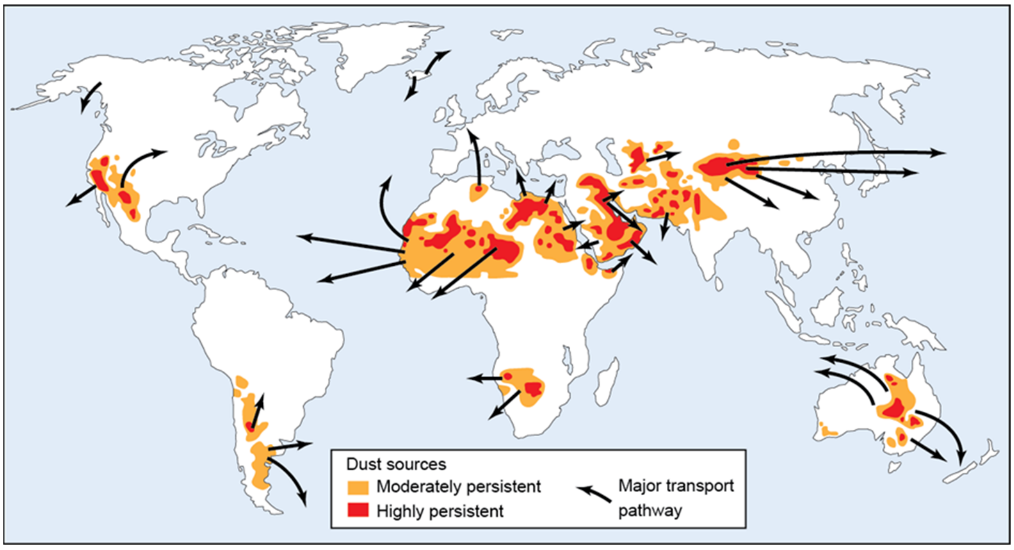

Figure 1. Map of main dust sources globally and major trajectories of long-distance transport (after [28]).

The urgency of filling these gaps in SDS hazard data and understanding is compounded by climate change projections that indicate greater aridity and worsening drought conditions (greater frequency, severity and duration) in drylands globally, and hence drier soil surfaces with less vegetation cover [29]. In consequence, the adverse impacts of SDS are likely to worsen further in the future unless appropriate interventions are implemented.

Building resilience to these SDS hazards is a major focus of the Sendai Framework for Disaster Risk Reduction 2015–2030 (Sendai Framework) and contributes to the achievement of Sustainable Development Goal 15 (Life on Land), which focuses on strengthening cooperation on desertification, dust storms, land degradation and drought. Building such resilience requires a range of mitigation and adaptation interventions designed to help manage the risks involved. These actions to reduce the damage and loss from SDS can be considered in two areas: impact mitigation and source mitigation (Figure 2). The methods involved in this two-fold approach were reviewed in a paper published in this journal in 2017 [30], which highlighted the fact that source mitigation strategies are relatively well known [31,32] and commonly used, especially in agriculture [33,34]. Techniques for mitigating the impacts of SDS are less developed, but some progress has been made in these areas since Middleton and Kang's study, making them worthy of focus in this paper, which draws on a comprehensive review of the scientific and grey literature to showcase selected case studies and good practice examples of the measures available to reduce the risks and impacts associated with SDS outside source areas.

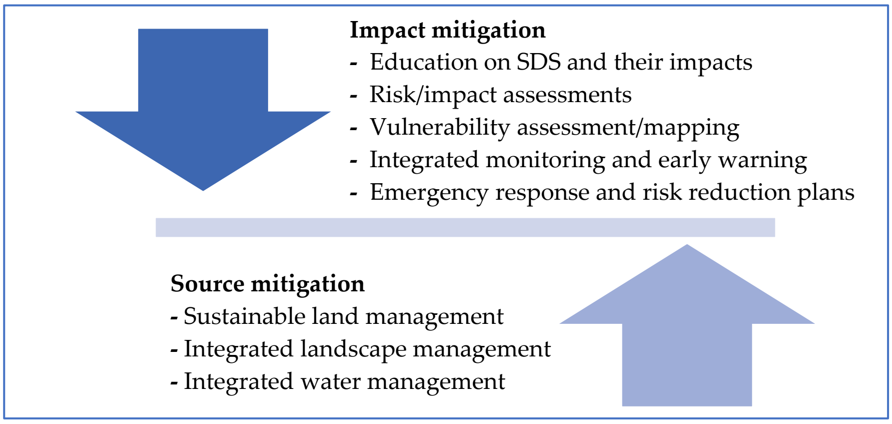

Figure 2. Two-part strategy for mitigating SDS hazards (after [30]).

2. Education on SDS and Their Impacts

Awareness of the risks posed by SDS is an essential precursor to minimizing or avoiding any adverse effects. There is a greater chance that people will take action to reduce the potential harm from natural hazards if they know something of the risks threatening their communities [35,36]. Knowledge and understanding can be enhanced in a number of ways. There is evidence to support the targeting of children for disaster education, benefitting not only the child but also the family and wider community [37], and the role of children and youth as drivers of change is acknowledged in the Sendai Framework [38]. Disaster risk reduction (DRR) has been integrated to some extent into school curricula at different levels in many countries [39,40] and appropriate educational packages created by national DRR authorities, including printed materials and online resources for teachers and pupils [41]. Numerous hazards are identified but, as far as we are aware, none exist specifically for SDS.

Disaster education and information programs, using websites, social media, printed leaflets and other information avenues, have historically targeted adults with information on disaster risks and advice on preparedness measures and evasive actions. Some examples of SDS infographics produced for human health awareness raising are shown in Figure 3. Educational and awareness campaigns can be tailored to specific sectors (e.g., agriculture) and vulnerable groups (e.g., asthmatics). SDS impact all members of society—men, women, girls and boys—but not necessarily all in the same ways [42]. For some individuals, such as those with existing adverse health conditions, SDS may be life-threatening. Other differences between groups in society may result from gender-based roles in particular spheres (e.g., economic, family and social). Some of these differences stem from the composite nature of SDS hazards. A strong, turbulent wind during an SDS may be a particular hazard for pedestrians in a city where trees, street furniture or parts of buildings become damaged and dangerous. The atmospheric concentration of fine particles may be the most hazardous aspect for those suffering from respiratory or cardiovascular diseases.

Low visibility during a dust storm may be the most dangerous aspect of an SDS for someone driving a motor vehicle—the loss of visibility can be sudden, often resulting in road traffic accidents. An effort to educate motorists in the USA about the dangers of driving in an SDS has been developed by the Arizona Department of Transportation under the headline 'Pull Aside and Stay Alive!' [43]. The safety campaign provides drivers with advice on how to stay safe if caught in a dust storm, comprising tips and video Public Service Announcements (PSAs), available at https://pullasidestayalive.org/home, accessed on 1 June 2024.

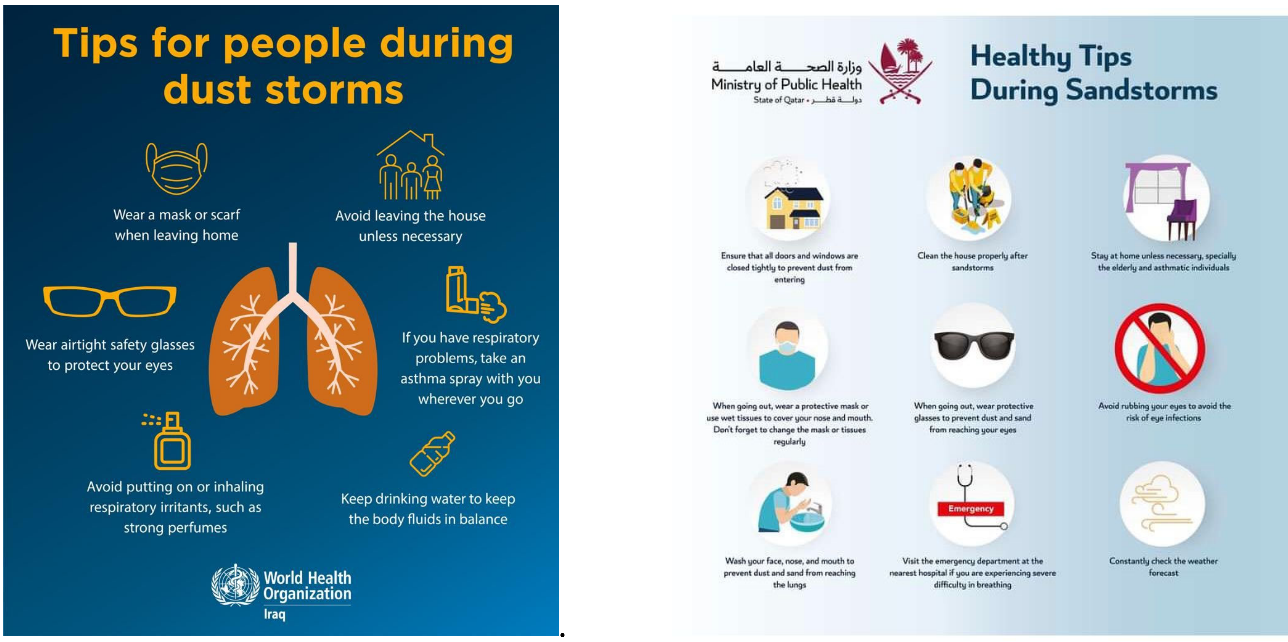

Figure 3. Public information on SDS health hazards in Iraq (**left**) and Qatar (**right**).

The design of information campaigns is also likely to vary between groups and communities. In terms of delivery, a distinction can be made between cities and small rural communities, where many of the common media used for disaster and emergency management public education, such as local radio, television and newspapers, may not be available, as reported from rural Canada [44]. The internet and social media are other common delivery mechanisms for public education, but there may be access difficulties in certain rural areas and computer literacy may be an issue in certain communities.

The collection and collation of photographs and videos of SDS and their impacts, for use in educational packages and campaigns, is a valuable preparatory stage in increasing hazard awareness. Such images represent a 'unique form of data that capture the transient consequences of Earth's periodic upheavals', as Dunbar p. 533 in [35] put it. Collected images serve as permanent reminders of events that are ephemeral by nature and can act as powerful warnings of the need to be prepared to tackle their consequences again in the future.

3. Risk/Impact Assessments

Information and understanding on natural hazard-related risks is crucial for all stakeholders working in DRR and spatial planning, as well as for (re-)insurance companies, which establish premiums for hazard-related insurance policies [45]. Risk is composed of three main factors: the hazard itself, the exposure of society directly or indirectly to the hazard and the level of physical, social and economic vulnerability to the hazard [46].

This knowledge of risk is obtained through a risk assessment, which involves the systematic collection and analysis of data on the dynamic nature of hazards and the associated exposure and vulnerabilities resulting from various drivers—for example, processes such as land use/cover change, environmental degradation and climate change in the environmental sciences [47]. The assessment of risk and impact can be accomplished in a variety of ways and the methodology(ies) selected will represent a trade-off between accuracy, cost and the timeliness of the results. A generalized process for an SDS risk assessment has been suggested by UNCCD [48] and is shown in Table 1.

Table 1. Framing the sand and dust storm risk assessment process (after [48]).

Step	Task	Notes
1	Establish a reason for the assessment	Link the assessment to SDS risk mitigation in a specific area where possible
2	Define the assessment area and whether the focus is on an SDS source or impact area or both	Source and impact areas overlap for some SDS. In general, the smaller the assessment area, the more precise the risk assessment. If the source area is some distance from the impact area, include a short description of the origin and movement of the SDS. Identify whether the SDS may contain any contamination or be a disease transmission vector
3	Identify the SDS type(s) *	For areas affected by more than one type of SDS, the risk assessment process treats each type of SDS separately, with comparable results
4	Assign return period for the SDS type assessed	Return periods can be defined using meteorological data from station(s) in the assessment area
5	Collect data on vulnerability to SDS and other factors	The assessment should include the analysis of existing vulnerabilities and capacities specific to particular groups (e.g., girls, women, boys and men, categorized by age and disability factors)
6	Repeat steps 2 to 4 for each type of SDS that can affect the area covered by the assessment	
7	Analyze results by SDS type and return period	Results can be compared by return period across type, but most likely by type for return periods. Analysis should include location, gender, age, disability, health conditions, social status and economic factors
8	Develop a report of the assessment results	The report, which should state the reason for the assessment and the process followed, should detail the results and their implications (e.g., for risk reduction)
9	Validate the results	The assessment results should be distributed to, and validated by, a representative group of the communities affected by the SDS. Comments from the validation should be incorporated into the report and used iteratively to improve the assessment process and the vulnerability assessment itself

* UNCCD suggest a six-fold SDS hazard typology dependent upon on the intensity (using visibility as a proxy) and area affected.

Formal SDS risk assessments involving information on the hazard, exposure and vulnerability have not been carried out anywhere, to the best of our knowledge. The availability of data is the most significant issue to be overcome in this regard. This is the case even in a country such as Kuwait, which has more information on SDS and their impacts than most other countries.

Knowledge of SDS in Kuwait is built on a history of scientific research that extends back 45 years and more [49]. Understanding of SDS meteorology, climatology, geomorphology and sedimentology has a very solid foundation, e.g., [50,51], as has the knowledge of major regional SDS sources and transport trajectories, e.g., [52,53]. The mineralogy, geochemistry and biological properties of dust are also well studied, e.g., [54,55].

The socioeconomic effects of SDS in Kuwait were first studied by Al-Hemoud et al. [3], who highlighted the impacts on transport: delays caused by dust storms at the country's seaports lead to a reduction in oil exports, and disruptions to operations at Kuwait International Airport also have negative economic consequences. However, only weak correlations were found between SDS and road traffic accidents and between SDS and crop production (field crops and greenhouses). A more in-depth study of SDS impacts on Kuwait's oil and gas industry concluded that sand—and, to a lesser extent, dust—were damaging to the industry's infrastructure, amounting to USD 9.36 million over an 8-year period [7]. A detailed study of how dust storms affected flight schedules at Kuwait International Airport found that the average arrival and departure times decreased by 42% and 17%, respectively, on days when dust incidents occurred [56]. Assessments of the power efficiency of solar panels in Kuwait have concluded that the effects of desert dust (via reductions in solar radiation, high deposition rates, and carbonate and mud content) have a substantial deleterious impact on their performance [57,58].

A number of studies of the human health effects related to desert dust have also been conducted in Kuwait. An investigation of the chemical and mineralogical character of dusts concluded that long-term exposure is likely to be hazardous, with links proposed to alkalosis and hypercalcemia and respiratory complaints [59]. Indeed, respiratory and asthma admissions to hospital are typically elevated during dust storm days in Kuwait [60], and a study of the association between atmospheric dust particles and morbidity and mortality rates for respiratory and cardiovascular diseases found good evidence of a consistent relationship between dust storm events, PM_{10} (particles with an aerodynamic diameter <10 μm) concentration levels and respiratory diseases [61]. Exposure to ambient $PM_{2.5}$ in Kuwait, from SDS but also regional industrial sources, is toxic and increases the risk for respiratory hospitalization [62]. Pollen contained in dust is another health issue; allergy patient admissions to hospital can be predicted from three pollen types common in Kuwait [63].

National hazard maps have been produced for dust storms and sand encroachment (Figure 4), as well as other priority hazards in Kuwait [64]. These are essential tools for hazard mitigation and emergency response, and the multi-hazard risk management approach of this work is important because the SDS risk is linked to others, including drought, desertification and land degradation.

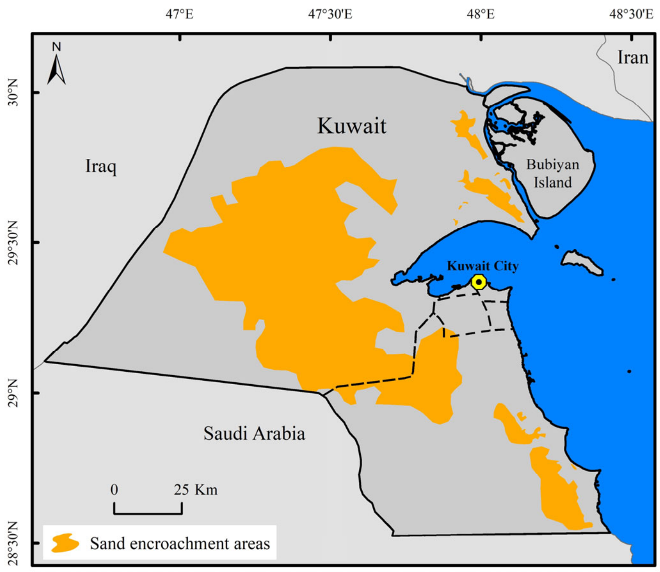

Figure 4. Sand encroachment hazard map for Kuwait [65,66].

Kuwait has amassed a significant amount of knowledge of SDS impacts, although additional work is still warranted. Further investigations are required in the energy sector (e.g., SDS impact on power distribution systems), agriculture (pastoralism), education, construction, business, industry and leisure. Nonetheless, although information on the SDS hazard is fairly well documented in Kuwait, formal SDS risk assessments lack information on exposure and vulnerability. UNCCD [48] outlines two alternative approaches to SDS risk assessment: one based on surveying at-risk populations and the other based on structured expert evaluation. Both approaches take into account the fact that detailed data on the SDS hazard, exposure and vulnerability may not be available. Both methods provide results that can guide risk management interventions.

- SDS risk management policy: using risk identification on which to base SDS risk reduction policy.
- SDS warning: identifying the most relevant triggers to at-risk populations.

- SDS response: raising the profile of the SDS response by recognizing which specific responses are most effective in reducing SDS impacts and identifying the best coping and adaptation strategies for at-risk populations.
- Risk reduction: detecting where risk reduction actions are best targeted and providing evidence to justify the cost and nature of these interventions. SDS risk assessments can also contribute to larger assessments and strategies designed for other hazards, such as drought or desertification.

4. Vulnerability Assessment/Mapping

Assessing the vulnerability of an individual, community or asset to the impacts of SDS is a key aspect of risk assessment because vulnerability assessments provide critical inputs to plans designed to strengthen socioeconomic resilience. Vulnerability mapping identifies and displays in an easily understandable manner the level of impact of SDS on at-risk geographical areas. Maps can then be used to inform decision-makers and policymakers on the location, extent and severity of the SDS risks, including who is most vulnerable. The information embodied in vulnerability maps will guide governments, emergency responses, health and social welfare bodies, donors, civil society and other stakeholders on where to direct SDS risk management efforts, thus helping to protect at-risk people and assets [48].

Vulnerability can be assessed by integrating Geographic Information System (GIS) analysis tools and Multi-Criteria Decision Analysis (MCDA) methods such as the Analytic Hierarchy Process (AHP), Analytic Network Process (ANP) and Best Worst Method (BWM) to combine Earth observation information on biophysical factors that affect the potential for damage with socioeconomic determinants such as demographics, employment, gender, institutions, health, culture and political conditions. This is the approach used in the only attempt to assess vulnerability to SDS published to date, in rural areas of Iran [67]. The indicators used in this study for the three interactive components of vulnerability—exposure, sensitivity and adaptive capacity—are shown in Table 2.

Table 2. Components and indicators used to assess vulnerability of rural areas to SDS in Iran (after [67]).

Component	Indicator	Description
Exposure	Precipitation	Mean annual cumulative precipitation
	Air temperature	Mean annual air temperature
	Aerosol optical depth (AOD)	Mean atmospheric dust concentration
	Visibility	Corroborating measure of measure of atmospheric aerosol concentration
Sensitivity	Occupancy	Persons per dwelling
	Female-headed households	Ratio of female-headed households to total female population
	Elderly	Ratio of persons >65 years old to total population
	Children	Ratio of persons aged 0–4 to total population
Adaptive Capacity	Literacy	Ratio of literate people to rural population >6 years old
	Active population	Ratio of persons aged 15–64 to total rural population
	Labor force participation	Ratio of labor force to active population
	Bank	Ratio of banks to 10,000 people
	Women's rural funds	Ratio of women's rural funds to 10,000 people
	Membership of cooperative companies	Ratio of rural cooperative companies to 10,000 people
	Road	Ratio of rural asphalt roads to total rural roads
	Agricultural machinery	Ratio of combine harvesters and tractors to cultivated area
	Agricultural yield	Ratio of agricultural production to cultivated area

5. Integrated Monitoring and Early Warning

Mitigation of the many impacts associated with SDS is based on information gleaned from a variety of monitoring, forecasting, prediction and early warning schemes. The monitoring of fine particles picked up and transported by the wind is accomplished by remote sensing and in situ terrestrial observations, the latter including networks of lidars and radiometers, air quality monitoring and meteorological stations [68]. Data from these sources are fed into models that develop our understanding of the relevant drivers and processes and are used to produce forecasts, early warnings and longer-term predictions.

Early warning is the provision of timely and effective information by identified institutions that enables the system exposed to a hazard to take action to avoid or reduce its risk and prepare for an effective response. With an overall view of all areas, effective early warning systems can forecast specific events that could lead to disasters. These systems identify and understand the hazard, the associated risk and the magnitude of the resulting damage. By using an early warning system, impending events can be forecasted and monitored, resulting in the dissemination of understandable warnings to the public and authorities, helping them to take appropriate and timely action. This can minimize devastation and reduce the loss of life, property and livestock [69]. The use of early warning systems to help populations to adapt to various hazards has become widespread around the world. Examples include those developed for heat waves [70], drought [71], earthquakes [72] and tsunamis [73].

In a scoping review of SDS early warning systems detailed in the international literature, most of which were in China, nearly half of the 30 systems reported were based on regional climate models [74]. Of the eight systems that are/were operational, six were models and two were ground-based sensor networks. A diverse range of numerical models has been developed and operational dust forecasts are issued by national meteorological authorities and a number of other centers around the world as part of the World Meteorological Organization's Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS). SDS-WAS works as an international network of research, operational centers and user groups. Established in 2007, it is composed of over 15 organizations that provide daily dust forecasts using 16 models covering a variety of geographical regions [75] organized by four nodes: the Northern Africa–Middle East–Europe node (hosted by Spain), the Asian node (hosted by China), the Pan-American node (hosted by Barbados) and the Gulf Cooperation Council node (hosted by Saudi Arabia).

The SDS-WAS multi-model median daily dust forecasts can be tailored to local requirements. An example is the Warning Advisory System for SDS developed for the 13 administrative regions in Burkina Faso [76]. The daily output is in the form of color-coded maps showing four levels of warning for the next two days (D + 1 and D + 2) in the country's 13 regions (Figure 5). The warnings are designed to assist with the planning of any activity that may be affected by atmospheric dust, including the activation of measures designed to mitigate disruption and/or damages caused in vulnerable sectors such as agriculture, transport or public health.

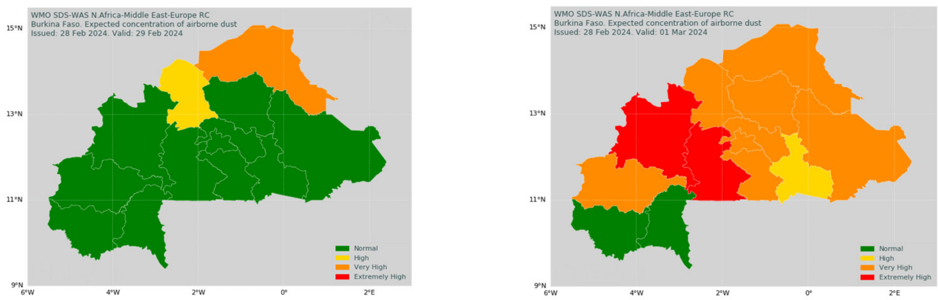

Figure 5. Burkina Faso dust warning level maps for 29 February and 1 March 2024.

The warning level for each of Burkina Faso's 13 regions is set according to the highest concentration value expected for the day at any model grid point within each region. The warning advisory thresholds have been set using percentiles, so that the thresholds are higher for the northern regions, which typically receive higher dust concentrations than the southern regions. Maps indicating the warning levels for D + 1 and D + 2 are available daily at https://sds-was.aemet.es/forecast-products/burkina-faso-dust-alert (accessed on 1 June 2024) and can also be distributed to users in an email message. The forecast outputs also require verification from in situ monitoring equipment, although this is yet to be conducted in Burkina Faso due to the lack of air quality monitoring sites in the country.

The output from a similar Warning Advisory System for SDS in any country could also be refined further to develop an impact-based SDS forecast, using the weather forecast as the hazard layer and adding other components of risk: the vulnerability and exposure of people, livelihoods and property. Impact-based forecasting goes beyond a weather forecast by estimating possible impacts, including where, when and how likely the impacts are. Impact-based forecasts can enable policy-makers and decision-makers in the planning, response and recovery phases of the DRR cycle to better reduce hazard impacts [77]. Impact-based forecasts and warnings are increasingly being developed for a number of hazards, including droughts [78] and floods [79]. The way in which effective early warning is reliant upon, and integrated with, other elements discussed in this paper is enshrined in the Early Warnings for All (EW4All) initiative of the United Nations, launched in 2022 (Figure 6).

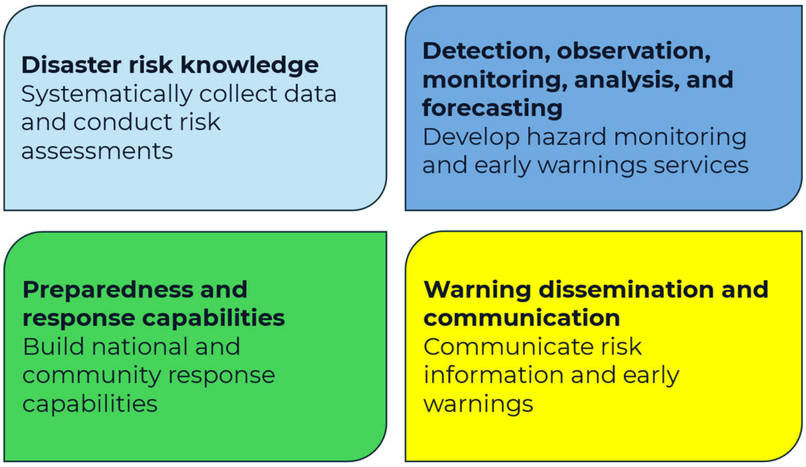

Figure 6. The four pillars of effective early warning in the United Nations Early Warnings for All Initiative [80].

Various single-hazard and multi-hazard early warning systems have been developed at regional and global scales. These systems necessarily include some or all of the four pillars shown in Figure 6 for hazards such as droughts, tsunamis, storm surges, floods, landslides, earthquakes, tropical cyclones and volcanic eruptions [81]. For example, the Indian Ocean Tsunami Warning System (IOTWS) includes all pillars, but the Pacific Tsunami Warning System (PTWS) covers just pillars 2 (dark blue box in Figure 6) and 4 (yellow box). Among systems that focus on multiple hazards, the Regional Integrated Multi-Hazard Early Warning System for Africa and Asia (RIMES), which is designed for tsunamis and other hydro-meteorological extreme events, covers all four pillars for effective early warning systems. Another multi-hazard system, the Global Disaster Alert and Coordination System (GDACS), which provides real-time alerts for sudden-onset hazards such as earthquakes, tsunamis, tropical cyclones, volcanic eruptions and floods, covers pillars 3 and 4. The Asian Disaster Preparedness Center (ADPC) is also a multi-hazard system that addresses hazards such as floods, landslides, earthquakes, cyclones and droughts through pillars 1 and 3. Of all these hazards, drought is probably most similar to SDS in terms of drivers and some consequences. However, the forecasting of windstorm impacts is still in its infancy [82] and conducting the same for SDS has not been attempted. SDS air pollution alerts, based on SDS early warning systems, are detailed in the following section.

6. Emergency Response and Risk Reduction Plans

Early warning alerts are an integral part of emergency plans to respond to hazards. In a review of worldwide practices [83], three key warning stages were identified:

1. Initiate preparations and monitor news media;
2. Prepare seriously for a disastrous situation;
3. Take immediate action.

There are many ways to communicate forecast or warning information to the public, ranging from traditional sirens, radio and television to email, social media, SMS text messages and push notifications. Best practice is to use at least two, and preferably three, different pathways. Warnings are issued by a mandated authority such as a government, company or organization and are intended to trigger specific (compulsory or voluntary) actions. Warnings for specific sectors—including transport, education and health—may also be issued by relevant authorities based on SDS forecasts—for example, requiring that traffic be stopped, facilities close or people particularly at risk take evasive action. The provision of timely, accurate, trustworthy, clear and understandable warnings can save lives, livelihoods and resources when disasters result from natural hazards [84].

Much of the evidence for the efficacy of early warning on air pollution events comes from the health literature and is based on more general warnings adopted in a number of countries where alerting the public to air pollution episodes can initiate a series of protective and avoidance reactions, e.g., [85,86]. In the case of SDS, there is evidence that dust alerts are a simple and effective means of prompting behavioral changes that lower exposure, thus reducing hospital admissions and harmful impacts on human health [87].

In South Korea, yellow haze comprising desert dust blown from sources >1000 km away in China and Mongolia is a common seasonal phenomenon, and notifications to the public based on measured PM_{10} levels have been generated by the Korea Meteorological Administration since 2002. These public alerts advise vulnerable individuals—the elderly, people with respiratory illnesses and children—to restrict any activity outdoors. Since exposure to air pollution during pregnancy has a significant negative impact on birth weight, the gestation time of the baby and the chances that a newborn is underweight, pregnant women are advised to close windows and stay indoors, and to wear protective masks if necessary. One study [88] showed how these public notifications during Yellow Dust Events have mitigated the adverse effects of atmospheric dust on infant health in Korean cities. In the USA, National Weather Service dust storm warnings were found to partially offset reductions in well-being associated with dust storm event days [11]. The same author also found strong evidence that dust storms in the USA were associated with violent crime but concluded that avoidance behaviors in response to dust storm warnings could largely mitigate the observed impacts of violent crime [10].

Building resilience to SDS also requires investment in longer-term DRR measures, which come in a variety of forms. One of these is contingency planning, a management procedure that assesses disaster risks to determine in advance arrangements that will mitigate the negative impacts of disruptions. A contingency plan is therefore a proactive approach to risk management in the sense that it seeks to minimize loss rather than respond to it.

Contingency plans for SDS are few and far between, but an example for pastoralists is shown in Table 3, which has been adapted for wider applicability from a case study developed for use in Mongolia [89]. The measures and actions proposed are designed to minimize the harmful impacts of SDS events on pasture, livestock and herder communities. They are for use at local levels, but these plans should be linked to higher-level strategies, including provincial and national development plans and other policies for sustainable land and water management, agricultural development, DRR and economic development [90]. A first attempt to develop a contingency plan for SDS risk reduction in agriculture (cropland and rangeland) in Iran has been made for a county in Khuzestan province [91]. The study also assesses how the SDS risk can be managed by appropriate policy and discusses options for integrating SDS at national and regional levels into multi-hazard DRR and disaster risk management strategies or sectoral development programs.

Table 3. District and subdistrict level activities to counteract SDS occurrence and impacts in herder communities (after [89]).

SDS Mitigation Activity	Timing	Responsibility
Plan and implement measures to prevent overgrazing of pastureland	2–3 years	Local/national government and leaders of herder groups
Organize awareness raising among herders to invest part of livestock income in risk preparedness activities	Annually	Agriculture unit, veterinary unit, herder groups
Provide herders and citizens with official information on SDS and related hazards (drought, land degradation), assess potential risks and ensure that herders take preparedness measures	When needed	Emergency commission?
Insure livestock and property	When possible	Herder households and absentee herd owners
Take and enforce decisions on receiving SDS early warning information	When needed	Emergency commission?
Develop rules for circulating SDS warning information and update with lessons learned		Emergency commission?
Promote use of mobile phones equipped with global positioning systems to herders and provide simple handouts on their use		Emergency commission?
Ensure that camels and off-road vehicles are ready and available to search for lost livestock	When needed	Herder households and absentee herd owners
Identify and map leeward places where livestock that have gone downwind can be kept and inform herders about how these places are reached	When needed	Emergency commission?, herder households and absentee herd owners
Keep livestock on nearby pastures or in shelters as soon as SDS warning is received	When needed	Herder households and absentee herd owners
Promptly access information about unexpected changes in wind speed and direction and visibility and deliver it to appropriate persons	When needed	Herder households and absentee herd owners
Promptly notify authorities/emergency commission if any person is lost	When needed	Herder households and absentee herd owners
Promptly organize searches for lost people and livestock	When needed	Emergency commission?, herder households and absentee herd owners
Take immediate measures to bury or destroy dead livestock carcasses	When needed	Veterinary unit, herder groups, herder households, absentee herd owners
Estimate SDS damage and loss	Annually	Herder households, absentee herd owners, local/national government, insurers' agents

Encouraging individuals and groups to adopt such measures and actions depends in large part on their perception of the risk. Many studies have shown that risk perception is the primary driver of preparedness actions: high risk perception leads to personal preparedness and hence to behavior that mitigates the risk. However, the risk perception influence is not always direct and positive [92]. An examination of this 'risk perception paradox' indicates that an individual's risk perception of natural hazards is primarily determined by their personal experience of the hazard and trust (or lack of trust) in authorities and experts, albeit with many intervening factors. The findings of this review [93] suggest that enhancing the awareness of potential disasters and building trust in public authorities are best achieved by participatory exercises such as workshops, in which all groups can learn from each other. Such public participatory engagement can also result in citizens taking more personal responsibility for protection and disaster preparedness, as has been the case in examples of droughts [94] and floods [95].

7. Governance for Disaster Risk Management and Reduction

Effective disaster risk management requires strong governance frameworks to guide and catalyze the technical and non-technical measures outlined in Section 2 to Section 6. Given the composite nature of SDS hazards, and the links between SDS and other risks (e.g., drought, desertification), it is most appropriate to integrate SDS into existing multi-hazard risk management frameworks, including laws, policies, plans and strategies. In this regard, the key instrument guiding policy is the Sendai Framework, the overarching goal of which is to reduce substantially 'disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and economic assets of persons, businesses, communities and countries' [38]. It is, therefore, critical in guiding policies designed to prevent and mitigate SDS impacts and to ensure timely prediction, preparedness, early warning and responses to SDS events.

The framework required for a unified, coordinated cross-sectoral approach to impact (and indeed source) management is summarized in Figure 7. This framework is structured around three core groups:

- Authorities, agencies and institutions tasked with establishing SDS risk management policies and implementing plans covering risk reduction, preparedness, warning and response;
- Academic and scientific research communities;
- The communities affected by SDS.

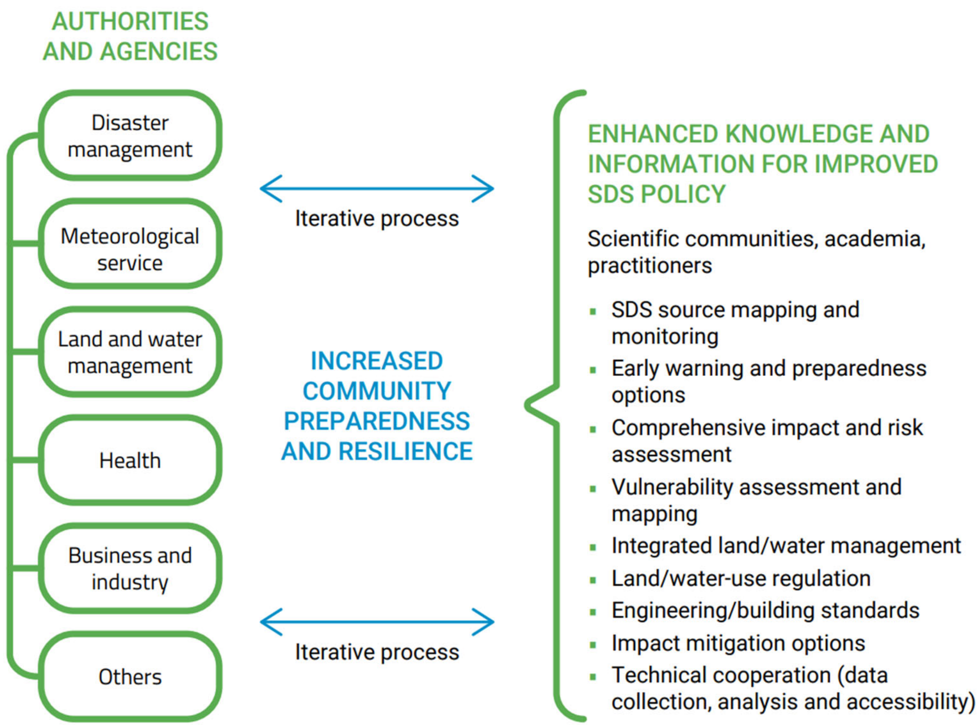

Figure 7. Framework for SDS risk management coordination and cooperation [48].

The process is iterative, as Figure 7 indicates: policies and activities to reduce SDS impacts are developed and improved by continual exchanges between the three core groups. To be most effective and supportive to all those at risk, the process should also consider the gender, age and health status of the individuals and communities impacted by SDS, who should be directly empowered to reduce the SDS risk. The success of this framework will depend on many factors and contexts, including the diversity of the cultural, socioeconomic and livelihood circumstances, as well as the environmental conditions (e.g., hydro-meteorological, topographical, soil characteristics) in different geographical areas. The importance of adjusting technical solutions for DRR and disaster response to specific contexts is emphasized in a recent overview of the politics of disaster governance [96] that highlights how the technical solutions are intimately reliant upon socio-technical, political and administrative systems and processes. For example, a study of the challenges in communicating flood early warnings to vulnerable people in Nepal found several governance issues to be important, including poor coordination among relevant agencies, a shortage of adequate personnel, limited budgets and unclear roles and responsibilities [97].

8. Conclusions

Sand and dust storms occur frequently in the world's drylands, and their significant impacts on society are felt in the drylands and beyond. Decades of scientific research on SDS provide a solid knowledge base for managing their adverse socioeconomic effects, but many of the disaster risk management aspects of this issue are not well understood. This situation undermines society's efforts to tackle SDS hazards and the risk reduction and mitigation responses of the bodies responsible for policy. The urgency of developing appropriate responses is highlighted by climate change projections that indicate more frequent and intense SDS emissions due to increased aridity and deteriorating drought conditions (greater frequency, severity and duration).

This paper highlights case studies and good practice examples of the measures available to reduce the risks and impacts associated with SDS. As far as we are aware, this is the first attempt to gather together a comprehensive set of impact mitigation measures for SDS hazards. These measures, which are interrelated and complementary, include short-term responses and long-term resilience-building activities. In certain cases, some evidence for their effectiveness in mitigating the SDS risk is available (e.g., for warnings issued to people vulnerable to medical effects) but, for most measures, support for their efficacy comes from similar techniques used to mitigate the adverse effects associated with other hazards. In all cases, further empirical research and data analysis are needed to verify the effectiveness of the proposed measures for SDS hazards.

In combination with source mitigation activities, the impact mitigation measures outlined here provide a comprehensive approach to managing the potential disaster risks that SDS pose at local and regional levels. Building resilience to SDS will be an iterative process, one that will benefit from the sharing and exchange of knowledge between countries on effective SDS policies and practices, not least because this is frequently a transboundary hazard.

Developing resilience to SDS hazards also requires strong governance frameworks to help catalyze technical and non-technical measures/actions at the local level, where context is particularly important. SDS should be addressed as part of national multi-hazard strategies for disaster risk management and reduction linked to the Sendai Framework and the 2030 Agenda for Sustainable Development.

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